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A low voltage actuated RF-MEMS shunt capacitive switch

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Micro electromechanical system switches (MEMS) have procured remarkable attention in recent years due to their perceptible accomplishment in RF and microwave areas. The major challenge in RF-MEMS is to minimize the actuation voltage deprived of restoring force losses. The proposed design presents the analysis of a low actuation voltage shunt capacitive RF-MEMS switch. The proposed switch comprises low actuation voltage, low insertion loss and very high isolation. A horizontal structure of bridge membrane is exhibited in this design and its vertical movement is presided by the electrostatics MEMS actuation technique, which actually provides the ON and OFF conditions of the switch. The actuation pad is fed by coplanar wave guide (CPW) transmission line. The switch performance is successfully evaluated for a large frequency range from 1 GHz to 40GHz. The actuation voltage of the proposed design has been observed to be 3.0 Volts for a vertical displacement of 1.5 μm. Moreover, the fixed-fixed flexures beam structure offers the isolation of -43 dB and insertion loss of -0.12 dB at 28 GHz.

Keywords —MEMS switch, Beam width, CPW, Spring constant, FEM.

1 Introduction

In recent years, RF-MEMS switch has been proven to be a prodigious part of advanced wireless technology. Now a days, RF-MEMS switches-based devices are in great demand due to the low losses even at very high frequencies. These switches offer many advantages over semiconductor diode and transistor switches to design a reconfigurable antennas and filters including negligible power degeneracy, high isolation, and impressive linearity[1]. These properties make them extremely promising in wireless applications, including ground as well as interstellar i.e., mobile communication, airborne and satellite system[2]. Nevertheless, these switches have certain limitations, such as high transition delay, long term life constraints and packaging problems[3,4]. The RF-MEMS switch requires high actuation voltage around 15 to 60 volts to produce a large electrostatic force. Therefore, these switches are barely compatible with control circuits and other devices[5,6]. Furthermore, the integration of these switches on a single chip is impossible.

Since, the pull-in voltage (V_{PI}) of MEMS switch is higher than the typical voltages of CMOS, which is operable at 5 volts or less, therefore, to design RF-MEMS switch with small pull-in voltage (V_{PI}) is one of the most critical challenge[7].

The proposed work is dedicated for the design of a low actuation voltage (less than 4 volts) shunt capacitive switch with small insertion loss. The switch has been realized by fixed-fixed flexures beam structure method. Specifications of the operating parameters of RF-MEMS switches are defined in Table 1.

2 Switch design and simulation strategy

Several designs of RF-MEMS switches have been presented in recent years including the cantilever structure, diaphragm structure and beam/bridge structure. A fixed-fixed beam structure is employed in proposed shunt capacitive switch, having the capabilities to limit the dominant parameters of switch. The magnitude of actuation voltage and isolation for the switch is decided by the dimensions and shape of the beam structure[8].

The pull in voltage (V_{PI})is given by;

$$V_{PI} = \sqrt{\frac{8M_z g_0^3}{27A\varepsilon_0}} \qquad \dots (1)$$

where, spring constant of bridge membrane is represented by M_Z, g_o is air gap between membrane

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Table 1 — RF switches specifications

S. No.	Parameter	Specifications	Applications
1.	Actuation voltage	Must be low (of the order of 3-5 V)	Reconfigurable antenna,
2.	Insertion loss (S_{21})	Very Low at High Frequency (up to 40 GHz) in ON state	Plane dipole antenna, Slot antenna, Micro-strip antenna,
3.	Isolation (S_{21})	Very high at High Frequency (up to 40 GHz) in OFF state	Aperture antenna, Micro-strip patch array antenna, Planer
4.	Impedance matching	Must be matched at both input and output (in ON as well as OFF states)	filter, Phase shifters, Programmable attenuators, Reconfigurable matching
5.	Transition time	The time between transition must be low from 10% to 90% and vice versa (for ON as well as OFF states)	networks
6.	Switching speed	The time between transition must be low from 50% to 90% (for ON state)	
7.	Power consumption	Must be very low during the ON states (for battery operated devices)	
8.	Bandwidth	Must be very high (1 GHz to 40 GHz)	
9.	Life time	Must be larger as much as possible (1 trillion cycle under cold cycle mode)	

and actuation pad, A is cross section of the pad and ε_0 is permittivity of free space.

There are three main approaches by which the pull-in voltage can be reduced as presented in the eq. *(1)*;

1 By reducing the air gap g_o.
2 By increasing the actuation area.
3 By reducing the value of spring constant M_Z.

The aforesaid methods to reduce the actuation voltage and increase the isolation have some consequences, like, when the air gap will be reduced, the isolation at higher frequencies will be decreased and insertion loss will be increased[9,10]. Therefore, the reduction in air gap makes the switch compatible for low frequency application. Whereas, the larger area of actuation pad leads to a bulky design, while compactness is a major concern of the switch design. The spring constant is another major parameter to reduce pull-in voltage. Lower spring constant leads to a lower actuation voltage but there is an undeniable constraint to reduce it. The mass of the beam cannot be reduced beyond one third of the total mass of beam[11].

A reduced Young's modulus is also accountable for lessening pull-in voltage as M_z directly depends on it. The relation between Young's Modulus and spring constant is presented by;

$$M_z = 4Ew\left(\frac{t}{l}\right)^3 \quad \ldots (2)$$

where, *t*, *E*, *l and w* are membrane thickness, Young's Modulus, beam length and width correspondingly.

The fixed-fixed beam structure has been depicted in Fig. 1.

Due to the attractive advantages of CPW feed such as, larger impedance bandwidth, low dispersion

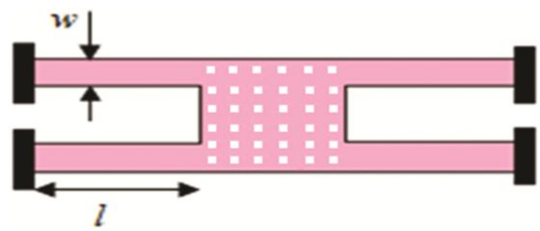

Fig. 1 — Fixed-fixed flexures Beam Structure

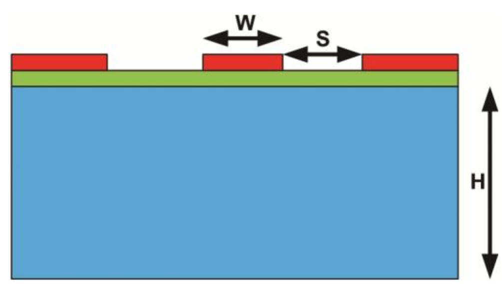

Fig. 2 — CPW Structure for switch

attributes, and ease of integration with active devices over the conventional microstrip feed, the CPW structure has been used for designing the RF-MEMS switch with S/W = 84/120 and H = 600 µm (50Ω) above the substrate (Fig. 2).

The process of the proposed switch design is explained below:

1. A 1 µm thick layer of silicon dioxide (SiO_2) is deposited on silicon substrate as buffer layer as displayed in Fig. 3(a).
2. A gold layer of 4 µm (Au) has been deposited above the SiO_2 layer to design transmission line, depicted in Fig. 3(b).
3. A 0.15 µm thick silicon nitride (Si_3N_4) layer is developed and patterned as an insulated layer

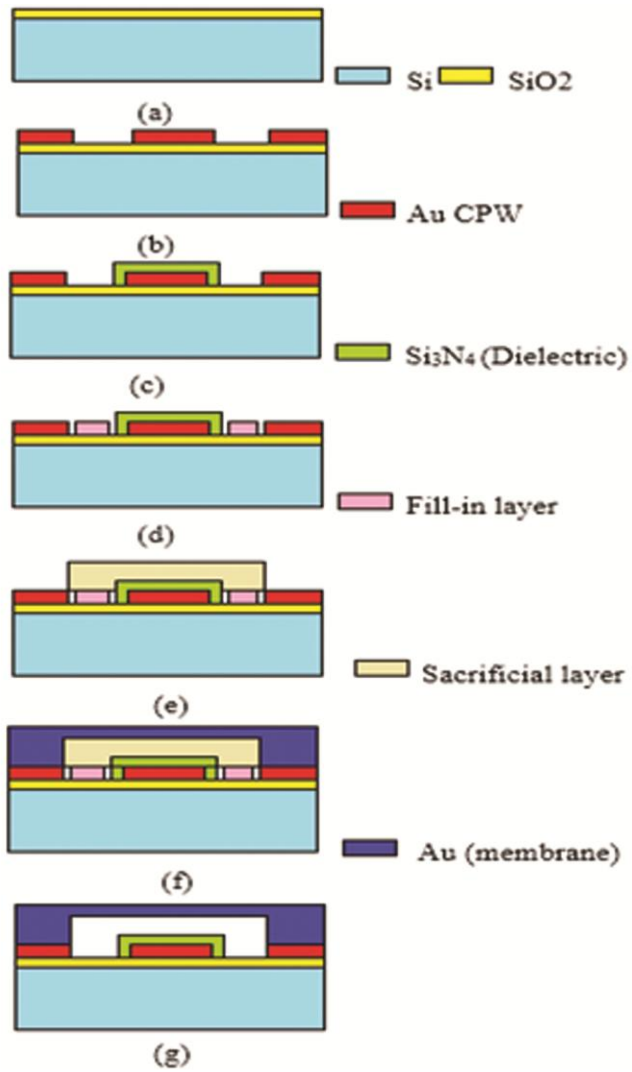

Fig. 3 — Design process flow of proposed switch

between bridge membrane and CPW line as given in Fig. 3(c).

4. A photo resistive film of 4 µm thickness is spun coated, which is filled in the CPW slots to achieve the flat membrane, as shown in Fig. 3(d).
5. Again, the coating and patterning of photo resist sacrificial layer of 1.5 µm thickness is implemented, as depicted in Fig. 3(e).
6. A gold (Au) layer of 0.6 µm thickness is dispersed and etched away to develop conduit as defined in Fig. 3(f).
7. Finally, the photo resist is etched away to release the bridge as shown in Fig. 3(g).

A micro level RF-MEMS switch can be designed by using the both techniques, Finite Element Method (FEM) and Finite Element Analysis (FEA). The proposed capacitive shunt RF-MEMS switch was designed by using Coventorware and HFSS v14 software. The performance of proposed switch is analyzed over the frequency range 1 GHz to 40 GHz. The detailed dimensions of the designed switch is given in Table 2.

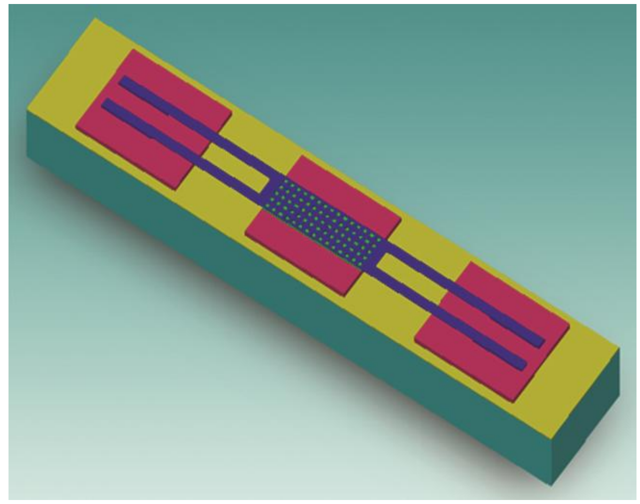

Fig. 4 — Three-dimensional model of designed RF- MEMS Switch

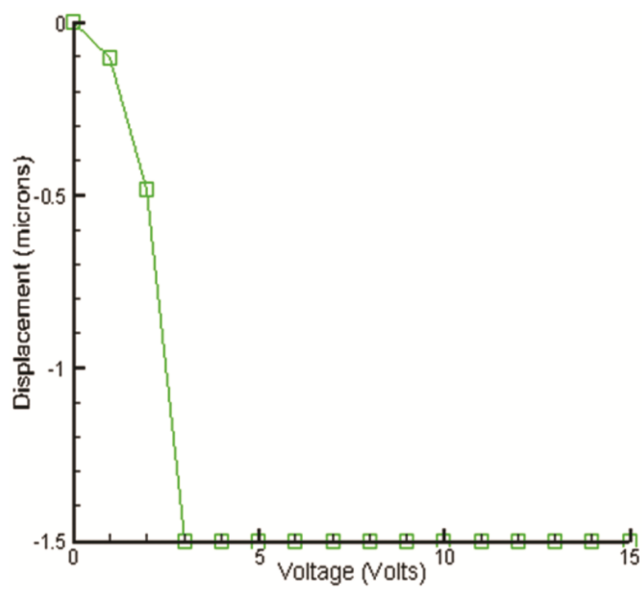

Fig. 5 — Displacement Vs Pull-in voltage characteristics.

Table 2 — Detailed dimensions of designed switch

g_0 (µm)	A (µm)	w (µm)	l (µm)	t (µm)	L (µm)
1.5	120×40	10	184	0.6	508

3 Simulation Results and Discussion

A. Electrostatic performance

The 3D model is simulated using Coventorware software and is shown in Fig. 4. The displacement verses pull-in voltage graph has been shown in Fig. 5,

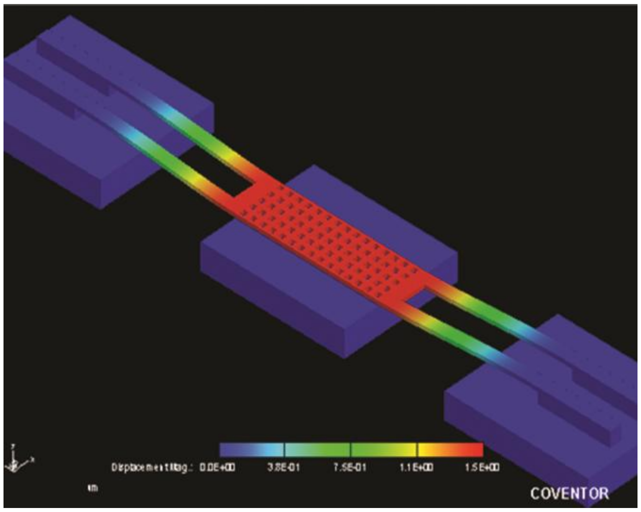

Fig. 6 — Electrostatic force distribution on the bridge membrane

which indicates a pull-in voltage of 3 Volts. The Electrostatic force distribution on the bridge membrane is shown in Fig. 6. The bridge membrane and CPW signal line develop a capacitor with Si_3N_4 as dielectric layer, which is positioned between bridge membrane and CPW signal line, and is known as down state capacitance (C_d). Subsequently, for upstate of membrane, Si_3N_4 thickness is very less as compared to air gap, so a capacitance is formed, which is represented as up state capacitance (C_u).

B. RF performance

The isolation (S_{11}) and insertion loss (S_{21}) are the valuable parameters of RF-MEMS switch, which helps to calculate the C_u and C_d and their respective relationships have been given in equations (3) and (4).

$$|S_{11}|^2 \approx \frac{\omega^2 C_u^2 Z_o^2}{4} \quad \ldots (3)$$

$$|S_{21}|^2 \approx \frac{4}{\omega^2 C_d^2 Z_o^2} \quad \ldots (4)$$

where, C_d, C_u, Z_0 and ω are down state capacitance, up state capacitance, characteristic impedance and resonant frequency respectively.

Simulations of S_{21} and S_{12} have been carried out in HFSS v14 and the obtained characteristics are depicted in Figs. 7 and 8 respectively.

From Fig. 7, the insertion loss is obtained in the range of -0.01 dB to 0.20 dB and maximum isolation of -45 dB at 28 GHz (Fig. 8).

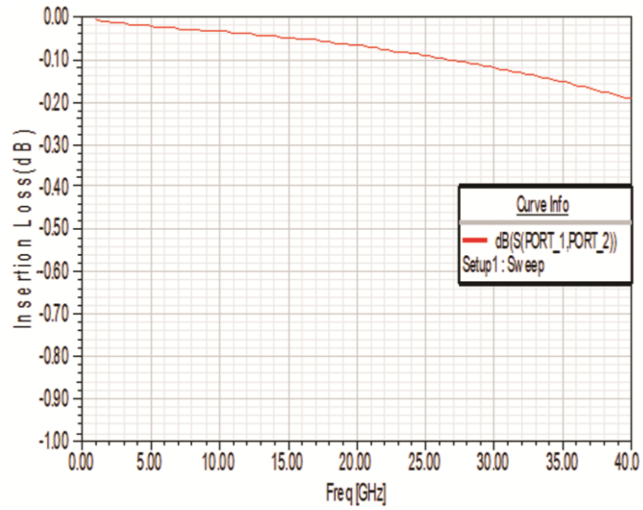

Fig. 7 — Insertion Loss (down state)

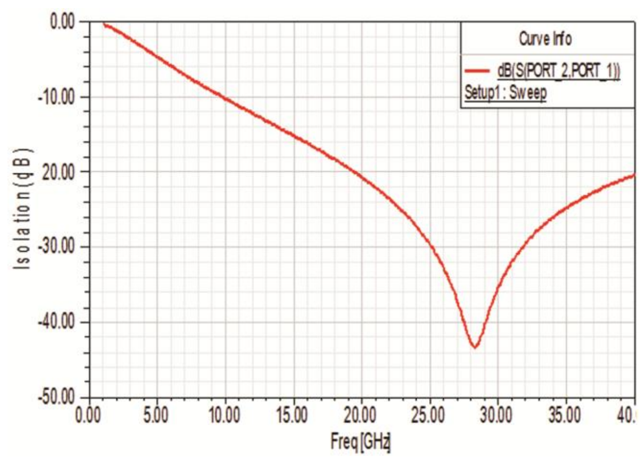

Fig. 8 — Simulated Isolation (upstate)

Conclusion

A novel capacitive shunt RF-MEMS switch is designed and analyzed. The overall performance of the proposed capacitive switch has been evaluated over the frequency range between 1 GHz to 40 GHz using FEM method. The fixed-fixed flexure beam structure has been employed to minimize the actuation voltage up to the acceptable level of 3.0V. The remarkable RF performance is perceived for all existing bands from simulation. A very low insertion loss and high isolation, which are desirable characteristics, are obtained. The results conclude good agreement towards new possibilities in RF-MEMS switch-based designs.

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