A High Reliability and Low Loss Lateral RF Micromachined Relay

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Abstract

New lateral metal-contact micromachined switch using high aspect ratio cantilever beam with quasi-finite ground coplanar waveguide (FGCPW) configuration is proposed. It is fabricated by deep reactive ion etching (DRIE) process of silicon-on-insulator (SOI) wafer and shadow mask technology. It has demonstrated the switch operation up to 25 GHz. The insertion loss is less than 0.2 dB and isolation is higher than 23 dB at DC-15 GHz. The switching time is 30 µs.

Keywords: lateral switch, microwave switch, RF MEMS, DRIE, SOI

1 INTRODUCTION

Microelectromechanical system (MEMS) switches have many potential applications including signal routing in transmit and receive applications, impedance matching networks, the wide-band tuning networks, etc. There are two possibilities for the direction of the motion of the actuation component of the switch: a vertical and a lateral switch. The vertical switch performs out of wafer plane displacement and surface contact. The lateral switch performs in wafer plane displacement and sidewall contact. The majorities of the reported MEMS switches are the vertical motion switches, including the fixed-fixed beam switch [1], cantilever beam switch [2], toggle switch [3], and push-pull switch [4], etc. The main disadvantages of vertical actuation are relatively complicated fabrication process and sticking problem during the release of the movable structures. Lateral contacting switches have also been studied. Contrary to the vertical actuation, a major benefit of lateral actuation is the ability to co-fabricate the actuator, the contacts, conductor paths, and support structures, all in a single lithographic step. Besides, it is easy to get a mechanical force in opposing directions even when using electrostatic designs.

Based on the fabrication process, three types of lateral switches have been reported until now, including lateral switches using nickel surface micromachining [5-7], using thick poly-silicon micromachining [8-9], or using bulk micromachining [10-11]. In nickel surface micromachined switches [5-7], high-aspect-ratio structures are fabricated by electroplating nickel into lithographically defined plating stencils. The lithographic approach allows nickel heights of 10-50 µm and smallest widths of 5 µm. In poly-silicon micromachined switches [8-9], the mechanical structures were made by 2 µm poly-silicon using surface micromachining process and sacrificial layer. The bulk micromachined switches [10-11] were fabricated by DRIE process on SOI wafer. The metal contact was realized by depositing a thin layer of metal directly on the whole surface of the switch structures. To avoid the short circuit, the deposited metal was less than 4000 Å thick which limit the
performance of the switch. All lateral switches mentioned above did not report acceptable RF performance at microwave frequencies due to the difficulties of integration of RF circuit design and the mechanical design. A lateral switch with coplanar waveguide (CPW) configuration have been reported in earlier work by the present authors [12], which shows an insertion loss of below 1dB and isolation of above 16 dB at 0.4 - 20 GHz.

In this paper, a novel lateral metal-contact switch fabricated on SOI wafer using DRIE and shadow mask technology is demonstrated. From DC to 25 GHz, the fabricated switch shows low insertion loss and high isolation, which are comparable to the vertical switch. By using a new designed high-aspect-ratio cantilever beam, the actuation voltage of the switch is less than 25 V.

II DESIGN AND MODELLING OF THE SWITCH

A. RF design

Figure 1 is a SEM micrograph of a typical lateral metal-contact switch. The switch consists of a quasi-finite ground coplanar waveguide (FGCPW) transmission lines and an electrostatic actuator. The FGCPW transmission lines are formed from three parallel waveguides, which are realized by forming each waveguide on a 35 µm thick single-crystal-silicon plate that has been coated with a thin layer of evaporated Al. Therefore the RF signal can propagate not only along the metal on the top surface, but also along on the sidewall of the transmission lines. With the help of commercial 3D FEM simulation software – Ansoft’s high-frequency structure simulator (HFSS), a 50-Ω transmission line can be obtained by simply adjusting the width of the CPW signal line, $S$; the width of the gap between the signal line and the ground line, $G$; and the width of the ground line, $G$. In this switch, parameters $S$, $W$ and $G$ at the input and output port were designed to be 66 µm, 67 µm and 100 µm respectively to accommodate the 150 µm-pitch ground-signal-ground coplanar probes.

A high-aspect-ratio cantilever beam with 2.5 µm width and 35 µm depth is located in the direction of the signal line, which acts as the movable electrode of the electrostatic actuator as well as forms part of the signal line. The ground lines beside the cantilever beam are extended toward the actuator as well as forms part of the signal line. The ground which acts as the movable electrode of the electrostatic actuator. The FGCPW transmission lines are formed from three parallel waveguides, which are realized by forming each waveguide on a 35 µm thick single-crystal-silicon plate that has been coated with a thin layer of evaporated Al. Therefore the RF signal can propagate not only along the metal on the top surface, but also along on the sidewall of the transmission lines. With the help of commercial 3D FEM simulation software – Ansoft’s high-frequency structure simulator (HFSS), a 50-Ω transmission line can be obtained by simply adjusting the width of the CPW signal line, $S$; the width of the gap between the signal line and the ground line, $G$; and the width of the ground line, $G$. In this switch, parameters $S$, $W$ and $G$ at the input and output port were designed to be 66 µm, 67 µm and 100 µm respectively to accommodate the 150 µm-pitch ground-signal-ground coplanar probes.

The dc bias voltage for actuation is applied between the signal line and ground line. When no dc bias voltage is applied, the switch presents a very small series capacitance, $C_g$, between the two parts of the signal line, which is equivalent to an RF open circuit and resulting in high isolation. This is called open or off state. On the other hand, if the applied dc bias voltage between the cantilever beam and the fixed electrode exceeds the threshold voltage, the cantilever beam is attracted toward the fixed electrode by the electrostatic force until its free-end touches the contact bar, resulting in the propagation of the RF signal with minimal loss. This is called close or on state. Once the bias voltage is removed, the mechanical stresses in the beam will overcome the stiction forces to pull the beam away, hence switching the device off.

B. Modeling

![Equivalent circuit of the lateral MEMS switch.](image)

Figure 2 Equivalent circuit of the lateral MEMS switch.

An equivalent circuit model shown in Figure 2 was developed for a lateral RF MEMS switch. The circuit was modeled using Agilent EESof's Advanced Design System. The model consists of a resistor $R_l$ of the cantilever beam in series with an inductor $L$ of cantilever beam and switch capacitor $C_s$ (open state) and contact resistor $R_c$ (close state) in shunt with a capacitor $C_g$. $Z_0$ represent the characteristic impedance of input and output sections of the FGCPW line. $C_g$ is the coupling capacitance between the cantilever beam and the fixed electrode which protuberates toward the cantilever beam from the ground line. This coupling capacitance is fairly large and dominates the loss mechanism in the open/ close state of the switch. Figure 3 shows the simulated effect of $C_g$ on the S-parameters of the MEMS switch at the open and close state respectively. Figure 3(a) shows that various capacitances, $C_g$, only result in marginal differences in the isolation of the switch at the open state. Figure 3(b) shows that the insertion loss and return loss of the close switch are improved when $C_g$ increases from 10 fF to 60 fF. Increasing $C_g$ further to 125 fF, the performance of the close switch begins to worse. $C_g$ can be estimated from the parallel-plate formula:

$$C_g = \frac{E_0 l_2 l}{g} + C_f$$

where $C_f$ is the fringing field capacitance and is about 60% of $C_g$. Therefore to achieve good RF performance and low threshold voltage, careful consideration must be taken when selecting $l_2$ and $g$. 
The cantilever beam resistance $R_l$, inductance $L$, switch open capacitance $C_S$ and close resistance $R_C$, and shunt capacitance $C_g$ are all varied to fit the model to the measured S-parameters. The physical parameters used to model the MEMS switch in this work are summarized in Table I.

The threshold voltage is given by

$$V_{th} = \sqrt{\frac{8kg_0^2}{27\varepsilon_0\varepsilon_r^3}}$$

where $g_0$ is the initial gap between the two electrodes, $\varepsilon_0$ is the permittivity of the air ($8.854 \times 10^{-12} \text{ F. m}^{-1}$).

Figure 5 shows the calculated threshold voltage $V_{th}$ with various geometrical dimensions. It is found in Figure 5(a) that $V_{th}$ is dependent more on the narrow part width of the beam $w_1$ than on the electrode part width of the beam $w_2$. Figure 5(b) shows that the threshold voltage $V_{th}$ decreases as initial gap distance between the two electrodes $g_0$ increases. This also shows that $V_{th}$ is not decreased significantly when the beam length ratio $l_2/(l_1+l_2)$ is in the range of 30%~70%.

Then the threshold voltage $V_{th}$ of the proposed switches is about 23.6 V when the dimensions are as listed in Table II.

### C. Mechanical design

The illustrated top view of the electrostatic actuator used in the switch is shown in Figure 4. The electrode part of the cantilever beam $w_2$ is designed to be a little wider than its other part $w_1$ in order to not only keep low threshold voltage but also avoid the deformation of the electrode part of the beam. Hence no separate bumpers are needed to structure as other reported lateral switches [11] did. Assuming that the electrostatic force is applied at the midpoint of the electrode part of the cantilever beam, the equivalent stiffness, $k$, of the cantilever beam can be derived using the following expression based on the beam vibration equation [13]:

$$k = \left( \frac{12EI_2}{(4l_1^2 + 9l_2^2)l_2} + \frac{5}{4}l_1^3 I_1 \right)$$

where $I_1 = \frac{1}{12}w_1t$ and $I_2 = \frac{1}{12}w_2t$

where $w_1$ and $l_1$ are the width and length of the narrow part of the cantilever beam, $w_2$ and $l_2$ are the width and length of the electrode part of the beam, $t$ is the thickness of the beam and $E$ is the Young’s modulus of the single crystal silicon (190 GPa).

Figure 3 Simulated S-Parameters of SPST switch with various capacitance $C_g$. 

Table I Physical parameters for model of the proposed lateral RF MEMS switch

<table>
<thead>
<tr>
<th>$Z_0$</th>
<th>$R_l$</th>
<th>$L$</th>
<th>$C_S$</th>
<th>$R_C$</th>
<th>$C_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 Ω</td>
<td>0.4 Ω</td>
<td>145 pH</td>
<td>6.7 fF</td>
<td>0.6 Ω</td>
<td>30 fF</td>
</tr>
</tbody>
</table>

Table II Design dimensions of the proposed switch

<table>
<thead>
<tr>
<th>$S$</th>
<th>$W$</th>
<th>$G$</th>
<th>$W'$</th>
<th>$w_1$</th>
<th>$w_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>132 μm</td>
<td>34 μm</td>
<td>300 μm</td>
<td>33 μm</td>
<td>2.5 μm</td>
<td>5 μm</td>
</tr>
<tr>
<td>450 μm</td>
<td>275 μm</td>
<td>165 μm</td>
<td>10 μm</td>
<td>6 μm</td>
<td>4 μm</td>
</tr>
</tbody>
</table>
Figure 5 Calculated threshold voltage $V_{th}$ of the switch: (a) with various beam widths ($w_1$, $w_2$), (b) with various length ratio of $l_2/ (l_1+l_2)$ and initial gap distance ($g_0$).

### III FABRICATION PROCESS

All the components of the switches were fabricated on a SOI wafer, which includes a 35 $\mu$m low resistivity (LR) device active silicon (Si) layer ($<0.1$ $\Omega$-cm), 2 $\mu$m buried thermal silicon dioxide (SiO$_2$) layer and 500 $\mu$m high resistivity (HR) handle silicon layer ($>4000$ $\Omega$-cm). The process flow is summarized in Figure 6.

The process began with a SiO$_2$ of 2.0 $\mu$m deposition on a SOI substrate using PECVD and patterning using RIE, as seen in Figure 6(a). After that, DRIE was employed to etch the LR Si to buried SiO$_2$ layer by using the top SiO$_2$ as the hard mask. The exposed SiO$_2$ was removed by buffered oxide etchant (BOE) (Figure 6(b)). Following that, the SOI wafer was temporarily bonded to a shadow mask [14] using photoresist as intermediate material. 0.6-1.5 $\mu$m Al film was deposited on both the surface and the sidewalls of the switches through the shadow mask via evaporation (Figure 6(c)). Finally, the shadow mask is de-bonded and separated from the SOI substrate (Figure 6(d)).

Figure 6 Fabrication process flow of the MEMS switch.

Fig. 7 SEM Micrograph of the contact bar of the switch

The fabricated switch size is 400 $\mu$m $\times$ 700 $\mu$m in area. The yield of the process is very high (> 90%) due to the high-
aspect-ratio single-crystal-silicon structures which are free from warping, pre-deformation and sticking during the wet etching process.

Due to the nature of the evaporation process, the Al coated at the sidewall is thinner than that coated at the surface. The deposited metal on the surface is 1.5 \( \mu m \) and the metal deposited on the sidewall is about 6000 \( \AA \). Figure 7 shows the zoomed view of the contact bar of the switch, in which the contact tip is a semi-round tip with a radius of 3 \( \mu m \). Due to about 6000 \( \AA \) metal coated at the sidewalls of the structures, the original distance between the cantilever beam and the contact bar, \( d_0 \), had reduced from 4 \( \mu m \) to about 2.8 \( \mu m \) and the original gap between the electrodes, \( g_0 \), had reduced to 4.8 \( \mu m \) from 6 \( \mu m \).

**IV RESULTS AND DISCUSSION**

**A. RF performance**

The RF response of the system was measured using the HP 8510C Vector Network Analyzer with tungsten-tip 150 \( \mu m \)-pitch Cascade Microtech ground-signal-ground coplanar probes. The system was calibrated using standard short-open-load-through (SOLT) on-wafer calibration technique.

The measured S-parameters of the fabricated lateral MEMS switch with simulated data both from EM software and equivalent circuit are given in Figure 8. In Figure 8(a), the isolation of the switch at the open-state is very high, about 32 dB at low frequencies around 5 GHz or below, and decreases with increasing signal frequency to about 23 dB at 15 GHz. In Figure 8(b) the insertion loss of the switch at the close-state is less than 0.2 dB and the return loss is above 24 dB at 15 GHz respectively. It is found that the simulation results from the equivalent circuit are in good agreement with the measured results up to 15 GHz, which shows the validity of the proposed equivalent circuit. However, the simulation results from the EM software do not match the measured results very well. The reason is the EM simulation using commercial software cannot consider the contact resistance of the switch at the close state and the real fabrication process is not as perfect as the simulation.

**B. Mechanical characteristics**

Figure 9 presents the calculated and measured displacement results of the cantilever beam as the applied voltage increases. The measurement shows a good agreement to the calculation result. The distance between the cantilever beam and the contact bar decreased with the increase of the applied voltage. When the bias voltage increased to about 22.5 V, the cantilever beam was attracted to touch the contact bar rapidly from 1.4 \( \mu m \) away. Therefore, the threshold voltage of the switch is about 22.5 V.

![Figure 8](image1.png)

**Figure 8** Comparison of the fabricated switch measured results with the circuit and EM simulated results (a) open state, and (b) close state.

![Figure 9](image2.png)

**Figure 9** Relation between distance and applied voltages of the lateral MEMS switches.
The measured switching-on time is 35 μs with 30 V applied voltage and 30 μs with 35 V applied voltage respectively. The switching-off time is 30 μs. Due to the high-aspect-ratio (>14) single-crystal-silicon structures, the switch has good reliability and stability. After one million times of switching on/off operations, the performance of the switch only changes marginally.

V CONCLUSIONS

A low loss lateral RF MEMS switch with FGCPW configuration is presented. Up to 20 GHz, the insertion loss of the switch is less than 0.4 dB and isolation is higher than 20 dB, which is comparable to the surface micromachined vertical switch. The advantages of the switch include simple fabrication process (3 mask process), good reliability (>10⁶ switching cycles) and high yield (>90%).

REFERENCES