Electrical performance comparision of Symmetric Toggle Switch for SiO_2 and HfO_2 dielectric layers

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ABSTRACT

This paper presents the comparison of electrical performance of symmetric toggle switch (STS) by incorporating hafnium oxide (HfO_2) as a dielectric layer instead of silicon dioxide (SiO_2). Change in dielectic layer leads to the change in ratio of down to up state capacitance, which determines the performance of capacitive type RF MEMS switches. Simulated results show that for the same switch dimensions, response of the SiO_2 based switch is in X-Band (8 - 12 GHz), whereas the switch having HfO_2 as a dielectric layer shows the resonance in C-Band (4 - 8 GHz). The advantage can be utilized for optimizing the size of STS to shift the operating frequency range in X-Band. Simulated isolation and insertion loss are also better in case of the optimized STS with HfO_2 dielectric layer; -43 dB and -0.014 dB for 11 GHz respectively as compared to SiO_2 dielectric layer with isolation of -29 dB and insertion loss of -0.016 dB at 11 GHz. The measured isolation for a SiO_2 device over the frequency range of 9-13 GHz is better than -20dB. For the similar device dimensions, STS with HfO_2 dielectric layer shows isolation better than -20 dB from 4-11.5GHz.

Keywords**:** rf mems switch, dielectric, symmetric toggle switch, insertion loss, isolation

1 INTRODUCTION

RF MEMS switches have drawn a lots of attention in the last two decades due to their excellent performance and highly linear characteristics over a wide range of frequencies. They are widely applied in wireless applications such as, phase shifters, switching networks, transmitters, and receivers, etc due to their high levels of integration, negligible current and low power consumption. MEMS devices offer better insertion loss and high isolation as compared to their solid-state counterparts like PINs and FETs. However, switching speed, RF power handling capability and reliability are some issues which are to be addressed more efficaciously [1]. 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 by different techniques [2]. The mechanism not only meliorates the reliability but also the RF characteristics of the switches. Based on such a technique, 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 Figure 1. The device consists of a pair of micro-torsion actuators placed symmetrically around the transmission line. This reduces the in-built stress related deformation, though devices become longer compared to other similar topologies [3]. Figure 2 shows the working principle of STS. 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 low insertion loss characteristics a large (>100) down/up capacitance (C_{down}/C_{up}) ratio is desirable. In general small overlap area, higher gap and dielectric materials with high dielectric constants can be used to achieve high capacitance ratio. Pull-in voltage is a strong function of the gap between the movable bridge and the transmission line. Increasing the gap will increase the pull-in voltage, which is generally not desirable.

In above context using a high-k material as a dielectric layer is advantageous. This paper presents the effect of change in dielectric layer of RF MEMS capacitive switch. Rplacing the dielectric layer changes the performance of the capacitive type RF MEMS switch as the bandwidth is decided by the capacitance values. Also, change in capaci-

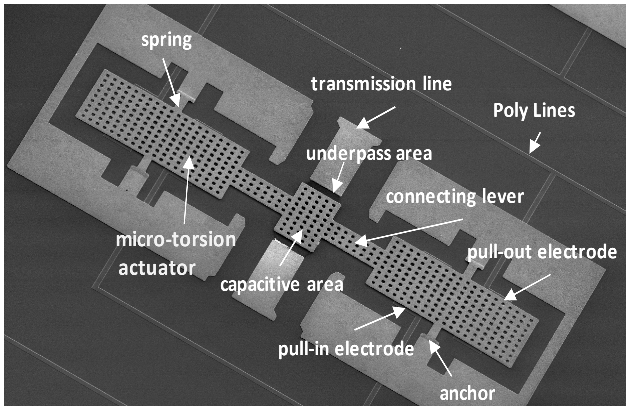

Figure 1: SEM view of fabricated STS

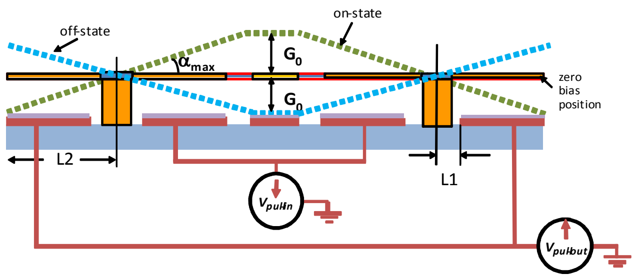

Figure 2: Working principle of STS.

-tance values. Also, change in capacitance ratio improves the performance of the switch.

2 DEVICE TOPOLOGY & WORKING PRINCIPLE

Figure 2 shows the working principle of STS. It is based on 50 Ω CPW configuration with the movable bridge anchored to the ground planes of the CPW. The bridge structure consists of two microactuators, connected with each other through levers and an overlap area. This movable bridge is anchored at a height of 3 µm from the central transmission line. There are two pairs of inner and outer actuation electrodes underneath the bridge for pull-in and pull-out. Depending on the applied actuation voltage, the movable bridge will ground the RF signal by snapping down ward (off-state) or will clamp at a height which is double the zero bias height of the bridge and passes the RF signal with low losses (on-state). Equation 1 describes the pull-in voltage in terms of geometrical dimensions of movable bridge.

$$V_{pull-in} = \sqrt{\frac{E}{2.3914\varepsilon_0 W}\left(\frac{g_0}{L}\right)^3\left[\frac{0.33}{(1-\nu)}\frac{h_t b_t^3}{l_t}+\frac{L}{l^2}\frac{bh^3}{6}\right]} \qquad (1)$$

where, L and W are length and width of actuation electrodes, g_0 is the gap, E is the Young's modulus of movable -bridge and l, b, h, l_t, b_t, h_t are length, width and thickness of lever and spring respectively [3].

3 DIELECTRIC MATERIALS FOR STS

Different dielectric materials can be used for RF MEMS switches. Silicon nitride (Si_3N_4, $\boldsymbol{\varepsilon_r}$ =7.5) and silicon dioxide (SiO_2, ε_r = 3.9) are the commonly used dielctric materials for the capacitive type RF MEMS switches. 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 [1]. 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 at very high frequencies, 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 due to large dimensions. Also, due to low dielectric constant the capacitance ratio is small. As an alternative, high-*k* dielectric materials have been reported in literature as a dielectric material but with very few related experimental studies [4- 5]. 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. Unfortunately, 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 [6, 7]. 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. For equivalent dimensions of symmetric toggle switch (STS), simulation and experimental study has been performed with SiO_2 and HfO_2 dielectrics layers. Simulated results of STS with HfO_2 dielectric layer shows better response at low frequencies

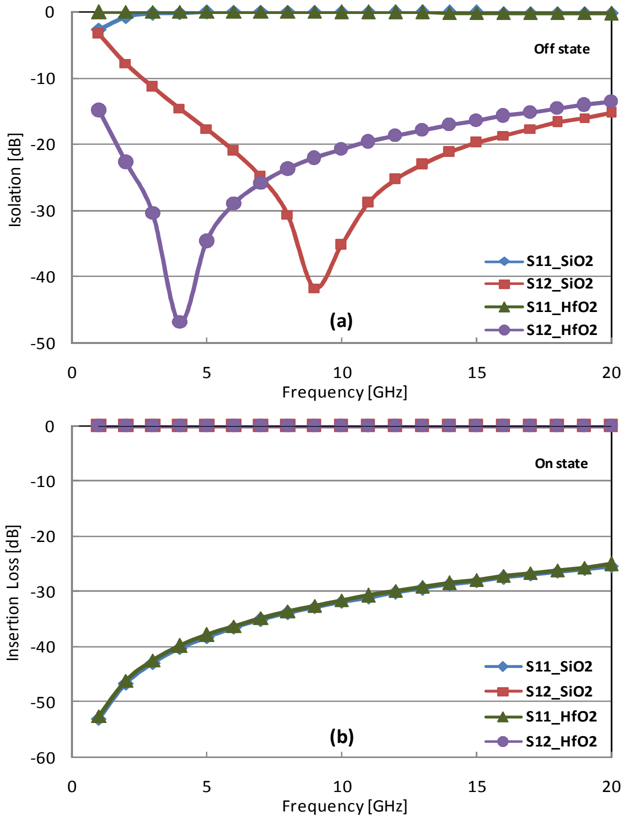

Figure 3. Simulated comparison of (a) off-state, (b) on-state response of STS with SiO_2 and HfO_2 as dielectric layers for same switch dimensions.

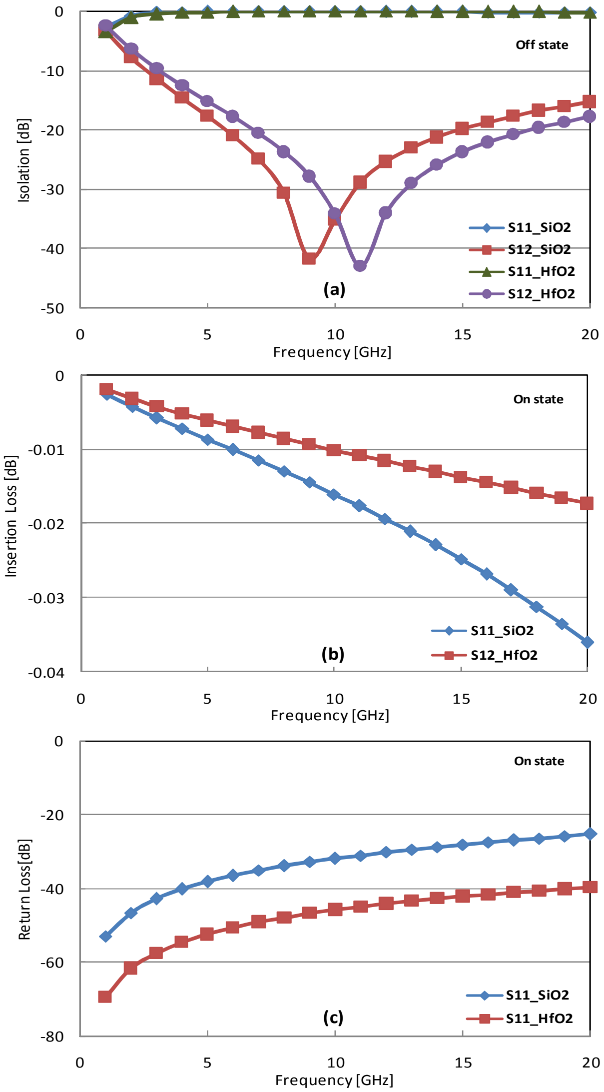

Figure 4. Comp. of (a) off-state, (b) & (c) on-state response of STS with SiO_2 and optimized STS with HfO_2 as dielectric layer.

(4GHz) as compared to the STS with SiO_2 as a dielectric layer. SiO_2 based STS shows the best response in X-Band (8GHz-12GHz). Also, implementing HfO_2 as a dielectric layer leads to more compact capacitive switches. For STS, in comparison to SiO_2 based devices 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 [8]. Figure 3 (a) & 3 (b) shows the off-state and on-state performance of STS with same switch dimensions but with different dielectric layers. Isolation peak shifts to the smaller frequency range with the change in dielectric from SiO_2 to HfO_2 indicating almost 10 times 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. Figure 4 (a), 4 (b) and 4 (c) shows the response of STS with SiO_2 as a dielectric layer and reduced dimension STS with HfO_2 as a dielectric layer in off and on state respectively. Both switches show maximum isolation and low insertion loss in X-Band. Isolation is better and insertion loss is low in the case of small STS with HfO_2 as a dielectric layer.

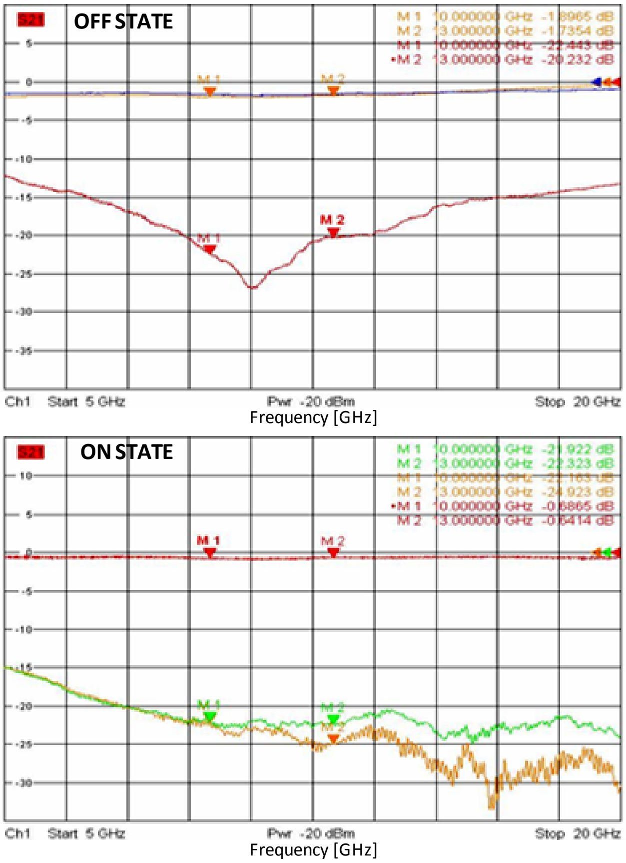

Figure 5. Off-state and On-state response of STS with SiO_2 as a dielectric layer.

4 MEASURED RESULTS

Figure 5 shows the measured off-state and on-state response of STS with SiO_2 as a dielectric layer. Isolation is above -20 dB from 9 - 13 GHz with insertion loss below -0.6 dB. Whereas, simulated results show that the isolation is above -20 dB from 6 - 15 GHz with insertion loss below -0.035 dB. Insertion loss in fabricated device is quite high as compared to the designed switch. In addition to the bridge gap, insertion loss is a function of metal properties used for CPW and measurement probe conatct. Insertion loss is expected to improve with appropriate packaging. Figure 6 shows the off-state and on-state response of STS with HfO_2 as a dielectric layer. 50 nm of HfO_2 is deposited using sputtering process at room temperature. From 4 - 11.5 GHz, isolation is above -20 dB and insertion loss is below -0.75 dB. The return loss in on-state is above -25 dB from 5 - 16 GHz. Also, simulated results show that the isolation is above -20 dB from 2 - 11 GHz with insertion loss below -0.02 GHz. The working frequency range of fabricated and designed HfO_2 based STS is almost similar, showing HfO_2 STS as a broadband switch.

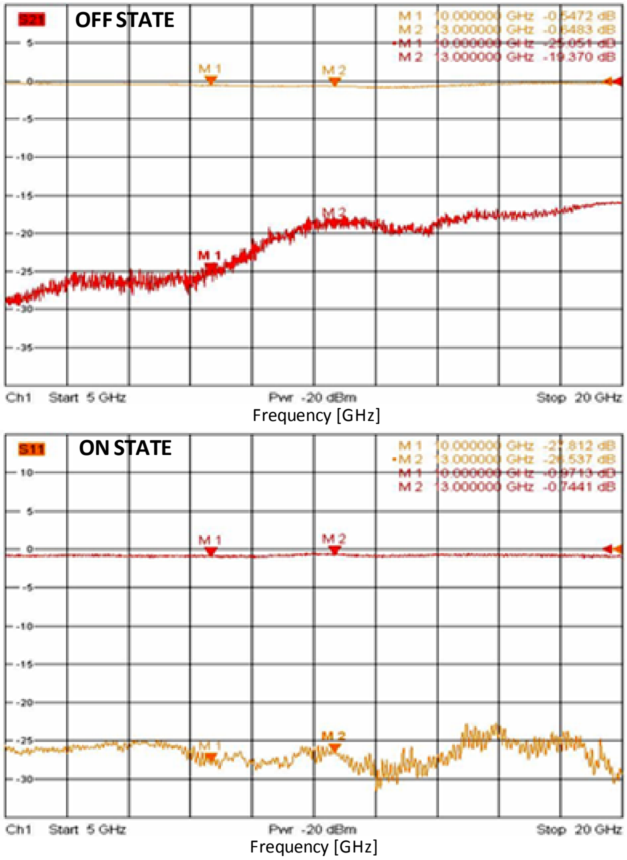

Figure 6. Off-state and On-state response of STS with HfO_2 as a dielectric layer.

5 FABRICATION PROCESS FLOW

Figure 7 shows the schematic view of fabrication flow for RF switch. The surface micro- machined devices are fabricated on high resistivity silicon (>5KΩ) substrates. Initial thermal oxidation is followed by the LPCVD deposition of polysilicon which is further doped and patterned to obtain actuation electrodes. Low temperature oxide 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 PECVD 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.

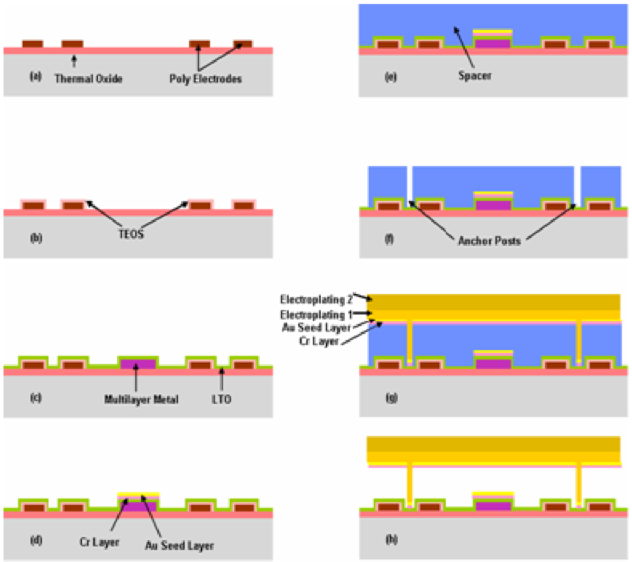

Figure 7 (a) - (h): Schematic view of Process flow for STS fabrication.

CONCLUSIONS

The electrical performance comparison of STS with different dielectric layers has been presented. Designed and measured results of STS, after fabrication with both types of dielectrics have been compared. Isolation is above -20 dB from 9 - 13 GHz with insertion loss below -0.6 dB. Whereas, simulated results show that the isolation is above -20 dB from 6 - 15 GHz with insertion loss below -0.035 dB. For HfO_2 based STS, from 4 - 11.5 GHz, isolation is above -20 dB and insertion loss is below -0.75 dB. The return loss in on-state is above -25 dB from 5 - 16 GHz. The simulated result shows that the isolation is above -20 dB from 2 - 11 GHz with insertion loss below -0.02 GHz. The working frequency range of fabricated and designed HfO_2 based STS is almost similar, showing HfO_2 STS as a broadband switch. The advantage of this shift can be utilized by reducing the dimensions of the switch to shift the resonance in X-Band. For the same frequency band, the dimensions of the HfO_2 dielectric switch can be reduced upto 47% of the SiO_2 dielectric switch with almost 10 times high capacitance ratio.

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