Design of compact, high capacitance ratio MEMS switch for X - Band applications using high-*k* dielectric materials

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ABSTRACT

The paper discusses the design aspects of capacitive RF MEMS Symmetric Toggle Switch (STS) with particular emphasis on device compactness, reliability, and improvement in isolation & insertion loss by incorporating hafnium dioxide (HfO_2) as a dielectric material. The major impact of the change from SiO_2 to HfO_2 having dielectric constant of 20, is the reduction in overall dimensions of the switch; capacitive overlap area is reduced by 75% leading to overall reduction of about 50%. Significant improvement in isolation (-43dB) and insertion loss (-0.014dB), at 11 GHz with 50 nm thick HfO_2 as a dielectric layer compared to -29 dB and -0.016 dB @ 11 GHz respectively for SiO_2 makes hafnium dioxide an attractive dielectric for RF micro-electro-mechanical systems (MEMS) switch for new generation of low-loss high-linearity microwave circuits.

Keywords: symmetric toggle switch, RF MEMS switch, insertion loss, isolation, dielectric, hafnium oxide.

1 INTRODUCTION

RF MEMS switches have drawn a lot of attention in the recent years and remarkable advances have been made in the research and development of RF MEMS switches [1-5]. The switches are widely applied in wireless communication systems such as switching networks, phase shifters, receivers and transmitters. Some of the switch designs have already been commercialized. MEMS switches closely resemble the electro-mechanical relays except the dimensional scale, superior performance and negligible power consumption. Analogous to other switches they have two stable states. Switching between these two states is achieved through the displacement of a movable membrane actuated by electrostatic, piezoelectric, electro-thermal or electromagnetic actuation mechanism. In comparison to contemporary state of the art solid state semiconductor switches like PIN diodes and FETs, MEMS devices show excellent performance characteristics in terms of lower insertion loss, good isolation, large power handling capability and linearity. Majority of MEMS switches rely on electrostatic actuation which offers extremely low power consumption, simple fabrication technology and high degree of compatibility with standard IC processing. The bandwidth of RF shunt switch is directly related to the ratio of the down-state to the up-state capacitance. In capacitive type switches, in order to achieve better isolation and insertion loss characteristics a large down/up capacitance (C_{down}/C_{up}) ratio (>100) is desirable. In general large overlap area, higher gap and dielectric materials with high dielectric constants can be used to achieve high capacitance ratio. The accompanied increase in overall dimensions of the device leads to in-built stress related deformation, limiting the usage over desired frequency range. Reliability against self biasing, external shocks & vibrations and the power handling capability of RF switches are other important issues which need to be considered along with electro-mechanical properties of the devices. Switch immunity to self-biasing and external vibrations can be improved, for example in meander based switches [6] by fabricating a second bridge to clamp the membrane in on-state thus making the structure impervious to self biasing and the external vibrations. The mechanism not only meliorates the reliability but also the RF characteristics of the switches. STS is a capacitive type switch, which is based on push – pull mechanism to obviate the problem of self-biasing and external vibrations. As shown in Fig. 1 the device consists of a pair of micro-torsion actuators placed symmetrically around the transmission. This reduces the in-built stress related deformation, though devices become longer compared to other similar topologies.

This paper introduces an approach to reduce the overall dimensions of STS and to improve the electrical parameters by incorporating Hafnium oxide as a dielectric material. Design approach and results of optimized STS with HfO_2 as

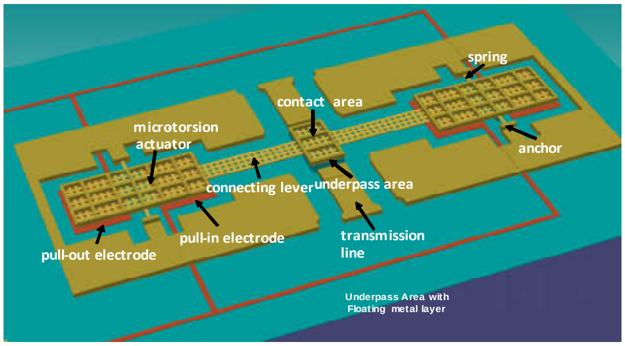

Figure 1. 3-D view of STS

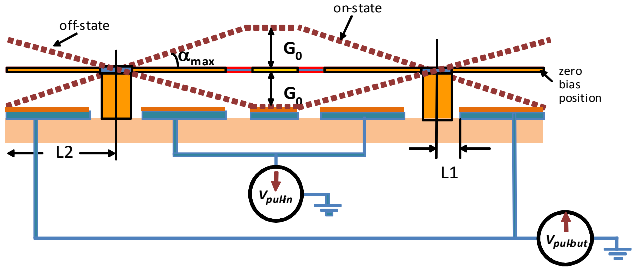

Figure 2. Working Principle of STS

a dielectric material are compared with those for SiO_2 as a dielectric material.

2 DEVICE TOPOLOGY

STS is based on 50Ω CPW configuration with torsion springs of movable membrane anchored to the ground planes of CPW. The bridge structure consists of two micro-torsion actuators, which are connected to each other through levers and an overlap area. The membrane is at a gap of 3 µm from central conductor. The pairs of inner and outer actuation electrodes of two micro torsion actuators are electrically shorted together by polysilicon lines and are called "pull-in" and "pull-out" electrodes respectively. Fig. 2 shows the working principle of STS. As shown in Fig. 2 when no bias voltage is applied, bridge is at a height of 3 µm from transmission line. Bias voltage applied at the inner electrodes, forces the bridge to make a contact with transmission line dielectric providing isolation (off-state), whereas when bias voltage is applied at the outer electrodes, bridge clamps to a height which is double the zero bias height of the bridge, giving low insertion loss (on-state). Eq. 1 describes the pull-in voltage in terms of geometrical dimensions of movable bridge.

$$V_{pull-in} = \sqrt{\frac{E}{2.3914\varepsilon_0 W}\left(\frac{g_0}{L}\right)^2\left[\frac{0.33}{(1-\nu)}\frac{h_t b_t^2}{l_t}+\frac{L}{l^2}\frac{bh^2}{6}\right]} \qquad (1)$$

where, L and W are length and width of actuation electrodes, g_0 is the gap, E is the Young's modulus of movable membrane material and l, b, h, l_t, b_t, h_t are lever and spring dimensions respectively [7].

3 HIGH-K DIELECTRIC MATERIALS FOR RF SWITCH

For RF MEMS capacitive type switches silicon nitride (Si_3N_4) and silicon dioxide (SiO_2) are the commonly used dielectric materials with dielectric constant 7.5 and 3.9 respectively. However, poor resistance to dielectric charging and charge trapping in the Si_3N_4 layers leads to stiction in MEMS capacitive switches, undermining the reliability severely. Also, it is difficult to deposit defect free (e.g. pin holes etc.) Si_3N_4 layers below 100 nm. SiO_2 provides defect free layers and has good process compatibility. However, due to the low dielectric constant of SiO_2 switches show better isolation characteristics only above 10 GHz; invariably leading to larger overlap area for lower frequency range. The later approach results in structures prone to in-built stress related deformation and poor reliability. High-*k* dielectrics have been reported as good candidate materials for capacitive MEMS switches but with very few related experimental studies. The high-*k* dielectric materials that could potentially replace SiO_2 and Si_3N_4 are tantalum oxide (ε_r = 25), hafnium oxide (ε_r = 19-25), barium strontium titanate oxide (ε_r = 28), and strontium titanate oxide (ε_r = 30 – 120), etc. Many of these materials are thermodynamically unstable on silicon or lack in other desirable properties such as high dielectric breakdown voltage, resistance to dielectric charging, low defect density, good adhesion, thermal stability, low deposition temperature and the ability to generate patterns. Hafnium oxide (HfO_2) is one of the dielectrics for next generation gate oxide because of its high dielectric constant (19 - 25) and excellent process compatibility with concurrent IC technology. Also, it presents an alternative material for RF MEMS switches, which can be deposited as a thin layer down to 45 nm [8, 9]. HfO_2 has dielectric strength higher than 10MV/cm, implying use of thinner layers to achieve better isolation performance. It also shows better resistance to dielectric charging, a major concern in capacitive MEMS switches.

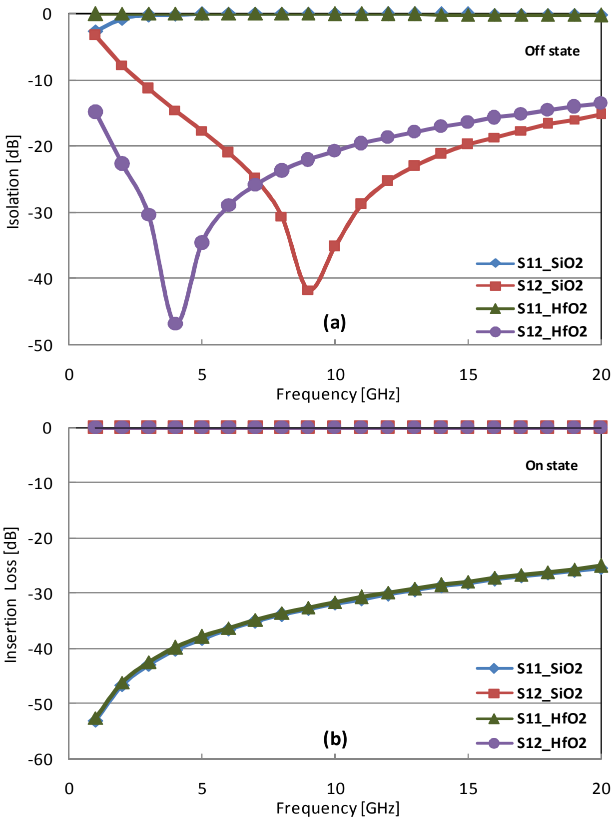

Figure 3. Comp. of (a) off-state, (b) on-state response of STS with SiO_2 and HfO_2 as dielectric layer for same switch dimensions.

For equivalent dimensions HfO_2 based devices show better isolation and lower insertion loss at higher frequencies compared to SiO_2. Alternatively, the choice of high dielectric materials like HfO_2 leads to more compact capacitive switches [9]. For STS, in comparison to SiO_2 based device for the same frequency band, the overall dimensions of the switch can be reduced by more than 47% while capacitive area reduction is about 78% when HfO_2 is used as dielectric. Fig. 3 (a) & 3 (b) show the off-state and on-state performance of STS with same switch dimensions but with different dielectric layer. Isolation peak shifts to the smaller frequency range with the change in dielectric layer from SiO_2 to HfO_2 indicating very high capacitance in case of HfO_2 STS. The advantage can be utilized by reducing the capacitive area to shift the operating frequency range in X-Band. Fig. 4 (a), 4 (b) and 4 (c) shows the response of STS with SiO_2 as dielectric layer and reduced dimension STS with HfO_2 as dielectric layer in off-state and on-state respectively. Both switches show maximum isolation and low insertion loss in X-Band. Isolation is better in the case of small STS with HfO_2 as a dielectric layer.

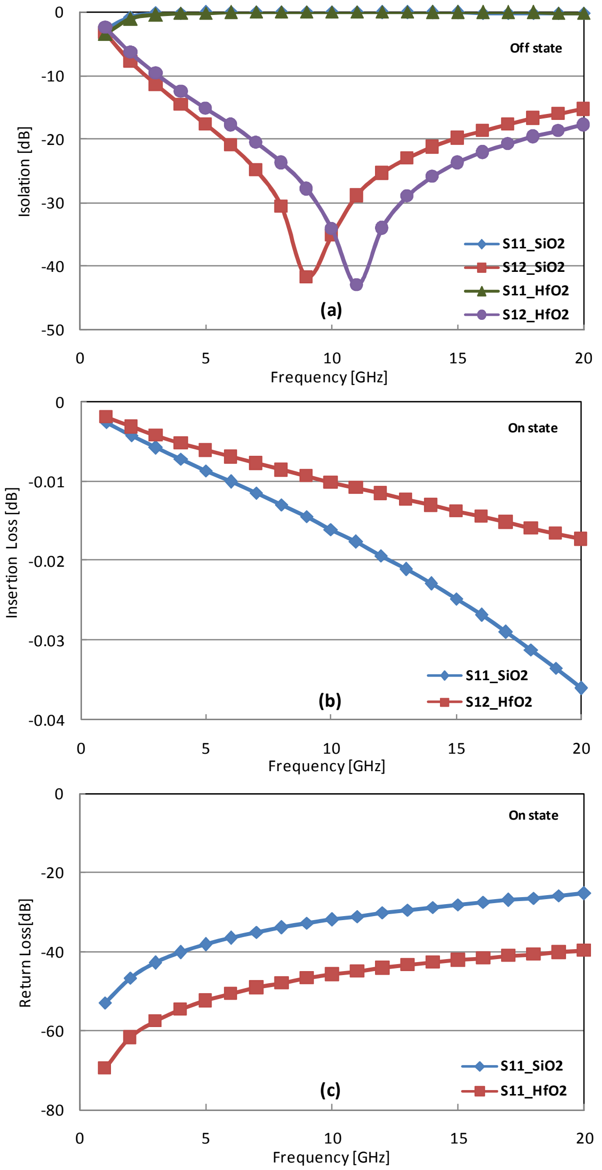

Figure 4. Comp. of (a) off-state, (b) & (c) on-state response of STS with SiO_2 and small STS with HfO_2 as dielectric layer.

In on-state dimensionally optimized STS with HfO_2 as a dielectric shows low insertion loss and better return loss as compared to STS with SiO_2, for the same frequency band.

The size reduction makes the structures more reliable especially in view of the surface micro-machining and electroplating techniques used for fabricating switches. Mechanically, optimized STS shows better response as compared to previous one. Hysteresis is minimal in the case of small STS with almost same actuation voltage of 11-12 Volts. Fig. 5 (a) & 5 (b) shows the comparison hysteresis graph for previous STS and dimensionally optimized STS.

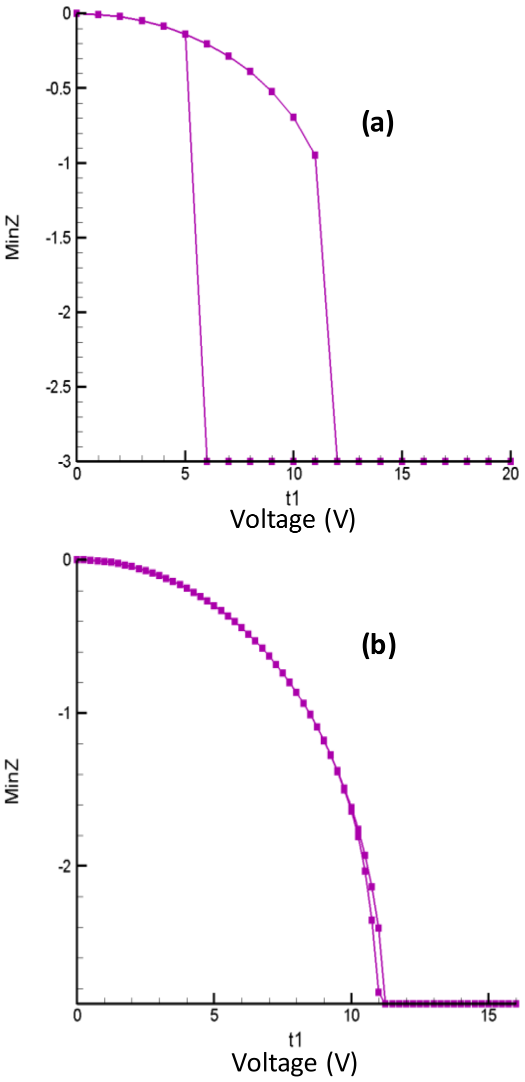

Figure 5: Comparison of Hysteresis curve for (a) STS & (b) Optimized STS.

4 PROPOSED PROCESS FLOW

Fig. 6 shows the schematic view of fabrication flow for RF switch. The surface micro- machined devices are fabricated on high resistivity silicon substrates. Initial thermal oxidation is followed by the LPCVD growth of poly-silicon which is further patterned to obtain actuation electrodes. Low temperature TEOS is deposited and patterned to open contact holes. The underpass area for signal transmission is a multilayer stack composed of sputtered Ti/TiN/Al:Si/Ti/TiN thin layers. A LPCVD oxide layer is deposited on the above stack and via holes are patterned through it. The dielectric layer prevents the short circuit conditions between the underpass area and movable bridge. A floating metal layer can be deposited to obtain optimum capacitance and eliminating the deposition of refractory metals to obtain smooth contact layers.

Movable structure is realized through two electroplating steps over a 3µm thick photoresist, used as a sacrificial layer. A seed layer of Cr/Au for electroplating is deposited by sputtering. This is followed by first gold electroplating step providing 1.5µm thick movable bridge. The second electroplating selectively increases the thickness to 5.0 µm for certain parts including CPW. After the removal of Au and Cr seed layers, switches are released by modified plasma ashing process to avoid stiction problem. The devices are being fabricated for the comparative study of high dielectric layers.

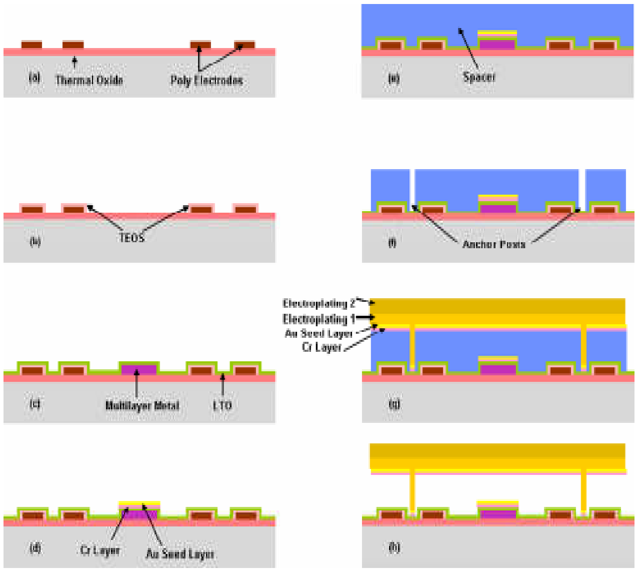

Fig. 6 (a) - (h): Schematic view of Process flow for RF Switch

CONCLUSION

The design optimization of Symmetric Toggle Switch has been presented by changing the dielectric layer form SiO_2 to HfO_2. Shift in resonance curve due to change in dielectric layer has been studied. STS has been optimized dimensionally to operate in X-Band. For same frequency band, the overall dimensions of the switch can be reduced by more than 50% while capacitive area reduction is about 75% when HfO_2 is used as a dielectric layer other than SiO_2, with increase in capacitance ratio. Mechanical behavior of two configurations is also compared.

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