Metal contact RF MEMS switch design for high performance in Ka band

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Abstract: RF/microwave systems require switches to achieve tunability and reconfigurability. MEMS switches have always been a priority due to excellent RF performance (low insertion loss and high isolation). In this work, we present an RF Micro-Electro-Mechanical-System (RF MEMS) series switch that provides insertion loss less than 0.6 dB (on switch) and isolation better than 15 dB (off switch) at 40GHz. The designed switch consists of serpentine arms on the fixed end and two free-moving arms on another end. These free arms have individual contact points to overcome asperity problem during on state. To avoid self-actuation, bumps (0.6um) are used at the bottom side. This electrostatically actuated switch requires a pull-in voltage of 3.1V for 2.4 μm displacement in 67.14 μs time. The proposed switch is analysed in COMSOL software, and its RF characteristics are simulated in HFSS.

1. INTRODUCTION

RF/Microwave and millimetre devices achieve controllability function using switches. These switches can be of different type such as P-I-N diode, MEMS etc. MEMS is the most promising technology among all as it offers high isolation and low insertion loss. MEMS switches are compact and can be easily integrated into RF systems. These switches use different mechanisms to actuate, but the most common one is electrostatic actuation due to its negligible power dissipation capability and low complexity. These switches can be integrated into a series or shunt configuration. These configurations can be either capacitive or ohmic. Series switches mostly use ohmic (metal contacts) due to the advantage of breaking the connection between the input port and output port and provides excellent isolation [1]. These metal contact series switches offer outstanding performance (in terms of low insertion loss and high isolation) from DC to millimeter frequency range [2]. These switches can be easily integrated with Co-Planar Waveguide (CPW) and other transmission lines. The performance of the switch depends on its electrical and mechanical design [1,3]. Hence, to achieve high performance in the switch, we need to focus on its design elements. However, these metal contact switches have self-actuation and asperity problem due to which a large amount of current flows through the small area [4]. The self-actuation problem in a series switch can be overcome by making a dimple in the cantilever or bump in the transmission line to avoid contact with the actuation electrode[5]. The parallel connection of microcontacts with individual actuation terminal can be used to avoid the asperity issue [6]. However, this results in a large pull-in voltage and up-state capacitance. Switch with several contact points can also be designed, but not every contact will touch the bottom due to asperities of different heights [4,7]. Asperities are irregular structures with different heights formed due to surface roughness. The asperity with the highest height only touches the bottom. Hence, results in a large current from a small area (temperature increases). This paper presents an RF MEMS series switch having two arms at the free end with individual contact points to avoid metal-metal contact issues. Asperities of one contact will not affect others due to being present on
different arms. These arms are designed to avoid movement of the free end at different heights and actuated by the same electrode. This structure design results in less increase in temperature at contact points. The proposed switch offers low pull-in voltage requirement, low switching time, and high RF performance. Simulations are done in COMSOL Multiphysics to validate the design. RF performance of the designed switch is analysed in HFSS software. This paper comprises five sections, as follows: Section II describes the design of the proposed switch. Equivalent circuit of the switch is discussed in section III. Simulations results are shown in section IV, followed by conclusions.

2. PROPOSED SWITCH DESIGN

The schematic design of the proposed switch is shown in Figure 1. It consists of a cantilever beam with one end fixed and another free.

![Figure 1](image1.png)

**Figure 1.** (a) Top view and (b) Side view of the proposed switch.

The proposed switch is divided into three parts, as shown. Section 1 shows the two serpentine arms to reduce the stiffness and hence pull-in voltage. Centre section of the switch contains holes to improve stiffness and facilitate easy releasing of the structure at the time of etching during fabrication. Section 3 has two microcontacts with individual contact points. Switch along with CPW dimensions, are shown in table 1. This parallel connection improves current-carrying capability and increases reliability due to multi contacts. This design has an advantage as asperity present in one contact will not affect another (as shown in Figure 2) as well as there is less probability of curling up of the microcontacts due to stress in the beam at different heights as both are connected at one end. Bumps in the transmission line are used to avoid contact of the bridge to the actuation electrode.

![Figure 2](image2.png)

**Figure 2.** (a) Surface profile of contact with several asperities [5] and (b) Surface profile of two contacts with several asperities (this work).
Table 1. Dimensions of Proposed switch and CPW

| Symbol | Description                                    | Value (μm) |
|--------|-----------------------------------------------|------------|
| G/W/G  | CPW transmission line                         | 60/100/60  |
| S      | width of the cantilever membrane              | 60         |
| L      | length of the cantilever membrane             | 200        |
| h      | the thickness of the cantilever membrane      | 1          |
| Lc     | length of the contact area                    | 20         |
| L2     | the length between the electrode and contact area | 80       |
| A      | the area of pull-in electrode                 | 60 * 60    |
| L1     | Serpentine structure length=Microcontact length | 70       |
| Ah     | Holes area                                    | 10*10      |
| S1     | Spacing                                       | 10         |
| S2     | Microcontact width                            | 10         |
| l_{dielectric} | Dielectric thickness                       | 0.3        |
| l_{oxide} | Oxide thickness                             | 0.5        |
| g      | The gap between the actuation electrode and the cantilever | 3          |
| h1     | Height of the bump                            | 0.6        |

The equivalent distributed circuit diagram of the MEMS switch integrated into CPW is shown in Figure 3. Substrate for the transmission line is silicon and silicon dioxide are taken as an insulating layer to improve RF performance. All the parameters are calculated using dimensions given in Table 1.

![Equivalent circuit model of the designed switch.](image)

Capacitance provided by the open switch ($C_u=3.69 \text{ fF}$) is calculated using equation (1) [1]:

$$C_u = \frac{(C_s/2)}{(1 + l/(2 \times Z_h \times c_s \times (c/\sqrt{\varepsilon_{eff}})))} \quad (1)$$

$$C_s = \frac{\varepsilon_0 A}{g \times l_{dielectric}} \frac{1}{\varepsilon_r} \quad (2)$$

Capacitance due to a gap between two transmission line ($C_p = 0.42 \text{ fF}$) is calculated using a gap of length ($l=190\mu m$) between two transmission line. $Z_h = 60\Omega$, $\varepsilon_{eff} = 6.1$. These parameters are extracted from the simulation in HFSS software.
3. SIMULATION RESULTS

A. Pull-in Voltage
The minimum voltage required to close the switch ($V_{\text{pull-in}}$) is calculated as [1]:

$$V_{\text{pull-in}} = \sqrt{\left(\frac{8kg^3}{27\varepsilon_0A}\right)} + \sqrt{\left(\frac{2kg^3}{3\varepsilon_0A}\right)} \left(\frac{t_d}{\varepsilon_r}\right)$$  

(3)

It depends on the stiffness of the cantilever beam ($k$), dielectric thickness ($t_d$), gap ($g$), dielectric constant ($\varepsilon_r$) and Area ($A$). Stiffness of a beam depends upon Young's Modulus ($E$). Hence, the material having the same Young's Modulus ($E_{\text{Au}} = E_{\text{Al}} = 70$ GPa) have the same pull-in voltages, as shown in Figure 4. Resonant frequency ($f_0$) of this proposed switch (simulated in COMSOL) is 3.84 KHz for Gold and 8.69 KHz for Aluminium. Von mises stress on the beam is shown in Figure 5. Material with high dielectric constant results in low pull-in voltage as well as improves RF performance also. This proposed switch has a pull-in voltage of 3.9V for silicon dioxide (dielectric constant = 3.9) and 3.1 V for silicon nitride (dielectric constant = 7.5).

![Figure 4](image_url)  
**Figure 4.** Displacement vs applied Voltage curve for different materials

![Figure 5](image_url)  
**Figure 5.** Von mises stress curve at different places on the beam.

B. Switching time
The time required to close the switch ($t_{\text{pulldown}}$) is given by [1]:
\[ t_{\text{pull down}} = 3.67 \left( \frac{V_{\text{pull-in}}}{V_{\text{applied}} + 2 \pi f_0} \right) \]  

(4)

From equation (4) and (5):

\[ t_{\text{pull down}} = 3.67 \left( \frac{\sqrt{\frac{8k_g^2}{3\eta_0d}} + \sqrt{\frac{2k_g}{3\eta_0d}}}{V_{\text{applied}} + 2 \pi f_0} \right) \]  

(5)

A comparison of different dielectric performance on the pull-down time is shown in Figure 6 (\(V_{\text{applied}} = 15\text{V}= 4.83 \times V_{\text{pull-in}}(\text{SiN}) = 3.84 \times V_{\text{pull-in}}(\text{SiO}_2))"). Table 2 shows pull-down time comparison among different parameters. Aluminium based switch is faster than Gold due to low mass density of the former despite having equal Young’s modulus.

| Condition | Dielectric Material | Pull-down time (\(\mu\text{s}\)) | Method   |
|-----------|---------------------|----------------------------------|----------|
| \(V_{\text{applied}} = 3.9\text{V}\) | SiO\(_2\) | Gold | 179.2 | Calculated |
|           |  | Aluminium | 67.14 |          |
| \(V_{\text{applied}} = 3.1\text{V}\) | SiN | Gold | 148.7 | Calculated |
|           |  | Aluminium | 55.77 |          |
| \(V_{\text{applied}} = 15\text{V}\) | SiO\(_2\) | Gold | 46.54 | Calculated |
|           |  | Aluminium | 17.45 |          |
| \(V_{\text{applied}} = 15\text{V}\) | SiO\(_2\) | Gold | 41.1 | Simulated |
|           |  | Aluminium | 16.9 |          |
| \(V_{\text{applied}} = 15\text{V}\) | SiN | Gold | 33.78 | Calculated |
|           |  | Aluminium | 11.54 |          |
| \(V_{\text{applied}} = 15\text{V}\) | SiN | Gold | 32.9 | Simulated |
|           |  | Aluminium | 11.4 |          |

**Figure 6.** Displacement vs applied Voltage curve for different materials

C. RF analysis

The proposed switch is integrated as an in-line component onto the CPW, as shown in Figure 7. There will be two stages of the switch as follow:
1) Off-state
When there is no voltage applied to the actuation electrode, then no physical contact is present between input and output. There is no transfer of signal. This results in high S21 (Isolation in the off state). Simulation results (in Figure 8) display the isolation of more than 15dB up to 50GHz. All the signal coming is being reflected. Isolation loss is found to be same for both types of the dielectric.

2) On-state
Actuation voltage greater than or equal to pull-in voltage results in the closing of the proposed switch. All the signals from the input port transfer to the output port and results in low insertion loss (S21). S11 is -26.6 dB and S21 in on state is -0.6 dB and up to 50GHz, as shown in Figure 9. On-state S-parameters simulated for both silicon dioxide and silicon nitride come out to be same.
Figure 9. Insertion (S21) and Return Loss (S11) in On-state

D. Comparison with state of the art
Table 3 shows a comparison of the proposed switch with the switches present in literature.

| S.no. | Ref.   | Gap g (µm) | Pull-in voltage (V) | Isolation (dB)       | Insertion loss (dB) |
|-------|--------|------------|-------------------|----------------------|---------------------|
| 1     | [7]    | 2.2        | 8                 | -15@20GHz            | -0.8                |
| 2     | [6]    | 0.7        | 4                 | -25@40GHz            | -0.65               |
| 3     | This work | 3         | 3.9(SiO₂)3.1(SiN) | 17.8@40GHz           | -0.49               |

4. CONCLUSION

Novel design with parallel arms and individual contact points of an ohmic in-line RF MEMS switch is presented in this article. This switch offers many advantages like low pull-in voltage, high rf performance and compact design. A comparative study between gold and Aluminium is done to find out the impact of different material properties on the parameters of a switch. Dielectric material on the top of the actuation electrode also affects the performance of the device. Parallel connection with individual contacts ensures high reliability as well as high current carrying capabilities. Pull-in voltage of the switch is found to 3.9V (silicon dioxide as dielectric). Switching time of the device can also be reduced by using a dielectric with a high dielectric constant. RF characteristics of the switch give (insertion loss to be -0.6dB during off state and isolation loss of -15.74dB up to 50GHz) excellent performance. Hence, it is suitable for reconfigurable RF application.

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