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TECHNICAL PAPER

Performance analysis of RF MEMS capacitive switch with non uniform meandering technique

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Abstract This Paper reports on investigation of High C_{on} C_{off} ratio Capacitive Shunt RF MEMS Switch and detailed comparison between uniform three meander beam with non-uniform single meander beam RF MEMS switch. RF MEMS Switches are designed for operation in the range 5–40 GHz. Pull in analysis is performed with gold as a beam material. Simulation reveals that use of high K dielectric material can drastically improve the capacitance ratio of switch. For the same geometry, pull in voltage is 2.45 V for HfO_2, 2.7 V for Si_3N_4 and Capacitive Ratio of the switch with Si_3N_4 is 83.75 and Capacitive Ratio with HfO_2 is 223 at $2g_0$ (air gap) and 0.8 µm thickness of beam. The Radio Frequency performance of RF MEMS switch is obtained by scattering parameters (insertion loss, Return loss and isolation) which are mainly dominated by down to up capacitance ratio and MEMS bridge geometries. RF analysis shows that insertion loss as low as −0.4 dB at 20 GHz and isolation as high as 80 dB at 20 GHz can be achieved. Investigation of three uniform meander Design and non-uniform single meander design reveals that use of non-uniform design reduces the design complexity and saves substrate area still maintaining almost same device performance. S-parameter analysis is carried out to compare device performance for both structures. DC analysis of the proposed switch is carried out using Coventorware and RF analysis is performed in MATLAB.

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1 Introduction

RF MEMS switches demonstrate better electrical performance and lower power consumption than their solid-state counterparts on equal size scales. The use of low resistivity metal beams combined with thin air gaps between switching parts provides high isolations (>20 dB) and small insertion losses (<0.2 dB). The non-linearity that are associated with semiconductor junctions in PIN diodes or GaAs FETs are not present except for the slight hysteresis that can be noted on CV characteristics of capacitive shunt switches. The high integration levels, non-measurable harmonics or intermodulations and negligible quiescent currents further improve the overall performance of the RF MEMS switches. Nevertheless, the lower RF power handling capability, lower switching speeds, higher actuation voltages (>10 V) and inferior reliability are issues that still prevent the widespread use of RF MEMS in many applications (Balaraman et al. 2002). MEMS shunt capacitive switches typically show very low loss and excellent trans- mission characteristics since in the up-state they mainly consist of a continuous signal line with a low shunt capacitance (Con) (Rizk et al. 2000). On the other hand when the switch is activated it short circuits the RF signal to ground, thus providing excellent isolation even at high frequencies. Nevertheless, there can be many factors limiting the switch performance. In particular, the down state capacitance (Con) is often degraded due to surface roughness and local bending of the movable bridge.

2 Description of RF MEMS switch in CPW configuration

The most common design of RF-MEMS switch is the fixed fixed beam capacitive shunt switch. Micro strip and coplanar waveguide (CPW) are the most popular transmission lines for

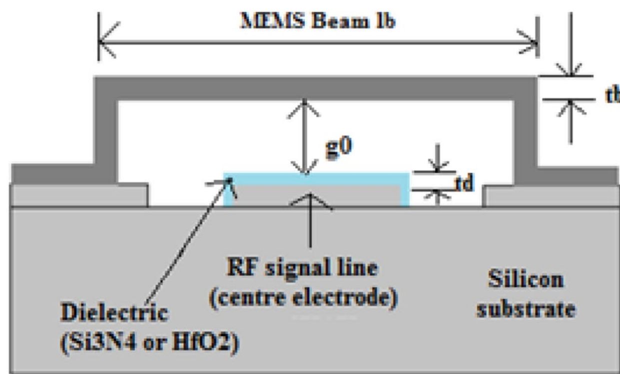

Fig. 1 Schematic of RF MEMS Switch with Si_3N_4/HfO_2 as dielectric

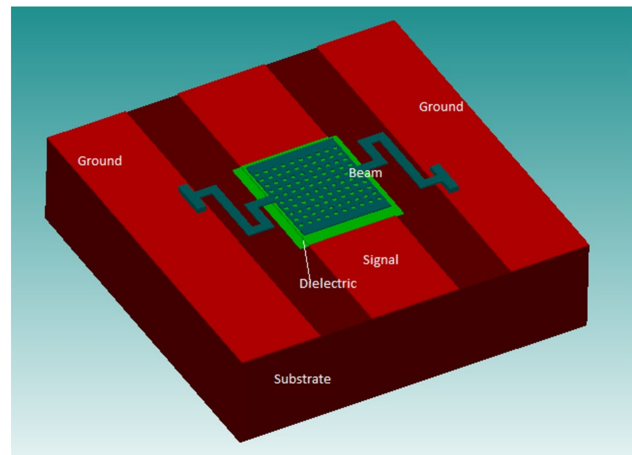

Fig. 2 3D model of non uniform one meander RF MEMS Switch

RF MEMS devices. CPW transmission line shows the integration capability of lumped component in series and shunt configuration which offers a easier access to the ground Plane and monolithic integration with RF MEMS devices whereas micro strip lines gives a limited integration capability With MEMS switches (Fedder 1994; Sharma and Gupta 2012) (Fig. 1).

When a DC voltage is applied between the MEMS Bridge and the CPW, an electrostatic force causes the switch beam to collapse on the dielectric layer, thus switch is electrostatically actuated and the switch-beam capacitance increases. This capacitance offers the connection between the ground and CPW transmission line (Hijazi et al. 2003). As switch is pulled down, the air beneath it squeezes, to reduce this damping and increase switching speed small holes are defined on the beam.

Reduction in pull in voltage can be achieved by reducing the spring constant of the beam. Over time, various designs have been proposed for shunt RF MEMS switch, mainly with more number of meander to reduce the pull-in voltage by reducing spring constant of beam. Crab- leg flexures, folded flexures and serpentine flexures are some of the common beam designs used to reduce the spring constant of beam thus reducing the pull in voltage (Sharma and Gupta 2014). After carefully examining the various designs, it is found that increasing number of meanders in the design reduces pull-in voltage at the cost of more area and increases design complexity of switch. We have carried out the comparison of the performance of uniform three meander design with non-uniform single meander design. The proposed non uniform single meander based design of RF MEMS shunt switch helped in reducing pull in voltage by reducing the spring constant at the same time saving precious switch area and reducing complexity of switch for fabrication (Sharma and Gupta 2013; Rayit 1997) (Fig. 2).

Design specification of Shunt RF MEMS switch is included in Table 1, for both uniform three meander design and non-uniform single meander design. To reduce the excitation voltage, meander structure is designed using Gold as it has smaller Young's modulus than other conductors. This results in reduction of stiffness on beam which reduces the spring constant and thus excitation voltage is reduced (Singh 2013). The beam plate over dielectric has holes of smaller dimensions to reduce damping of switch; fringing field due to these smaller holes can be neglected (Rebeiz 2003) (Fig. 3).

3 Description of RF MEMS switch

Non uniform meander RF MEM switch is designed on a coplanar waveguide (CPW) with characteristic impedance (Z_0) of 50 Ω and dimensions (G/W/G) of 60/100/60 (all in

Table 1 Design specification of uniform three and non uniform one meander perforated switch with Si_3N_4 as dielectric

Parameters	Symbols	Uniform three meander	Non uniform one meander
Beam width (μm)	w	120	120
Electrode width (μm)	W	100	100
Beam thickness (μm)	t_b	0.8	0.8
Beam height (μm)	g_0	3.0	3.0
Beam length (μm)	l_b	350	260
Dielectric constant	ε_r	7.6	7.6
Young modulus (GPa)	E	79 (Gold)	79 (Gold)
Mechanical resonant frequency (kHz)	$\mathbf{w_0}$	15.1	8.6

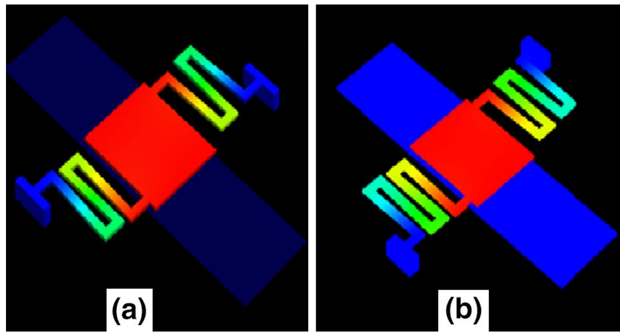

Fig. 3 Schematic view of **a** 2 meander serpentine beam **b** 3 meander serpentine beam

µm) (Rebeiz 2003). The switch is designed over a silicon substrate and separate anchors are provided for the fixed of the gold beam. In RF MEMS switches, since resistivity of the membrane directly impacts the RF performance (low RF loss), gold are the preferred choice. In this design, gold is chosen for both CPW transmission line and beam.

3.1 Operation of the switch

Electrostatic actuation is the widely used actuation mechanism in RF MEMS switches because of low power consumption and compact size, but high pull-in and low switching speed are the challenges. Although thermal and piezoelectric actuation requires less voltage to pull the beam down, they are not preferred over electrostatic method because of their complex fabrication. Electrostatic actuation overcomes the spring force to pull the membrane towards the CPW centre conductor resulting in capacitive loading of the transmission line. The pull-in voltage is given by (Muldavin and Rebeiz 2000).

$$V_p = \sqrt{\frac{8Kg^3}{27\varepsilon_0 Ww}} \tag{1}$$

The Pull in voltage is directly proportional to root over spring constant, which is a material as well as structure dependent (Jaspreet et al. 2014). Uniform three meander switch has lower value of V_{pi} of 1.4 V, whereas for same design specification non uniform one meander design has 2.7 and 2.8 V for Si_3N_4 and HfO_2 dielectrics respectively (Table 2). Deflection of beam with applied voltage shown in Fig. 4 shows the beam bending corresponding to increase in applied voltage.

3.2 ON and OFF capacitance

In the un actuated state (switch OFF), RF signal travels through the CPW transmission line unhindered by the low capacitance (a few femto farads). The UP (TX line ON) state capacitance is given by (Hijazi et al. 2003; Muldavin and Rebeiz 2000).

$$C_{ON} = \left(\frac{\varepsilon_0 Ww}{g + \frac{t}{\varepsilon_r}}\right) + C_f \tag{2}$$

where C_f is the fringing field capacitance and ε_r is relative dielectric constant. In the actuated state (switch ON), the electrostatic force pulls the membrane down, resulting in capacitive loading of the CPW transmission line. The Off state (TX line OFF) capacitance is given by (Sharma and Gupta 2012).

$$C_{off} = \frac{\varepsilon_0 \varepsilon_r Ww}{t} \tag{3}$$

The capacitance ratio is the ratio of the down-state (off state) capacitance and the up-state (on state) capacitance and is given below:

$$C_{ratio} = \left(\frac{C_{down}}{C_{up}}\right) = \frac{\frac{\varepsilon_o \varepsilon_r Ww}{t_d}}{\frac{\varepsilon_o Ww}{g_0 + \frac{t_d}{\varepsilon_r} + C_f}} \tag{4}$$

Use of High-K dielectric material improves the capacitance ratio of the switch which gives the better performance of the switch by improving the S-Parameter. Si_3N_4 with dielectric constant of 7.6 gives C_{ratio} of 83.76 and 85.5 for non uniform one meander and uniform three meander switch respectively whereas use of HfO_2 as dielectric gives C_{ratio} of 223 for beam thickness of 0.2 µm and beam height of 2.0 µm.

Table 2 Simulation data of pull-in voltage and capacitance of shunt switch for different beam structure

Parameter	Non uniform 1 meander beam								Uniform 3 meander beam			
Dielectric layer	Si_3N_4				HfO_2				Si_3N_4			
Beam thickness (µm)	0.8			0.6	0.8			0.6	0.8			0.6
Beam height (µm)	2.0	2.5	3.0	2.0	2.0	2.5	3.0	2.0	2.0	2.5	3.0	2.0
Pull down voltage (V)	2.7	3.87	4.87	2	2.8	3.87	4.9	2	1.4	2.2	2.6	1.2
Up-capacitance (fF)	60.89	51.09	44.41	60.70	63.00	53.05	46.62	62.70	64.32	53.64	46.46	63.5
Down capacitance (pf)	5.1	5.23	5.4	5.46	14.1	14.45	14.3	14.9	5.5	5.34	5.54	5.7
Capacitance ratio	83.76	102.3	121.5	89.9	223	272.3	306.7	237.6	85.5	99.5	119	89.7

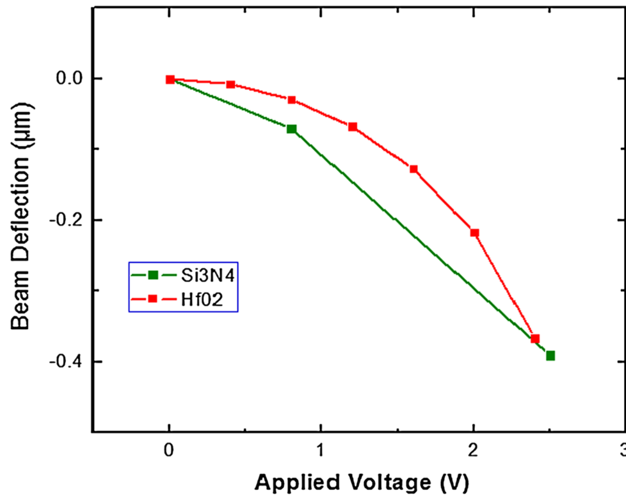

Fig. 4 Pull in voltage for Si_3N_4 and HfO2 at 2go gap height non uniform one meander beam

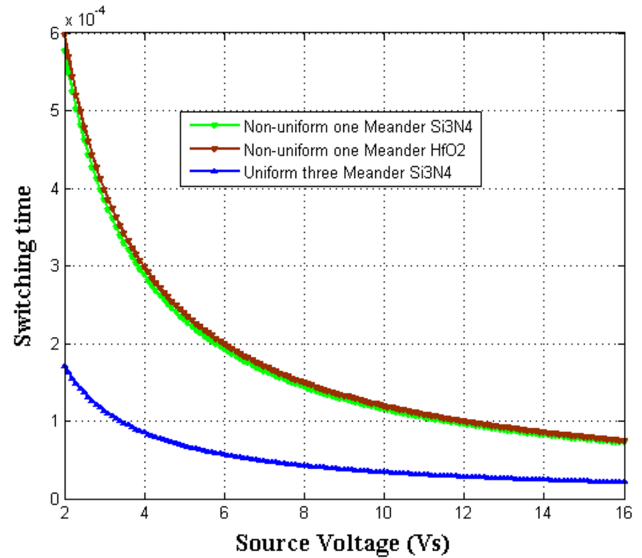

Fig. 5 Switching time comparison of uniform and non-uniform structure beams

3.3 Switching time analysis

Switching time is the important characteristics for RF MEMS switch. The switching time is a function of the pull-in voltage (V_{pi}), the applied voltage (V_s) and the mechanical resonant frequency (ω_0) of the RF MEMS switch. Switching time gives the rate at which the switch toggles from one state to the other. The switching time depends largely on the applied voltage, since larger voltage lead stronger electrostatic force thus overpowering the mechanical restoration force at faster rate. The switching time is dependent on the applied voltage by the relation shown (Fig. 5).

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

Mechanical resonant frequency of the uniform three meander and non uniform single meander design is calculated by Coventorware simulation of the shunt switch model as 15.1 and 8.6 kHz respectively (Table 1). Increase in number of meander reduces the stiffness of beam as a result we have V_p of uniform three meander beam lesser than that of one meander structure (Bedier and AbdelRassoul 2013). Also from relation (5) switching time is directly proportional to V_p, thus we see the switching time of switch t_s, at $V_s = 2$ V, is 0.18 ms for uniform three meander and for non-uniform one meander beam it is 0.6 ms.

4 Performance of scattering parameters

RF MEMS switch electrical performance has been characterized by s-parameter in up and down state of the MEMS Bridge. This RF MEMS switch can be modelled as two port network with a shunt connection. The general S parameter for RF-MEMS switch can be given as (Fedder 1994):

$$S_{11} = -20 \log \left| \frac{-Z_b}{2Z_b + Z_0} \right| \tag{6}$$

$$S_{21} = -20 \log \left| \frac{2Z_b}{2Z_b + Z_0} \right| \tag{7}$$

where Z_b is the MEMS bridge impedance and Z_0 is the CPW characteristic impedance. The S-parameters S_{11} and S_{21} have been estimated in upstate position of the MEMS bridge, which represents the return loss and insertion loss. In downstate position S_{21} represents the isolation of the RF MEMS switch. Here the return losses S_{11} have been estimated in both up and down state positions. The total capacitance of the RF-MEMS switch in actuated and un actuated state determine the insertion and isolation over the range of frequencies (Rayit 1997). All RF MEMS switches require a large down to upstate capacitance ratio to maintain high isolation and low insertion loss. These scattering parameters have been calculated for different up state capacitance and down state capacitance with bridge resistance, bridge inductance, CPW transmission line impedance (Z_0) of 0.5 Ω, 7 pH, 50 Ω respectively.

S-Parameter of a RF MEMS switch is a best indicator of its performance as an efficient switch. With the help of Eq. (6), we can calculate the parameter of RF MEMS switch such as return loss, insertion loss and isolation loss given the capacitance of the switch. Uniform three meander switch with Si_3N_4 as dielectric has un-actuated capacitance of 64.32 fF and actuated capacitance of 5.5 pF. For non-uniform one meander beam structure un-actuated and

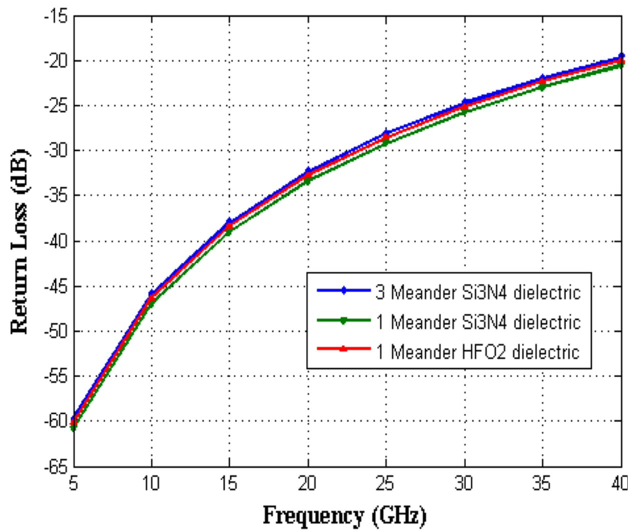

Fig. 6 Return loss of RF MEMS switch in un-actuated state

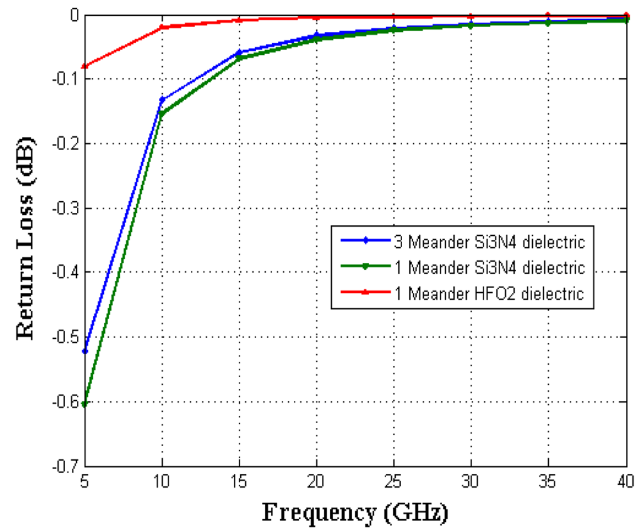

Fig. 8 Return loss of RF MEMS switch in actuated state

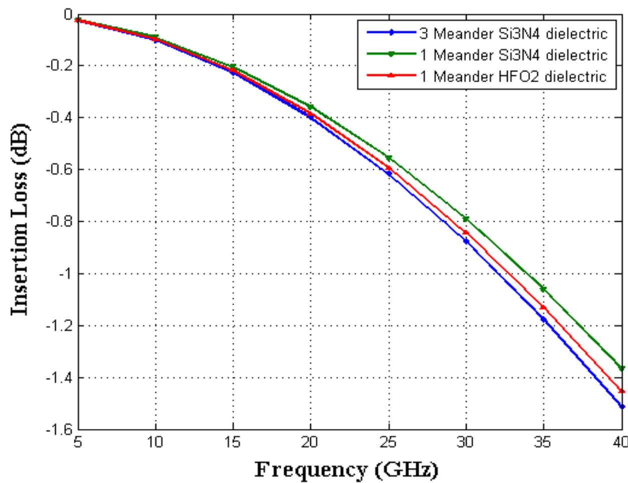

Fig. 7 Insertion loss of RF MEMs switch in un actuated state

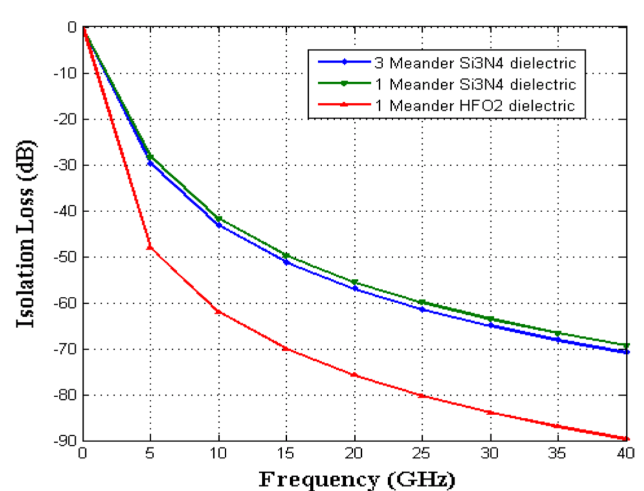

Fig. 9 Isolation of RF MEMS switch in actuated state

actuated capacitance details for Si_3N_4 and HfO_2 as dielectric is tabulated in Table 2.

The isolation improves for higher downstate capacitance as frequency increases. This higher downstate capacitance is required for higher isolation at higher frequencies, and it can be achieve by using higher bridge width. The return loss decreases and approaches to almost 0 dB for different down state capacitances at higher frequencies. At low frequencies in actuated state, these return losses can also be further improved by using a MEMS bridge with large width (Fig. 6).

The isolation improves for higher downstate capacitance as frequency increases. This higher downstate capacitance is required for higher isolation at higher frequencies, and it can be achieve by using higher bridge width. The return loss decreases and approaches to almost 0 dB for different down state capacitances at higher frequencies. Insertion loss, return loss and isolation graphs are plotted for three different configurations like three uniform meander, one non uniform meander with Si_3N_4 and one non uniform meander with HfO_2 respectively (Figs. 7, 8, 9).

4.1 S-parameter for non uniform one meander switch with different dielectric thickness

The S_{11} and S_{21} parameters for one-meander non-uniform switch in un-actuated state and actuated state for different dielectric thickness are discussed in this section. Up-state capacitance shows negligible variation with dielectric thickness, thus no change in the return loss (Fig. 10) and

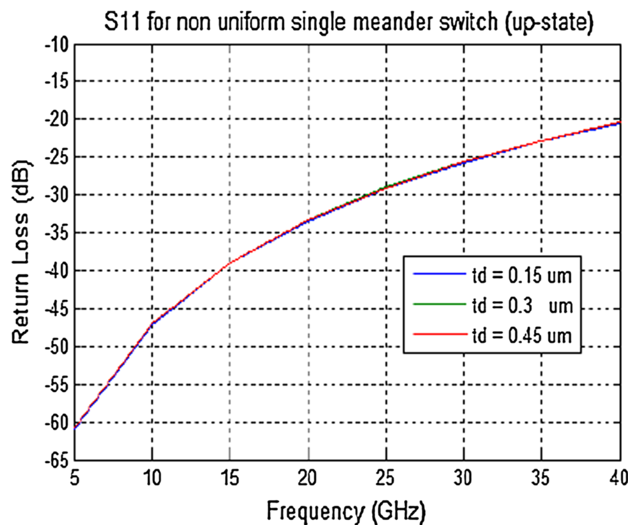

Fig. 10 Return loss (dB) in ON state for different dielectric thickness

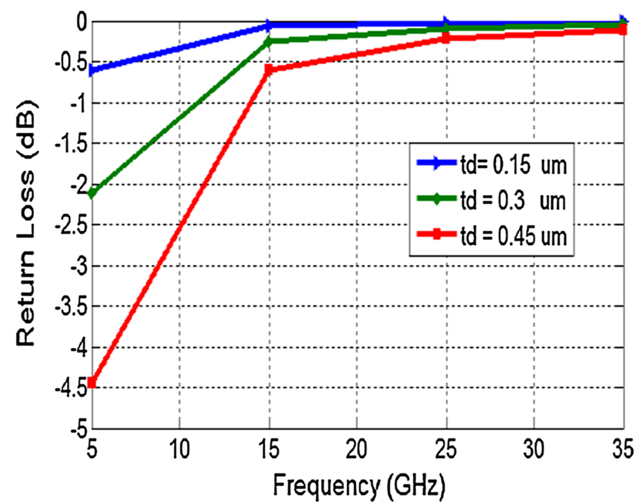

Fig. 12 Return loss (dB) in OFF state for different dielectric thickness

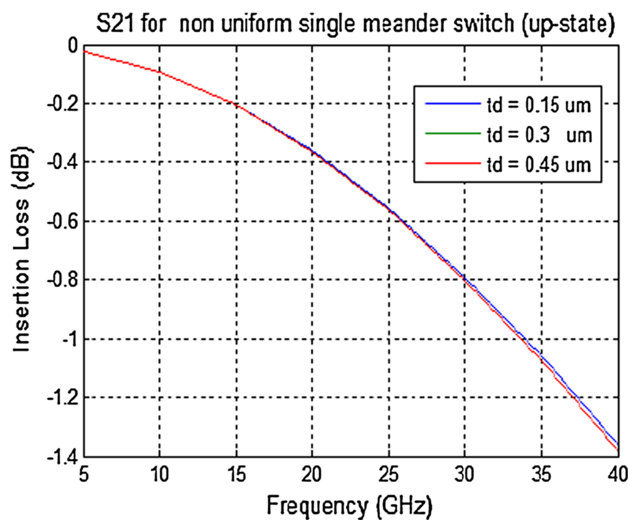

Fig. 11 Isolation loss (dB) in OFF state for different dielectric thickness

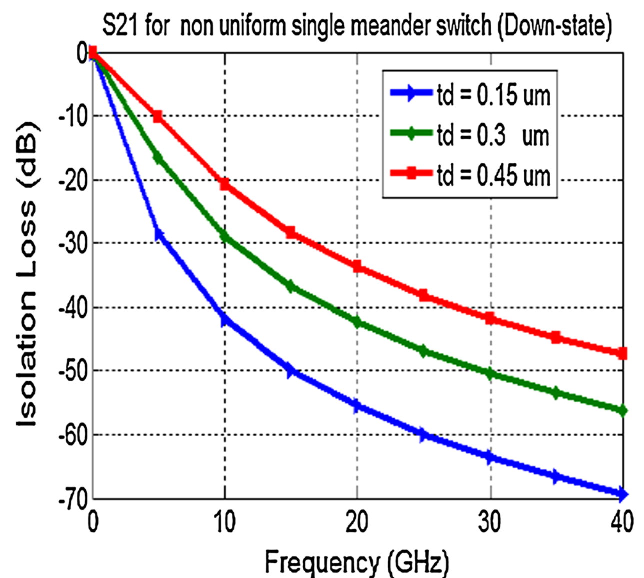

Fig. 13 Isolation loss (dB) in OFF state for different dielectric thickness

also no change in the insertion loss (Fig. 11) of the switch is noticed with various dielectric thicknesses. The ON state return losses (S_{11}) are <−20 dB for all the dielectric thickness, from DC up to 40 GHz and insertion losses (S_{21}) are <−0.6 dB at 25 GHz.

In the down state, air gap is absent; the separation of beam with electrode is only due to dielectric thickness. Thus the return losses, S_{11} (Fig. 12) and isolation loss, S_{21} (Fig. 13) vary with the variation of the dielectric thickness. At lower frequency of 15 GHz return loss is −1 dB and the isolation is vary with the variation of the dielectric thicknesses.

5 Comparison between contemporary result and proposed enhancement

The current work has been compared with other recent works in this field in terms of Actuation Voltage, Up and Down state capacitances and S-parameter (Table 3). Our proposed work is in accordance with contemporary works in the field and its performance is found to be better in terms of Pull up voltage, Capacitance ratio and s-parameter. In the ON-state, the up-state capacitance was found to be 44.41 fF for the switch at height of 3.0 μm, and thus

Table 3 Comparison between contemporary work in RF MEMS switch and proposed work

Parameters	Similar work (Mafinejad et al. al 2012)	Similar work (proposed value) (Ramli and Sidek 2012)	Similar work (Verma and Singh 2013)	Similar work Three uniform meander with-out perforated beam with Si_3N_4 (Taye et al. 2013)	Non uniform one meander perforated beam with Si_3N_4 (This work)	Non uniform one meander perforated beam with HfO_2 (This work)
Pull down voltage (V)	<12	3	35	6.25	4.87	4.9
Up capacitance (fF)	–	39.9	82	47.2	44.41	46.42
Down capacitance (pF)	–	3.38	6.32	5.53	5.4	14.3
Capacitance ratio	–	84.7	77.073	117	121.5	306.7
Mechanical resonant frequency (kHz)	–	9.2	–	21.21	8.6	8.7
Switching time (µs)	–	–	–	11.47	21.7	21.4
At frequency (GHz)		40	25	25	25	25
Return loss (up state)	<−10 dB	−11.8 dB	−20 dB	<−40 dB	<−40 dB	<−40 dB
Insertion loss (up state)	−0.5 dB	−0.29 dB	–	<−0.3 dB	<−0.3 dB	<−0.3 dB
Return loss (down state)	–	–	–	0 dB	<−0.1 dB	<−0.1 dB
Isolation (down state)	<−10 dB	−26.69 dB	−30 dB	>−60 dB	>−60 dB	>−80 dB

gives a good return loss (S_{11}) of −20 dB at 40 GHz. The insertion loss (S_{21}) was found to be <−0.75 dB for DC up to 40 GHz. In the OFF-state, the down-capacitance of the switches was found to be 5.4 pF with Si_3N_4. This gave isolation (S_{21}) higher than 40 dB at frequencies of 10–20 GHz for the switch in the actuated state.

It is observed from pull in voltage expression (Eq. 1) and can thus be concluded from simulated results (Table 2) that the spring constant of the beam can be reduced by increasing the meander sections and the lesser spring constant will result in lower actuation voltage with other parameters remain same. Low spring constant of the switch depends on the beam material used. For low insertion loss in the ON-state, the up-state capacitance should be as low as possible, thus preventing any capacitive coupling between the beam and the t-line. The low up-state capacitance depends on the beam height and can be achieved at larger air gaps. For high isolation in the OFF-state, the down-state capacitance should be as high as possible, thus shorting maximum amount of signal to the ground.

A high down-state capacitance can be achieved at a higher actuation area of the beam. But increasing the actuation area also increases the up-state capacitance, thus leading to trade-off in both the capacitance values.

6 Result analysis

Analysis of capacitive shunt RF MEMS switch for applications in the range of 5–40 GHz is discussed. Simulation results show that the performance of uniform three meander switch is at par with non-uniform one meander Si_3N_4 switch. Further non uniform one meander HfO_2 has the higher capacitance ratio than non uniform one meander Si_3N_4. We have seen that the insertion loss is −0.4 dB at 20 GHz for both non-uniform one meander HfO_2 and Si_3N_4 but no changes in the return loss in the up state. Return loss in down state for HfO_2 is <−0.1 dB but for Si_3N_4 is—0.6 dB whereas for uniform three meander Si_3N_4 it is −0.5 at 5 GHz and isolation is also very good almost 90 dB at 40 GHz for non-uniform one meander HfO_2 and for non-uniform one meander Si_3N_4 is 70 dB at 40 GHz.

7 Conclusions

The comparative analysis between contemporary work in RF MEMS Switch and proposed work (Table 3) reveals the advantage of non uniform meander RF MEMS switch over uniform meander switch in terms of pull in voltage and up capacitance. It is also observed that the no. of meander sections in non uniform meander suspension is required less than that of in uniform meander structure to attain nearly

equal pull in voltage which can lead to less structure complexity. Further we have analysed the advantage of non-uniform one meander HfO_2 over Si_3N_4 switch in terms of improvement of C_{on}/C_{off} ratio. We have further investigate the s-parameter of the switch and found that it shows negligible difference in up-state but in the down state it shows improvement in isolation because isolation depend on the downstate capacitance and the air gap of the Switch.

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