JOURNAL OF CRITICAL REVIEWS

ISSN- 2394-5125 VOL 7, ISSUE 05, 2020

Detailed Electrostatic and Electromechanical Analysis of MEMS Shunt Switch

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Received: 28 February 2020 Revised and Accepted: 06 March 2020

Abstract

This article describes electrostatic and electromechanical analysis for capacitive shunt RF switch operating in the frequency range of 10-50 GHz. Two different conducting materials (Aluminum and Gold) have been used in this studied. This work focuses on the quantitative parameters, e.g., electric charge, field, pull-in voltage, electrostatic force and spring constant for different geometrical configuration of the switch. MATLAB, HFSS and COVENTOR software's have been used for the analytical and full wave analysis of 3D structure, respectively. The electrostatics, electromagnetic and electromechanical results are well in good agreements with the analytical results.

Keywords: CPW, critical stress, full-wave analysis, FEM, hysteresis, quasi-static analysis, residual stress, shunt switch

1. Introduction

Switches are indispensible parts of RF system. In RF application, micromechanical systems (MEMS) are gaining popularity due to many advantages such as low power consumption, high isolation, low insertion loss, wide bandwidth operation; no inter modulation products and simple biasing network compared to solid state switches like as FETs and PIN diodes [1-7, 18]. Capacitive and ohmic contacts are two basic switches categorization. Operational life of ohmic contact switches is restricted by the stiction. Capacitive switches are of two type namely, series and shunt switches [2, 3]. The limitation of series switches is its power handling capability and range of operation i.e. 1-10 GHz [7-10, 19]

University of Michigan started the development of low voltage MEMS switches using low spring system [8]. The purpose behind using low spring system is to gain low actuation voltage. The number of membrane structures and its thickness affects the actuation voltage. The researchers demanded for low actuation voltage and therefore different mechanical systems were adopted. In 2003 Peroulis [11] developed MEMS switches where the actuation voltage required was 6- 12 V with a gap of 4-5μm between transmission line and the bridge. In this system actuation voltage was reduced by 80% by increasing the number of meanders from 1 to 5. The actuation voltage for 5 meanders observed is 3V . The similar structures are used to lower the value of spring constant as well [4]. But the problem with this is its slow response time and Brownian noise [1].

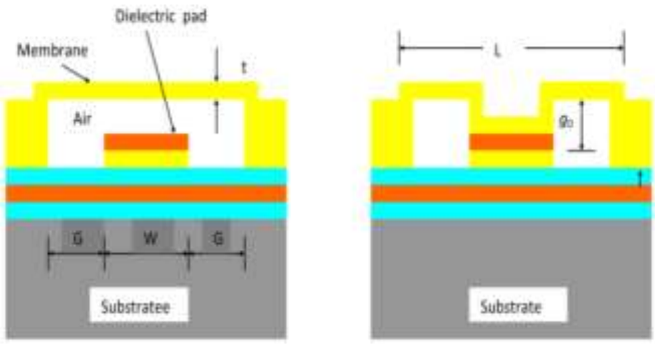

Fig. 1. Cross-section view of a capacitive shunt switch in (a) up-state and (b) down-state

University of Michigan designed a low height shunt switch on 0.8 - 1.0µm Ti/Au membrane and maintained a gap of 1.5-2.2µm [12]. The voltage required was 12-24V. This switch has got advantages like high resonant frequency and fast switching speed and the applications as in phase shifters. Guo reported that the bridge material made of aluminum silicon alloy had low actuation voltage. This alloy had an actuation voltage of 5V whereas if gold material was used the actuation voltage was found to be 45V. Another capacitive shunt switch was developed by Park (2001) [13-14]. This is a fixed beam capacitive shunt switch. The switch had a dielectric material made of strontium titanate oxide having dielectric constant value of 30 and 120 at 200◦C and 300◦C temperature respectively. Down state capacitance was found to be 50 pF and up state capacitance was found to be 70- 80 fF [15]. This shows that the capacitance ratio is comparatively high .These switches have better isolation than - 40dB at 3-5 GHz. Researchers also developed low voltage MEMS switches without the meander structures [16]. Segueni developed a flexible bridge shunt switch. On the sides of supporting pillars the switch has two sets of electrodes. The voltage is applied to operate the switch. The pull up voltage required is 1.5V whereas pull down voltage is 3.5 V. This had isolation of - 30dB and had good RF performance.[17].

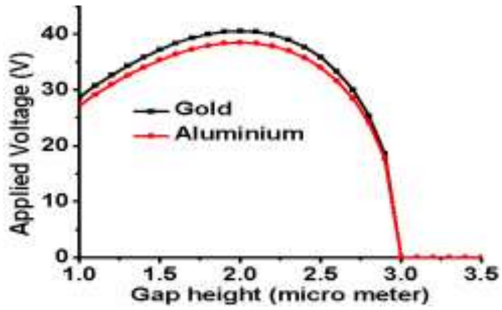

Fig. 2. The applied voltage change due to variation in gap height

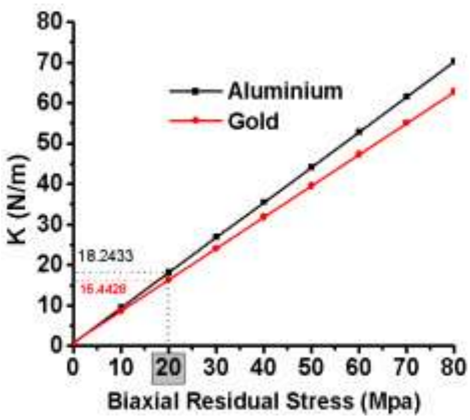

Fig. 3.Variations of stress with spring constant K(N/m)

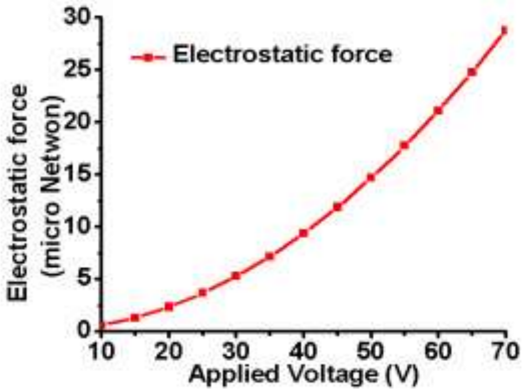

Fig. 4 The electrostatic force with respect to voltage

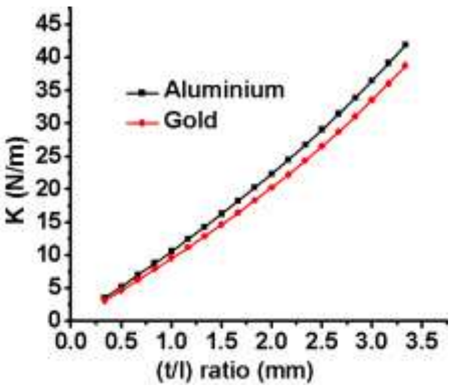

Fig. 5. The spring constant (K) shows a linearly increase with increase in (t/l) ratio

This work outlines the behavior of pull-in characteristics for capacitive shunt switch structure. Two commonly used conducting materials (Aluminum and Gold) are considered during simulation of 3D structure. This paper also studies the effect holes in the membrane and effect of coplanar waveguide on RF analysis using different center conductor width.

2. Electrostatic Analysis of the Shunt switch

An important optical flow method is Lucas - Kanade method. This method used the fact that the displacement of two nearby instants (frames) is small and approximately constant within a neighbourhood of the point under examination The Lucas-Kanade algorithm for motion estimation is used and implemented in Matlab due to the fact that most of the matrix operation functions needed are already available and hence saves time required to implement these functions again.

A. Switch Design

High resistive silicon (ρ>8kΩ-cm, tan δ=0.01 &ε_r=11.7) of 675±20 µm thickness is used as a substrate for switch designing. The systematic structures of switch using fixed-fixed beam in different conditions are shown in Fig 1(a) & (b). To minimize the losses and dispersions in the substrate, a layer of oxide-nitride-oxide (4000A° -3000A°-2900A°) is introduced, over which CPW structure (90/120/90 in µm) is realized. The top metal membrane of thickness‘t’ is suspended at height ‘g_0’ above dielectric layer which is on bottom electrode metal surface supported by two anchors. Thin dielectric layer of SiN is used to provide the isolation between top and bottom electrode and covered small portion of the bottom electrode [2, 4]. With the application of DC bias, electrostatics charges are induced between top and bottom electrode which results in µN level electrostatics force, sufficient to snapping down the upper electrode. Above a certain threshold voltage (V_p), top electrode comes in vicinity of the bottom electrode, termed as Down state of switch. The typical dimension of switch structure taken in this work are: length (L)-280 µm, width (w)-100 µm, membrane thickness (t)-1 µm, dielectric thickness (t_d)-1200 A° and initial air-gap (g_0)-2.5 µm.

Theswitch acts as a two state digital capacitor: a smaller capacitance (fF) is obtained while switch is in up position while larger capacitance value of capacitor (pF) is resulted in down state of the switch. Electrical and mechanical parameters for switch designing are membrane thickness, length, width, initial gap, CPW dimension, beam material and finally thickness of dielectric material [1, 4].

B. Actuction mechanisms of switch

Broadly the actuation mechanisms of the switch are classified in four categories, electrostatic, thermal, piezoelectric, and megnatostatics [4, 5]. Out of this electrostatic actuation are preferred in IC technology because of planar configuration, for actuation compatible with IC layout. It is preferred because of its inherent zero power consumption, and small electrode size.

C. Parametric Analysis of the Switch

The most important parameter of the RF MEMS shunt switch like electrostatic force, pull-in characteristics, actuation voltage, and effect on stress by varying the beam spring constant have been analyzed for both membrane material (Aluminum and Gold) using MATLAB. While DC voltage is applied between the electrodes, actuation mechanism get activated due to generation of electrostatic force caused by the actuation voltage V_a and is given by [6].

$$F = \frac{\varepsilon_0 w W {V_a}^2}{2\left[g_0 + \left(\frac{t_d}{\varepsilon_r}\right)\right]^2} \text{ and } V_a = \sqrt{\frac{2Kg^2(g_0 - g)}{\varepsilon_0 w W}} \qquad (1)$$

where g_0 and g are the preand post actuation gap heights of the beam. The change in the electrostatic force with DC applied voltage, and change in voltage due to initial gap areshown in Figs. 2.

Decreasing the air gap height, actuation voltage as well as electrostatic forces is reduced in capacitive switch structure. Higher probability of stiction and smaller capacitance ratio phenomena are the two major drawbacks of low height switch membrane at 2/3 of initial gap height, electrostatic force become just greater than the restoring force, which results in snapping down of the switch membrane. Pull down voltage is a function of switch initial gap, width, length, and type of fixed-fixed beam material. The beam spring constant of the fixed-fixed beam depends on mechanical properties as follows [6, 7].

$$K = 32E' w\left(\frac{t}{l}\right)^3 + 8\sigma_0(1-v)w\left(\frac{t}{l}\right) \quad \text{and} \quad E' = E(1-v^2)$$

Where σ_0 is bi-axial residual stress, v is Poisson's ratio of beam, and E is Young's modulus of the fixed-fixed beam material [6]. Fig.3 demonstrate the spring constant (K) shows a linearly increase with increase in (t/l) ratio for both conductive materials gold and aluminum. Fig.4 shows variation in spring constant with biaxial residual stress for both conducting materials.

During the operation of a switch, electric charges are accumulated with in thin dielectric layer above the actuation pad. Which in-turn decided the life time of the devices? Dielectric charging becomes a major issue in this kind of MIM (metal-insulator-metal) capacitor [8]. This effect can be explained explicitly with the accurately modeled proposed Frenkel-Poole emission field. The Frenkel-Poole emission is given by [8].

$$J = V_{\exp}\left(\frac{2a\sqrt{V}}{T} - \frac{q\phi_B}{kT}\right) \qquad (3)$$

where k is Boltzmann's constant, φ_B is barrier height, T isabsolute temperature, V is applied DC voltage, J is current density, and 'a' is fixed value consisting of film thickness, dynamic insulator permittivity, and electron charge.

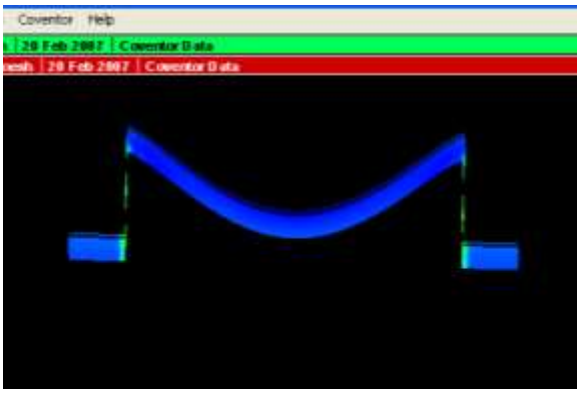

Fig. 6.shows the movement of a fixed-fixed beam

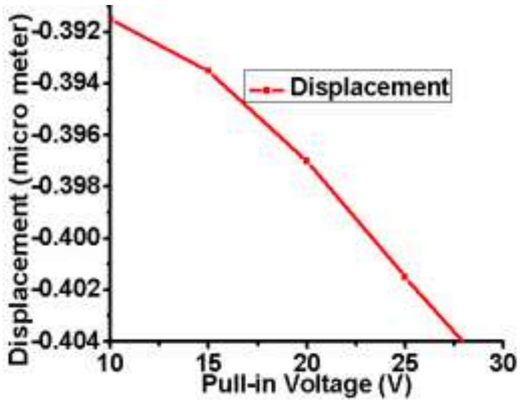

Fig. 7. The displacement in beam with applied pull-in voltage.

3. Electromechanical Analysis

The finite element method based solver coventor has been used to analyze the pull-down characteristics and hysteresis of the capacitive shunt switch [6]. Figs. 6 and 7 demonstrate the displacement in beam with applied pull-in voltage and movement of fixed-fixed beam, respectively. The actuation voltage of 30V by analytical method and 28.73 V by simulation was achieved.

4. RF Analysis

RF analysis of switch is simulated in HFSS Ansys software. S_{11} and S_{21} represent the return loss and insertion loss, when switch is unactuated state. Figs. 8 and 9 show the better insertion loss and return loss greater than 30 dB and 0.2 dB of the proposed switch, respectively. Isolation of the switch better than 25 dB, when switch is in actuated state as shown in Fig. 10. As width of centre conductor (*W*) increases, isolation of the switch increases. The isolation are 58, 60, and 62 dB for CPW of centre conductor width are 100, 120, 130 µm, respectively.

ISSN- 2394-5125 VOL 7, ISSUE 05, 2020

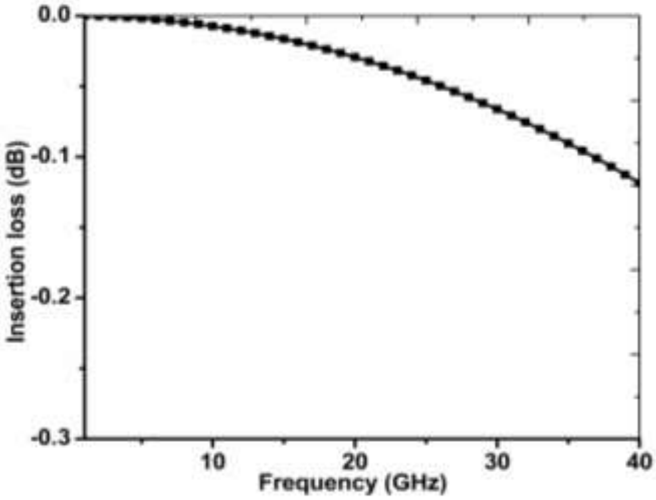

Fig. 8.Insertion loss of the proposed switch in upstate as a function of frequency.

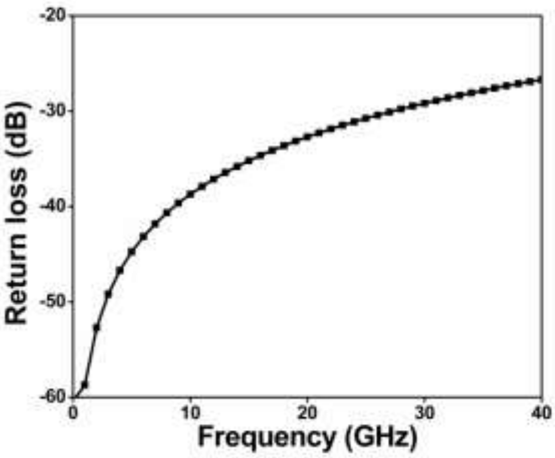

Fig. 9. Return loss of the proposed switch in upstate as a function of frequency

There is negligible effect of centre conductor width on return loss and insertion loss as shown in Table 1. Fig.10 shows the hole size of 10×10 µm, which are introduced in beam to increase the switching speed of the switch and reduce residual stress squeeze air film damping.

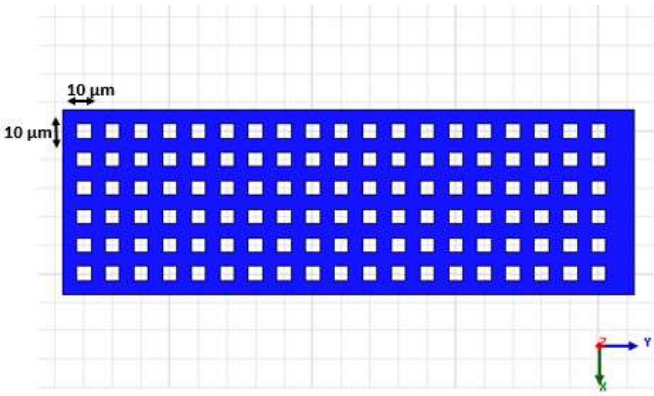

Fig. 10. Holes size of 10×10µm in movable beam

ISSN- 2394-5125 VOL 7, ISSUE 05, 2020

Effect of holes in upstate condition is negligible because hole area are filled by fringing field while in down state holes are dominant which further reduce the isolation. Table 1.depicts the isolation values of 60, 62 dB with and without holes, respectively.

Table 1. Shows the effect of holes and centre conductor width on RF analysis

CPW	CPW		Up state without Holes		Down state without Holes	Up state with Holes		Down state With Holes
S-W-S	RL (db)	IL (db)	RL (db)	IL (db)	Isolation (db)	RL (db)	IL(db)	Isolation (db)
60-100-60	-50.634	-0.050	-17.511	-0.151	-60.758	-17.837	-0.142	-58.320
70-120-70	-42.011	-0.044	-16.064	-0.173	-62.349	-16.635	-0.158	-60.641
80-130-80	-35.451	-0.044	-15.539	-0.183	-64.380	-15.854	-0.173	-62.145
Operation frequency at 15 GHz RL- Return loss, IL- Insertion loss *Material used for beam gold*								

5. Conclusion

This article emphasis the electromechanical and electrostatic analysis of RF MEMS shunt switch. Detailed analysis covers effect geometrical dimensions on the switch on various performance parameters. A CMOS compatible MEMS switch structure is discussed here with practical fabrication data. The effect of different metals on the switch performance has also been outlined in this work. Both coventorware and HFSS have been used and demonstrated to have nearby values. The Return loss, insertion loss and isolation of the proposed switch are with in 25, 0.2, 20 dB, respectively for the operating frequency range of 1– 40 GHz. Further the simulated pull-in voltages are in well accordance with analytical value.

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