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Parametric Optimization of Symmetric Toggle RF MEMS Switch for X-Band Applications

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***Abstract* — This paper presents the parametric optimization of Symmetric Toggle RF MEMS Switch (STS), particularly for reduction of overall dimensions and improvement in isolation and insertion loss. The variations in device topology, especially the connecting lever length demonstrates a significant change in resonance frequency and overall device dimensions. The impact of multilayer metal structures used to realize the bridge portion of the switch is also studied by changing the number and composition of metal layers. A single layer structure shows better insertion loss characteristics compared to more complex multilayer stack with added advantage of reduction in fabrication complexity. The relative change in residual stress for single and multilayer structure is also discussed. Additional compactness in size (46%) is achieved by changing the switch dielectric from SiO_2 to HfO_2 with dielectric constant 20.**

Keywords: Symmetric Toggle Switch, RF switch, insertion loss, isolation, hafnium oxide.

I. INTRODUCTION

The drive for RF MEMS applications in communication has been mainly due to the highly linear characteristics of the switches over a wide range of frequencies. The MEMS devices offer better isolation (>30 dB) and low insertion loss (<0.15 dB) compared to contemporary solid state devices. With high levels of integration, negligible current, low power consumption and improved overall performance, RF switches are preferred for space, air borne and hand held communication applications [1]. Phase shifters, switch matrices, receivers and transmitters sections are some of the applications being developed using MEMS switches. However, switching speed, low RF power handling capability and reliability are some issues which are to be addressed more efficaciously. Reliability against self biasing, external shocks & vibrations and the power handling capability of RF switches are 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 [2] 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. 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]. Fig. 1 shows the working principle of STS.

Optimization of above discussed STS is presented in this paper. Variations in lever length are discussed, which result in significant shift of resonance frequency peak representing change in inductance of the bridge. Comparison of single layer and multi metal layer bridge membrane is also discussed. With multilayer approach and variation of metal thickness ratio, fabrication complexity can be reduced. Also, optimization in switch length is realized by changing dielectric material from SiO_2 to HfO_2. Further advantage of having two pairs of electrodes is discussed followed by a brief description of the process flow.

II. 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 over-lap area. The membrane is at a gap of 3 μm from central conductor. The pairs of

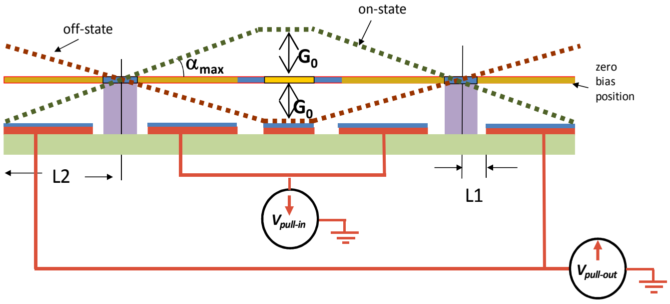

Fig. 1. Working Principle of STS

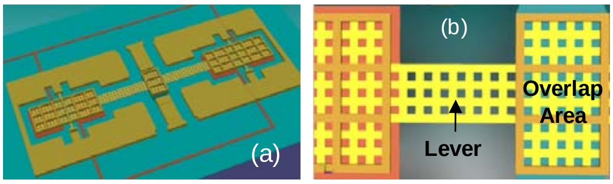

Fig. 2.: (a) 3-D view of STS, (b) Lever area of STS

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. As shown in Fig. 1 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.

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

where, L and W are length and width of actuation electrodes, g_0 is the gap, E is the Young's modulus of movable membrane material and l, b, h, l_t, b_t, h_t are lever and spring dimensions respectively [4].

III. STRUCTURAL OPTIMIZATION

The impact of variations on the structural dimensions and composition of the 'metallic bridge' suspended above the transmission line is studied by using commercially available tools like CoventorWare®, and HFSS. The major emphasis has been on the connecting lever length, composition of bridge materials, transmission line – bridge overlap area and dielectric layer on the transmission line.

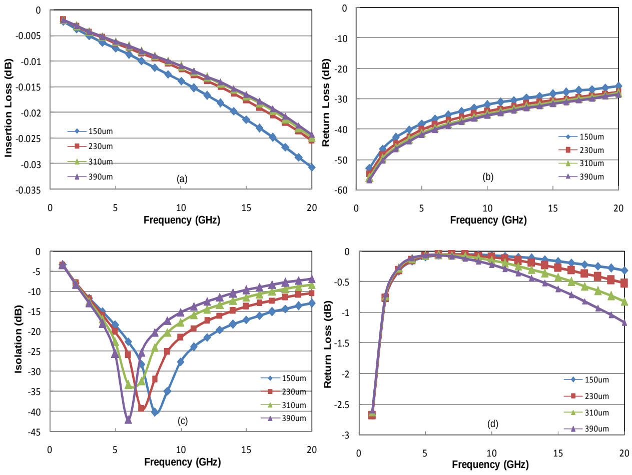

Fig. 3: (a) Insertion loss (b) Return loss in on state (c) Isolation and (d) Return loss in off state. Curve (c) shows better isolation response of small lever switch in X - Band

A. LEVER LENGTH & ELECTRICAL RESONANCE FREQUENCY

The full layout of STS is depicted by the 3-D view in Fig. 2(a). The micro-torsion actuators which determine the pull-in voltage and vertical travel range of STS, are connected to central overlap area by a thin connecting 'lever' as shown in Fig. 2(b). Dimensions of the connecting lever have deterministic effect on the switch properties such as the overall deflection profile, pull-out gap when bias is applied on the outer electrodes and pull-in and pull-out voltages [5]. Impact of lever length especially on the electrical resonance frequency of STS is shown in Fig. 3. The shift in well-defined LC resonance curves for a change in lever length from 150 microns to 390 microns is depicted in Fig. 3(c). An appropriate combination of lever length and capacitive overlap can be selected for a given frequency range as demonstrated by the electrical response of the devices in Fig. 3.

B. MULTI METAL LAYER RESPONSE

For fabricating movable bridges, associated transmission lines and ground pads on silicon substrate using surface micromachining, thin sputtered layers of Cr and Au act as diffusion barrier and seed layer for next electroplating step [6]. Sintering of the composite structure after the removal of sacrificial layer may further change the composition of constituent metals e.g. formation of chromium oxide as the bottom layer. Simulated electromechanical response of the structure reveals an increase of 3 - 5 V in pull-in voltage for multilayered structure (Cr – Au – plated Au) as compared to a structure having only one layer. For a structure with the Cr-Au layers, maximum stress for Cr layer, at the anchors for 3 µm deflection is 16 MPa and at levers it is nearly half. For the corresponding Au layer, maximum stress at the anchors is 8.2 MPa. In the case of a single layer structure of equivalent thickness maximum stress at the anchors for similar deflection is 8 MPa. The reduction in stress to half shows that the stiffness of a structure can be more effectively controlled by varying the thickness of

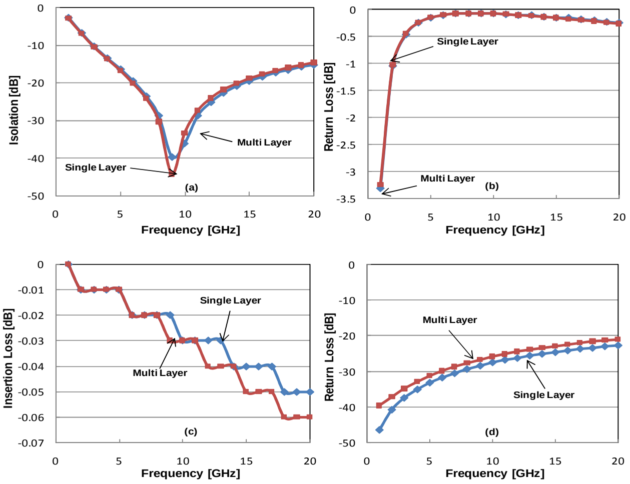

Fig. 4: (a) Isolation (b) Return loss in off state and (c) Insertion Loss (d) Return Loss in on state

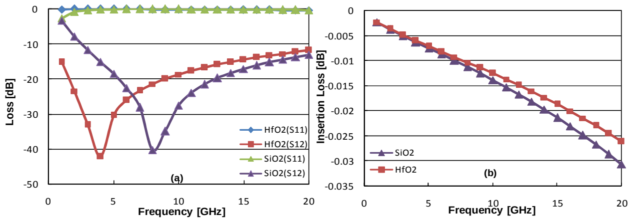

Fig 5: Comparison between HfO_2 and SiO_2 as dielectric for STS (a) in off state, resonance changes from 8 GHz to 4 GHz with HfO_2 as dielectric and (b) in on state insertion loss improves using HfO_2.

chromium layer as an alternative to reinforcing using electroplated layers. It also simplifies the fabrication process. In terms of electrical parameters change in Cr/Au thickness ratio has impact on bridge inductance and bridge resistance resulting in a decrease in isolation for multilayer case. Fig. 4 (a) to (d) compares the 'off' state and 'on' state response of STS with multilayer and single layer.

C. DIELECTRIC LAYER OPTIMIZATION

Silicon dioxide is the preferred dielectric material for capacitive switches. However the SiO_2 based switches show better isolation characteristics only above 10 GHz; invariably leading to larger overlap area for lower frequency range. Higher dielectric constant materials lead to more compact devices with equivalent response. Usage of silicon nitride with higher dielectric constant (7.5) is limited by higher defect density especially when deposited less than 100 nm. Hafnium oxide with dielectric constant ranging from 19-25 presents an alternative material which can be deposited as a thin layer down to 45 nm [7, 8]. For equivalent dimensions HfO_2 based devices show good isolation and low 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]. In STS, for example in comparison to SiO_2 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 a dielectric layer. The simulated change in isolation and insertion loss of a switch with HfO_2 and SiO_2 layers is shown in Fig. 5 (a) and (b).

IV. ADVANTAGE OF OUTER ELECTRODES

The advantage of having a pair of outer electrodes is significant in terms of (a) restoration to zero bias position and (b) on state gap.

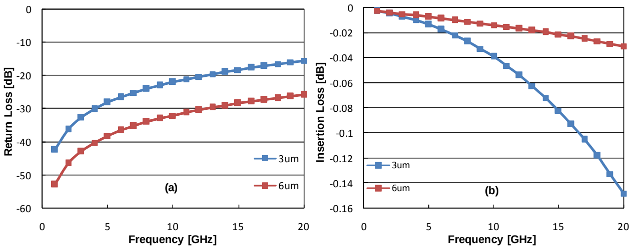

Fig. 6: Comparison of (a) Return loss and (b) Insertion loss of STS in on state with increase in gap height.

(*a) Restoration to zero bias gap*: After pull-in, when actuation voltage is removed from the pull-in electrodes, restoring force comes in action to relax the movable membrane to its original position. During this, if stiction occurs due to capillary force or self weight, the pair of outer electrodes can be biased to generate electrostatic force, greater than the stiction force, thus restoring the switch back to its original zero bias position.

(b) On state gap: In on state, insertion loss of a capacitive switch can be improved by increasing the gap between the transmission line and the movable bridge. In STS, this can be done by applying actuation voltage at the outer electrodes. As shown in Fig. 1, by choosing the appropriate dimensions of torsion mirror and anchor posts, bridge can be biased from outer electrodes to clamp at a height which is double the zero bias height, thus improving the return loss and insertion loss. Fig. 6 (a) and (b) shows the return loss and insertion loss in on state respectively for 3 and 6 µm gap.

V. PROPOSED PROCESS FLOW

Fig. 7 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 polysilicon 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

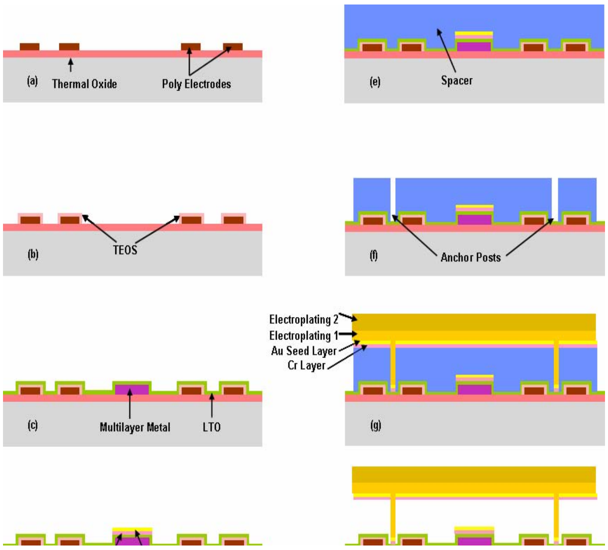

Fig. 7 (a) - (h): Schematic view of Process flow for RF Switch by first gold electroplating step providing 1.5μm thick movable bridge. The second electroplating selectively increases the thickness to 5.0 μm for certain parts including CPW. After the removal of Au and Cr seed layers, switches are released by modified plasma ashing process to avoid stiction problem.

CONCLUSION

The design optimization of Symmetric Toggle Switch has been presented. Shift in resonance curve due to change in bridge inductance and resistance as an effect of lever length change has been studied. Bridge fabrication complexity can be reduced by varying the metal ratios during fabrication, with minor increase in pull-in voltage. The shift in resonance curve has also been demonstrated as a function of dielectric (SiO_2 to HfO_2) implying that length of the switch can be reduced further. Proposed fabrication process has also been discussed. A switch length optimization approach using HfO_2 and use of multilayer stack with corresponding reduction in stress has also been presented.

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