Design and Electromechanical analysis of Shunt configuration-based RF MEMS Switch for Tunable filter applications

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Abstract

This paper gives an overview of Radio Frequency Micro Electromechanical Systems (RF MEMS) shunt switch design and electromechanical analysis. The performance, efficiency and reliability of the switch structure depends on numerous factors. The materials used in various layers of switch like beam, dielectric is varied along with the thickness and width of both beam and dielectric. The comparisons are made regarding the performance of the switch for different materials, thicknesses, and widths. The switch which is giving lower displacement for the applied voltage is selected which will result in better performance from the above combinations. The designed shunt switch's electromechanical performance like pull-in voltage, switching time, upstate and downstate capacitance are analyzed using FEM analysis

Introduction

The new MEMS technology is the base that enabled the event of mechanically strong, high-performance switch designs. The design process was crucial in delivering reliable long-life MEMS switches. Basically, there are two types of switches supported by RF MEMS. From them, a Series switch may break the signal conductor which results in an open circuit or it makes the signal conductor flow from metal to metal contact. A shunt switch either short the signal conductor to the ground conductor that is a short circuit or leaves them unconnected allowing the signal to pass. The series switch is most suited for lower frequency operations between 0-30GHz. Whereas the capacitive shunt switch is used for the high frequency of operation that is from 15-100GHz.Other than RF MEMS switches the other switches used are PIN diodes or FET switches [7].

Some Drawbacks of PIN diodes or P-HEMT switches now RF MEMs switches diligently using in smartphones, Laptops. Several industrial and university groups have been Seriously working on Development of RF MEMS switches [19, 20]. The benefits of RF MEMS switches over the other are low insertion loss, high isolation loss and low power consumption [11, 19, 20]. As the power consumption is low the cost for the device is reduced and increase in the efficiency. The MEMS Switches thus offer high isolation and compact device size, so the size of the circuit is small.

This RF MEMS shunt switch consists of a dielectric layer over which a very thin mechanical bridge is suspended as shown in Fig. 1. When a voltage larger than the pull-in voltage is applied across the switch, the bridge will collapse over the dielectric which increases the capacitance of the device. For the shortening of the switch, electrostatic force is responsible which allows the flow of current to achieve high performance within the MEMS.

Some RF MEMS switches are already proposed with different structures [16–18]. In this paper impact of materials, width, and thickness of various layers of switch structure on the electromechanical analysis is done. Firstly, we design and simulate a shunt capacitive switch and study the behavior on a substrate made of high resistivity silicon. Various materials of the switch were chosen very rigorously [6]. For the designed fixed-fixed beam switch or shunt capacitive switch, Modeling equations are derived. The design of the switch is carried out with the parameters mentioned in a tabular column and plotted the voltage Vs displacement graphs by changing the combination of materials for different layers.

Device Structure And Its Working Principle

Initially, a substrate with silicon material is placed with the dimensions of length 500μm, 500μm width and 20μm thickness. The substrate provides mechanical and electrical support to build further layers. An oxide layer of thickness 10μm is placed on the substrate, which helps to avoid the metal-metal contacts between the other layers. The three lines in the CPW transmission are Ground (G), Signal (S) and Ground (G) lines (140μm/100μm/140μm). Shunt Capacitive switches require high capacitance in the actuated areas as a very thin dielectric is needed over signal line and fixed metal electrodes to have a repeatable capacitance, to reduce the negative effects caused by the deformation of membrane induced by stress [3]. Anchor left and right is placed on oxide layer with width 40 μm, length 100 μm and height 1.1 μm and there formed a beam on the anchors with width 300 μm, depth 100 μm and height 0.5 μm.

Table .1 Proposed switch dimensions

S. No	Component	Width (μm)	Length (μm)	Depth (μm)
1	Substrate	500	500	20
2	Substrate Dielectric	500	500	10
3	Left Ground	140	500	15
4	Right Ground	140	500	15
5	Signal line	100	500	15
6	Dielectric	100	300	0.1
7	Left Anchor	40	100	1.1
8	Right Anchor	40	100	1.1
9	Beam	300	100	0.5
10	Square hole	10	10	0.5

In the RF MEMS switch, there are two important components that play a vital role. They are metal beam and bottom electrode for electromagnetic actuation and electrostatic actuation respectively. Membrane not only determine the operation frequency and pull-down voltage, but also it is the cause for many failure mechanisms within the shunt switch. The membrane should be robust for restoring force to overcome the friction, so the switch performs precise operation. The membrane is mechanically connected to the electrode using the anchors [1].

After the membrane is developed, the holes are added so that they help to improve the performance of the switch. A thin metallic bridge which is fixed at both the ends is suspended over the conductor and the ground of the CPW line is consisted by the switching element. The holes are formed depending on beam thickness and having width 10m, depth 0.5m and length 10m. As the number of holes increases then the pull-in-voltage decreases. As the considered type of switch is a shunt, initially CPW line is connected and at the end of the membrane there is a metal plane.

When this applied voltage increases periodically, after a certain time the value of applied voltage because of the spring constant of the material is greater in magnitude than the restoring force which is exerted by the anchor. In case of switch ON state, for the applied voltage, electrostatic force dominates over the restoring force, which pulls the beam towards the electrode, providing a path for the signal to move from input to the output. In case of OFF state, the top metal layer forms coupling of capacitances between the ground and the signal. Here the membrane performs as a dielectric. Because of this, RF signal, instead of travelling to the output port, it gets bypassed through the ground [12].

Results And Discussions

3.1. Electromechanical performance analysis without holes

When there are no holes in switch designed, obtained displacement is 2.04×10^{-6} μm for the applied actuation voltage is 10 volts.

3.2. Electromechanical performance analysis with holes

When there are holes in the design of the switch, then the displacement obtained is 2.03×10^{-6} μm for the applied voltage of 10V, which is less than the displacement obtained when there are no holes. From which it is understood that holes play a major role in improving the performance of the switch. As the number of holes increases up to a limited number, pull in voltage decreases and the switching time is also decreased. Due to the presence of square holes in the switch structure, damping effect is also reduced [4]. Above theory is observed from the figures So the further simulations and observations are carried out on the switch with holes for better performance results.

3.2.1. Pull in voltage

When the electric field is exerted on the electrode, the electrostatic force is exerted upon the beam. The applied electric field is what the working of the cantilever predominantly dependent on. The spring constant is given by the equation

$k = \frac{w\epsilon t^3}{l^3}$ (1) Where,

K is Spring Constant

l is Length of the beam

W is Beam Width

t is Thickness of the Beam

E is Young's modulus

Pull in voltage is given by the equation,

$$v_p = \sqrt{\frac{8kg_o{}^3}{27\epsilon_o A}} \quad (2)$$

Here the actuation voltage is V. A is the area between beam and electrode. The spring constant is K. As the voltage which is applied increases uniformly, the electrostatic force that is developed on the membrane will be increased which will tend to pull down the beam towards the electrode. This eventually decreases the gap that is present in between the beam and the electrode. When the original gap between the beam and the electrode fixed is reduced to two-third then that voltage is called the pull-in voltage [13].

A. Metal change

Effect of change in the material of the switch among gold aluminum, copper, and chromium on the performance of the switch is analyzed while keeping the dielectric material as silicon nitride. It is observed from the displacement vs. voltage graph obtained in COMSOL software that aluminum is having the best performance in the terms of displacement.

B. Dielectric material change

When the material used for the dielectric of the switch among generally used materials like silicon nitride, aluminum nitride, Hafnium dioxide, silicon dioxide, it is observed that the silicon nitride is giving optimum performance from the graph below, when the metal is fixed to aluminum.

C. Beam thickness change

When the thickness of the beam is varied among 0.5 μm,1 μm,1.5μm,2μm by keeping the metal as aluminum and dielectric as silicon nitride, it is observed that as the thickness of the beam is 0.5 μm, the displacement is low which gives the best performance.

D. Beam Width Change

When the width of the beam is varied between 100 μm,60 μm and 80 μm, it is observed from the graph by keeping the metal as aluminum and dielectric as silicon nitride, it is observed that as the beam width is 100 μm, the displacement is low which gives the best performance.

E. Dielectric Thickness Change

When the thickness of the dielectric is varied in between 0.1 μm ,0.3μm and 0.5 μm, it is observed from the figure that how the displacement is varied when a voltage of 10v is applied.

It is observed that as the dielectric thickness is 0.1μm, the displacement is low which gives the best performance when compared to 0.5 μm and 0.3 μm values, from which it can be concluded that the thickness of dilelectric is inversely proportional to the displacement[15] .

3.2.2. Up state (C_u) and Down state (C_d) Capacitance.

The structure is in UP state when the actuation voltage is not applied to the membrane. the capacitance of the shunt switch putting the device in OFF state. As the voltage for actuation is applied, the structures membrane starts moving downwards towards the electrode. This capacitance is called the downstate capacitance which allows the RF signal to pass, putting the device in ON state. By decreasing the upstate capacitance and increasing the downstate capacitance, RF MEMS switch performance can be improved [14]. The capacitance variation depends mainly on material chosen for dielectric. In this simulation, silicon nitride is considered.

The equation for upstate capacitance of the membranes

$$c_u = \frac{\left(\epsilon_\circ A\right)}{\left(g_\circ + \frac{t_d}{\epsilon_r}\right)} \quad (3)$$

Where,

ε_0 - the permittivity of the free space,

ε_r- the relative permittivity of the electrode material

A - the overlapping Area between electrodes,

g_0 - the gap between the electrodes and beam

t_d - the dielectric layer thickness electrodes

The equation for downstate capacitance of the membranes

$$C_d = \frac{\left(\varepsilon_0\ \varepsilon_r A\right)}{t_d}$$

4

The capacitance ratio which is referred as Cd/Cu tells about the device's capacitance sensitivity [6]. In this case the obtained capacitance ratio is 76.25. Hence, the results of capacitance of shunt membrane need to be in the range of upstate and downstate capacitance.

The shunt membrane is simulated by applying electro- mechanics physics using COMSOL tool.

3.2.3. Switching Time Analysis

For opening and closing any connection a switch is used. For fast processing speeds in electronic devices, the reduction in switching time is essential. It is the time required to achieve the touching of bottom electrode and beam structure. Switching time depends on source voltage, pull-in voltage and resonant frequency [9].

$[9]\;\; T_s = \frac{3.67 V_p}{\omega_0\, V_s}$ (5)

Where,

V_s is the input source voltage,

V_p is the pull – in voltage,

ω_0 is the resonant frequency,

The spring constant and effective mass of the membrane, is determine the resonant frequency

$$\omega_0 = \sqrt{\frac{k}{m}}$$

6

The switching response of the shunt membrane is 0.54 μs. The performance of the device increases when the switching time is minimized.

Conclusion

This paper gives a brief study regarding the electromechanical analysis of a shunt switch. This paper also gives an understanding of the impact of holes in the switch structure to improve performance. By assigning different metals to each layer of the switch structure, the effects on the performance of the switch are analyzed by comparing the combination of materials. From the above observations, it can be concluded that Aluminum (Al) for metals and silicon nitride (for a dielectric) gives the optimum results and good performance for the low pull-in voltage. The comparisons are also made by varying the thickness and width of beam and dielectric. It is observed that the dielectric and beam which is having less thickness of 0.1 μm and 0.5μm respectively are having less displacement when compared to the other thicknesses considered. The beam with widths 100μm which is higher than60 μm and80 μm is having less displacement. Switch parameters like switching time, pull in voltage, upstate and downstate capacitance are also simulated using FEM tool. The switch operating with less pull-in voltage of around 8V.

Declarations

Ethical Approval and Consent to participate: Not applicable

Human and Animal Ethics: Not applicable

Consent for publication: Not applicable

Availability of supporting data: Not applicable

Competing interests: Not applicable

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Authors' contributions: study conception and design: G.V.Ganesh. Author; data collection: P.Pardhasaradhi. Author; analysis and interpretation of results: N.Siddaiah. Author; draft manuscript preparation: G.V.Ganesh. Author. All authors reviewed the results and approved the final version of the manuscript.

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Figures

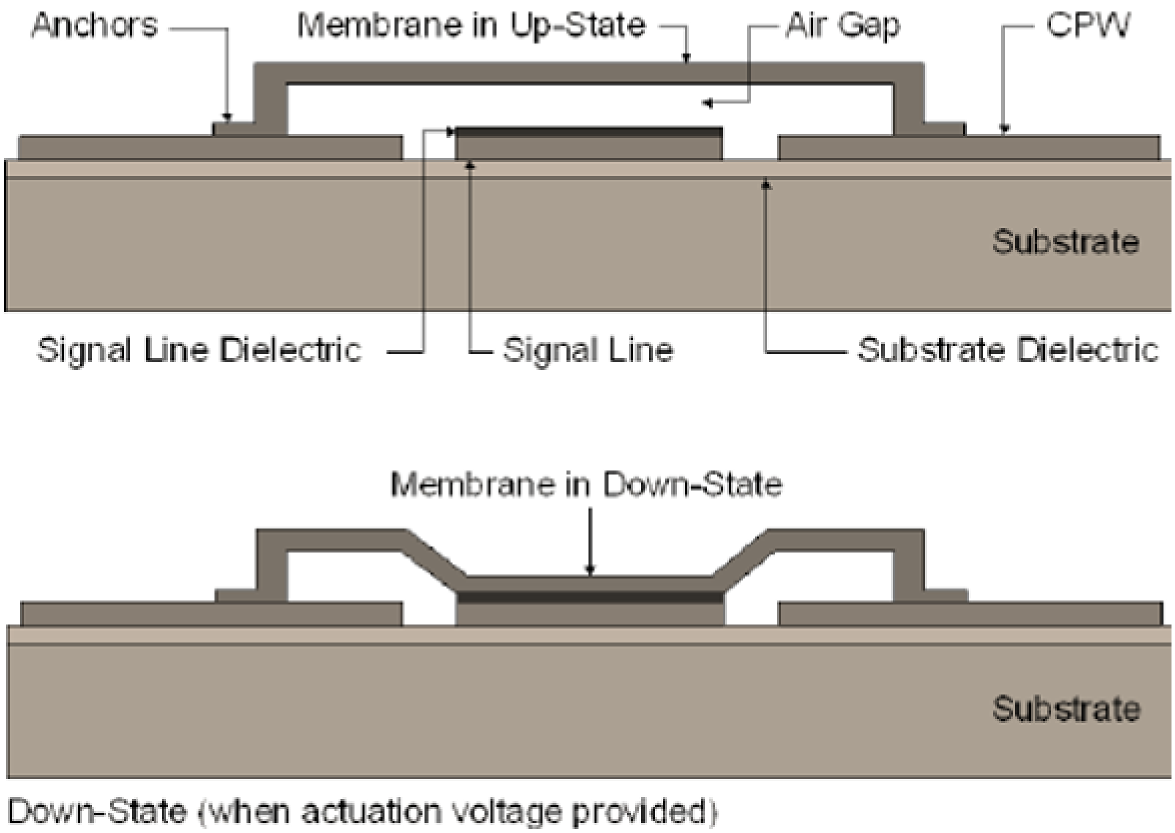

Figure 1

Shunt and series switch

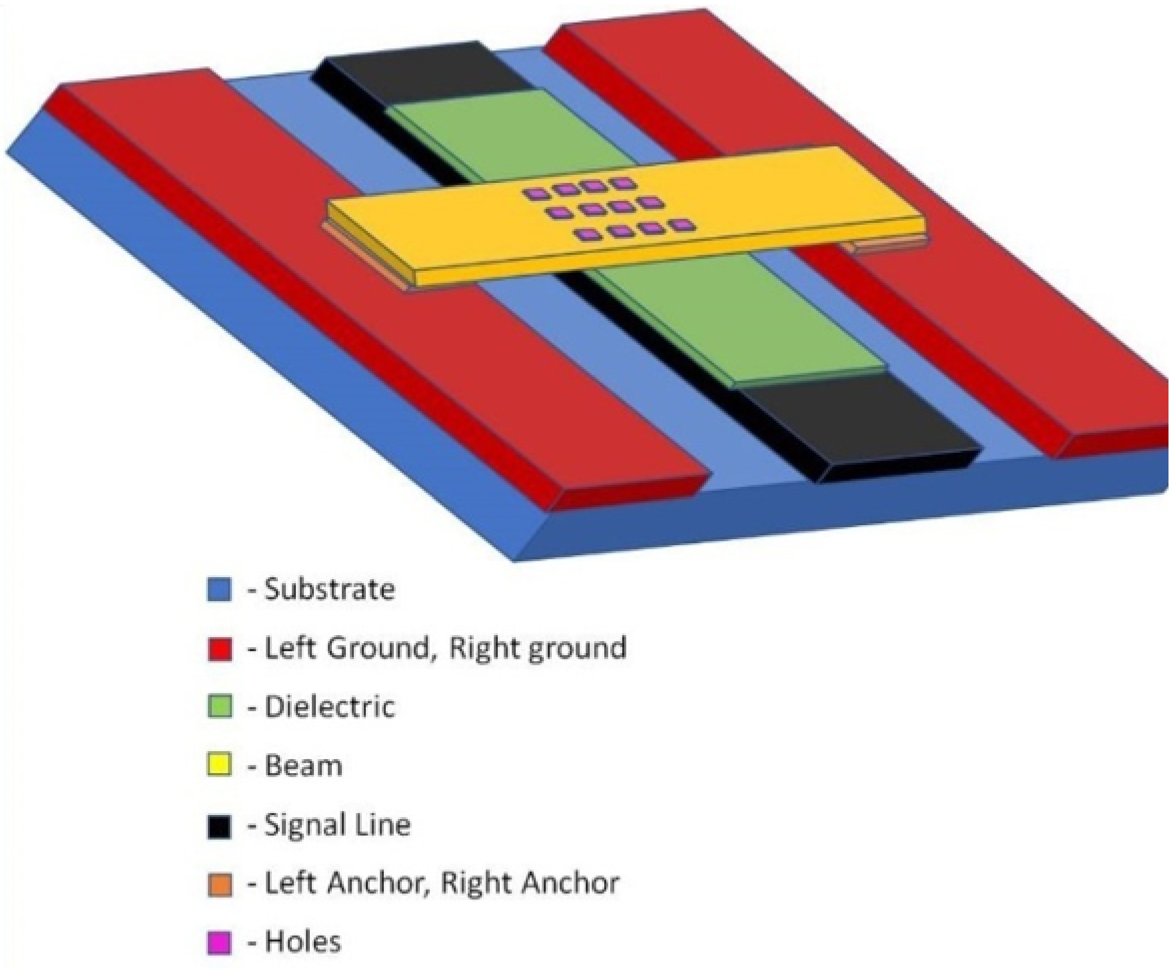

Figure 2

Proposed shunt switch structure

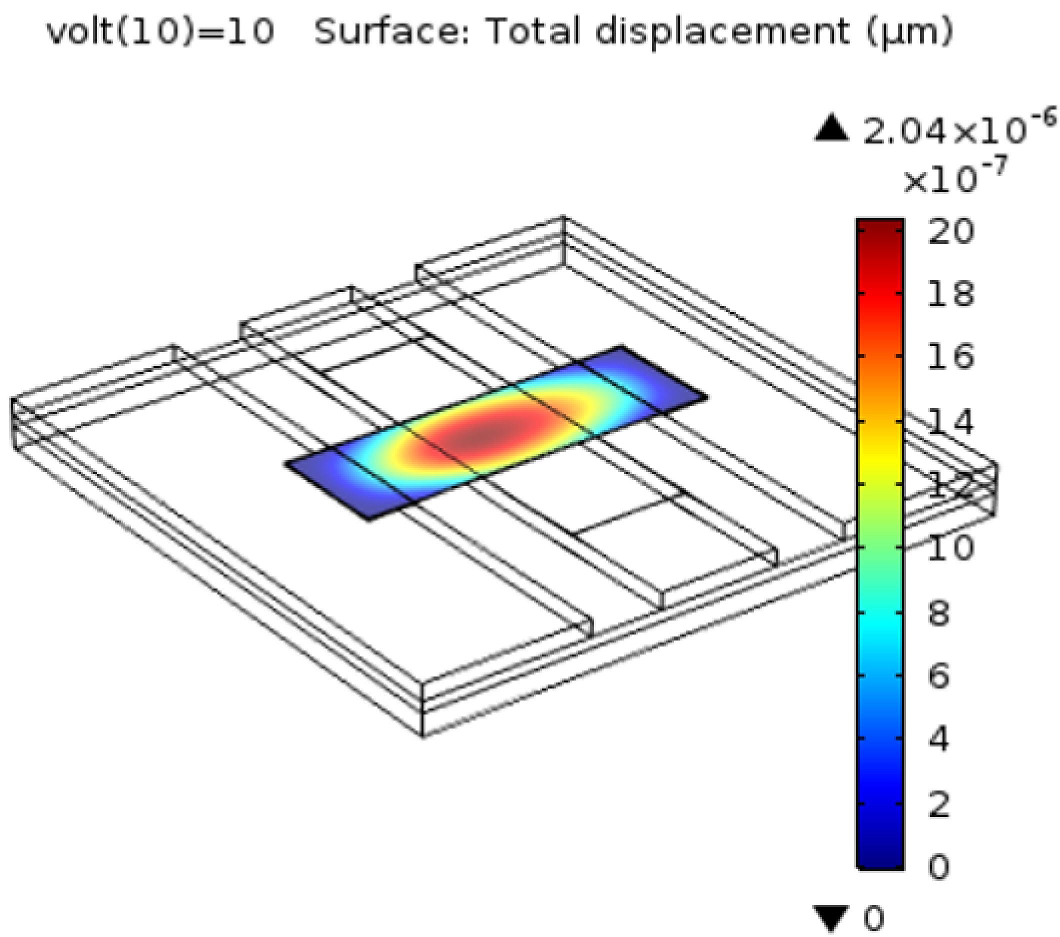

Figure 3

Maximum displacement of 2.04µm for applied voltage of 10v for the designed switch.

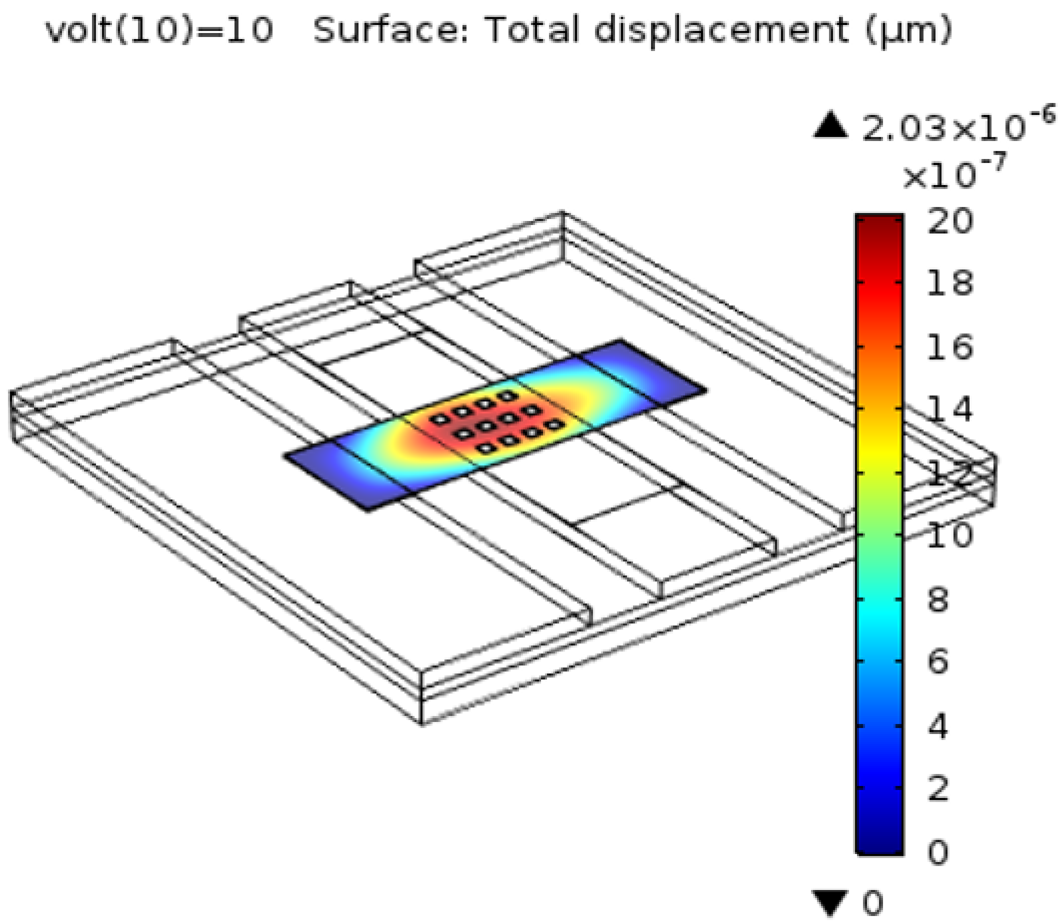

Figure 4

Maximum displacement of 2.03µm for applied voltage of 10v for the designed switch.

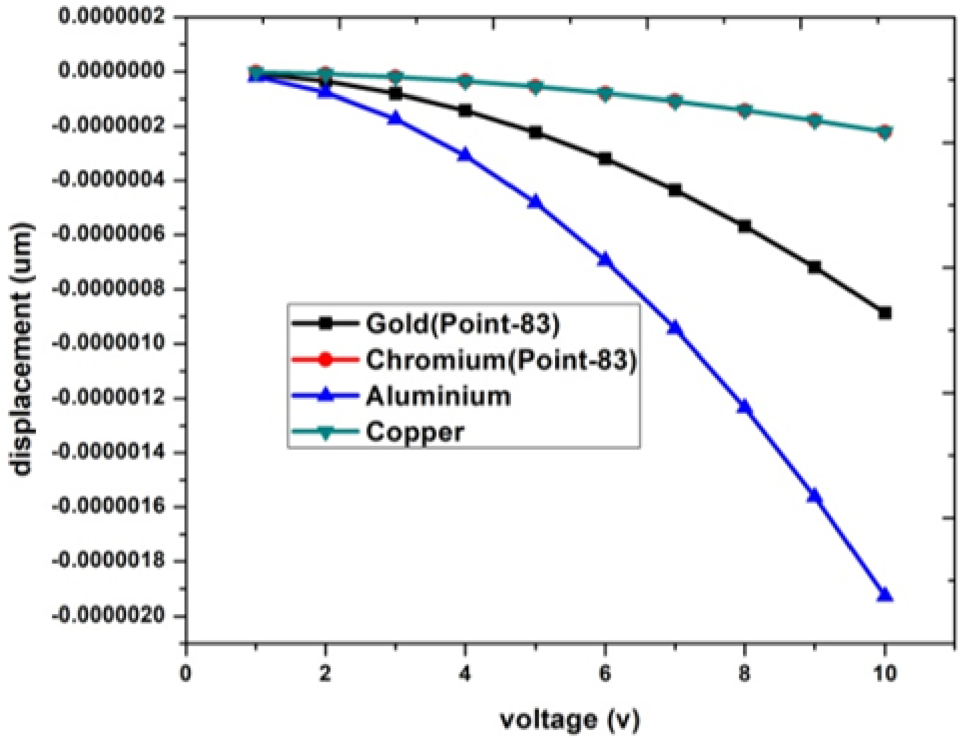

Figure 5

The performance of shunt switch membrane for different conductor materials.

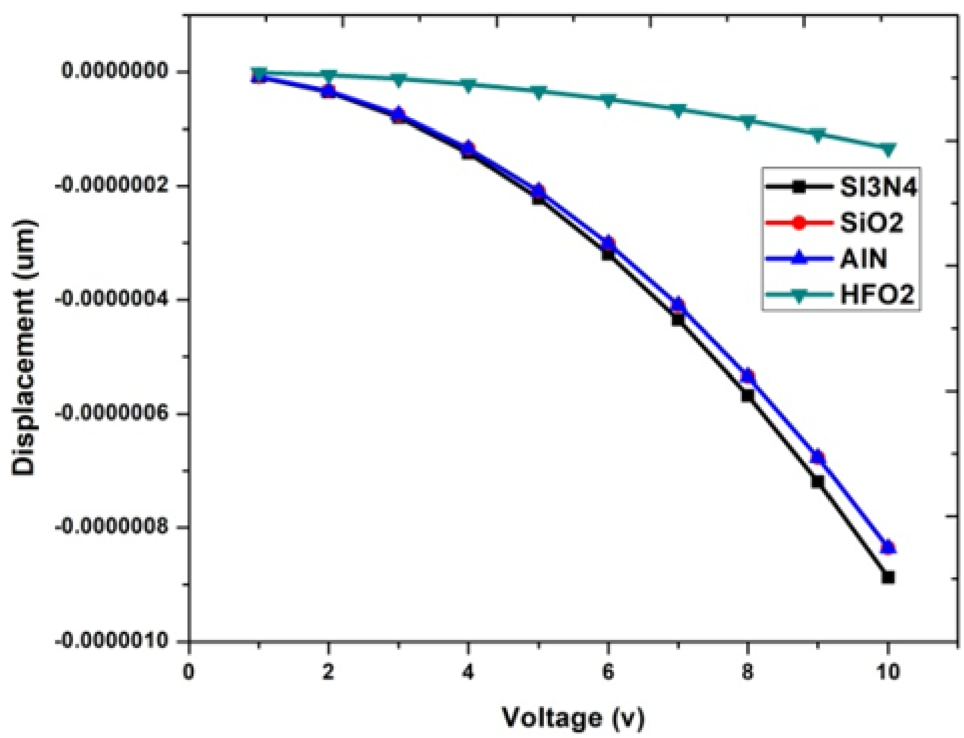

Figure 6

The performance of shunt switch membrane for different dielectric materials.

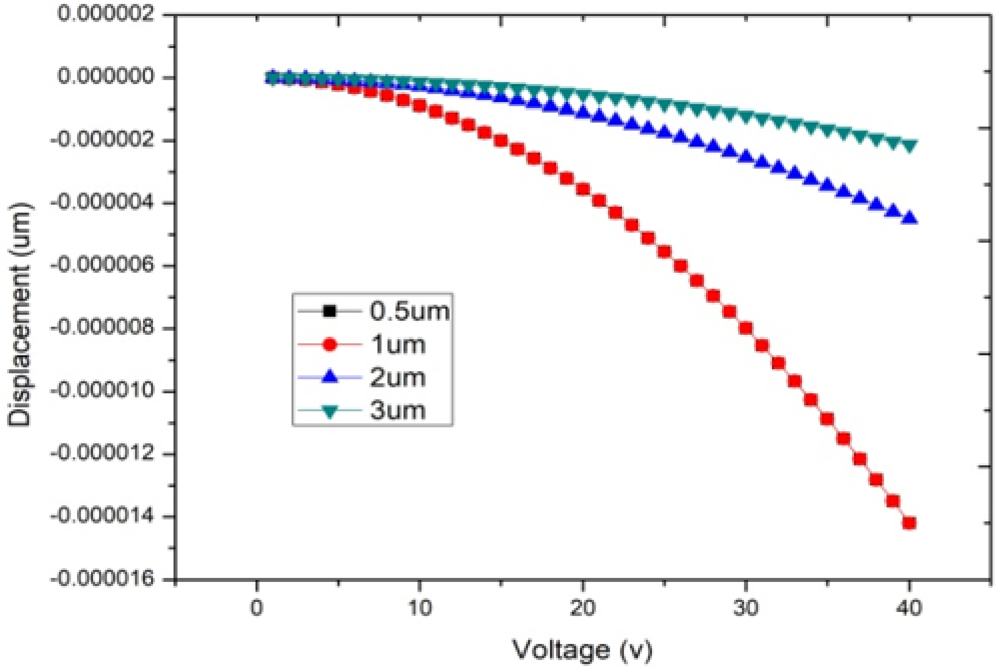

Figure 7

The performance of shunt switch membrane for different beam thicknesses.

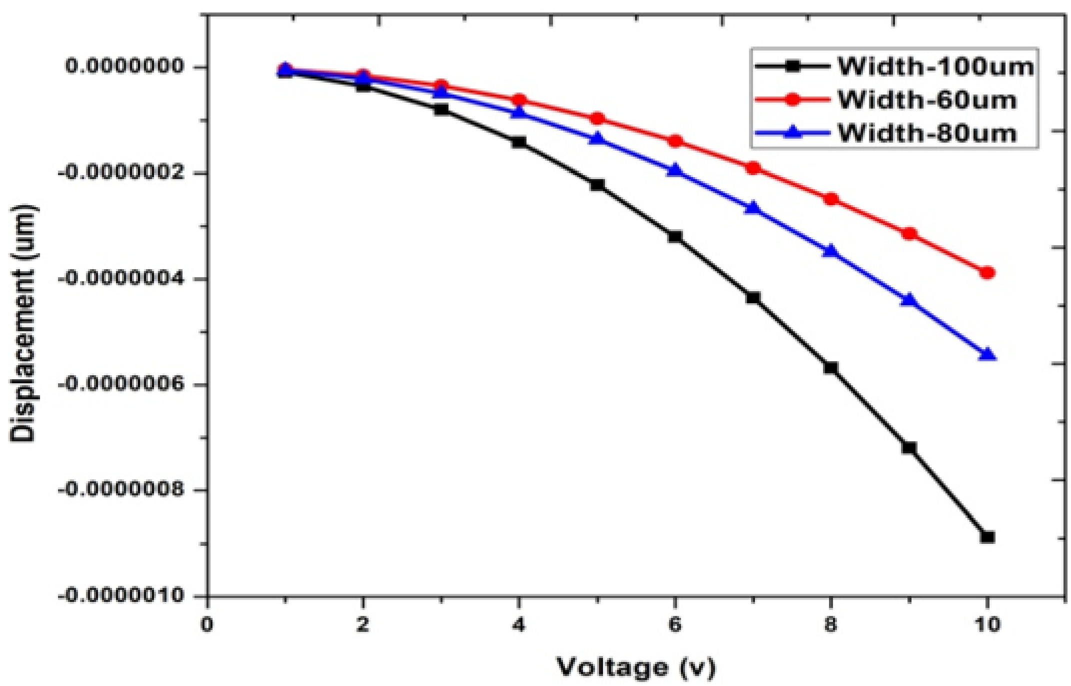

Figure 8

The performance of shunt switch membrane for different beam widths.

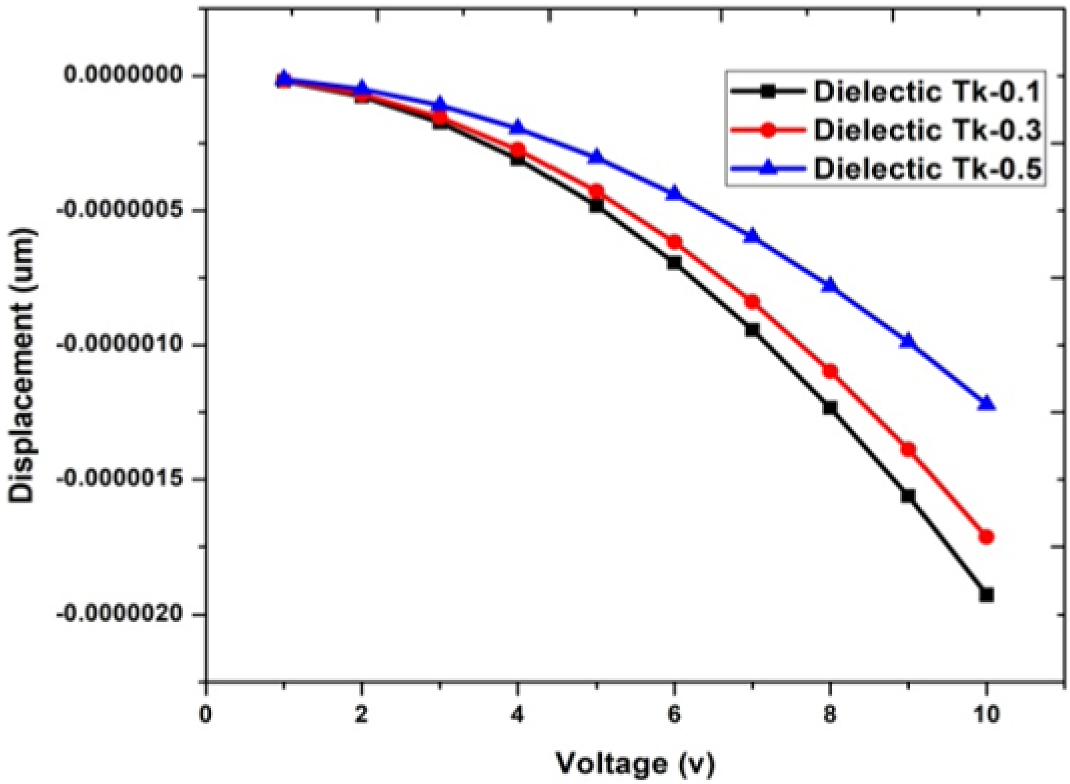

Figure 9

The performance of shunt switch membrane for different dielectric thicknesses.

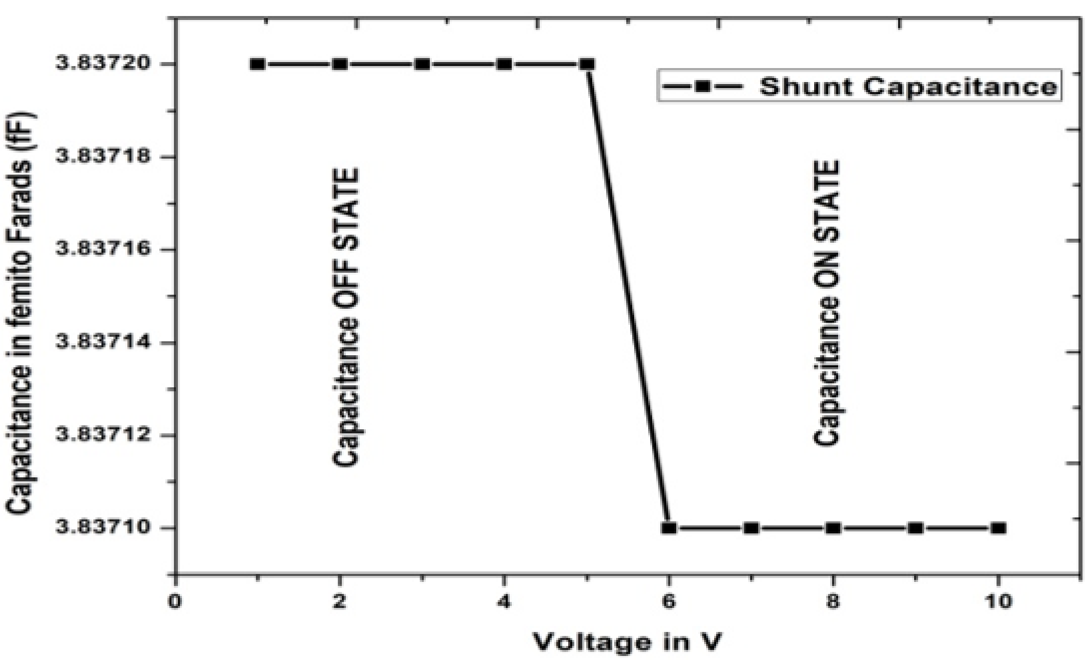

Figure 10

Shunt switch Capacitance Vs voltage curve.

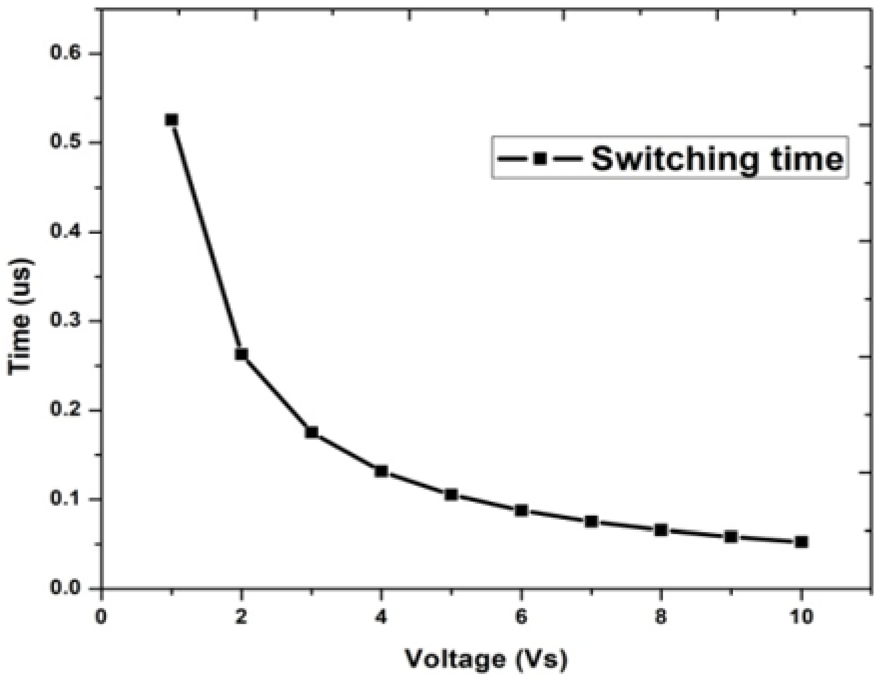

Figure 11

Switching time Vs Source voltage