



# Improve the Performance of a Novel Capacitive Shunt RF MEMS Switch by Beam and Dielectric Materials

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Received: 29 December 2018 / Revised: 18 June 2019 / Accepted: 18 October 2019 / Published online: 30 November 2019  
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## Abstract

This paper deals with design and simulation of RF MEMS Shunt type switch having non-uniform meanders. The device is optimized and done various electromechanical and RF performance analysis in the COMSOL multiphysics and HFSS tools. By varying the thickness of beam, gap and changing the beam materials such as Gold, Copper, Nickel, we done simulation and calculation of spring constant, pull-in voltage, capacitance analysis of the proposed switch. Out of all these different materials, Gold is best by its material properties. The pull-in voltage of proposed switch is 16.9 V, the switch have fast switching time i.e. 1.2  $\mu$ s. The capacitance analysis like Up state and down state capacitance of the proposed switch is 7.46 fF and 1.25 pF. The RF-Performance of the proposed switch exhibits at low frequencies (2–12 GHz). The return and insertion loss are carried out by proposed switch is  $-41.55$  dB,  $-0.0865$  dB respectively. The switch having good isolation is  $-47.70$  dB at 5 GHz. The proposed shunt type switch is used for low frequencies such as microphones, radar and satellite applications.

**Keywords** Pull-in-voltage · RF shunt switch · Capacitance analysis · Beam materials

## 1 Introduction

MEMS technology consists of both electrical and mechanical components. Integrated circuit (IC) technology is the first to discuss the history of the MEMS [1]. The MEMS field is determined from the integrated circuit industry. The MEMS devices are developed by IBM in a micro magnetic sensor in 1970. In recent years, telecommunication industries have been growing at a rapid place. New wi-fi standards are developing which require alternative of bulky, highly-priced and rancid-chip passive RF additives with small length, high linearity, low energy consumption, and multi-band devices to make sure reconfigurability of the front-stop without compromising the performance of the machine. RF-MEMS technology has covered that approach for the development of devices like RF MEMS Switches, Inductors, Filters,

Resonators [2–4]. The front-end of a first-rate-heterodyne wi-fi transceiver generally contains an awesome variety of off-chip, high-Q components which can be probably replaceable by means of their micro machined versions. RF-MEMS switches are essentially used to discover open or short circuit inside the RF- transmission line. MEMS switches outperform the robust-country switches alongside FETs and PIN diodes. They display high isolation loss, low insertion loss respectively because of the high conductivity of the metallic and air hole. MEMS switches are their superior RF performance so being much low insertion loss, high isolation, near-zero power consumption and good linearity. RF MEMS switches can be metallic-to-metallic touch, capacitive in series or shunt configurations [5, 6]. Capacitive MEMS switches are preferred over the DC-contact switches because the latter is constrained to low-frequency applications.

From literature survey, the RF MEMS capacitive switch is designed with thin film metallic membrane [7]. The pull-in voltage of switch is 60 V and having isolation is about 30 dB it is applicable for low frequency. In literature they designed and optimization of RF MEMS Capacitive shunt switch. In this they used both electrical and mechanical model to measure pull-in voltage is 20.4 V [8], and isolation is 16–28 dB at 10–13 GHz for X-band applications. They

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designed single crystal silicon RF MEMS Capacitive switch for using silicon on glass substrate. The switch is actuated for low pull-in voltage is 19 V and the isolation and insertion –38, –0.18 in dB's [9]. This switch is tested both electrical and mechanical performance. This switch is also fabricated which is used for low frequency band.

The paper is organized as follows, in Sect. 2, we have discussed the design of proposed RF switch, working principle and it's specifications. Section 3, presents the Electromechanical analysis such as spring constant, pull-in voltage, capacitance analysis, and stress analysis and RF performance analysis like return, insertion and isolation losses. Section 4, is concluded the paper.

## 2 Design of the Proposed RF MEMS Switch

### 2.1 Proposed Switch and Its Working Principle

The device consists of a silicon substrate having a length of 450  $\mu\text{m}$  length and CPW, which consists of ground and signal line. The gap between the dielectric and beam is having 1  $\mu\text{m}$ , and in this to develop the capacitance analysis. The non-uniform meanders are attached to the beam these are used to reduce the pull-in voltage. The beam is fixed between the two anchors which are fixed on the ground planes. The schematic view of RF MEMS shunt switch is as shown in Fig. 1.

The proposed switch consists of metallic bridge with perforations and is suspended between the ground planes over the signal line of CPW with fixed–fixed meanders. MEMS switch is shunt type depending on signal path and it can also be electrostatic, magneto static depending on the actuation mechanism.

The shunt type switch is initially on state condition. There is a gap between the beam and signal line, when the voltage is applied on the beam the switch membrane is actuated using two bottom electrodes by incorporating electrostatic actuation [10–12]. The oxide layer is made up of silicon

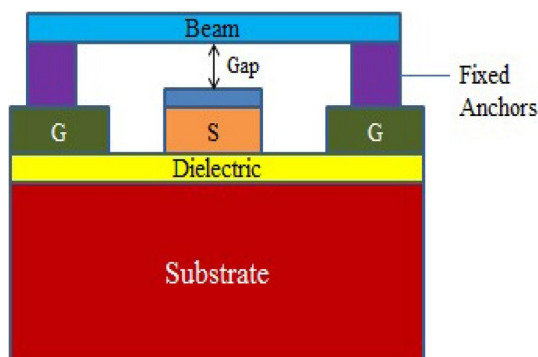


Fig. 1 Basic diagram of a RF MEMS capacitive shunt switch

oxide and it is placed above the substrate layer. The dielectric layer is made up of silicon nitride ( $\text{Si}_3\text{N}_4$ ) and it is placed above the signal line. The signal line is transmits the RF signal.

The meanders and perforations are reduce the overall spring constant of the switch thereby decreases pull-in voltage. The bridge consists of the two components the central metallic beam and the actuation upper electrodes and state of the bridge can be changed from ON state to OFF state by applying the bias voltage. Silicon nitride insulating metal is placed on the signal line under the MEMS bridge is considered as the dielectric a layer of the switch. Gold which is having high conductivity is taken as the material for the beam and meanders. The capacitance is depending on the air gap, On reducing the air gap present between the bridge and dielectric layer change in the capacitance occurs. The perforations on the bridge are taken to decreases the air force and damping and residual stress. The switch is depending on the up and down state capacitance analysis. The schematic view of proposed shunt switch as shown in Fig. 2.

## 3 Results and Discussions

### 3.1 Electro-Mechanical Analysis

#### 3.1.1 Spring Constant

The key step in the following mechanical performance of the RF MEMS switch is the spring constant. The total spring constant of the MEMS switch is the whole of spring constant of the beam stiffness and spring constant due to biaxial residual stress.

$$k = \frac{4Ewr^3}{l^3} \quad (1)$$

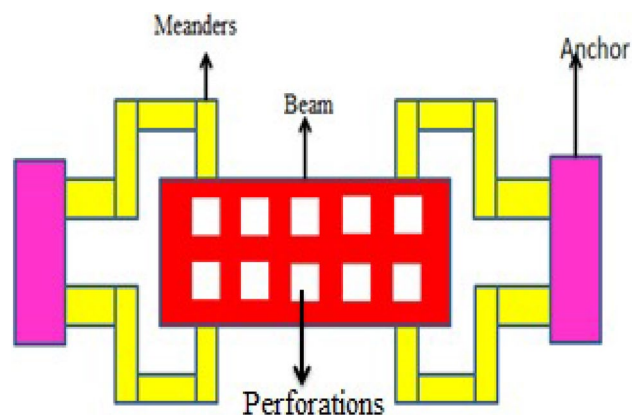


Fig. 2 Beam with non-uniform meandering technique along with perforations in RF MEMS capacitive shunt switch

**Table 1** Device parameters of a proposed switch

Parameters	Length (μm)	Width (μm)	Thickness (μm)	Materials
Substrate	450	400	4543	Si
Oxide layer	450	400	100	SiO <sub>2</sub>
CPW ground	151.5	400	100	Gold
CPW signal line	67	400	100	Gold
Dielectric layer	67	67	0.1	Si <sub>3</sub> N <sub>4</sub>
Anchors	30	80	1	Au
Beam	120	44	5	Au, Cu, Ni
Meander d	10	25	5	Au, Cu, Ni
c	30	10	5	
b	10	35	5	
a	25	12	5	

**Table 2** Spring constant and pull-in-voltage to different beam materials

Materials	Spring constant (K) (N/m)	Pull-in-voltage (V <sub>p</sub> ) (V)
Gold (Au)	204.32	16.9
Copper (Cu)	412.29	31.28
Nickel (Ni)	586.42	43.53

where, E is young’s modulus of a given material, w is width of the beam, ‘t’ is thickness of a beam and ‘l’ is the length of a beam (Table 1).

### 3.1.2 Pull-In Voltage

The switch is an electrostatically actuated switch, which require a actuation voltage to deform the beam is known as pull-in voltage. This actuation voltage defeats the force present in the spring to pull the beam towards the signal line of a transmission line [13].

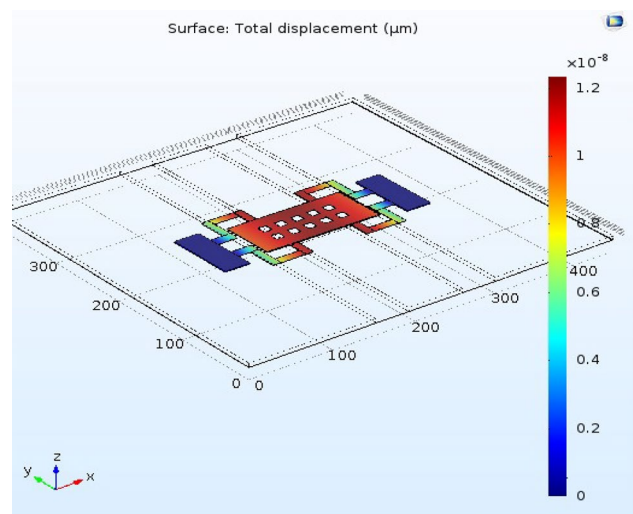
The electromechanical analysis mainly depends on spring constant and actuation voltage to analyze the various parameters like by changing the dielectric materials, beam material, air gap, and Beam thickness.

$$V_p = \sqrt{\frac{8kg_0^3}{27\epsilon_0 A}} \tag{2}$$

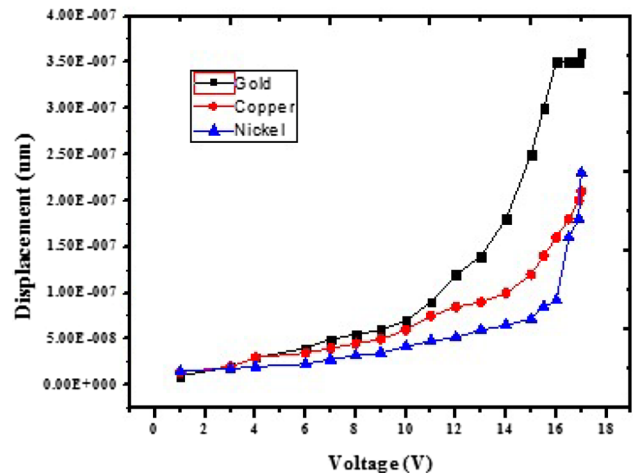
where, k is spring constant, g<sub>0</sub> is Air gap between signal line and beam, ε<sub>0</sub> is relativity of air.

The pull-in voltage of proposed switch is 16.9 V.

Table 2 shows that spring constant and pull-in voltages of different beam materials.



**Fig. 3** Electromechanical analysis using Gold as a beam material



**Fig. 4** Voltage versus displacement to different materials of beam

The Fig. 3 shows that electromechanical analysis of Finite Element Modeller (FEM) such as COMSOL software. In COMSOL software, design a proposed structure with various results in terms of Voltage versus Displacement. The Fig. 4 shows that voltage V<sub>s</sub> displacement of three different beam materials like Gold, Copper, Nickel.

### 3.1.3 Capacitance Analysis

The capacitive RF MEMS switch performance can be developed by reducing the upstate capacitance and improving the downstate capacitance. The capacitance change mainly depends on the dielectric material used within the

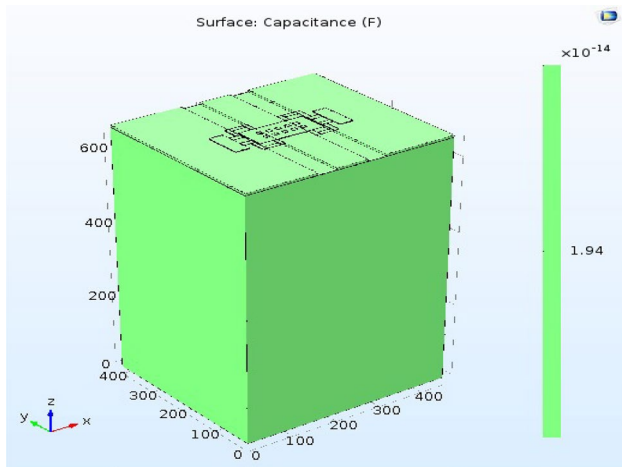


Fig. 5 Capacitance analysis of proposed switch

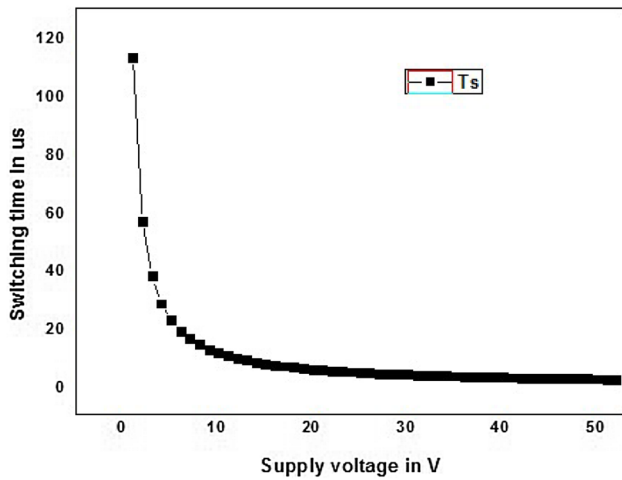


Fig. 6 supply voltage versus switching time of the beam with material gold

Table 3 Capacitance analysis of a proposed RF MEMS switch

Dielectric thickness( $t_d$ ) ( $\mu\text{m}$ )	$C_{up}$ (fF)	$C_{down}$ (pF)	$C_r$
1.5	6.66	4.17	6.26
1	7.04	6.26	8.90
0.7	7.28	8.95	12.28
0.5	7.46	1.25	16.75

bottom electrode and membrane. The upstate capacitance of the proposed switch is 7.46 fF.

$$C_u = \frac{\epsilon_0 A}{g_0 + \frac{t_d}{\epsilon_r}} \quad (3)$$

Table 4 Stress analysis of a Meander type switch

Beam	Force (N)	Stress (MPa)
Gold (Au)	$1.627E-5$	$3.86E-2$
Copper (Cu)	$2.156E-4$	$2.84E-4$
Nickel (Ni)	$2.9638E-4$	$3.65E-4$

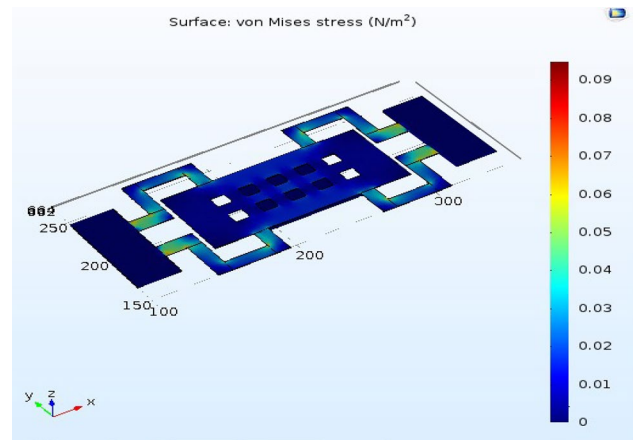


Fig. 7 Stress analysis of proposed switch

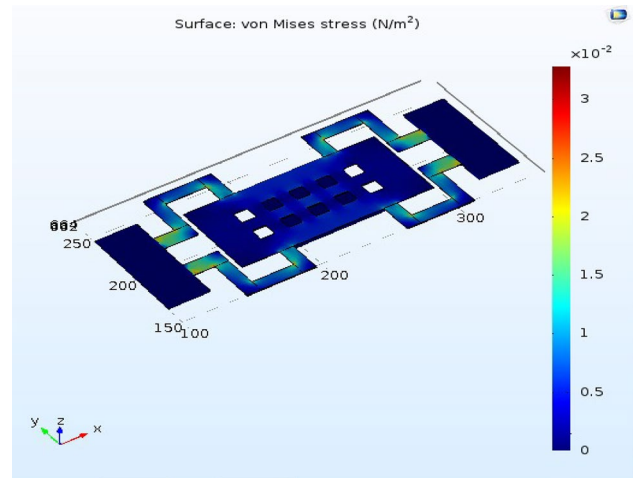
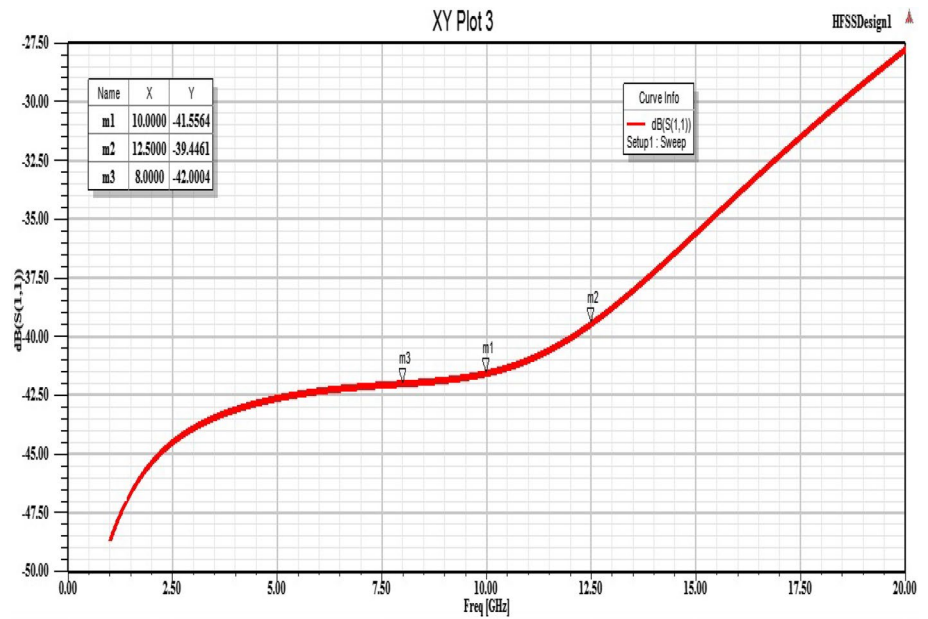


Fig. 8 Stress analysis of proposed switch with gold

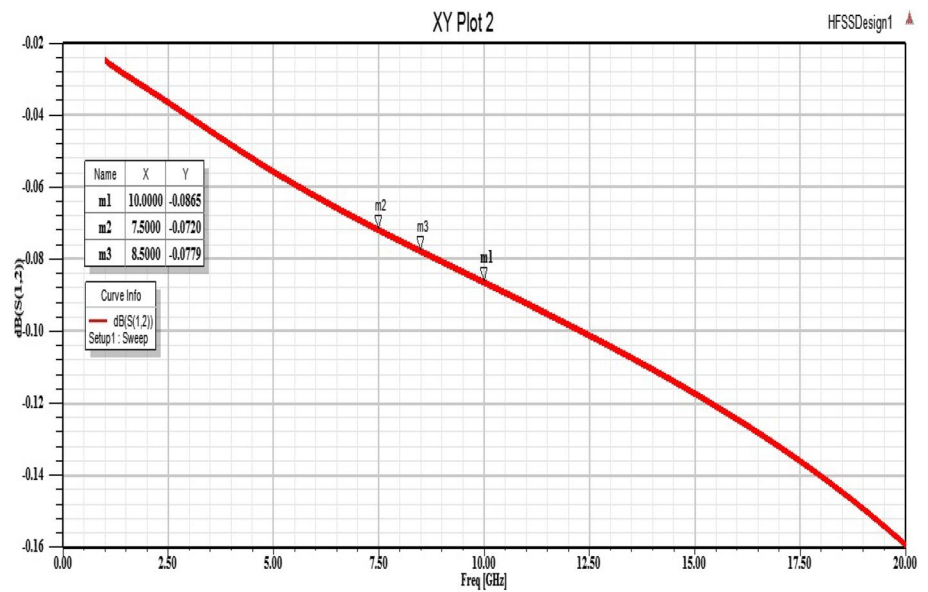
where  $A$  is length and width of a beam,  $\epsilon_r$  is Relative permittivity of beam material,  $\epsilon_0$  is relativity of air,  $A$  is area of the beam,  $t_d$  is dielectric layer material thickness,  $g_0$  is air gap between the signal line and beam.

When the actuation voltage is utilized the bridge starts deforming downwards due to the electrostatic force acting on it. When the actuation voltage of  $V_p$  the bridge totally deforms and touches the signal line dielectric. Under this condition, the switch will be in OFF state and capacitance generated at the downstate is as shown in Fig. 5.

**Fig. 9** Return loss of the proposed structure using HFSS software



**Fig. 10** Insertion loss of the proposed structure using HFSS software



$$C_d = \frac{\epsilon_0 \epsilon_r A}{t_d} \tag{4}$$

where,  $\epsilon_r$  is Relative permittivity of beam material,  $\epsilon_0$  is relativity of air, A is area,  $t_d$  is dielectric layer material thickness (Fig. 6).

The Table 3 shown that capacitance analysis of proposed switch.

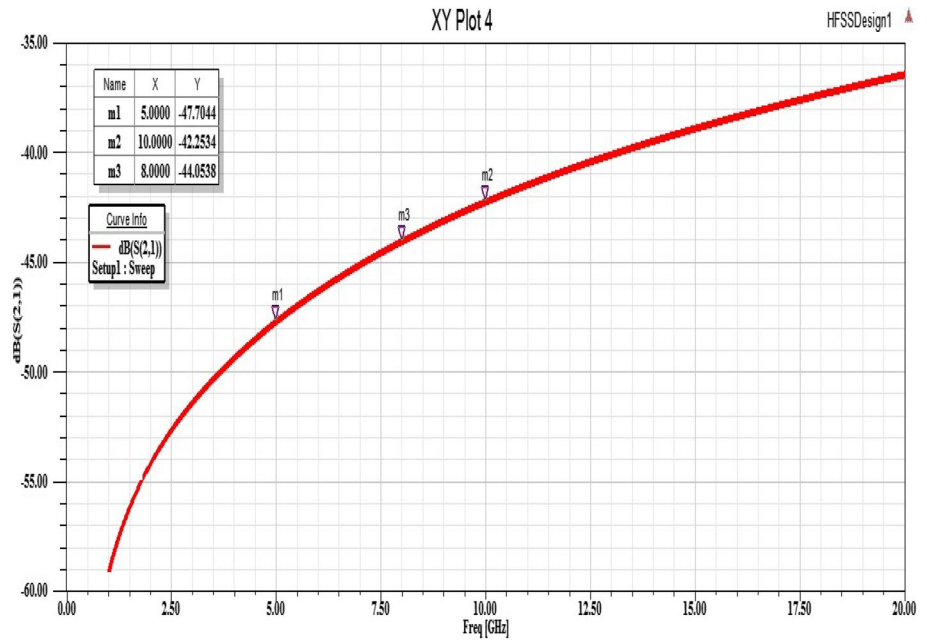
### 3.1.4 Switching Time Analysis Using Resonant Frequency

The switching speed is decided by the switching time of the switch, the switching time depending on the actuation voltage ( $V_p$ ), supply voltage ( $V_s$ ), and the resonant frequency

The switching time can be expressed as

$$t_s = \frac{3.67 V_p}{V_s \omega_0} \tag{5}$$

**Fig. 11** Isolation of the proposed structure using HFSS software with different dielectric thickness



**Table 5** Scattering parameters with different thickness values of the dielectric layer

RF Performance	Proposed switch in (dB)
Return loss	- 41.55 dB ( $S_{11}$ )
Insertion loss	- 0.0865 dB ( $S_{12}$ )
Isolation loss	- 47.70 dB ( $S_{21}$ )

where,  $V_p$  is pull-in-voltage,  $V_s$  is supply voltage,  $\omega_0$  is angular frequency,  $f_0$  is resonant frequency.

The formula for angular frequency is

$$\omega_0 = 2\pi f_0 \tag{6}$$

And the formula for resonant frequency is

$$V_s = 1.4V_p \tag{7}$$

The graph shows that switching time verses supply voltage.

### 3.1.5 Stress Analysis Using Solid Mechanics

The force is utilized on the beam the stress is equally distributed. The stress analysis is analyzed in FEM tool by adding solid mechanics.

$$Stress = \frac{Force}{Area} \tag{8}$$

Force is calculated by using formula

$$Force(f) = \frac{\epsilon_0 \epsilon_r V^2}{2d^2} \tag{9}$$

**Table 6** Comparison of proposed RF MEMS switch results with previous works

Parameters	Ziaei	Tang	Kim	Proposed switch
Pull-in-voltage (V)	60	20	19	16.9
Beam material	Gold	Gold	Gold	Gold
Stress analysis (MPa)	–	–	–	1.286
Switching time analysis ( $\mu$ s)	15	–	25	1.2
Upstate capacitance (fF)	40	137	8	7.46
Downstate capacitance (pF)	3.1	4.26	–	1.25
Capacitance ratio	77	–	–	16.75
Return loss (dB)	–	–	–	- 41.55
Insertion loss (dB)	- 0.1	0.1–0.35	- 0.18	- 0.0865
Isolation loss	- 30 dB	16.25 dB	- 38 to - 39 dB	- 47.70 dB at 5 GHz
Frequency range	8–12 GHz	10–13 GHz	2–12 GHz	5–12 GHz

where  $\epsilon_r$  is relative permittivity of beam material,  $S$  is the length and width of a beam,  $V$  is pull in voltage voltage of a proposed switch,  $\epsilon_0$  is relativity of air space,  $d$  is airgap between signal line and beam.

The Table 4 shown that stress analysis of proposed switch.

By this analysis in Figs. 7 and 8 it can be observed that Stress in terms of MPa and Total displacement in terms of  $\mu\text{m}$  using different beam materials such as Gold, Nickel.

### 3.1.6 Damping Ratio and Quality Factor

The damping ratio of the proposed fixed–fixed flexure type Capacitive switch is given

$$b = \frac{3}{2\pi} \frac{\mu(A^2)}{g^3} \quad (10)$$

‘ $\mu$ ’ is a constant value of  $1.885\text{e}-4$ , ‘ $A$ ’ is the area of the beam and ‘ $g$ ’ is the air gap between the dielectric layer and beam thickness.

$$Q = \frac{K}{2\pi f_0 b} \quad (11)$$

where  $K$  is the spring constant,  $b$  is the damping coefficient and  $f_0$  is the resonant frequency and  $Q$  is the quality factor.

## 3.2 Electromagnetic Analysis

RF analysis is done by using Ansoft HFSS. The Scattering parameters are essential across a broad range of frequency. When no voltage is applied across the beam the switch will be ON state, in this the insertion and return losses are generated. When the switch is OFF state the isolation is developed [14, 15].

The Figs. 9, 10, and 11 shows that S-parameters of proposed switch like insertion loss i.e. less than  $-0.0865$  dB, return loss in on state position i.e. to be less than  $-41.55$  dB and isolation in off state position i.e.  $-47.70$  dB at 5 GHz frequency.

The Table 5 shows that S-parameters of proposed switch.

A proposed switch is having good isolation it is suitable for low frequencies. The Table 6, shows that the Comparisons of the proposed Switch design with previous results.

## 4 Conclusions

In this paper, the design, analysis and simulation of the proposed RF MEMS shunt switch is done using different beam materials, thickness, air gap with non uni-form meanders.

The electromechanical analysis are done by using COM-SOL Multiphysics software. The pull-in voltage of proposed switch is 16.9 V. The switching time of non-uniform meander type obtained  $0.18 \mu\text{s}$ . By taking different beam materials like gold, copper and nickel, among these materials gold is best material for the beam. The up state and down state capacitance of the proposed switch is 7.46 fF, 1.25 pF. The RF-Performance is done in HFFSS tool, we observed that the S-parameters of the proposed switch, the return, insertion losses are  $-41$  dB,  $-0.0865$  dB, and the isolation is  $-47.70$  dB at low frequency between 5 and 12 GHz. This switch is applicable for low frequencies like satellite and radar applications.

**Acknowledgements** The authors would like to thank NMDC, supported by Govt. of India, for providing necessary design facilities through NPMAS.

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