Research Article

Design and Simulation of Capacitive MEMS Switch for Ka Band Application

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In this paper, RF MEMS switch with capacitive contact is designed and analyzed for Ka band application. A fixed-fixed beam/meander configuration has been used to design the switch for frequency band 10 GHz to 40 GHz. Electromagnetic and electromechanical analysis of three-dimensional (3D) structure/design has been analyzed in multiple finite element method (FEM) based full-wave simulator (Coventorware and high-frequency structure simulator). A comparative study has also been carried out in this work. The high resistivity silicon substrate (\(\tan\delta = 0.010, \rho > 8k\Omega - cm, \epsilon_r = 11.8\)) with a thickness of 675 ± 25 μm has been taken for switch realization. The designed structure shows an actuation voltage of around 9.2 V. Impedance matching for the switch structure is well below 20 dB, loss in upstate, i.e., insertion loss >0.5 dB, and isolation of >25 dB throughout the frequency band is observed for the aforesaid structure. Furthermore, to increase the RF parameters, AIN dielectric material has been used instead of SiO\(_2\) resulting in capacitance in downstate that increases hence improved the isolation. The proposed switch can be utilized in various potential applications such as any switching/tunable networks phased-array radar, reconfigurable antenna, RF phase shifter, mixer, biomedical, filter, and any transmitter/receiver (T/R) modules.

1. Introduction

The Micro-Electro-Mechanical-System (MEMS) is an agglomeration of submicron mechanical moving parts and electronic components/elements on a single module/chip [1]. In the last 20 years, MEMS has spread into the RF regime also. RF MEMS switches are building blocks for this technology, without the existence of these switches; RF MEMS seems to be unimaginable [1, 2]. Nowadays, RF MEMS capacitive shunt switch has a major role for designing in an advanced communication application. RF MEMS switches are preferable to design filters, reconfigurable microwave antenna, and space communication than solid-state switch like field-effect transistor (FET) and PIN diode. RF MEMS switches based on MEMS technology offer many advantageous over solid-state switches, for example, high isolation, low insertion loss, zero DC power consumption, low noise, more linearity, and used up to millimeter wave [2–4]. MEMS technology-based RF switches have the advantages of miniaturization, monolithically integrated with other IC using batch processing technology as compared to other conventional switches. The performance of the RF MEMS shunt switch depends upon the material used for the membrane and also depends upon return loss, pull-in voltage, insertion loss, isolation, and switching time [1]. Metal-metal contact in the switch creates the stiction problem in the switch. Based on MEMS technology, RF MEMS switches have two types such as shunt switch and series switch [3]. These series and shunt configuration further classified as a capacitive switch and resistive switch base upon contact [2]. Series switches are used for a
A switch based on metal-metal contact normally always been a concern during long-term reliability tests or communication systems need to be highly reliable. So, each and every component, be in launch vehicle or communication systems need to be highly reliable [1, 2, 10]. The reliability of space systems is of utmost importance for their mission. A single point failure may cause catastrophe for the whole mission. So, each and every component, be in launch vehicle or communication systems need to be highly reliable [8, 11, 12]. Metal contact reliability in series switches has always been a concern during long-term reliability tests [13]. A switch based on metal-metal contact normally suffers from various issues like electromigration, stiction, metal creep, dielectric charging, and fatigue over a period of time [12, 14]. Stiction issue in MEMS switch occurs, when surface adhesive forces are larger than the restoring force of the beam structure [15]. Electromigration is a high current density phenomenon which causes voids in metal lines. While creep describes the trends of a material to deform or to move permanently to relieve stresses, resulting in a long-term revelation to levels of stresses due to material deformation, which are below the yield or final strength of the material [8, 14]. Keeping in mind all the abovementioned issues associated with metal contact switches, capacitive contact switch was taken into consideration [8]. A MEMS capacitive shunt switch serves as a two-state digital capacitor: a smaller capacitance (fF) is obtained while the switch is in up position, while a larger capacitance value of capacitor (pF) results in downstate of the switch [1, 2]. Generally, RF MEMS capacitive switch uses silicon nitride as dielectric layer due to its medium dielectric constant ($\varepsilon_r = 7.5$), which provides the isolation between both electrodes [16]. Other dielectric material such as TiO₂ ($\varepsilon_r = 32$), strontium titanate oxide ($\varepsilon_r = 120$ [16]), hafnium dioxide (HfO₂, $\varepsilon_r = 25$ [17]), piezoelectric lead zirconate titanate (PZT, $\varepsilon_r = 190$ [18]), and aluminium nitride (AIN, $\varepsilon_r = 9.8$ [19]) can also be utilized because of high dielectric constant in place of silicon nitride layer for impressive RF performance.

Many researchers and industries around the globe have reported various RF MEMS switches using different materials with various technologies and by varying the electromechanical and RF parameters. Somayye et al. developed the shunt switch with reduced air gap using step structure, and AIN dielectric layer is used instead of SiO₂ and Si₃N₄ for improved isolation, i.e., -58 dB. Chan et al. have developed the DC contact switch using GaAs substrate at National Taiwan University as shown in Figure 1. In this switch, the coplanar waveguide (CPW) line and center conductor are fabricated using gold material and SiO₂ was used as a dielectric layer. The authors reported the return loss $>20$ dB, isolation of $>20$ dB, and actuation voltage around 26-30 V [15-23]. Furthermore, Guo et al. [24] developed the low actuation voltage MEMS switch by utilizing aluminum alloys for movable beam. The designed switch shows the low pull-in voltage of 5 V for alloy instead of gold material, i.e., 45 V. Rao et al. fabricate the MEMS switch using the clamped-clamped structure of gold beam having thickness 500 Å, and the dielectric layer of AIN is deposited by plasma-enhanced chemical vapor deposition (PECVD) process. The authors reported the actuation voltage of 5.5 V and behaviors of dielectric charging to characterize by the capacitance–voltage (CV) curve method. Goel et al. developed the MEMS series switch having low actuation voltage, improved RF performance for reconfigurable antenna, and sufficient switching speed. The authors reported the pull-in voltage of 5 V with return loss $>20$ dB and insertion loss $>0.4$ dB from DC to 60 GHz. Further, the capacitive shunt switch was fabricated on a four-mask silicon wafer by utilizing surface micromachining process technology to report the low actuation voltage. The PECVD is used to deposit a thin AIN dielectric layer to improve isolation in the downstate due to a high dielectric constant. Therefore, Thelluir et al. developed the low pull-in voltage MEMS switch using gold as a beam material with improved RF performance. Chu et al. fabricate the MEMS switch on GaAs substrate using a pull-in electrode and inline cantilever beam to achieve “On” and “Off” states as shown in Figure 2. In this train, spaced holes are etched into cantilever beam to achieve the lower pull-in voltage. The measured insertion loss of $>3$ dB and isolation of $>20$ dB in the frequency range 1-40 GHz was reported.

2. RF Actuation Mechanism

Mechanical actuation and electrical actuation are two parts of the RF MEMS switch. Mechanical movement can be realized
by piezoelectric, electromagnetic, electrostatic, and thermal mechanisms. The common approach used now days is electrostatic actuation mechanism, due to its advantages like low DC power consumption, low switching speed, thin layers of material, wide range of contact forces of 50–200 μN, and most importantly tiny electrode size. Its ON-OFF capacitance ratio is also very high, but a higher actuation voltage is required. In comparison to electromagnetic actuation, voltage requirement is low but current consumption is high. Coil and ferromagnetic armature are used as an electromagnetic actuator in electromagnetic actuation. In this type of mechanism, semihard magnetic materials or permanent magnets allow the addition of a self-latching mechanism. The example of MEMS device that uses this mechanism is a micromechanical relay. A thermal actuator can also be used to simplify the relay. Thermal actuators include the armature of a soft magnetic material, permanent magnets, and thermosensitive magnetic materials stators. The piezoelectric mechanism depends upon the piezoelectric effect, and it provides exceptional material characteristics, where elastic deformation is generated by electrical field stimulation. To actuate ON or OFF conditions, a downward force is created by attaching a designed piezoelectric actuator to switch the membrane. Reduced pull-in voltage may be obtained by enabling the switch to have a high force by using this mechanism. This high force permits the air gap height to be increased with no reduction in another parameter of the switch such as critical stress and switching speed. The switch can also be actuated by using a thermal actuation mechanism. This actuation mechanism includes the thermal microactuators. For example, two thick metal posts are linked with the two thermal actuators which act as the centerline of the CPW transmission line, and the MEMS switch may be trigger ON and OFF by utilizing current or voltage pulses. A very few researchers had been developed the MMES switch using thermal actuation with a huge contact force and large beam spring constant to achieve the low contact resistance and hence enhance the power handling capacity. Table 1 shows the comparisons between four actuation technologies, which are used to actuate the RF MEMS switch.

### Table 1: Different actuation techniques for MEMS switch.

| Technology    | Contact force (μN) | Current (mA) | Size    | Voltage (V) | Switching time (μs) | Power (mW) |
|---------------|--------------------|--------------|---------|-------------|---------------------|------------|
| Magnetostatic | 50-200             | 20-150       | Medium  | 3-5         | 400-1000            | 0-100      |
| Thermal      | 500-3500           | 5-100        | Large   | 3-5         | 200-10,000          | 0-200      |
| Piezoelectric| 50-250             | 0            | Medium  | 3-20        | 50-500              | 0          |
| Electrostatic| 50-1500            | 0            | Small   | 20-80       | 1-200               | 0          |

3. Design and Working Principal

A high resistive silicon wafer (thickness of 675 ± 20 μm, dielectric constant and 11.8) has been used for the development of MEMS switch using fixed-fixed beam configuration. Figures 3(a) and 3(b) show the cross-section view of the proposed MEMS capacitive switch in upstate position and downstate position, respectively. The coplanar waveguide transmission line with dimension (G/W/G) of 90/120/90 (all in μm) is designed to support the RF MEMS switch whose characteristics impedance is 50 Ω. The grounds of the CPW line are connected to both ends of the MEMS.
The material used for anchors, transmissions line, and bridge is gold because resistivity is higher than other conducting materials such as aluminum, silver, and copper. A thin dielectric layer is used above the center conductor transmission line, which is used to prevent the upper electrode and bottom electrode from short-circuit. The dielectric materials between both conducting electrodes are chosen in such a way that having high relatively permittivity results in the low losses and lower pull-in voltage. The proposed switch has been simulated using SiO₂ and AIN dielectric materials to study the impact on the RF performance of the switch.

The electrical actuation and mechanical actuation are two sections of the RF MES switch. To actuate the mechanical section, there are four types of actuation mechanism, i.e., piezoelectric, electrostatic, thermal, and electromagnetic mechanisms. The common approach used nowadays is the electrostatic actuation mechanism.

When there is no DC voltage applied between the beam and bottom electrode, the switch is in ON state and signal pass from one port to another port. On the other hand, when the DC voltage is applied between them, the switch is in the OFF state. Hence, membrane collapses on the dielectric layer which is above the center transmission. Due to electrostatics force between top and movable beam the signal pass from one port to another port blocks. This electrostatic force is caused by actuation voltage applied between both electrodes and is given as [1, 2].

\[
F = \frac{\varepsilon_0 \omega W V_a^2}{2(g_0 + (t_d/\varepsilon_r))^2},
\]

where \( V_a \) is actuation voltage and is given by [1].

\[
V_a = \frac{2kg^2(g_0 - g)}{\varepsilon_0 \omega W},
\]

where \( W \) is the width of the CPW transmission line, \( g_0 \) and \( g \) are pre- and postair gap height from membrane, \( \omega \) is the beam width, and \( k \) is the spring constant of the beam in negative \( z \) direction and is given as [1, 5]

\[
K = K' + K'',
\]

\[
K = 32Ew(t/l)^3 (27/49) + 8\sigma(1 - \nu)\omega(t/l),
\]

where \( E \) (GPa) is Young’s modulus, \( \sigma \) (MPa) is biaxial residual stress due to fabrication process, \( K' \) is due to the stiffness of structure, \( K'' \) is spring constant contribution due to residual stress, and \( \nu \) is Poisson’s ratio of beam. The detailed
dimension and material used for the switch structure are given in Table 2.

Above a definite threshold voltage, the electrostatic force is increased due to an increase in charge and overcome the mechanical restoring force of the beam. An increase in electrostatic force results in a decrease in the beam gap height and at the same time which in turn enhances the downstate capacitance, and resulting beam becomes unstable and this threshold voltage is called pull-in voltage given as [1, 14]

\[
V_p = V \left(2g_0/3\right) = \sqrt{\frac{8k g_0^3}{27\varepsilon_0\omega W}} \quad (4)
\]

4. Electrical Model of Shunt Switch

The electrical equivalent model describes a shunt switch as CLR (capacitance, inductance, resistance) series resonant circuit as shown in Figure 3(d). The movable metallic beam of the MEMS shunt switch is sketched by switch variable capacitance, lumped resistance, and switch inductance. Depending upon the ON and OFF conditions of the switch, the variable capacitance is changed. When the switch in ON condition, the variable capacitance is represented by \( C_{\text{up}} \) and in OFF condition it is represented by \( C_{\text{down}} \). From Eq. (6), if the frequency of operation is less than LC resonance frequency, the CLR model works as a capacitor, while it works as an inductor above LC resonant frequency. At the series LC resonant frequency, the CLR (capacitance, inductance, resistance) model reduces as series resistance and is represented by \( R_s \). Capacitances in up- and downstate define the insertion and isolation of shunt switch, respectively. The following subsections explain these points elaborately. The impedance of the capacitive shunt switch is given as [5]

\[
Z_s = R_s + j\omega L + \frac{1}{j\omega C}, \quad (5)
\]

\[
Z_s = \begin{cases} 
\frac{1}{j\omega C} & \text{for } f<<f_0 \\
R_s & \text{for } f=f_0 \\
j\omega L & \text{for } f>>f_0 
\end{cases}, \quad (6)
\]

where \( C \) is the capacitance of the switch it may be up capacitance \( (C_u) \) and down capacitance \( (C_d) \) depends upon the switch position, \( R_s \) is the bridge resistance and it depends upon the resistivity of bridge, and \( L \) is the bridge inductance and it depends upon the gap between signal line ground of CPW. The LC series resonant frequency of the capacitive shunt MEMS switch is given as [1]

\[
f_0 = \frac{1}{2\pi \sqrt{L/C_u}}. \quad (7)
\]

5. Result and Discussion

5.1. Pull-In Analysis. The modal analysis and pull-in voltage for fixed-fixed beam has been carried using the finite element method- (FEM-) based Coventorware software. At the pull-in voltage, the movable bridge/membrane suddenly collapses on the thin dielectric layer due to the mechanical action of electrostatic force and causing the system to unstable (Figure 4). The electromechanical analyses in Coventorware are shown in Figure 5. It can be seen from the plot as voltage increases on the center conductor the top movable metallic beam starts to snap down from the top in the negative \( z \) direction towards the dielectric layer due to electrostatic force. When the metallic beam travel 1/3rd gap of the total initial gap from the topside, the movable beam enters into the instable region/area, and at this condition, electrostatic force overcome the restoring force. Small diameters \((10 \times 10 \, \mu m^2)\) holes are introduced in the top metal membrane to reduce the stiction problem and residual stress during the release process as shown in Figure 4.

5.2. Switching Time. The switching time depends upon the mechanical resonant frequency of the movable beam, applied source voltage, and pull-in voltage. It is defined as a time taken by the movable metallic beam to toggle from actuated state to unactuated state and vice versa is called switch speed and is given as [1].

\[
T_s = 3.67 \frac{V_p}{V_s \omega_0}, \quad (8)
\]

where \( V_s \) is the source voltage and given by \( V_s = 1.35V_p \), \( \omega_0 \) is the mechanical resonant frequency and given by as \( \omega_0 = \sqrt{k/m} \), \( m \) is the beam mass, and \( k \) is the spring constant in negative \( z \) direction. Figure 6 demonstrates the variation of switching speed/time with beam thickness to beam length \((t/l)\) ratio. The switching in gold membrane is three times slower compared to aluminum.

5.3. RF Analysis. The ANSYS HFSS software has been used to extract the RF performance of the designed fixed-fixed beam configuration-based MEMS switch. RF parameters such as insertion loss \( (S_{21} \text{ in dB}) \) and return loss \( (S_{11} \text{ in dB}) \) are defined in upstate, whereas isolation \( (S_{21} \text{ in dB}) \) is defined

| Parameters | Value |
|------------|-------|
| Beam length \((L)\) | 400 \(\mu m\) |
| Beam width \((w)\) | 120 \(\mu m\) |
| Center conductor width \((W)\) | 120 \(\mu m\) |
| Overlap area \((A)\) | 120 \(\times 120 = 14400 \, \mu m^2\) |
| Dielectric material and constant | AlN & Si11 |
| Beam thickness \((t)\) | 1 \(\mu m\) |
| Beam material | Gold |
| Dielectric thickness \((t_d)\) | 0.1 \(\mu m\) |
| Air-gap \((g_d)\) | 2.5 \(\mu m\) |
| Substrate thickness \((h)\) | 675 \(\pm 20 \, \mu m\) |
| CPW dimension | G/W/G-90 \(\mu m/120 \, \mu m/90 \, \mu m\) |
| CPW thickness | 1 \(\mu m\) |
in downstate. When there is no voltage applied to the bottom electrode, the switch is in unactuated state, and in this state, two RF parameters such as return loss and insertion loss of the switch have been analyzed. Return loss state that how much power is reflected back by the input/exciting port of coplanar waveguide transmission line. This is due to the improper impedance matching between switch and CPW line. Figure 7 shows the return loss or impedance matching as a function of frequency is better than 20 dB over whole frequency band. The return loss ($S_{11}$) in the up state of the switch is mathematically calculated by [1]

$$|S_{11}|^2 \approx \frac{\omega_0^2 C_{up} Z_0^2}{4}. \tag{9}$$

Insertion loss is also calculated in upstate and is it change the flow of RF signal between the input port and output port to control the power dissipations in transmission line and is given as [1].

$$|S_{21}| = \left( \frac{1}{1 + j\omega_0 C_C Z_0/2} \right). \tag{10}$$

Insertion loss happens at low frequency due to the resistive loss between contact resistance region of the switch and finite resistance of CPW line while at high frequency is due to skin depth. Figure 8 shows the insertion loss better than 0.5 dB throughout the frequency band.
When the proposed shunt MEMS switch is in an actuated state, switch capacitance is a large increase in downstate by factor 20-100 resulting in the good isolation. Isolation defines as how much power is present between port 1 and port 2 when the switch is in OFF state and is given as [2].

\[
|S_{21}|^2 = \frac{4}{\omega_0^2 Z_0^2 C_{down}^2},
\]

where \(C_{down}\) is the downstate capacitance and is given by [1].

\[
C_{down} = \frac{\varepsilon_0 \varepsilon_r A}{t_d}.
\]

The ratio of capacitance in downstate to upstate is defined as the figure of merit (FOM). The FOM factor for the proposed switch is greater than 50. Figure 9 shows the isolation for the proposed switch is better than 20 dB for the entire frequency band and maximum isolation is 50 dB @18 GHz and 55 dB @12 GHz for SiO\(_2\) and AIN dielectric materials, respectively.

In MEMS shunt switch, small diameter holes play the vital role in RF performance as well as in mechanical performance. Minor diameters holes are inserted into the top movable beam to overcome the squeeze air film damping and improve the switching speed of the switch. The total holes area may be 65% of the whole structure. Therefore, holes discharge some of the residual stress in the membrane and decrease the young modules of the MEMS switch. The effect of holes is negligible in upstate if the holes sizes are less than the 3-5 initial air gap because the fringing field can fill the hole area. In downstate, the holes reduced capacitance as well as isolation of the switch. Figure 10 shows the for holes dimension \(5 \times 5 \mu m^2\) isolation is 65 dB and for \(10 \times 10 \mu m^2\) isolation is 60 dB.

6. Conclusion

In this work, a detailed analysis of a designed RF MEMS capacitive type shunt switch is outlined. Fixed-fixed beam configuration is chosen here for ease of realization. The
operating frequency is targeted for the 10 to 40 GHz band. MATLAB is used for all analytical calculation, whereas HFSS and Coventorware are used for the full-wave analysis of the switch structure. The proposed switch shows the pull-in voltage around 9.2 V for the gold membrane. The RF parameters such as isolation, insertion loss, and return loss are >20 dB, >0.5 dB, and >25 dB, respectively, over the whole frequency band for SiO₂ as a dielectric layer. Furthermore, to improve the RF parameters, here, an AIN dielectric material is used instead of SiO₂ because of the higher dielectric constant to increase the downstate capacitance and thus improve the isolation. The reported maximum isolation in downstate is 55 dB at 15 GHz.

Data Availability
Data will be made available on request.

Conflicts of Interest
The authors declare that there is no conflict of interest regarding the publication of this paper.

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