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Original scientific paper

DAMPING ANALYSIS TO IMPROVE THE PERFORMANCE OF SHUNT CAPACITIVE RF MEMS SWITCH

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Abstract. *This paper describes the significance of the iterative approach and the structure damping analysis which help to get better the performance and validation of shunt capacitive RF MEMS switch. The micro-cantilever based electrostatic ally actuated shunt capacitive RF MEMS switch is designed and after multiple iterations on cantilever structure a modification of the structure is obtained that requires low actuation voltage of 7.3 V for 3 µm deformation. To validate the structure we have performed the damping analysis for each iteration. The low actuation voltage is a consequence of identifying the critical membrane thickness of 0.7 µm, and incorporating two slots and holes into the membrane. The holes to the membrane help in stress distribution. We performed the Eigen frequency analysis of the membrane. The RF MEMS switch is micro machined on a CPW transmission line with Gap-Strip-Gap (G-S-G) of 85 µm - 70 µm - 85 µm. The switch RF isolation properties are analyzed with high dielectric constant thin films i.e., AlN, GaAs, and HfO_2. For all the dielectric thin films the RF MEMS switch shows a high isolation of -63.2 dB, but there is shift in the radio frequency. Because of presence of the holes in the membrane the switch exhibits a very low insertion loss of -0.12 dB.*

Key words: *Vibration analysis, RF MEMS switches, material science, FEM tools analysis.*

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1. INTRODUCTION

RF MEMS switches are becoming prominent because of their low power consumption and high linearity [1]. Shunt capacitive RF MEMS switches are extremely useful in RF MEMS technology which has great potential in the design of reconfigurable antennas [2]. The frequency range of 1.5 - 15 GHz is the major band which will cover significant wireless applications like GPS, GSM, Wi-Fi, Wi-Max, and UMTS [3]. Potential major research challenges of Electrostatically actuated RF MEMS switches are how to reduce the required actuation voltage, improve their switching time and reliability. A proper iterative study helps to obtain better mechanical, electrical and RF properties of the switch. The cantilever-based, serpentine, fixed-fixed, folded membrane structures are popular in the design of MEMS devices. Among these, the cantilever based devices offer low actuation voltage and better switching properties [4-6].

But, there is still room to improve the cantilever performance by the iterative analysis. Material science also helps to choose the most suitable thin film for the substrate, the transmission line and the membrane [7].

2. RELATED WORK

In the early decades, several researchers advanced the research on RF MEMS switches. Electrostatic, magneto static, piezo resistive, and thermal are the popular actuation techniques. Among these, electrostatic actuation offers major advantages [8]. However, there are still a few potential research challenges in electrostatically actuated RF MEMS switches, like improving the reliability, reducing the actuation voltage, and improving the switching time [9, 10]. The prior iterative analysis obviously helps to improve the performance of the RF MEMS switches. Material science has a prominent role in the selection of thin films for the transmission lines and the membranes. Silicon or glass materials are generally used for the substrate [11]. The CPW and the membranes are micro machined in Au, Al, Cu, and Ti. For capacitive MEMS switches the dielectric material used plays an important role in improving the RF properties [12]. The RF properties i.e., insertion and isolation losses of the switch truly rely on the capacitance ratio. The ratio of downstate capacitance to upstate capacitance is known as the capacitance ratio [13].

3. MATHEMATICAL ANALYSIS

The rectangular cantilever critical stress analysis is indispensable because it primarily determines the switch reliability. The critical stress (σ_c) in terms of cantilever dimensions and the Young's modulus (E) can be expresses as [14],

$$\sigma_c = \frac{\Pi^2 E t^2}{48 l^2 (1-\upsilon)} \tag{1}$$

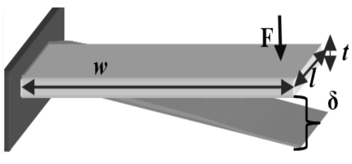


Fig. 1 Cantilever membrane

For the cantilever membrane as shown in Fig. 1, the stiffness is equal to that of the spring constant (K). The mathematical equation can be given as [15],

$$K = \frac{EWt^3}{4l^3} \tag{2}$$

The resonant frequency of the cantilever membrane can be written as

$$f_r = \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K}{m}} \tag{3}$$

Where, m denotes membrane mass is given as m=ρ*l*w*t. The time required for the MEMS switch to come from the up state to the down state is known as the switching time. For an electrostatically actuated MEMS switch, the switching time can be expressed as

$$t_s \approx 3.67\frac{V_{pull-in}}{V_s\omega_0} \tag{4}$$

The capacitive switch insertion and the isolation properties truly depend on the switch capacitance ratio. The RF MEMS switch upstate and down state capacitance can be expresses as [16],

$$C_{up} = \frac{\varepsilon_0 A}{g_1 + \frac{t_d}{\varepsilon_r}} \tag{5}$$

$$C_{down} = \frac{\varepsilon_0 \varepsilon_r A}{t_d} \tag{6}$$

'A' is the cross sectional area among the membrane and the CPW strip, and 't_d' is the dielectric thin film thickness. In terms of the return loss and the upstate and downstate capacitance the insertion losses (S_{21}) can be expressed as

$$|S_{21}|^2 = \frac{1}{|S_{11}|^2}\left(\frac{C_{up}}{C_{down}}\right)^2 \tag{7}$$

The isolation losses (S_{21}) depend on the characteristic impedance and the RF frequency (f_0) of the switch and can be expressed as

$$|S_{21}|^2 = \begin{cases} \frac{4}{\omega^2 C_{down}^2 Z_0^2} & for \quad f \ll f_0 \\ \frac{4R_s^2}{Z_0^2} & for \quad f \approx f_0 \\ \frac{4\omega^2 L^2}{Z_0^2} & for \quad f \gg f_0 \end{cases} \tag{8}$$

4. Membrane Iterative Analysis

A rectangular cantilever structure as shown in Fig. 2, is considered from the point of view of the desired radio frequency requirement. Its dimensions are given in Table 1. We have performed the iterative analysis which helped decrease the required actuation voltage.

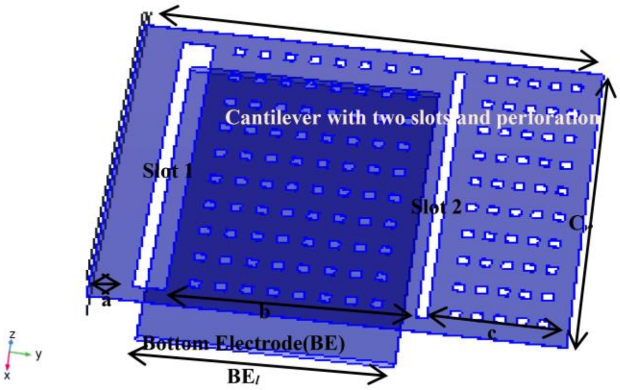


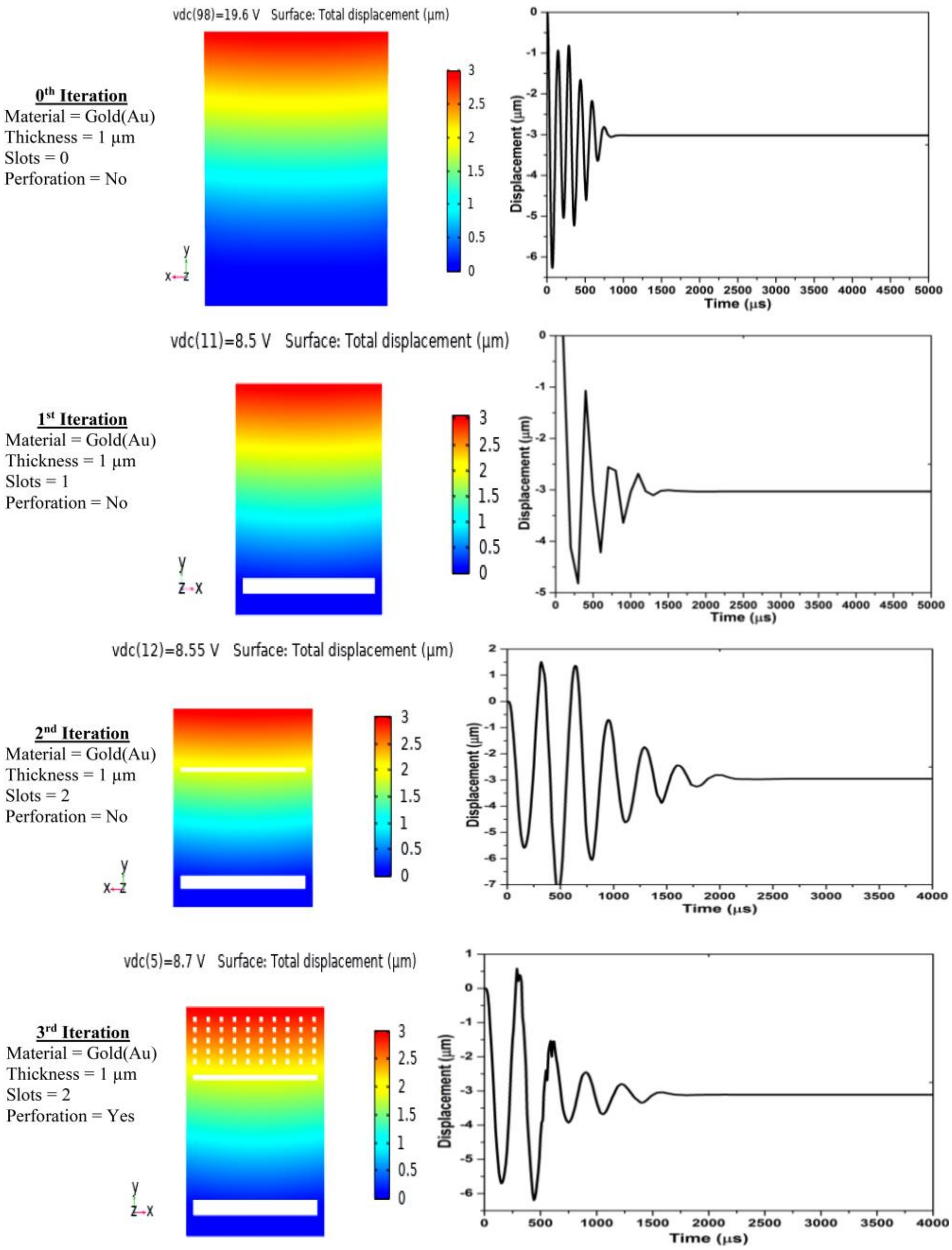
Fig. 2 Performance improved cantilever structure with bottom electrode.

Table 1 Performance improved cantilever structure dimensions.

Parameter	Variable	Value (µm)
Cantilever	C_l	220
	C_w	200
	C_t	0.5
$Slot_1$	l	10
	w	160
$Slot_2$	l	5
	w	180
Perforation	--	5x5
Bottom Electrode (BE)	BE_l	120
	BE_w	200
	BE_t	0.6

Overall we have performed the multiple iterations on cantilever membrane by varying the membrane thickness, by placing slots and by incorporating the perforation. The iterations are started with 220 µm length, 200 µm width and 1 µm thickness cantilever designed with gold material as shown in Fig. 3.

In the design of RF MEMS switches, the validation of the membrane properties is very important. The reliability of the switch depends on the multiple parameters in the membrane damping analysis. With the primary goal of the switch validation, we have considered membrane damping in every iteration. On the whole, we have observed the cantilever damping up to 8000 µs. In this iterative process, we have noticed a few important points i.e., the incorporation of slots into the membrane leads to an increase in the damping duration but also helps to reduce the actuation voltage. Incorporating holes into the membrane helps to reduce the damping duration but at the same time it leads to an increase of the actuation voltage.


vdc(98)=19.6 V Surface: Total displacement (μm)
0th Iteration
Material = Gold(Au)
Thickness = 1 μm
Slots = 0
Perforation = No
Displacement (μm)
Time (μs)
vdc(11)=8.5 V Surface: Total displacement (μm)
1st Iteration
Material = Gold(Au)
Thickness = 1 μm
Slots = 1
Perforation = No
Displacement (μm)
Time (μs)
vdc(12)=8.55 V Surface: Total displacement (μm)
2nd Iteration
Material = Gold(Au)
Thickness = 1 μm
Slots = 2
Perforation = No
Displacement (μm)
Time (μs)
vdc(5)=8.7 V Surface: Total displacement (μm)
3rd Iteration
Material = Gold(Au)
Thickness = 1 μm
Slots = 2
Perforation = Yes
Displacement (μm)
Time (μs)

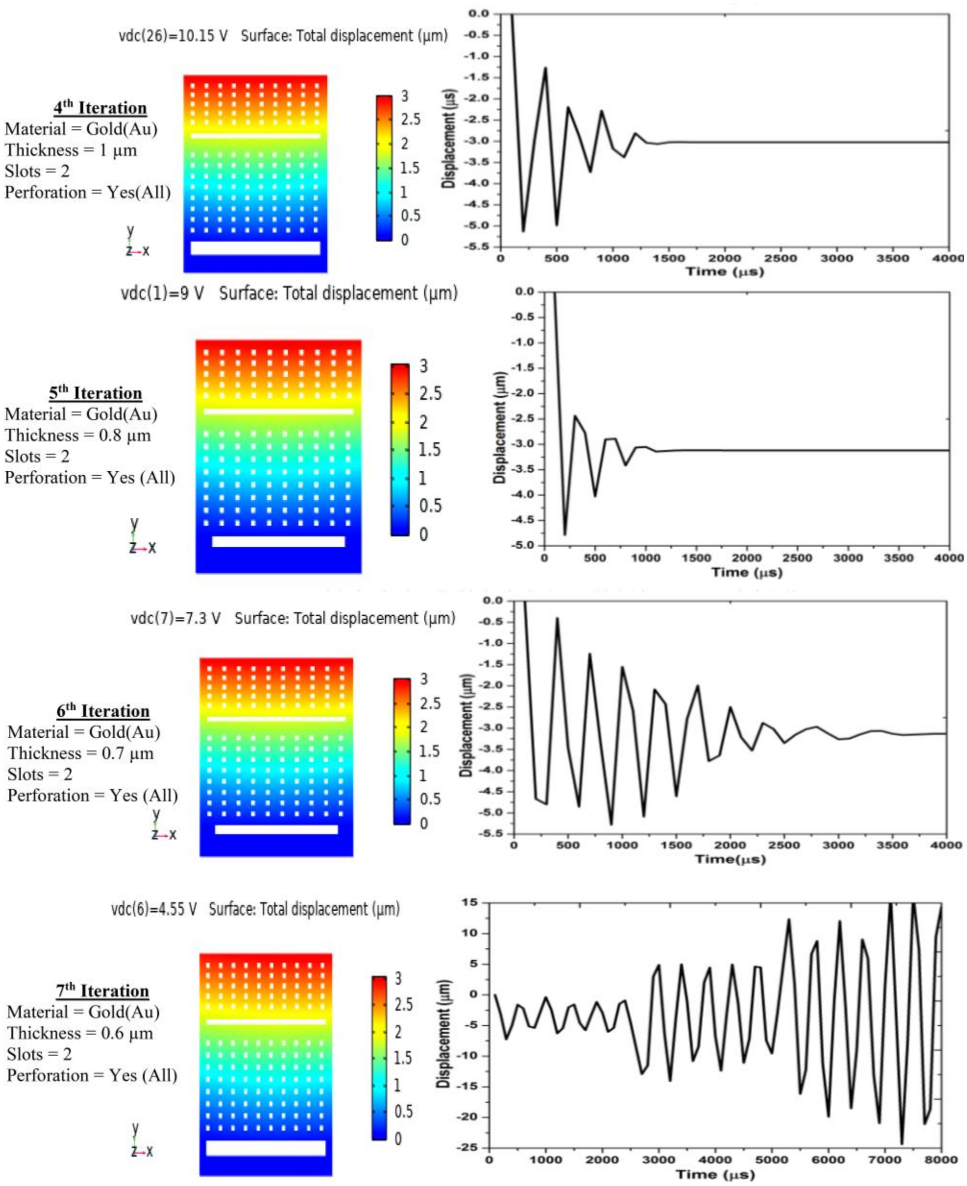
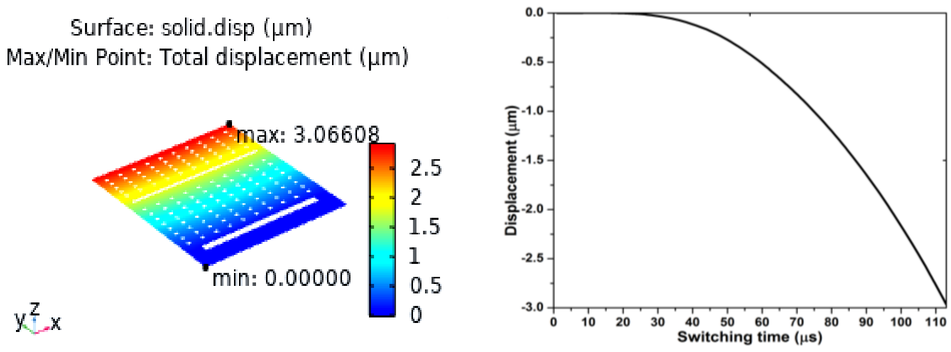


Fig. 3 Cantilever Structure Iterative Analysis

However, we have considered the 6th iteration membrane for the design of the final RF MEMS switch i.e., a gold membrane with two slots, perforation and 0.7 µm thickness. This requires an actuation voltage of 7.3 V for 3 µm displacement and switching time is 110 µs as shown in Fig. 4.



(a) (b)

Fig. 4 Cantilever membrane, (a) The displacement distribution under electrostatic actuation, (b) Displacement versus switching time

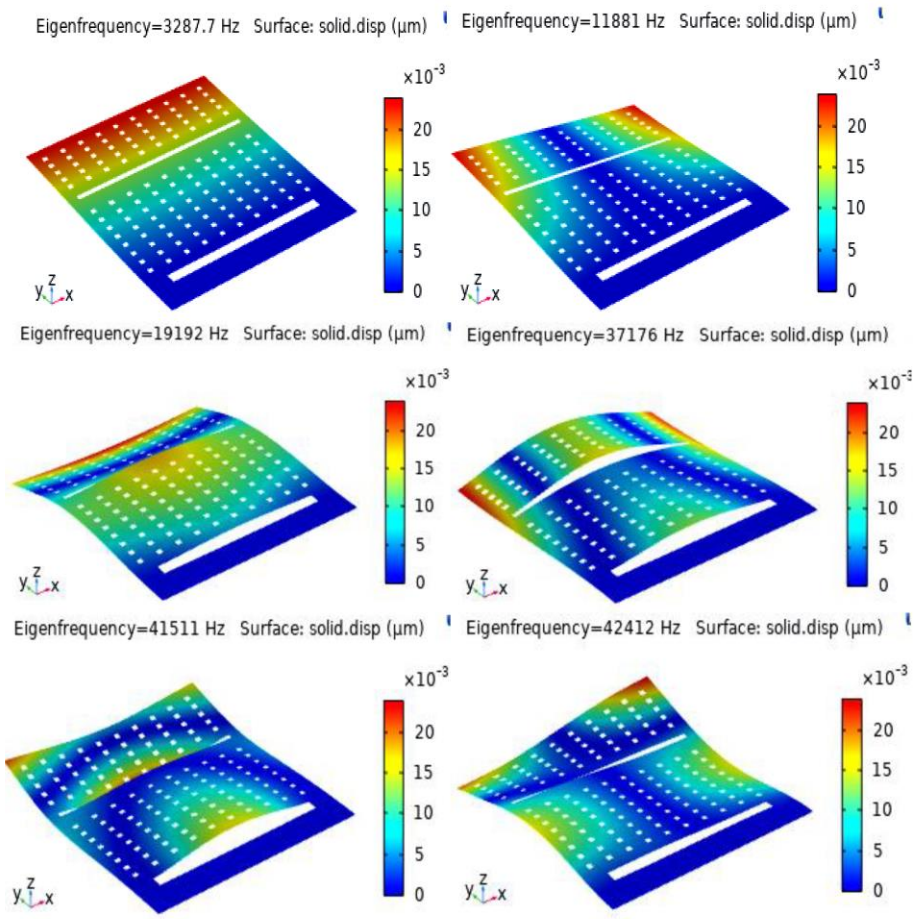


Fig. 5 Eigen frequencies

In the RF MEMS switch performance analysis, Eigen frequencies help to analyze the deformation of the membrane during electrostatic actuation as shown in Fig.5. The real advantage of introducing holes into the membrane is that it helps to improve the insertion properties of the switch. This facilitates the electrostatic actuation and at the same time the holes make the release of the membrane during the fabrication process easier. The membrane thickness reduction helps reduce the required actuation voltage but up to some level the damping duration becomes limited. However, if the membrane thickness is below 0.7 µm, the membrane damping duration exceeds the limits. In the 7th iteration, we have notices that for a 0.6 µm thickness the membrane undergoes continuous damping which will lead to membrane collapse. So eventually, we have taken the membrane with 0.7 µm thickness which requires 7.3 V for a 3 µm displacement. The designed membrane is resonating at 27 KHz in electrostatic actuation as shown in Fig. 6.

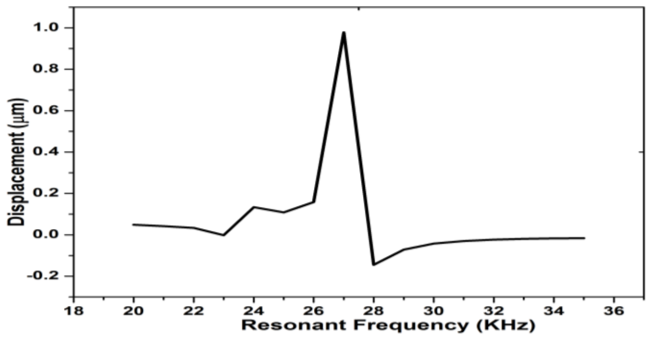


Fig. 6 Resonant frequency

The real advantage introduced by perforating the membrane is to ensure an improved stress distribution. Consequently, the reliability of the switch will improve. The stress distribution in the cantilever membrane is shown in Fig. 7.

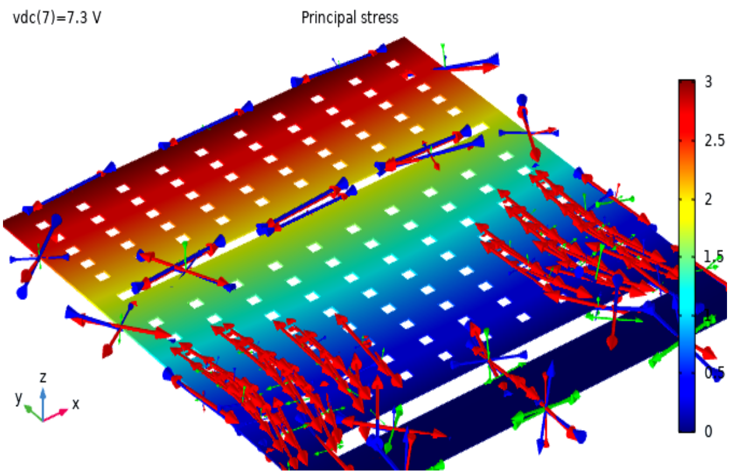


Fig. 7 Stress distribution in the designed cantilever membrane

5. RF MEMS SWITCH

The RF MEMS switch is designed using performance improved rectangular membrane with slots and perforation. The CPW transmission line with silicon used as a substrate is shown in Fig. 8. The height of the silicon substrate is 800 µm.

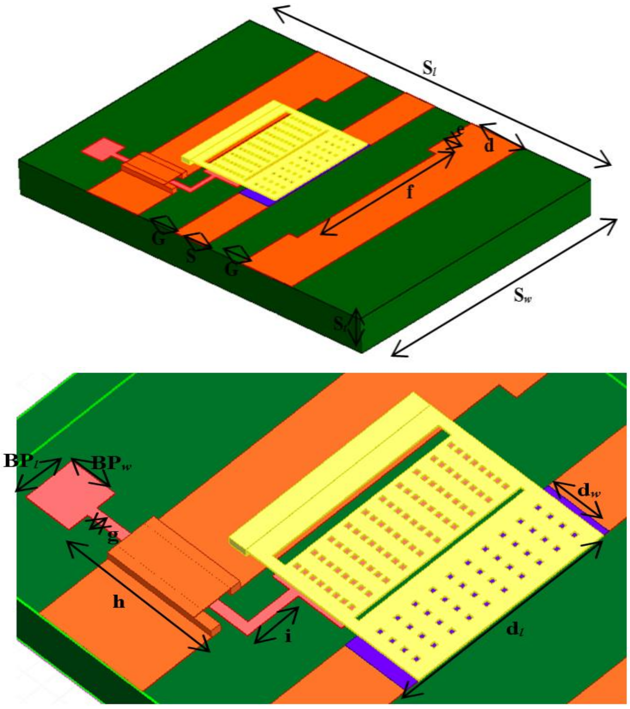


Fig. 8 Shunt capacitive RF MEMS switch with cantilever membrane

A dielectric thin film of 1 µm thickness is placed on the top of the silicon substrate for better insulation. A CPW transmission line with G-S-G of 85 µm - 70 µm - 85 µm is micromachined in gold (Au). Unlike the traditional RF MEMS switches, in this work we have incorporated a separate actuation electrode of 120 µm -200 µm - 0.6 µm to be used for cantilever electrostatic actuation, which helps reduce the noise in the RF CPW line.

HfO_2 of 220 µm length and 70 µm width is used as a dielectric material. Its relative dielectric permittivity (ε_r) is 23. The complete switch dimensions are presented in Table 2. The electrostatic actuation with 7.3 V creates an electrostatic force of 7.5 x 10^{-7} N. The membrane spring constant is 0.25 N/m. The capacitance analysis results with high relative permitivity thin films are listed in Table 3. The designed RF MEMS switch shows an isolation of -63.2 dB and an insertion of -0.12 dB as shown in Fig. 9 and Fig. 10, respectively. Our presented work is compared to the state of art as presented in Table 4.

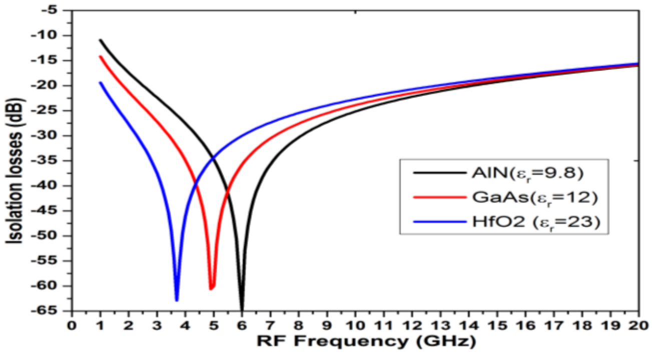


Fig. 9 Isolation Losses

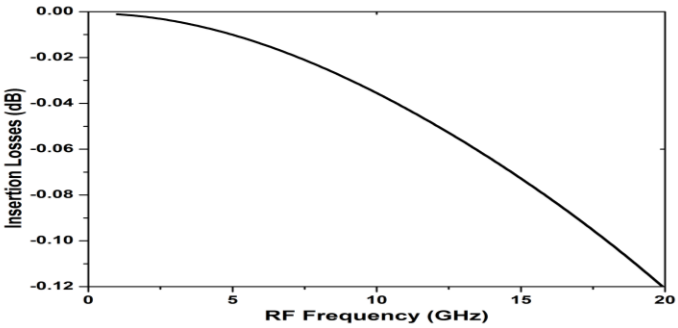


Fig. 10 Insertion Losses

Table 2 Shunt capacitive RF MEMS switch dimensions

Parameter	Description	Value(µm)	Parameter	Description	Value(µm)
S_l	substrate dimensions	800	d_l	dielectric	220
S_w		500	d_w		70
S_t		800	BP_l	bias line	50
G-S-G		85-70-85	BP_w		50
d	CPW line &	120	g		10
e	slots	40	h		185
f		300	i		50

Table 3 Capacitance Ratio

Material	Dielectric constant (ε_r)	Dielectric thickness (d_t)	Upstate Capacitance (C_{up})	Downstate capacitance (C_{down})	Capacitance ratio = C_{down}/C_{up}
AlN	9.8	0.1 µm	73.9 fF	11 pF	148.8
GaAs	12	0.1 µm	75.6 fF	13.5 pF	178.5
HfO_2	23	0.1 µm	77.3 fF	26 pF	336.3

Table 4 Our work comparison with state-of-art

Parameter	[17]	[18]	Our work
Substrate	Glass	Silicon	Silicon
Insulator	--	SiO_2	SiO_2
Micro mechanical structure	Cantilever	Cantilever	Cantilever
Damping analysis is performed	No	No	Yes
Air gap (µm)	3	3	3
Actuation voltage (V)	16	19	7.3
Total Reaction Electrostatic Force (N)	---	---	$7.5 * 10^{-7}$
Displacement (µm)	3	3	3
Spring Constant (N/m)	---	---	0.25
Upstate & Downstate capacitances	-- & 2.75 pF	-- &0.02 pF	77.3 fF & 26 pF
Insertion Loss (dB)	-0.41	- 0.05	-0.01 to -0.12
Isolation Loss (dB)	-20	-43	-20 to - 63.2

6. Conclusion

The micro-cantilever based electrostatically actuated shunt capacitive RF MEMS switch is designed and after multiple iterations on cantilever structure modification the proposed structure requires low actuation voltage of 3.34 V for 3 µm deformation. This low actuation voltage is a result of identifying the critical membrane thickness of 0.5 µm, and incorporating two slots and an array of holes into the membrane. A similar iterative approach is used to design the final RF MEMS switch. The RF MEMS switch is micro-machined on a CPW transmission line with G-S-G of 85 µm - 70 µm - 85 µm. The switch RF isolation properties are analyzed for different high dielectric constant thin films including AlN, GaAs, and HfO_2. For all the dielectric thin films the RF MEMS switch shows a high isolation of -63.2 dB, but there is a shift in the radio frequency.

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