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A Novel Design of Cantilever RF MEMS Series Switch

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Abstract: *This paper presents novel design of various configurations of cantilever type Radio Frequency Micro Electro Mechanical Systems (RF MEMS) Series Switch. The paper emphasizes on study of Actuation Voltage of RF MEMS switches. Actuation voltages of uniform cantilever switches has been compared with cantilever switches supported on three bars (non-uniform switch) for various geometric configuration and material properties. It is observed from the simulation results that reduction in actuation voltage as high as 5V can be achieved by reducing the anchorage width. Also, use of mica with higher dielectric constant over silicon nitride as dielectric layer yields considerable reduction in actuation voltage.*

Keywords**:** *Actuation Voltage, Anchorage, Cantilever Switch, RF MEMS*

I. Introduction

In the last decade, several new technologies have come to the forefront and have made their mark in the field of Electronics & Telecommunication Engineering. One such technology that has captured interests and is extremely popular among designers across the globe is Micro Electro Mechanical Systems (MEMS). MEMS combine the advantages of mechanical switches and semiconductor switches and thus finds a wide range of applications. RF MEMS switch can be described as an integrated device which uses micromechanical movement to achieve a short circuit or open circuit in the RF transmission line.

RF MEMS switch can be used as the basic building block in RF communication system. As a key circuit element in the field of microwave control, RF MEMS switch has wide application in phase arrays and configurable apertures for defense and telecom systems, switching networks for low power applications etc [4]. The basic beam type for the switch can be a cantilever beam or a fixed-fixed beam. A cantilever beam is fixed at one end and the other end of the beam is free. The fixed-fixed beam is one in which both the ends of the beam are fixed. As the actuation voltage is applied to the top & bottom electrodes, the electrostatic force developed causes the mechanical movement of the beam to enable switching action. This assembly can be used to design an entire switch structure on a substrate with associated electrodes, bias lines, anchors, materials etc. for respective applications.[5]

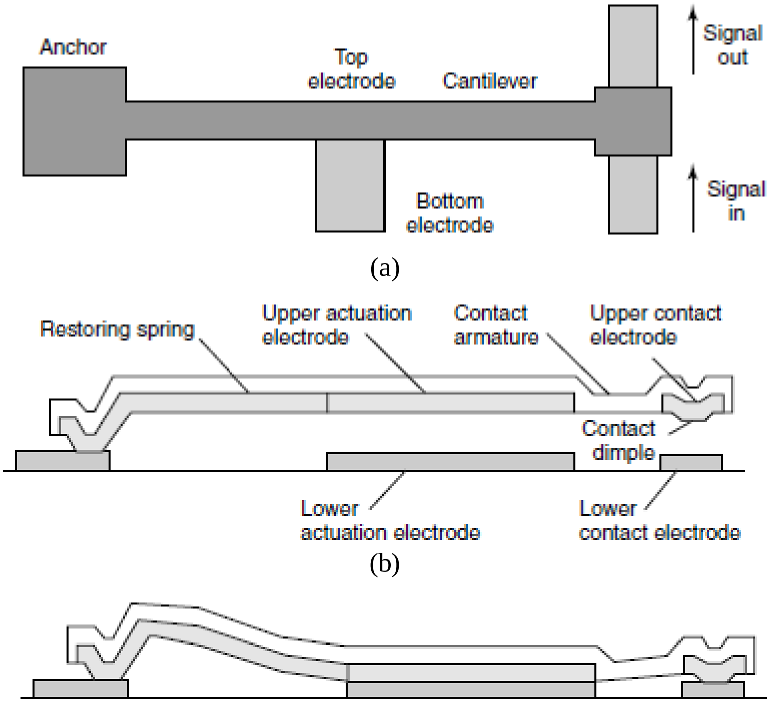
For effective implementation and further enhancement, RF MEMS switches need to overcome issues of higher actuation voltages, stiction, switching time and power handling capacity. This paper emphasizes on study of Actuation Voltage for various configurations of RF MEMS switch. COMSOL Multiphysics Software has been used for simulation of MEMS switches. The paper provides path forwards in reduction of Actuation Voltages for RF MEMS switches and encourages designers to provide innovative solutions to overcome other challenges of RF MEMS switches.

The subsequent modules in this paper provide an Introduction to RF MEMS Cantilever Switch, Design Parameters to be considered in switch design, Switch Configurations presented in this paper, followed by Simulation Results and lastly the Conclusions derived from the case studies performed.

II. RF MEMS Series Cantilever Switch

Series switch and shunt switch are the two basic switches used in RF to millimeter-wave circuit design. The ideal series switch results in an open circuit in the transmission line when no bias voltage is applied (up-state position), and it results in a short circuit in the transmission line when a bias voltage is applied (down-state position). “Fig.1” shows series cantilever switch in “On” State and “Off” State position.

Ideal series switches have infinite isolation in the up-state position and have zero insertion loss in the down-state position. MEMS series switches are used extensively for 0.1 to 40-GHz applications. They offer high isolation at RF frequencies, around -50 dB to -60 dB at 1 GHz and rising to -20 to -30 dB at 20 GHz. In the down-state position, they result in very low insertion loss, around -0.1 to -0.2 dB at 0.1 to 40 GHz.[5]



(a) (b) (c)

Fig. 1 (a) Schematic view of cantilever series RF MEMS switch (b) Off-state switch position (c) On-state switch position [6]

III. Design Parameters

The switch design begins with selection of actuation technique. Different parameters to be considered in the design of RF switches are Transition Time, Switching Rate, Switching Transients, RF Power handling, Bandwidth, Insertion Loss, Isolation, Series Resistance, Actuation Voltage, Lifecycle, Resonant Frequency, Interception and Level of Distortion, Phase and Amplitude tracking. This paper aims at reduction in actuation voltage for uniform and non-uniform switch configuration. The actuation voltage of MEMS Switches can be written as:

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

Where, k is the spring constant of cantilever beam, ε_0 is permittivity of free space, g_0 is beam height and A is area of pull down electrode.

Thus, to reduce the actuation voltage designers can either reduce the spring constant of beam or reduce the gap height or increase the area of electrodes. However, reduction in gap height shall compromise the isolation aspect and RF performance parameters.

Reduction in spring constant of cantilever beam can be achieved by using low density material, by increasing the cantilever length of beam, by using lesser thickness of beam or by reducing the anchorage width. For miniature switch design increasing beam length is definitely not preferable. The parameter ‘A’ in (1) represents effective field area and can be maximized by increasing length of pull down electrode.

IV. Switch Configuration

Two distinct geometric configurations of the cantilever beam have been considered in the simulation design: Uniform Cantilever Beam, Cantilever beam supported on three bars at anchor location (Non-uniform beam) as shown in “Fig. 2”.

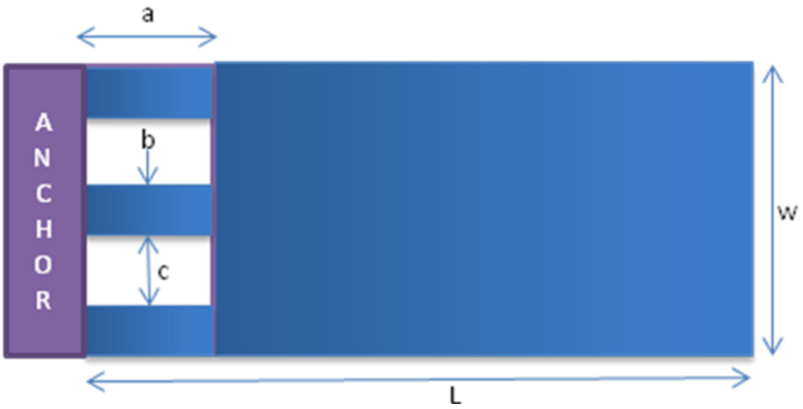


Fig. 2 Plan of cantilever switch supported on three bars at anchor location

Beams of varying material properties and geometric properties were considered to minimize the Actuation Voltage. “Table 1” and “Table 2” provide detail of beam configurations considered in simulation.

Table 1 Non-Uniform cantilever switch configurations

Study No	Non-Uniform Cantilever Switch		
	Top Electrode	Bottom Electrode Length	Dielectric Material
Study 1	L:140µm, w: 60µm. Material Gold, a: 20µm, b: 10µm, c: 15µm.	60µm	Silicon nitride (ε = 7)
Study 2	L:140µm, w: 60µm. Material Gold, a: 20µm, b: 10µm, c: 15µm.	75µm	Silicon nitride (ε = 7)
Study 3	L:140µm, w: 60µm. Material Gold, a: 20µm, b: 10µm, c: 15µm.	95µm	Silicon nitride (ε = 7)
Study 4	L:140µm, w: 60µm. Material Gold, a: 20µm, b: 10µm, c: 15µm.	75µm	Mica (ε = 6)
Study 5	L:140µm, w: 60µm. Material Gold, a: 20µm, b: 10µm, c: 15µm.	95µm	Mica (ε = 6)
Study 6	L:140µm, w: 60µm. Material Gold, a: 20µm, b: 10µm, c: 15µm.	95µm	Mica (ε = 9)
Study 7	L:140µm, w: 60µm. Material Gold, a: 20µm, b: 10µm, c: 15µm.	60µm	Mica (ε = 9)

Table 2 Uniform cantilever switch configurations

Study No	Uniform Cantilever Switch		
	Top Electrode	Bottom Electrode Length	Dielectric Material
Study 8	L:140µm, w: 60µm. Material Gold.	60µm	Silicon nitride (ε = 7)
Study 9	L:140µm, w: 60µm. Material Gold.	75µm	Silicon nitride (ε = 7)
Study 10	L:140µm, w: 60µm. Material Gold.	95µm	Silicon nitride (ε = 7)
Study 11	L:140µm, w: 60µm. Material Gold.	75µm	Mica (ε = 6)
Study 12	L:140µm, w: 60µm. Material Gold.	95µm	Mica (ε = 6)
Study 13	L:140µm, w: 60µm. Material Gold.	95µm	Mica (ε = 9)
Study 14	L:140µm, w: 60µm. Material Gold.	60µm	Mica (ε = 9)

V. Simulation Results

Case-1 Non-Uniform Beam Simulation Results

The basic geometric configuration (Study 1) of non-uniform MEMS switch (Cantilever switch supported on three bars) presented in this paper is referred from conference paper [1]. Several case studies have been further developed by varying the geometric and material properties for the MEMS switch.

The non uniform beam has a low spring constant of $3.37N/m^2$ [1]. Low Spring constant of beam leads to low actuation voltage. Comsol Multiphysics software is used to simulate the RF MEMS cantilever switch. Table 3 provides the simulation results of non-uniform beam cantilever switch.

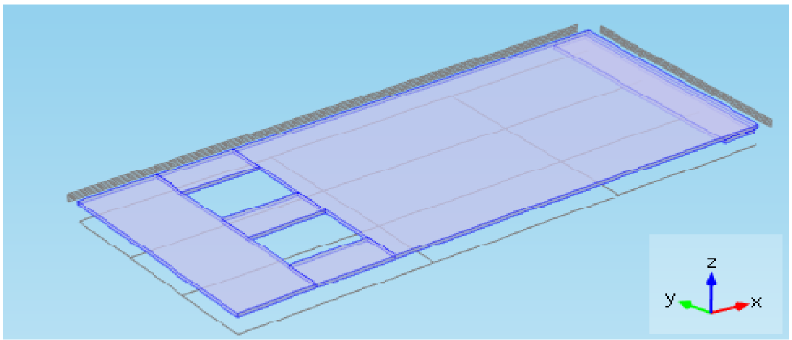
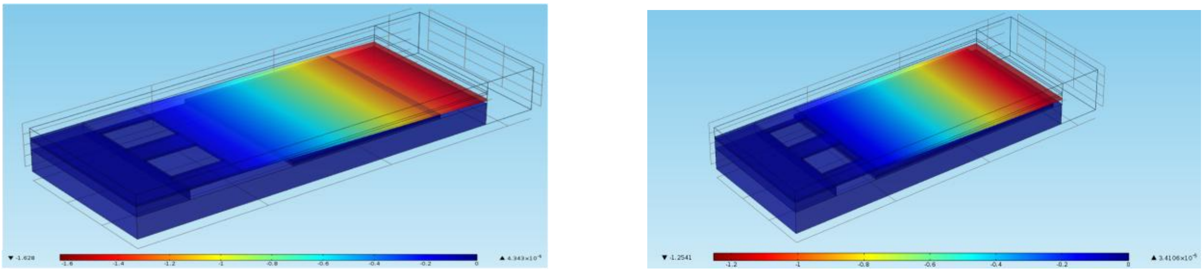


Fig. 3 Simulation schematic of cantilever switch supported on three bars at anchor location

Table 3 Actuation voltage for non-uniform cantilever switch configurations

Study No	**Non-Uniform Cantilever Switch**		
	Bottom Electrode Length	**Dielectric Material**	**Actuation Voltage**
Study 1	60μm	Si3N4 (ε = 7)	17.2V
Study 2	75μm	Si3N4 (ε = 7)	17.6V
Study 3	95μm	Si3N4 (ε = 7)	13.3V
Study 4	75μm	Mica (ε = 6)	17.9V
Study 5	95μm	Mica (ε = 6)	13.5V
Study 6	95μm	Mica (ε = 9)	12.9V
Study 7	60μm	Mica (ε = 9)	17.0V



(a) (b)

Fig. 4 (a) Study 1 Deflection - Actuation Voltage 17.2V (b) Study 6 Deflection - Actuation Voltage 12.9V

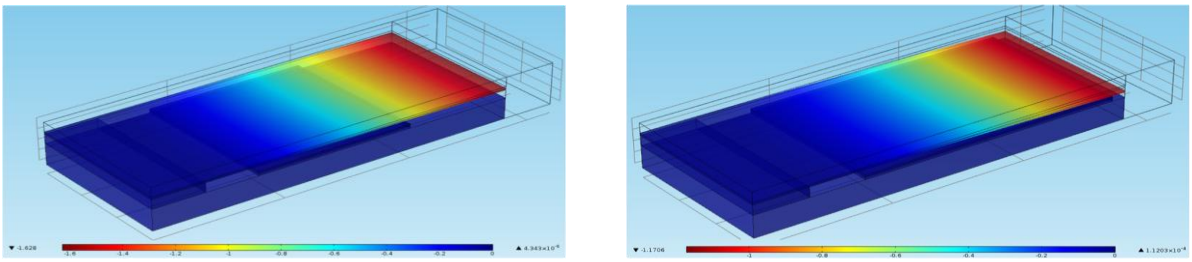
"Fig. 4" and "Fig. 5" present the Comsol Multiphysics Ssoftware simulation results for non-uniform and uniform beam RF MEMS switch respectively. The alumina material is used for substrate to achieve a good RF performance because of low loss of alumina with dielectric constant 9.9 and for beam Gold material is used because of its properties like young's modulus is 79GPa, density is 19300 and it has low compressive residual stress.

Case-2 Uniform Beam Simulation Results

A uniform cantilever beam made of gold has been considered for simulation using COMSOL Multiphisysics software. Table 4 presents the simulation results for uniform cantilever switch for various configurations.

Table 4 Actuation voltage for uniform cantilever switch configurations

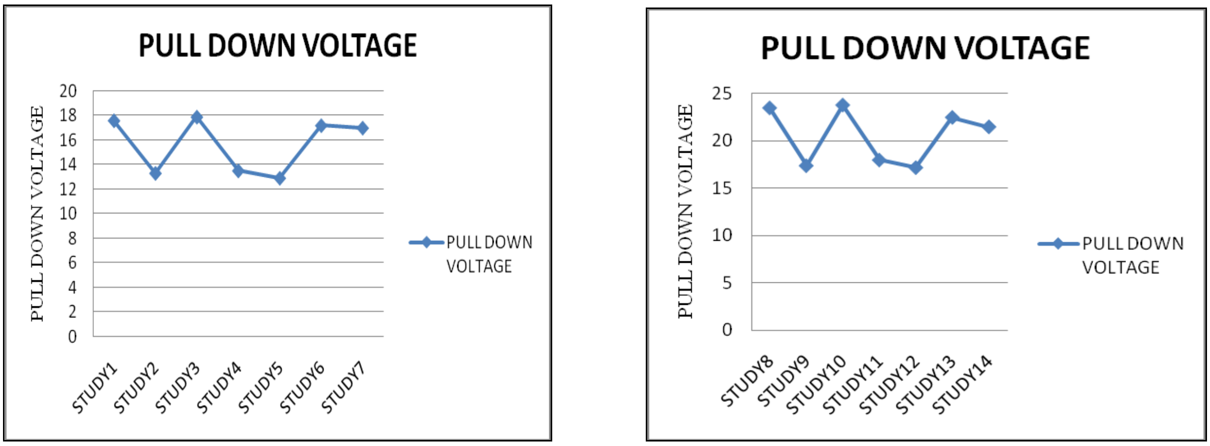
Study No	**Uniform Cantilever Switch**		
	Bottom Electrode Length	**Dielectric Material**	**Actuation Voltage**
Study 8	60μm	Si3N4 (ε = 7)	22.5V
Study 9	75μm	Si3N4 (ε = 7)	23.5V
Study 10	95μm	Si3N4 (ε = 7)	17.4V
Study 11	75μm	Mica (ε = 6)	23.8V
Study 12	95μm	Mica (ε = 6)	18.0V
Study 13	95μm	Mica (ε = 9)	17.2V
Study 14	60μm	Mica (ε = 9)	21.5V



(a) (b)

Fig. 5 (a) Study 8 Deflection - Actuation Voltage 22.5V (b) Study 13 Deflection - Actuation Voltage 17.2V

The actuation voltage for uniform switches is observed to be higher than non uniform switches of similar configuration by approximately 5V. “Fig. 6” and “Fig. 7” provide graphical representation of simulation results obtained for various case studies.



(a) (b)

Fig. 6 (a) Actuation voltages of non-uniform beam with different configurations (b) Actuation voltages of uniform beam with different configurations

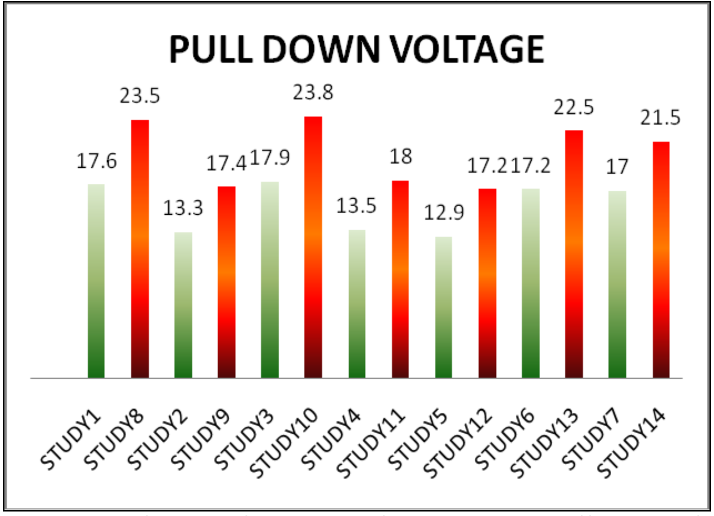


Fig. 7 Comparisons of non-uniform and uniform beam with different configurations

VI. Conclusion

Novel uniform and non-uniform cantilever switches were presented. Geometric parameters and dielectric material were varied to study the effect on actuation voltage of RF MEMS series cantilever switch. Actuation voltage as low as 12.9V could be obtained for non-uniform switch by using Mica as dielectric material with $\varepsilon = 9$ and by adopting 95µm length of bottom electrode. Owing to higher stiffness actuation voltages for uniform switches is observed to be higher than non-uniform switches of similar configuration by approximately 5V. Minimum actuation voltage of 17.2V could be obtained for uniform switch (Study 13) as compared to 12.9V for non-uniform switch with similar configuration.

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