Design and simulation of low actuation voltage RF MEMS shunt capacitive switch with serpentine flexures&rectangular perforations

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Abstract

This paper presents the design and simulation of RF MEMS shunt capacitive switch with low actuation voltage, low insertion loss and high isolation. Actuation voltage depends on the parameters like air gap, spring constant and actuation area. In this design, we have proposed a serpentine meander structure to reduce the spring constant of the beam thus reducing actuation voltage. The rectangular perforation is used to reduce the squeeze film damping by decreasing the mass of the switch. The proposed switch has attained a low actuation voltage of 4.5V for a displacement of 0.84μm. The air gap between the beam and the dielectric is 1μm. This radio frequency (RF) MEMS shunt switch is designed and simulated using COMSOL Multiphysics 5.2. The RF performance of the shunt switch is analyzed in Ansoft HFSS 13 and the results show that the return loss was about -13.50 dB at 20GHz in the OFF state and -8.5 dB at 18 GHz in the ON state. A high isolation of -36.00 dB was achieved in the OFF state at a frequency of 5GHz and a low insertion loss is obtained. The results show that the switch is suitable for wireless applications operating in the frequency range from 5 to 20GHz.

Keywords: Actuation voltage, serpentine structure, MEMS switch, spring constant.

1. Introduction

MEMS imply Micro Electro Mechanical Systems. It is a small-scale machine that has both mechanical (springs, levers) and electrical segments (resistors, capacitors, inductors). The electrical and mechanical systems are integrated on a single silicon substrate. The components of MEMS are scaled miniaturized sensors, structures and actuators. MEMS are comprised of parts in between 1 and 100 micrometers in size. The incorporated electrical and mechanical components in MEMS are utilized for various applications from display technologies to sensor frameworks to optical systems. In view of their small size they have less weight and cost and they can be fit in any place. RF refers to radio frequencies. The radio frequencies range from 3 KHz to 300 GHz. The RF MEMS are those small-scale devices that can be utilized for radio frequency applications. RF MEMS have numerous helpful applications particularly in radars, remote, wireless and communication systems. Different RF MEMS parts are RF MEMS switches, RF MEMS tunable inductors, switched capacitors, varactors and Filters. F-MEMS (Radio Frequency Micro Electro Mechanical Systems)switches are the one which replaces the convectional GaAs FET and PIN diode switches in Radio frequency communication because of their low cost, low power utilization, low insertion loss, high isolation, ultra-wide frequency band and because of its linearity and intermodulation practices(Rebeiz and Muldavin 2001).MEMS switch can be classified based on mechanical structure as cantilever beam, fixed-fixed beam and diaphragm, actuation mechanism as electrostatic and electrothermal, contact type as resistive and capacitive, RF circuit configuration as series and shunt. The structure of cantilever beam is generally utilized for design of series switches, Fixed-Fixed type of beam is utilized for shunt switches. Series switches are used for low frequency range (gigahertz) and shunt switches are used for high gigahertz applications. The spring constant is high in fixed-fixed beam when compared with cantilever beam. The diaphragm structure is mainly used as MEMS pressure sensor. Among the actuation mechanisms, the electrostatic actuation mechanism is the most widely recognized technique because of its simplicity and low consumption. In the capacitive switches, the transmission signal is a radio frequency signal. When a switch is in the upstate, the signal cannot cross through CPW line. By applying an electrical voltage, the switch is closed, and the signal is transmitted through the switch to the ground. In fact, in the capacitive switches, ON or OFF state is obtained by a change in the capacitance value between movable switching and signal transmission line. Resistive contact switches utilize metal to metal contact for ohmic contact between signal line and contact beam. For series switch operation initially, the switch is in off state, when an actuation voltage is applied the switch will be on and signal transfers from input to output. The parameters that can be considered in MEMS switches are transition time, spring constant, RF power handling, switching transients, bandwidth, insertion loss, isolation, switch resistance, Actuation voltage, Life time of switch, resonant frequency. The main aim is to design a switch with low actuation voltage by overcoming various difficulties such as low power handling capability, low isolation, insufficient reliability, large transition

time and high insertion loss. To obtain low actuation voltage without effecting the RF performance of the switch the parameters such as spring constant and air gap must be decreased, and the actuation area must be increased.

In this paper, a shunt capacitive switch with a fixed-fixed beam structure and with electrostatic actuation mechanism is designed. Specifically, gold is used in the design of beam and CPW lines because of its high conductivity. This paper is organized as follows. In section II, the design, working principle and the parameters of the switch are clearly reported. Finally, in section III, the results of the switch displacement, its RF performance is presented, and the proposed switch parameters are compared with the results of previous papers.

2. Design and working principle

Working principle

The capacitive shunt switch consists of bridge, CPW line, dielectric layer and substrate. The shunt switch has a thin metallic bridge structure suspended over the CPW line. The bridge structure is supported by two anchors which are connected to the CPW lines. A dielectric layer is present on the signal line. When no actuation voltage is applied on the beam, the shunt switch is in 'ON' state. The signal flows from input to output. When an actuation voltage is applied on the beam, the electrostatic force moves the beam on to the dielectric layer. When the beam touches the dielectric layer, which is present on the signal line then the switch is said to be in 'OFF' state. There will be a short circuit and no signal flows from input to output. The side view of a shunt capacitive switch is shown in Fig 1.
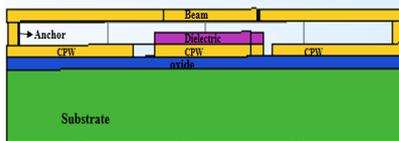
Fig. 1: Structure of MEMS shunt switch

Design of proposed switch

The proposed switch is designed over a silicon substrate with dimensions 370μm length, 200μm width, 60μm height. An oxide layer of thickness 0.1μm is placed over the substrate. Silicon dioxide material is used for the oxide layer. Gold(Au) material is used in the design of coplanar waveguide (CPW) lines.The thickness of CPW lines is 0.1μm. Silicon Nitride (Si$_3$N$_4$) is used as dielectric material between the beam and the signal line, with dielectric constant of 9.7 and a thickness of0.1μm. Siliconnitride is selected as di-electricas it is having high di-electric constant, high thermal conductivity. The bridge is designed with three blocks and serpentine meanders by using gold(Au) material with thickness 1μm. The rectangular holes that are formed in the actuation structure are uniform, they reduce the mass of the beam. The dimension of each hole is 1μm width and 3μm length. The holes also improve the efficiency of the switch by decreasing the air damping and switching time. A bridge structure is arranged over the dielectric with a gap of 1μm. Two anchors are placed at the two ends to support the beam. Gold is used in the design of the two anchors. The 3D structure of the switch is shown in Fig 2.The switch dimensions are shown in Table 1 and Fig 3.
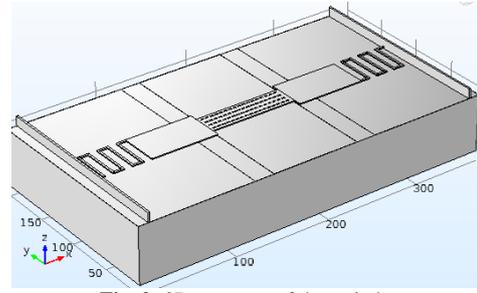
Fig. 2: 3D structure of the switch

Table 1: Switch Parameters

Parameter	Dimensions (μm)
Silicon Substrate	370×200×60
Oxide Thickness	0.1
Thickness of CPW lines	0.1
Dielectric layer thickness	0.1
Gapbetween beam and Dielectric layer	1
Overlap area	90×25
Dielectric thickness	0.1
Dielectric Constant	9.7
Beam thickness	1

Actuation voltage

Actuation voltage is that which is used to activate the switch. Actuation voltage can be achieved for the switches by using various mechanism methods like electrostatic, thermal, piezoelectric and magnetic. Commonly used actuation mechanism is electrostatic actuation because of its almost negligible power consumption, minute size and low switching time. Actuation voltage can be reduced by overcoming difficulties like low power dissipation, low actuation, insufficient reliability, more insertion loss and high transition time. To decrease actuation voltage of RF MEMS switches we can decrease air gap, decrease spring constant and can increase electrostatic field area. A minute changes in these three parameters effect the other parameters of actual switch like insertion loss and return loss. Other way to reduce actuation voltage is to decrease the spring constant. Isolation of metal contact switches is mainly affected while reducing actuation voltage. The pull in voltage is the voltage for which the beam touches the dielectric.

$$V_p = \sqrt{\frac{8Kg_0^3}{27AC_0}} \qquad (1)$$

Where A is actuation area, g_0 is the air gap, K is spring constant.
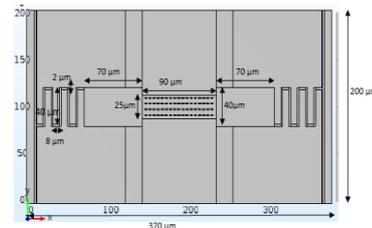
Fig. 3: Dimensions of switch

As the spring constant is proportional to the pull in voltage, by reducing the spring constant we can reduce the pull in voltage. The pull in voltage can also be reduced by decreasing the air gap and increasing the actuation area. The actuation voltage can be decided by the spring constant. The spring constant can be written as:

$$K = \frac{EWt^3}{l^3} \qquad (2)$$

where W width, E young's modules, t is thickness, l is the length of beam.

The structure of meander used for this design is serpentine meander structure. The meander structure used in the proposed switch is shown in Fig 4.
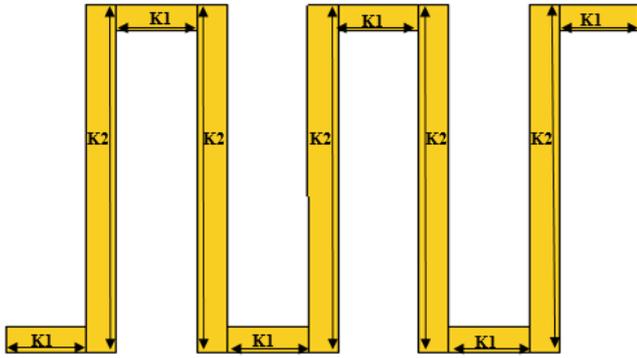
Fig. 4: Meander with spring constants

There are eleven meanders on each side with two different spring constants k_1 and k_2. K_m is the mean spring constant and it can be expressed as:

$$\frac{1}{k_m} = \frac{6}{k_1} + \frac{5}{k_2} \tag{3}$$

The total effective spring constant (k_{eff}) of the actuation structure can be expressed as:

$$K_{eff} = 2K_m \tag{4}$$

Here the mean spring constant k_m is multiplied by 2 because the structure consists of two meanders on two sides.

Table 2: Dimensions of Meanders

Type	Length(μm)	Thickness(μm)	Width(μm)
K_1	8	1	2
K_2	40	1	2

Capacitance ratio

The capacitance ratio is the ratio of un-actuated to actuated state is given as

$$C_{ratio} = \frac{C_{down}}{C_{up}} \tag{5}$$

Where C_{down} is the capacitance in down state and C_{up} is the capacitance in upstate.

$$C_{down} = \frac{\epsilon_0 \epsilon_r A}{t_d} \tag{6}$$

$$C_{up} = \frac{\epsilon_0 A}{g_0 + t_d} + c_r \tag{7}$$

where A is the effective area, ϵ_r is the dielectric constant, ϵ_0 is the permittivity of free space, t_d is the thickness of the dielectric, g_0 is the gap between the dielectric and bridge, c_r is the fringing field capacitance. Mainly the capacitance ratio depends on the dielectric material and gap between dielectric layer and deforming structure.

Switching time

It is the time taken by the switch to toggle from one state to another. Hence, it is one of the most important parameters for the analysis of function of a switch. Switching time is directly proportional to the pull in voltage, inversely proportional to the source voltage and resonant frequency. Low pull in voltage results less switching time.

$$t_s = 3.67 \frac{V_p}{V_s w_0} \tag{8}$$

Where V_P is pull in voltage, w_0 is resonant frequency and V_s is source voltage of the switch.

$$w_0 = \sqrt{\frac{k_{eff}}{m}} \tag{9}$$

Where the effective spring constant is k_{eff} and m is the mass of the beam.

3. Results and discussions

The shunt switch performance parameters (mechanical and electrical) are calculated by using COMSOL tool and RF characteristics are calculated using HFSS software. An electrostatic actuation voltage of 4.5V is applied between membrane and actuation electrodes. The voltage causes the bridge to touch the dielectric and the switch is OFF. There will be a uniform displacement of the membrane with the applied voltage. The total displacement of the switch with a pull in voltage of 4.5V is shown in Fig. 5. Theoretically the pull in voltage of the designed switch is 3.6V for a calculated spring constant of 0.867N/m and practically the pull in voltage is 4.5V. There is a slight difference in the theoretical and practical values of pull in voltage.
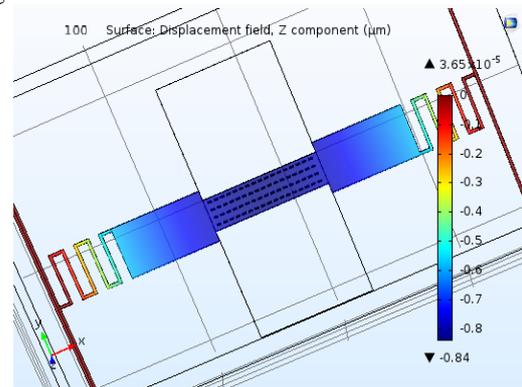
Fig. 5: Displacement of the switch with 1μm gap

The displacement of the switch is 0.84μm towards the dielectric for a pull in voltage of 4.5V. This is the maximum distance the beam has displaced for an air gap of 1μm. The displacement of the switch is also observed with air gap of 2μm and 3μm. In both the cases the beam showed a good displacement of -1.31μm for an air gap of 2μm and -2.62μm for an air gap of 3μm. The displacement of the switch with an air gap of 2μm and 3μm are shown in Fig 6 and Fig 7.
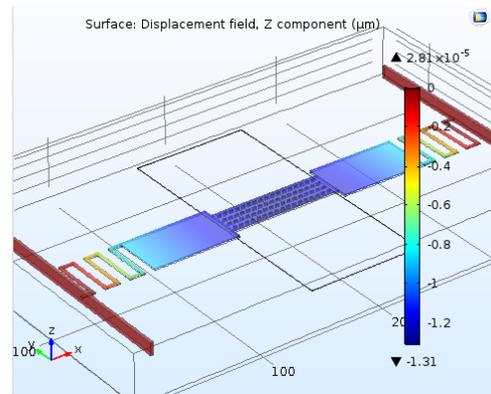
Fig. 6: Displacement of switch with 2μm gap
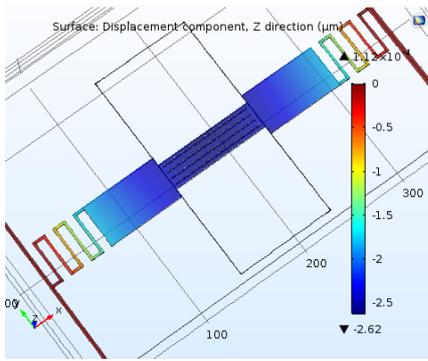
Fig. 7: Displacement of switch with 3μm gap

The beam bends with the applied voltage. The displacement of the beam with respect to the voltage applied is shown in Fig 8.
The graph shows that the displacement of the switch increases with increase in voltage. As the beam bends downwards, the displacement is negative. The displacement is proportional to the applied voltage.
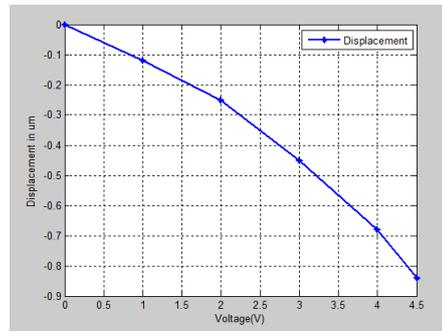
Fig. 8: Voltage vs Displacement graph (1μm gap)

The S_{11}(Return loss), S_{12}(Insertion) losses in up position and S_{21}(Isolation) in down position for the designed switch is measured using AnsoftHFSS 13. The S – parameters for the proposed switch is feasible for X band and Ku band applications. At up state, S_{11} is below -8.5 dB for frequency range up to 18 GHz shown in Fig.9, in down state S_{11} is about -13.50dB at 20GHz shown in Fig 10. Fig.11 shows the insertion lossat 5 GHz. At down position S_{21}, the maximum isolation of the switch is -36 dB obtained at frequency of 5 GHz (Fig 12). Comparisons of the previous work and proposed work is shown below in Table 3.

Table 3: Comparison of the Designed Switch with Previous Designs

Switch parameters	Persano (2011)	Saffari (2017)	Shekhar (2017)	Proposed Switch
Suspender material	Tantalum Nitride	Gold(Au)	Gold(Au)	Gold(Au)
Bridge Thickness	120nm	2μm	0.5μm	1μm
Air gap(μm)	3	2	2	1
Dielectric	Ta2O5(400nm)	Silicon Nitrate(0.1μm)	Si3N4(1500Å)	Silicon Nitride(1μm)
Actuation Mechanism	Electrostatic	Electrostatic	Electrostatic	Electrostatic
Actuation voltage(V)	15-20	5.8	4.8-6.3	4.5
Isolation(dB)	-40	-49	-30	-36
Return loss(dB)	-10 dB below 28 GHz	-0.24 at 13GHz	12 at 50GHz	-8.5 at 18GHz
Perforations	Square	-	Square	Rectangle
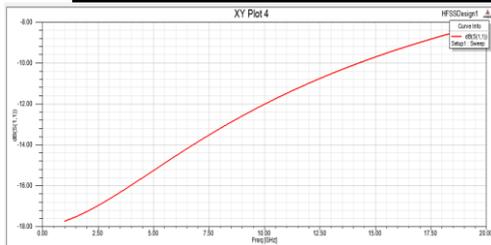
Fig. 9: Return loss(S_{11}) in ON state
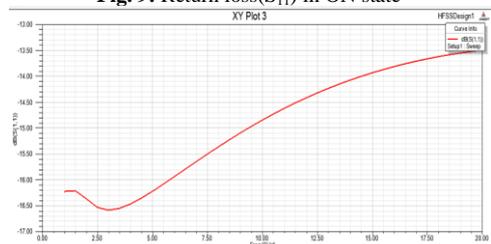
Fig. 10: Return loss(S_{11}) in OFF state

Fig. 11: Insertion loss (S_{12}) in ON state

Fig. 12: Isolation (S_{21}) in OFF state

4. Conclusion

In this paper a low actuation voltage RF MEMS shunt capacitive switch is designed and simulated using COMSOL Multiphysics 5.2 software. Low actuation voltage is obtained by decreasing the air gap, spring constant and increasing the actuation area. The designed switch has an air gap of 1μm. The beam structure used in the design is serpentine meander structure with a spring constant of 0.867N/m. With reduction in these parameters, the pull-in voltage is reduced to 4.5V for a displacement of 0.84μm. Rectangular perforations are used on the actuation structure to reduce the mass of the switch. Gold material is used in the design of beam and CPW lines because of its high conductivity. The RF performance of the switch is analyzed in An soft HFSS 13 and the results show that the return loss was about -13.50 dB at 20GHz in the OFF state and -8.5 dB at 18 GHz in the on state. A high isolation of -36.00 dB at 5GHz was achieved in the OFF state and a low insertion loss is obtained. The results show that the switch is useful for wireless applications operating in the frequency range from 5 to 20GHz.

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