On the investigation of an interdigitated, high capacitance ratio shunt RF-MEMS switch for X- band applications

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ABSTRACT

This paper presents a novel, highly compact capacitive shunt RF MEMS switch. In the presented configuration interdigitation of signal lines with actuation electrodes is considered. The compactness has been achieved further by incorporating HfO_2 a high -k dielectric material in place of traditionally used SiO_2. The capacitive overlap area reduces by 70% , leading to the overall reduction of about 15% in the switch size. Switch with HfO_2 optimized for X - band shows -56.78 dB isolation and - 0.058 dB insertion loss at 10 GHz as compared to the -40.8 dB isolation, -0.1 dB insertion loss for the switch with SiO_2. Significant improvement in switching time is also observed. Pull-in voltage of 5.6V is obtained at a gap of 1um between bridge and transmission line. The compact switch can be useful for the future communication applications.

Keywords: Compact switch, Dielectric, HfO_2, Interdigitated, RF MEMS.

1 INTRODUCTION

The advantages of RF-MEMS switches over their mechanical and solid state counterparts are low insertion loss, less power consumption, high isolation, wide bandwidth and integration with electronics. These switches are broadly classified as series metal to metal contact and shunt capacitive and can be used in a variety of RF applications including cellular based station, mobile handsets, tunable filters, phased array antenna, signal routing and phase shifters [1-4]. The shunt capacitive switches require high down state to up state capacitance ratio in order to have good insertion loss and isolation. The large overlap area, higher gap and materials with high dielectric constant can be used to achieve high C_{down}/ C_{up} ratio. However, for large area devices in-built stress related deformation and slow response puts the limit on the avaliable options. Further in the future wireless trans-receives higher compactness will be required. A number of switch structures have been reported in the literature for capacitive shunt RF-MEMS switches which requires moderate pull-in voltage and large area [5-8].

2. Device Description

In the present work a novel capacitive shunt RF-MEMS switch has been investigated. Transmission line is continous in shunt switches therefore switch is normally ON. Broadside shunt capacitive switch based on a 50 Ω CPW is implemented with a bridge structure because of its low sensitivity to variation in pull-in voltage due to stress gradient developed during the fabrication process. In order to reduce the pull-in voltage four flexures and a perforated central plate have been used. Switch is anchored on the ground plane of CPW. The signal lines are interdigitated with the actuation electrodes to reduce the overall area occupied by the switch [9]. The actuation electrodes are placed below the central plate of bridge structure to further reduce the pull-in voltage. In off state of switch there is a gap of 2 µm between switch and central conductor of CPW. Transmission line is at a height 0.5 um from the actuation electrodes. This is done to avoid stiction, enhance the contact reliability and to decrease the switching time. Figure 1 shows flexure used in determing the spring constant and Figure 2 (a,b) shows the models of the switches.

3. Mechanical Design

In mechanical design the important parameter is the spring constant k of the structure. The bridge is modelled as four cantilevers with guided end. The spring constant for a guided end cantilever [3] is given by the equation

$$k_z = EWt^3/L^3 \quad (1)$$

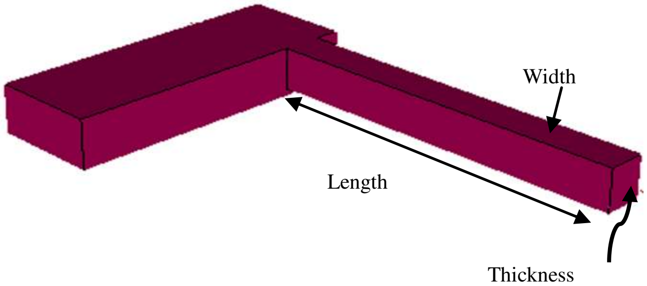


Fig.1. Magnified view of flexure.

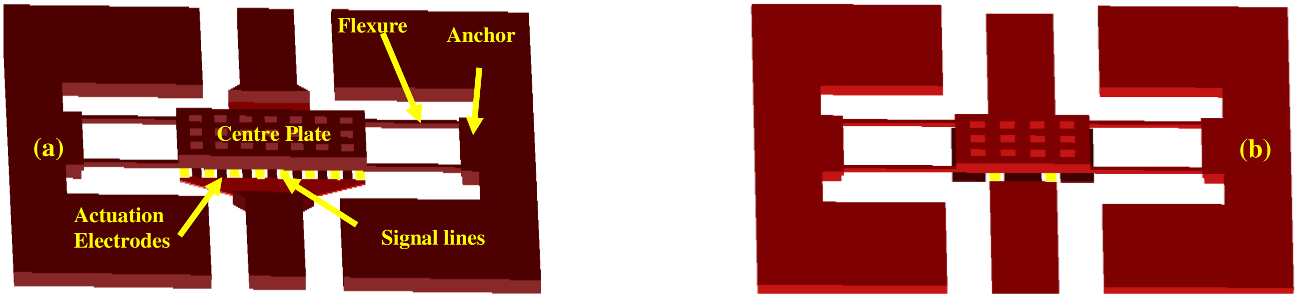


Fig.2. Model of the switch optimized for X - band using (a) SiO_2 (b) HfO_2.

where k_z = spring constant in the z direction, E (80 GPa) = Young's Modulus of the beam, E' (effective Young's Modulus = $E/(1-v^2)$ when $W \geq 5t$ [10] , v = Poisson's ratio, W (10µm) = width of flexure, t (1.5µm) = thickness of flexure, L (150µm) = length of flexure**.** As there are four such beams in parallel so the equivalent spring constant of the structure is $K_z = 4k_z = 3.65$ N/m.

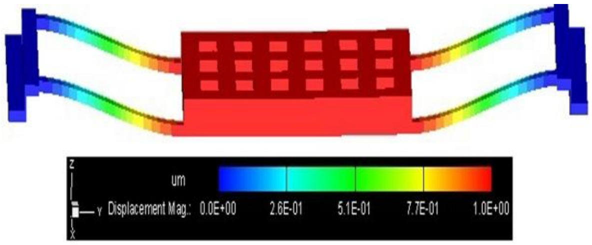


Fig.3 Displacement of the beam in Z-direction.

4. Electro-Mechanical Design

At pull-in condition (when beam has travelled a distance of d/3) spring force becomes equal to electrostatic force [3] i.e.

$$0.5\varepsilon_o A V_p^2/(d-d/3)^2 = (K_z d)/3 \tag{2}$$

$$V_p = \sqrt{(8\ K_z d^3/27\varepsilon_o A)} \tag{3}$$

where ε_o = air permittivity, A =22450,13400 μm^2 = area of actuation for SiO_2 and optimized HfO_2 switch respectively, d (2.55 µm) = initial distance between movable beam and actuation electrode, V_p= pull-in voltage. Figure 3 shows the displacement of beam in z direction under pull-in condition. Figure 4 and 5 shows the simulated result of pull-in voltage for the switches with SiO_2 and HfO_2 at d= 2.55 µm, 1.55 µm respectively. The results are in close agreement with analytically calculated values.

5. Dynamic Response

The switching speed of MEMS switch is of main interest for many telecommunication applications. The switching time depends on various mechanical and electrical parameters like natural frequency of the movable parts, damping and ratio of pull-in to supplied voltage. In the present case switching time simulation is done when supply voltage is equal to the pull-in voltage and under the undamped condition. Figure 6 shows the switching time resopnse for the switches. It can be observed that optimized HfO_2 switch is having less switching time as mass of the central plate is decreased resulting in increase in natural frequency of the bridge.

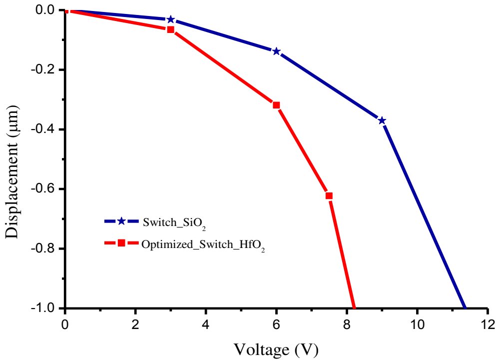


Fig.4. Pull-in voltage of switch with SiO_2 and optimized switch with HfO_2 at d = 2.55 µm

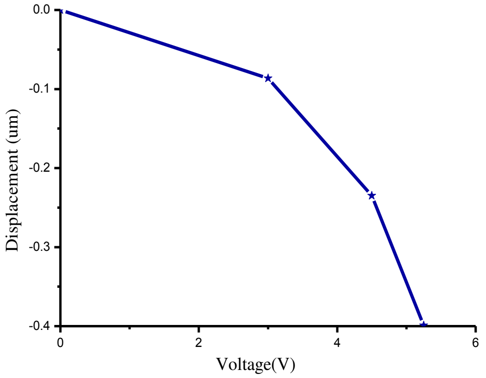


Fig. 5. Pull-in voltage of optimized HfO_2 switch at d = 1.55 µm

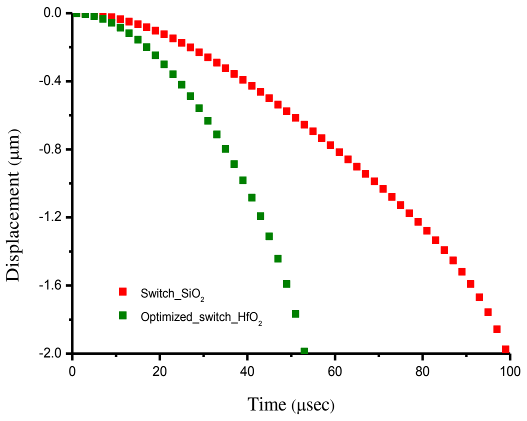


Fig. 6. Switching time response of switch with SiO_2 and optimized switch with HfO_2

Furthur bridge spends the majority of time in reaching the d/3 distance. Increasing the electrostatic force during this phase can decrease the switching time. This can be done by applying $V_s / V_p \geq 1$, where V_s = supply voltage.

6. RF Response

RF-MEMS capacitive switches use SiO_2 as a dielectric material. However low dielectric constant requires larger overlap area for the same frequency band operation as compared to high-k dielectric material as per equations given below.

$$C_{up} = \varepsilon_o A/ (g_o + t_d / \varepsilon_r) \qquad (4)$$

$$C_{down} = \varepsilon_o \varepsilon_r A/t_d \qquad (5)$$

$$C_{ratio}\ (C_{down}/ C_{up}) = 1 + g_o\, \varepsilon_r / t_d \qquad (6)$$

where g_o = initial gap between bridge and central conductor of CPW, A = capacitive overlap area, ε_r = relative permittivity, C_{up} = capacitance in the up state of the switch, C_{down} = down state capacitance of the switch and C_{ratio} = ratio of the capacitance in down state to the up state. A high capacitance ratio is desirable as more down capacitance provides good isolation and less capacitance in upstate provides good insertion loss. The High-k materials that can replace SiO_2 are Si_3N_4, Ta_2O_5, BST, strontium titanate oxide but HfO_2 (ε_r = 17 - 25) can be good alternate. It can be deposited up to 45 nm and has dielectric strength higher than 10MV/cm. It also shows better reisitance to dielectic charging and compatible with IC technology [11].

Figure 7 shows the OFF state response of the switch with same dimensions but using SiO_2 and HfO_2 with a deposited thickness of 50 nm. Isolation peak shifts to lower frequency range for HfO_2 switch because of high capacitance ratio. Figure 8 compares the ON state response of the switches. The response is almost simillar as C_{up} formation is same. For tuning the HfO_2 switch in the X-band capacitive overlap area has reduced by 70% which leads to overall reduction of 15% of switch size. Further brining the compactness in the switch structure.

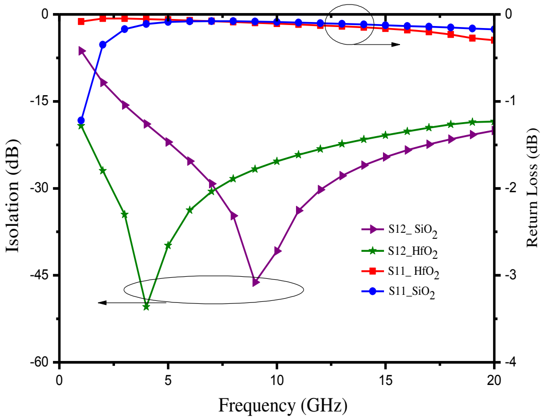
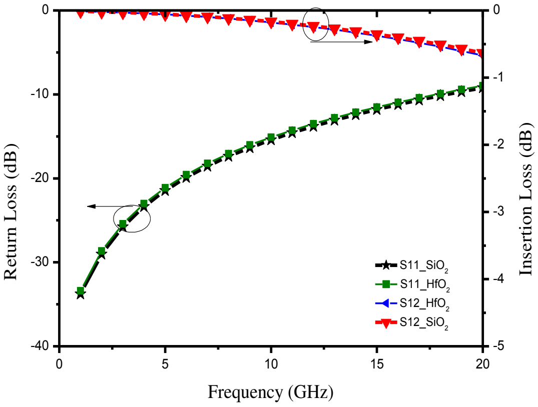


Fig.7. Switch isolation and return loss as a function of frequency (down position)



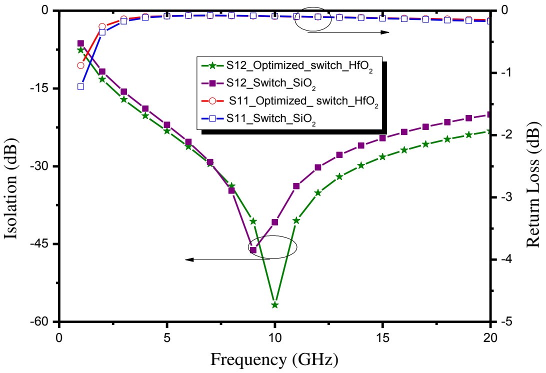


Fig.8. Insertion and return loss as a function of frequency

Fig.9. Comparision of OFF state reponse of switch with SiO2 and optimized Switch with HfO_2

Fig. 9 and 10 show the improveemnt in isolation and insertion loss for optimized switch at g_o = 2 µm. It is observed that even at $g_o = 1$ µm doesn't hamper the RF performance of the optimized HfO_2 switch because of reduced overlap area.

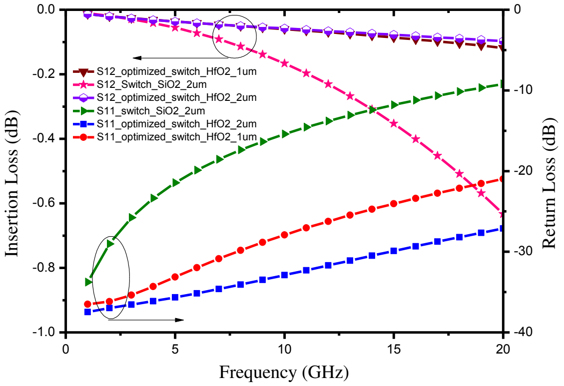


Fig. 10. Comparision of ON state reponse of switch with SiO_2 and optimized Switch with HfO_2

CONCLUSION

A novel shunt capacitive RF- MEMS switch with HfO_2 has been investigated. It is observed that switch shows significant imrovement in RF, electomechnical and dynamic performance with higher compactness as compare to the switch with SiO_2. Further the switches with the same dimensions and masks having different dielectic materials can be tuned for different frequency bands. The designed switch can be a good alternate for the future multiband, highly compact wireless trans-receivers as compared to the conventional RF- MEMS switches.

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