OHMIC RF MEMS SWITCH WITH LOW LOSS AND LOW FORCE ON QUARTZ FOR RECONFIGURABLE CIRCUITS

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ABSTRACT

This paper presents the novel Ohmic RF MEMS switch design and fabrication in broad frequency range for reconfigurable circuits like tunable antennas and filters, switching matrix and Phased array applications. In this work ohmic contact switch has been developed using a customized process flow. The cantilever structure was split into small strips to enable it for complete sacrificial removal for good RF characteristics. The design was carried out for the low force but keeping in view the sufficient restoring force requirement for smooth operation of the switch. This configuration was fabricated using with metal contact to ensure its operation from DC onwards. The Quartz substrate was used for fabrication to exploit its properties for high frequency operation. A low actuation voltage of 18.1V was achieved with an insertion loss of 0.18dB and return loss better than 20dB in the frequency range of DC-12GHz. The isolation of 40dB was achieved in the off state.

KEYWORDS: Reconfigurable, Isolation, Restoration Force, Spring Constant, Electrode, Actuation Voltage

INTRODUCTION

The Radio frequency MEMS (RF MEMS) [1] are gaining significance in the field of communication, radar and the navigation applications for reconfigurable circuits like tunable filters, switching matrix and Phased array reconfigurable antenna applications [2]. The radio-frequency MEMS (RF MEMS) switch is defined as a contact switch fabricated using micro-machining technology. RF MEMS switches are known to have the excellent features like low insertion loss due to low ON resistance and large isolation due to small parasitic in comparison to the PIN diode and MESFET switches [3-7]. Additionally these provide benefits such as reduced power consumption, noise, weight, size and cost etc. Major problem associated with RF MEMS reliable operation is the degradation of the metal-to-metal contact between the actuation electrode and the cantilever. This is mostly due to the contamination and the electro-migration of materials across the contact, the creeps, the ductile, and the brittle wearing of the contact and the hardening of the contact area.

However, these issues were addressed by some researchers by designing the device such that the actuation voltages do not exceed 50V [8]. In spite of some active research in this area stable switching of signals is a problem, which stems from the insufficient restoration force. This necessitates examining some new design and process of these devices. In this paper a novel configuration has been proposed and a hysteresis response was studied in detail so as to provide the restoration capable of stable operation [9]. This analysis is important as the stable RF performance is determined by the mechanical behaviour of the RF MEMS switch. In this work the design of the MEMS switch, manufacturing process and analytical results have been discussed which approves the superiority of the proposed RF MEMS switch.

The paper is organized as follows. Section II introduces the simple but efficient design, simulation and behavioural model of the RF MEMS switch taken up for fabrication. Section III presents the fabrication details and flow followed during fabrication. Section IV presents the details of the inspections carried out during and after fabrication. Section V summarizes the experimental results. Section VI finally concludes with overall results.
DESIGN AND SIMULATION

This work was carried out with main emphasis on the design of the cantilever configuration of MEMS switch with low force and low loss having electrostatic actuation. This configuration was provided actuation electrode under the cantilever with bias pad on the periphery in view of smaller length of bond wire during assembly and packaging to avoid the parasitic effects at high frequencies.

The design of this switch was done using split beams in rectangular shape instead of holes from other reported work which makes this design unique. This configuration in comparison to the rectangular holes has the advantage of low stress at the anchor junction, higher spring constant, and higher mechanical resonant frequency making it more robust to the environmental effects and ease in structure release due to continuous larger gap for etchant percolation. The Fig. 1 (a) and (c) shows the 3D models of the split beam and rectangular holes analysed with FEM for stress analysis. The cantilever outer dimensions have been taken as same for both the configurations except for the internal structural design. The mass of the cantilever structure has been maintained same for both the configurations so as to analyse the proposed split structure with respect to the rectangular holes structure. The holes dimension is 10x10 µm$^2$ and the edge to edge gap between the holes has been optimized in order to achieve the same mass as of the split beam structure. The split cantilever details are given subsequently. The analysis shows that the stress of the order 36 MPa in case of rectangular holes and 26 MPa for the split beam configuration has been observed. The stress analysis shows the superiority of split beam design with respect to the conventional rectangular holes concept. The units of the displacement and force shown are in µm and µN.

The Fig.1 (b) and (d) shows the force versus displacement graphs for these two configurations redrawn from the displacement versus voltage data of the CoventorWare finite element analysis using equation 1.

\[ F = \frac{\varepsilon AV^2}{2g^2} \]

Where

- $A$ = Area of electrode
- $g$ = gap between electrodes, 2.9 µm
- $\varepsilon$ = permittivity of air
- $V$ = applied voltage
The spring constant was derived using the slope of force versus displacement graphs at different points in the linear region using equation 2. The derived values of $k$ have been found to be 2.86 N/m and 1.39 N/m for split beam and rectangular holes respectively clearly showing the advantage of split beam configuration in terms of superior spring constant leading to higher mechanical resonant frequency.

$$F = k\delta x$$

(2)

Where $k = $ Stiffness

$\delta x = $ displacement

The above analysis clearly demonstrates the superiority of the split beam cantilever structure to the rectangular holes in terms of numerous parameters responsible for realization and the stable operation [10-14]. Fig. 2(a) shows the cross sectional view. The Coplanar Waveguide (CPW) of 50Ω impedance with Ground/Signal/Ground (GSG) configuration was used for design. The G/S/G dimensions for the CPW configuration are 19/200/19 µm. The air gap of 3.0µm was maintained for this design.

![Figure 2(a): Cross Section for Cantilever Having Actuation Electrode. Figure 2 (b) and 2(c): Shows the Details of the First Metal Layer and of the Actuation Electrode Respectively. All Dimensions Shown in Figures are in µm](image)

The actuation electrode was provided with the Si$_3$N$_4$ dielectric which makes this configuration less prone to stiction issues arising due to micro welding effects [15]. The CPW metal thickness was taken as 3.0µm for this design. In this structure, the 3D full wave electromagnetic simulation was carried out by a finite element method using Ansoft HFSS. The EM simulation results of RF parameters are shown in comparison to the measured results in the experimental results and discussion section V. The cantilever was split into six strips each having width of 15µm and gap of 12µm. This was done keeping in view the air damping and the easy removal of the sacrificial layer during the fabrication of MEMS switches. The pull in voltage was calculated using following equation (3) and values of parameters used are given in table 3.

$$V_p = \sqrt{\frac{8kd^4}{27\varepsilon A}}$$

(3)
Where \( k \) = Spring Constant

\[ d = \text{gap between electrodes, } 2.9 \, \mu\text{m} \]

\[ A = \text{Area of electrode} \]

\[ \varepsilon = \text{permittivity of air} \]

Spring constant has been calculated using equation (4)

\[ k = \frac{2(\varepsilon E/L)Wt^2}{d^2} \]

(4)

Where \( t \) = Thickness of membrane = 1.5 \( \mu \text{m} \)

\[ E = \text{Young’s Modulus} = 79 \text{ GPa} \]

\[ W = \text{width of the beam} \]

\[ v = \text{poisson’s ratio} \]

A 3D view of the cantilever under electrostatic simulation is shown in the Fig. 3 displaying maximum deflection at the edge of the cantilever. Based on the model values used in equation (4), the spring constant was found to be 4.04 N/m for the cantilever. These values were inserted in equation (3) and the pull in voltage was calculated as 12.53V. By simulation the pull in voltage is found to be 15.8V [16]. Beyond the pull in voltage point a sudden snap down was observed and analyzed under contact and hysteresis analysis. The cantilever was analyzed for the hysteresis response which is quite crucial for the smooth operation of the switch. This analysis estimates the spring constant responsible for the cantilever restoration to the original position. Fig. 4 shows the contact analysis and hysteresis curve after removal of the DC bias from the actuation electrodes and the cantilever comes back to its original position under force of spring constant at 13.6V for air gap of 3.0\( \mu \text{m} \).

Figure 3: 3D Model of Cantilever under Pull in Analysis

Figure 4: Contact Analysis and Hysteresis Curve. The Simulations were Carried Out Using FEM Model of the Switch. The Hysteresis Curve Shows the Pull Back of the Cantilever after Removal of the Actuation Voltage
The mechanical resonance is significant from the structural integrity point of view. The cantilever was subjected to modal analysis using CoventorWare to estimate the resonant frequency so as to analyze the effects of various vibrations when implemented in field applications. Keeping in view the effect of split beam the damping was considered zero during simulation. The structural resonance frequency was found to be 11.199 KHz. The value is quite satisfactory in response to the environmental effects this could face in the field applications. Table I shows the values of the resonance frequency of the first six modes.

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Frequency (KHz)</th>
<th>Mass (kg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.199</td>
<td>1.73x10^-11</td>
</tr>
<tr>
<td>2</td>
<td>41.908</td>
<td>1.10x10^-11</td>
</tr>
<tr>
<td>3</td>
<td>64.125</td>
<td>1.93x10^-11</td>
</tr>
<tr>
<td>4</td>
<td>132.803</td>
<td>9.60x10^-12</td>
</tr>
<tr>
<td>5</td>
<td>141.402</td>
<td>1.04x10^-11</td>
</tr>
<tr>
<td>6</td>
<td>185.063</td>
<td>2.14x10^-11</td>
</tr>
</tbody>
</table>

The dynamic response of the switch was carried out using Intellisuite finite element analysis. The cantilever was split into smaller width with air gap in between the strips to improve the time response of the switch [17-18]. The switching time can be computed by the equation (5) [19]. It has been observed that by keeping more gap between the strips time response can be improved.

$$ts \cong 3.67 \frac{V_p}{V_s} \frac{1}{2\pi f_0}$$

(5)

Whereas $V_p$ is the pull in voltage, $V_s$ is the source voltage and $f_0$ is the resonant frequency. From the simulation ON-time (downward transition) is 21 µsec and OFF-time (upward) transition was found to be 19µsec for the switch as shown in the Fig. 5[20]. A potential of 21.0V was applied to switch on the device.

![Figure 5: Switch Transition Analysis for On / Off Time](image)

**FABRICATION**

The fabrication of the switch was carried out using surface micromachining techniques. Process was customized according to the design requirements. A four mask batch process was used to fabricate the micromechanical switches. The fabrication flow is shown in the Fig. 6. The quartz substrate of 525µm thickness with 4” diameter was taken for fabrication. The first metal (Au) of 3.0µm thickness for CPW was deposited through E-beam evaporation and patterned as shown in Fig. 6(b) using mask 1. In order to avoid metal-metal contact a Si$_3$N$_4$ (Silicon nitride) layer of 0.1µm was deposited using PECVD and patterned over the actuation electrode as shown in Fig.6(c) using mask 2. The 3.5µm of photo resist above the CPW metal was coated using spin coating in two steps. A novel technique of photo resist planarization was
implemented to avoid the beam deposition on uneven surface [21-22]. Mask 3 was used for opening through the sacrificial layer for the beam anchor. The opening is shown in the sacrificial layer in Fig. 6 (d). The beam structure with 1.5µm thickness was realized through RF sputter deposition in Fig. 6 (e). At the last sacrificial layer was ashed out using plasma etching and release of the switch is shown in the Fig. 6 (f).

**Figure 6: (a) to (f) Shows the Fabrication Flow Followed during the Switch Fabrication**

**INSPECTION**

The air gap measurement was carried out by non contact methodology using laser vibrometer under the surface topography mode. The switch was scanned along the length and it shows the single step which also includes the thickness of the cantilever as shown in Fig. 7.

**Figure 7: Air Gap Measurement of Cantilever from the Bottom Electrode in Non Contact Mode Using the Laser Vibrometer**

The cantilever was scanned across the length so as to confirm the planarity. X and Y axis shows the width and length respectively. Z axis shows the gap height of the cantilever as 2.9 µm from the bottom electrode.

The results were observed in agreement to the design and after fabrication was found to be having the air gap as 2.9µm. SEM inspection was carried out to analyze the surface topology of the fabricated device. Fig. 8 shows the complete surface view and the zoomed SEM view of the device.
This analysis has given clear view of the edge definition and interspacing of the split membranes. SEM inspection also revealed the complete removal of the sacrificial layer enabling the device to properly perform electrically during the deflected state.

![SEM view](image)

**Figure 8: SEM View of the Complete Series Switch and Zoomed SEM View Cantilever Area**

**EXPERIMENTAL RESULTS AND DISCUSSIONS**

**DC Characteristics**

\[ C_{up} \text{ and } C_{down}, \text{i.e. Capacitance in upstate and deflected state was measured at 1MHz using the parametric analyzer of the Agilent. The capacitance ratio } (C_{down}/C_{up}) \text{ has been measured in the range of 30-35.} \]

**RF Characteristics**

The RF measurements for the ‘S’ parameters were carried out from DC-12 GHz. The semiautomatic RF probe station of Cascade Microtech Summit 11000 series with Vector Network Analyzer E8363B of Agilent make was used to characterize the switch device. The short open load thru (SOLT) technique was used to calibrate the test set up. A separate standard impedance substrate was used for calibration. The measurement accuracy is traceable to international standards. The Fig. 9(a) shows the device setup for measurement. The S parameters are shown in the Fig.9 (b) and 9 (c) for the up and down state respectively. The isolation is better than 40 dB. The insertion loss in on state is better than 0.18 dB with minimum return loss of 20dB from DC-12 GHz. The rf measurement results indicate the series switch has good ohmic contact with RF line for low loss transmission of the signal [23-24]. The measured parameters show a very good consonance with the simulated results.

![RF measurement setup](image)

**Figure 9: (a) Fabricated Switch Measurement Set up Showing the CPW GSG Configuration Measured with 200 Micron Pitch Probe**
Figure 9: (b) Shows S Parameter Results in Upstate of the Switch. Measured Results of the Return Loss and Isolation are Compared Against the Simulated Results (OFF state)

Figure 9: (c) Shows S parameter Results in Downstate of the Switch. Measured Results of the Return and Insertion Loss are Compared Against the Simulated Results (ON state)

The parameters of the designed, simulated, fabricated and measured Ohmic switch are listed in Table 1.

Table 2: Summary of Parameters for the Developed Ohmic Switch

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [µm]</td>
<td>200</td>
<td>Sacrificial layer</td>
<td>Photoresist</td>
</tr>
<tr>
<td>Width [µm]</td>
<td>150</td>
<td>Membrane Type</td>
<td>Cantilever</td>
</tr>
<tr>
<td>Height [µm]</td>
<td>2.9 (measured)</td>
<td>Dielectric [Å]</td>
<td>1000 (on actuation pad)</td>
</tr>
<tr>
<td>Membrane Layer</td>
<td>Au</td>
<td>Actuation area [µm²]</td>
<td>140x150</td>
</tr>
<tr>
<td>Thickness [µm]</td>
<td>1.5</td>
<td>Actuation voltage [V]</td>
<td>18.1</td>
</tr>
<tr>
<td>Spring Constant [N/M]</td>
<td>4.04</td>
<td>Switch time [µs]</td>
<td>15-25</td>
</tr>
<tr>
<td>(Calculated value)</td>
<td></td>
<td>(simulated)</td>
<td></td>
</tr>
<tr>
<td>Effective mass [Kg]</td>
<td>8.69 x 10⁻³</td>
<td>C_s [fF] (measured)</td>
<td>168.0</td>
</tr>
<tr>
<td>Density of Material [Kg/m³]</td>
<td>19.320</td>
<td>C_d [pF] (measured)</td>
<td>5.59</td>
</tr>
<tr>
<td>Mechanical Resonance frequency [KHz]</td>
<td>10.85 calculated</td>
<td>Loss [dB] (measured)</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Isolation [dB]</td>
<td>&gt; 40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(measured)</td>
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</table>
CONCLUSIONS

Ohmic RF MEMS switch with low loss and low force on quartz has been fabricated with novel concept of split beam design having metal contact. Split beam approach has been successful in achieving the low stress, high spring constant, higher mechanical resonant frequency and yielded a very good structure release due to the more continuous area available through the split beam for etching the sacrificial layer. The RF characteristics show an insertion loss better than 0.18 dB, return loss better than 20 dB and isolation of 40 dB at 12 GHz. The lower actuation voltage, very close to the simulated values, of the order of 18.1V has been achieved with good restoration action required for the stable operation. The results of this proposed fabricated switch make it suitable for the reconfigurable circuit applications.

REFERENCES


