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Design and Simulation of Compact, High Capacitance Ratio RF MEMS Switches using High-K Dielectric Material

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Abstract

In this paper, RF MEMS Capacitive Switches for two different dielectrics hafnium oxide (HfO_2) and silicon nitride (Si_3N_4) are presented. The switches have been characterized and compared in terms of RF performance. The major impact of the change from Si_3N_4 to HfO_2 having dielectric constant 20 is the reduction in overall dimension of the switch; capacitive area is reduced by 66% leading to overall reduction of about 41%. For 50nm thick HfO_2, the HfO_2 switches systematically shows an improvement in the isolation by more than -8dB (-35.16 versus -26.03 dB) and better insertion Loss at 12 GHz frequency compared to Si_3N_4. This makes HfO_2 an attractive dielectric for RF MEMS switch for new generation of low-loss high – linearity microwave switches.

Keywords: RF Switch; Actuation voltage; Coplanar waveguide; Down-state capacitance; Insertion loss.

1. Introduction

RF MEMS switches have drawn a lot of attention in the recent years because o their superior characteristics such as low insertion loss, high isolation and negligible power consumption compared with semiconductor switches. Due to the excellent performance at microwave to mm- wave frequencies have found applications in wireless and satellite communication system. A variety of RF MEMS switches have been designed with various actuation mechanisms such as electrostatic , piezoelectric or electro-thermal to operate the switch between two states (ON and OFF). Electrostatic actuation is most commonly preferred because of its low power consumption and simple fabrication technology. In capacitive type switches, in order to achieve better RF characteristics, a large capacitance ratio is desirable. Different methodologies have been adopted in order to achieve high capacitance ratio such as [1] Large overall Area, [2] Higher Gap and [3] Dielectric material with high-dielectric constant. This results in increase in overall dimension of the devices leads to in-built stress related deformation. Reliability is another main issue in RF MEMS switches. Stiction is a major limiter in the reliability of RF MEMS Capacitive switches due to dielectric charging. Charge trapping in Si_3N_4 dielectric layer results in the stiction of the switches when switches are actuated between the two states, high dielectric field across the thin dielectric layer causes positive and negative charge to tunnel into the dielectric and become trapped which depends upon the polarity of bias voltage. To eliminate this problem, many different solutions have been proposed such as the use of dielectric free capacitive switches, leaky dielectric so that charges can be easily detrapped, the bipolar activation alternatively switching actuation voltage between positive and negative levels and the other suitable dielectric by replacing Si_3N_4. This paper presents RF MEMS Capacitive Switch based on HfO_2 dielectric which results in reduction in overall dimension of the switch and results are compared with those for Si_3N_4 as a dielectric material.

2. Description of Switch

2.1 Device Concept

Three terminals RF Capacitive switch is based on 50Ω CPW configuration with movable metal beam made of conductive materials like Gold, Al etc. is mechanically anchored and electrically connected to the ground of CPW. The movable beam is suspended over a signal line as well as actuation electrodes at a gap of 2.5 µm on which a thin dielectric film is deposited. Two actuation electrodes introduced an additional degree of freedom. Figure [1] shows the working principle of switch. As shown in figure, when no bias voltage at the actuation electrode, the beam is at a 2.5 µm gap from the signal line; provides low insertion loss. Bias voltage applied at the actuation electrodes forces the beam to make a contact with signal line dielectric providing isolation in OFF- state. Equation 1 describe the pull-in voltage in terms of geometrical dimension of movable beam

$$V_P = \sqrt{\frac{8K_z g^3}{27\varepsilon_0 A}} \qquad (1)$$

Where g is the gap, A is the overall area and K_z is the spring constant of beam respectively.

2.2 High-K Dielectric Material

Different types of high-k dielectric materials are available that could replace Si_3N_4 are tantalum oxide, hafnium oxide, barium strontium oxide, Al_2O_3 etc. Many of these materials are thermodynamically unstable on silicon and doesn't meet other properties such low leakage current, high dielectric breakdown etc. Hafnium Oxide is one of the best materials in high- k dielectric because of its high dielectric constant and good process compatibility with concurrent IC technology. It also shows better resistance to dielectric charging, low leakage current and can be deposited as a thin layer down to 45nm. So hafnium oxide is suitable for various applications. The design parameters of RF MEMS Capacitive switch are shown in table 1.

Table 1: Design Parameters of RF MEMS Capacitive Switch.

Dimension of Switch		
	Reference Switch	Optimized Switch
Beam Thickness	1.5µm	1.5µm
Beam Length	500 µm	425 µm
Beam Width	100 µm	58µm
Gap Height	2.5 µm	2.5µm
Area	100×100 µm2	58×58 µm2
Electrode Thickness	1 µm	1 µm
Oxide Thickness	1 µm	1 µm
Dielectric Thickness	0.1 µm	0.05 µm
Secondary Meander Length	100 µm	100 µm
Primary Meander Length	30 µm	20 µm
CPW	60/100/60	40/58/40
Young's Modulus of Gold	79GPa	79GPa
Poisson's ratio of Gold	0.44	0.44
Dielectric constant	7.6(Si3N4)	20(HfO2)

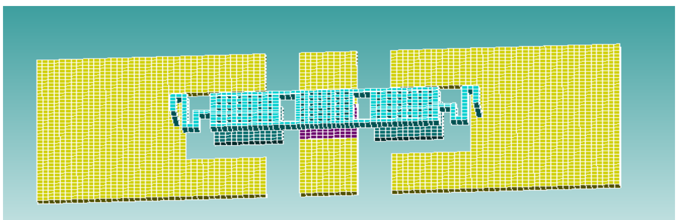
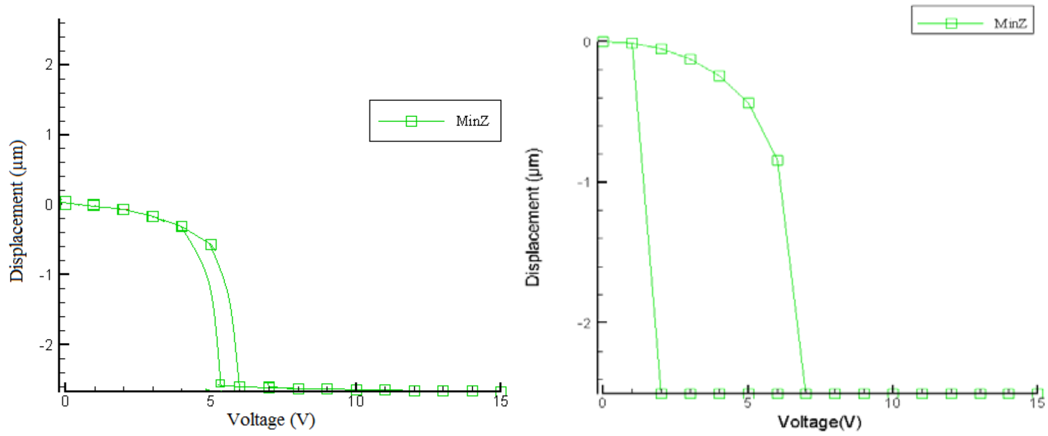


Figure 1: RF Capacitive Switch

3. Simulation Results

3.1 DC Simulation

DC Simulations are done using CoventorWare software. 3D model of switch made using this software is shown in figure 1. Pull-in voltage, charge, capacitance, electrostatic force for switch is studied under DC simulation. . Pull-in voltage comes out to be 4.8 to 5.2V for switch based on Si_3N_4 and for optimized switch based on HfO_2 as a dielectric. Mechanically optimized switch shows better response as compared Si_3N_4 based switches. Hysteresis loss is minimal in case of HfO_2 based optimized switches as shown in fig.2(a) as compared with Si_3N_4 based switches as shown in fig 2(b).



(a) (b)

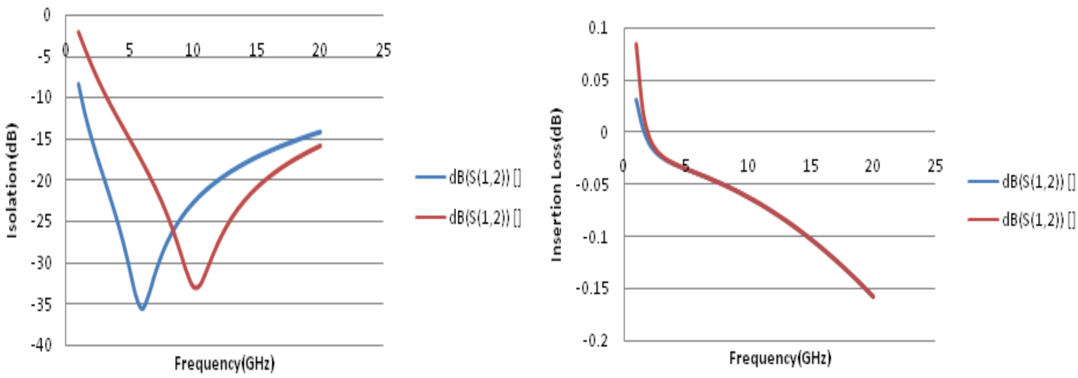
Figure 2: Comparison of Hysteresis Curve for Optimized HfO2 (a) and Si3N4 (b) based switches.

3.2 RF Simulation Comparison between HfO_2 and Si_3N_4

S-parameters measurements have been performed to compare the RF performance of the switches with different dielectric material using eq.(2) and (3). For equivalent dimension HfO_2 based switches shows better isolation and insertion loss at lower frequencies compared to Si_3N_4. Fig. 3(a) and 3(b) shows ON state and OFF state parameters of switch having same dimension but with different dielectric material. Isolation peak shifts to lower frequencies range with change in dielectric layer from Si_3N_4 to HfO_2 due to high capacitance of HfO_2. The advantage can be utilized by reducing the capacitive area to shift the operating frequencies in X-band. Using high –k dielectric materials results in reduction in overall dimension of the switch. Using HfO_2 as a dielectric in switch results in reduction of capacitive area of switch to almost 66% and this shows that the dimension of overall switch reduces upto 41 % of the dimension of Si_3N_4 based switches.

$$|S_{11}|^2 \approx \frac{\omega^2 C_u^2 Z_0^2}{4} \tag{2}$$

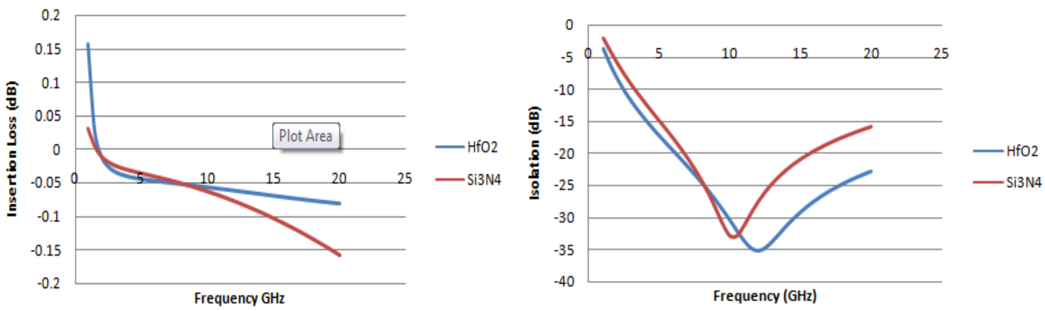
$$|S_{21}|^2 \approx \frac{4}{\omega^2 C_d^2 Z_0^2} \tag{3}$$



(a) (b)

Figure 3: Comparison of (a) OFF state,(b) ON state response of switch with different dielectric materials for same dimension.

Fig. 4(a) and 4(b) shows the response of switch with Si3N4 as a dielectric and optimized switch with HfO2 as a dielectric in OFF and ON state respectively. Isolation in OFF and Insertion Loss in ON state is better in case of optimized switch with HfO2 as a dielectric as compare to Si3N4 based switch.



(a) (b)

Figure 4: Comparison of (a) ON, (b) OFF state response of switch with Si3N4 and Optimized switch with HfO2 as dielectric.

4. Conclusion

The design optimization of switch has been presented by changing the dielectric from Si_3N_4 to HfO_2 for X-band (8-12GHz) applications. The shift in isolation curve due to change in dielectric layer has been studied. For X- band, the overall dimension of the switch can be reduced upto 41% while capacitive area reduction is 66% when changing dielectric to HfO_2 from Si_3N_4. Mechanical behavior of two configuration are also compared.

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