A single-pole double-throw (SPDT) circuit using lateral metal-contact micromachined switches

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Abstract

A dc 6 GHz single-pole double-throw (SPDT) switching circuit that employs lateral metal-contact micromachined switches is investigated. The lateral metal-contact switch consists of a set of quasi-finite ground coplanar waveguide (FGCPW) transmission lines and a high-aspect-ratio cantilever beam. A single-pole single-throw (SPST) lateral micromachined switch has an insertion loss of 0.08 dB and a return loss of 32 dB at 5 GHz. The isolation is 32 dB at 5 GHz. The measured insertion loss of the SPDT switching circuit is below 0.75 dB, whereas the return loss is higher than 19 dB at 5 GHz. The isolation at 5 GHz is 33 dB. Pull-in voltage of the switch is 23.3 V and switching time is 35 μs.

The size of the SPDT switching circuit is 1.2 mm × 1.5 mm. A main advantage of this circuit structure is simple fabrication process with high yield (>90%) based on the deep reactive ion etching (DRIE) technique of silicon-on-insulator (SOI) wafer and shadow mask technology.

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1. Introduction

Single-pole double-throw (SPDT) switching circuits are widely employed in microwave and millimeter wave communication systems. These include signal routing in transmitting and receiving applications, switched-line phase shifters in phased array antennas and wide-band tuning networks. Traditional integration of GaAs MESFETs and PIN diodes in the SPDT switching circuit [1,2] has less favorable as it suffers from high insertion loss and low isolation at high frequencies over the gigahertz (GHz) range. As an alternative, microelectromechanical system (MEMS) switches are more attractive due to their low insertion loss, high isolation, negligible power consumptions and good linearity. To date, different types of SPDT switching circuits are developed using MEMS switches to replace the conventional solid-state semiconductor switches. The first type of MEMS SPDT switching circuit involves two capacitive shunt MEMS switches placed a quarter wavelength from the center of the T-junction [3,4]. When one switch is actuated, the virtual RF short is transformed to an open at the T-junction thus blocking nearly all the signal from passing to that port. The insertion loss of 0.81 dB and the isolation of 20.3 dB at X-band [3] , and the insertion loss of 0.43 dB and isolation of 28.7 dB at K-band [3] have been demonstrated. The pull-in voltage of 9 V is achieved through changing the shape of the beam. The second design is a monolithic SPDT MEMS switching circuit [5,6] , which places two MEMS series switches at two output armatures to operate in a 2.3 GHz diversity antenna. This switching circuit has an insertion loss of 0.2 dB and an isolation of 50 dB from dc to 4 GHz. The pull-in voltage is 30 V, switching time is 20 μs and mechanical life span is 10 9 switching cycles. The third design is a Ku-band SPDT switching circuit based on toggle switches [7] . Two toggle switches are perpendicular to each other where both have fixed connections with a flexible metal band to the two output ports. If one toggle switch is on, the switch can be connected to the input port and the signal...
is routed to the output port. This SPDT switching circuit exhibits an insertion loss of 0.96 dB and an isolation of 30 dB from 7 to 20 GHz. The switching voltages are 30 V to close and 35 V to open. Finally, the latest design is a 35–60 GHz SPDT MEMS switching circuit [8] in which two direct contact series switches are placed at the end of each output line and a short-ended 50 Ω line is connected at the cross-junction. When one switch is actuated, the open-ended line formed by the off-state of the switch and the short-ended line comprise double resonance pair which transform to be open at the cross-junction. This circuit presents the insertion loss below 1 dB and the isolation higher than 19 dB from 35 to 60 GHz. The actuation voltage is 35 V. All these SPDT switching circuits use vertical MEMS switches, which are fabricated by surface micromachining process. This fabrication process is less favorable due to its complexity and stiction problem that arises during the wet release of the switching structures. Recently, lateral switches have also been studied [9–11]. Compared to the vertical switches, the lateral switches have the benefit of co-fabrication. The actuator, contacts, the conductor paths, and the support structures can be fabricated in a single lithographic step. Besides, it is easy to get a mechanical force in opposing directions even when electrostatic designs are used.

In this paper, a dc to 6 GHz SPDT switching circuit is designed, simulated and fabricated. It utilizes new lateral metal-contact switches that are implemented in a quasi-FGCPW transmission line. The actuation structure is high-aspect-ratio single-crystal-silicon (Si) cantilever beam, which is coated with a thin aluminum (Al) layer. This guarantees low insertion loss and high reliability (>10⁶ cold switching cycles) of the switch. The actuator, contacts, conductor paths, and support structures of the SPDT switching circuit, can be patterned in a single lithographic step and structured using DRIE technology, which is a high yield process (>90%).

2. Design and modeling of SPDT switching circuit

2.1. RF circuit design

The circuit schematic diagram of the implemented SPDT switching circuit is shown in Fig. 1. The circuit consists of a T-junction with a lateral metal-contact MEMS switch located at each of the output arms. The signal can therefore be routed to the two different output ports with one switched off and the other switched on. Fig. 2 shows the schematic view of the proposed MEMS SPDT switching circuit. The circuit is implemented on quasi-FGCPW transmission lines. The quasi-FGCPW transmission line is formed by three parallel waveguides. Each waveguide is a 35 μm thick single-crystal-silicon plate coated with a thin layer of metal. The cross-sectional view of the FGCPW along A–A′ is shown in Fig. 1(d). Hence, the RF signal can propagate not only along the metal on the top surface, but also along the side-
walls of the transmission lines. A 50 Ω transmission line can be obtained by simply adjusting, (1) the width of the signal line, S; (2) the width of the gap between the signal line and the ground line, W; and (3) the width of the ground line, G. In this circuit, parameters, S, W and G at each port were selected to be 132, 34 and 300 μm, respectively, to accommodate the 150 μm-pitch ground-signal-ground coplanar probes.

The lateral metal-contact switch placed at each output port involves a cantilever beam in the direction of the signal line. The top view of the cantilever beam is shown in Fig. 5 and its cross-sectional view along B–B′ is shown in Fig. 8(d). The cantilever beam is equipped with a fixed connection at the ground line. Fig. 4 shows the simulated effect of Cg on the S-parameters of the FGCPW transmission line, (2) the resistor, Rl, of cantilever beam, (3) an inductor, L, of cantilever beam, (4) switch capacitor, Cs (open-state) or contact resistance, Rs (closed-state), and (5) a coupling capacitor, Cg.

Cg is the coupling capacitance between the cantilever beam and the fixed electrode, which protuberates toward the cantilever beam from the ground line. Fig. 4 shows the simulated effect of Cg on the S-parameters at the open- and closed-state, respectively. Fig. 4(a) shows that various capacitances, Cg, only result in marginal differences in the isolation of the switch at the open-state. Fig. 4(b) shows the insertion loss and return loss of the switch get to their optimal value since a resonance occurs at the operating frequency range and the losses only depend on the total resistance of the circuit. Cg can be estimated as:

\[ C_g = \frac{\mu_0 l_{2} t}{\varepsilon_0} + C_f \]  

where \( \varepsilon_0 \) is the permittivity of the air (8.854 × 10^{-12} Fm^{-1}), \( l_2 \) the length of the electrode part of the cantilever beam, \( t \) the thickness of the beam, \( \varepsilon \) the real-time distance of the gap between two electrodes, and \( C_f \) the fringing field capacitance.

Therefore, to achieve good RF performance and low pull-in voltage, careful consideration must be taken in selecting \( l_2 \) and \( \varepsilon \). Once the switch is actuated, the gap between the two electrodes, \( \varepsilon \) decreases. Hence the coupling capacitance at the closed-state, \( C_{g,close} \) is a little bigger than that at the open-state, \( C_{g,open} \).

The cantilever beam resistance (\( R_b \)), inductance (\( L \)), switch open capacitance (\( C_s \)) and closed resistance (\( R_c \)), and shunt capacitance (\( C_g \)) are allowed to vary to fit the model in the measured S-parameters. Upon the determination of the model parameters for the MEMS switch, the SPDT switching circuit can be easily modeled by connecting the physical transmis-

2.2. RF circuit modelling

An equivalent circuit model shown in Fig. 3 was developed for a SPST MEMS switch. The circuit was modeled using Agilent EESof’s Advanced Design System (ADS). The model consists of: (1) characteristic impedance, Z0, of the input and output sections of the FGCPW transmission line, (2) the resistor, Rl, of cantilever beam, (3) an inductor, L, of cantilever beam, (4) switch capacitor, Cs (open-state) or contact resistance, Rs (closed-state), and (5) a coupling capacitor, Cg.
Fig. 4. Simulated S-parameters of SPST switch with various capacitance \( C_g \) at (a) open-state and (b) closed-state.


2.3. Mechanical design

To design a micromachined circuit, the switching voltage is considered. The low actuation voltage can be achieved through the optimization of the geometrical dimensions of the actuation part. The top view of the electrostatic actuator used in the circuit is shown in Fig. 5. The electrode part of the cantilever beam \( w_2 \) is designed to be relatively wider than the other part \( w_1 \) so that low pull-in voltage can be maintained and deformation of the electrode part of the beam can be avoided. Assuming the electrode part of the cantilever beam is subject to a uniform load, the equivalent stiffness, \( k \), of the cantilever beam has been derived using the following expression based on the method of superposition [12]:

\[
k = \frac{12E_1E_2I_1I_2}{(l_1^2 + 2l_1l_2)E_1I_1 + (4l_1^2 + 9l_1^2l_1 + 6l_1l_1^2 + 6l_1l_1l_2)E_2I_2}
\]  
(2)

where \( l_1 \) is the length of the narrow part of the cantilever beam and \( l_2 \) the length from the end of the electrode to the end of the beam. \( E_1 \) and \( E_2 \) are the Young’s moduli of the narrow part and wide part of the beam, respectively. \( I_1 \) and \( I_2 \) are the moments of inertia of the cross-sectional area of the narrow part and wide part of the beam, respectively. Before the deposition of the metal, the beam is merely made up of single-crystal-silicon. \( E_1, E_2, I_1, \) and \( I_2 \) are given by

\[
E_1 = E_2 = E_{Si} \tag{3}
\]

\[
I_1 = \frac{1}{12} w_1^3 t \tag{4a}
\]

\[
I_2 = \frac{1}{12} w_2^3 t \tag{4b}
\]

where \( E_{Si} \) is the Young’s modulus of the single-crystal-silicon (140 GPa), \( w_1 \) and \( w_2 \) the widths of the narrow part and wide part of the single-crystal-silicon beam, respectively. After the deposition of Al, the beam is made of single-crystal-silicon partially covered with Al. Therefore, \( E_1, E_2, I_1, \) and \( I_2 \) can be expressed as:

\[
E_1 = E_{Si}w_1 + 2E_{Al}w_{Al} \quad \frac{w_1}{w_1 + 2w_{Al}} \tag{5a}
\]

\[
E_2 = E_{Si}w_2 + 2E_{Al}w_{Al} \quad \frac{w_2}{w_2 + 2w_{Al}} \tag{5b}
\]

\[
I_1 = \frac{1}{12} (w_1 + 2w_{Al})^3 t \tag{6a}
\]

\[
I_2 = \frac{1}{12} (w_2 + 2w_{Al})^3 t \tag{6b}
\]

where \( E_{Al} \) is the Young’s modulus of Al (70 GPa), \( w_{Al} \) the thickness of Al deposited at sidewalls of the silicon beam. Since \( E_{Si}w_1 \approx 10E_{Al}w_{Al} \), the equivalent stiffness is dominated by the silicon structures.

Since the switching is carried out by an electrostatic force, one has to know the relation between the electrostatic force...
\( F_e \) and the real-time distance \( g \) of the gap between the ends of two electrodes. \( F_e \) can be written as:

\[
F_e(g) = \varepsilon_0 l^2 V^2 / 2g^2
\]

(7)

where \( V \) is the applied voltage. At equilibrium, the electrostatic force \( F_e \) is equal to the restoring force \( F_r \), which can be written as:

\[
F_r(g) = k(g_0 - g)
\]

(8)

where \( g_0 \) is the initial gap between the two electrodes. The relation between \( g \) and the applied voltage \( V \) can be obtained by solving the following equation:

\[
F_e(g) = F_r(g)
\]

(9)

Eq. (9) can be used before the cantilever beam becomes unstable or \( g = 2g_0 / 3 \). However, when \( V \) is above a pull-in voltage, \( V_p \), the real-time gap, \( g \), cannot obtain a solution by solving Eq. (9). The reason is the increase in the electrostatic force, \( F_e \), is greater than the increase in the restoring force, \( F_r \) when \( V > V_p \). As a result, the beam position becomes unstable and abruptly collapses to touch the contact tip.

Fig. 6 shows the calculated pull-in voltage, \( V_p \), with various geometrical dimensions. It is found in Fig. 6(a) that \( V_p \) is more dependent on the width of the narrow part of the silicon beam \( w_1 \) than on the width of the wide part \( w_2 \) and the metal thickness deposited at sidewalls \( w_{Al} \). The effect of the wide part width of the silicon beam \( w_2 \) on \( V_p \) is negligible when \( w_1 \leq w_2 \). With Al deposited at sidewalls of the silicon beam, \( V_p \) increases when \( w_1 = 3.5 \mu m \) and decreases when \( w_1 > 3.5 \mu m \). The reason is the metal deposition causes two effects. First, it increases the stiffness of the whole beam, which tends to increase the restoring force, \( F_r \), and increase \( V_p \). Second, it reduces the initial distance between the two electrodes to \( g_0 = 2n_{Al} \), which tends to increase the electrostatic force, \( F_e \) and reduce \( V_p \). Generally the change of the pull-in voltage due to the metal deposition is less than 5 V. Fig. 6(b) shows that the pull-in voltage \( V_p \) increases as the initial distance between the two electrodes \( g_0 \) increases. This also shows that \( V_p \) will not change significantly when the beam length ratio \( l_2 / (l_1 + l_2) \) is in the range of 30–70%. The dimensions of the proposed switch are as listed in Table 2. We can find that the pull-in voltage, \( V_p \), of the proposed switches is about 20 V before metal deposition and 23 V after 0.6 \( \mu m \) Al is deposited at sidewalls from Fig. 6(b). In this case, the Al deposition will cause a 15% increase in the pull-in voltage.

Table 2

<table>
<thead>
<tr>
<th>Parameters</th>
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<td>( l_2 )</td>
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</tr>
<tr>
<td>( l_9 )</td>
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3. Fabrication process

The SPDT switching circuit was fabricated on SOI wafer, which includes a 35 μm low resistivity (LR) device active Si layer (<0.1 Ω·cm), 2 μm buried thermal silicon dioxide (SiO₂) layer and 500 μm high resistivity (HR) handle Si layer (>4000 Ω·cm). The process flow along A–A’ and B–B’ is shown in Fig. 8. The process began with a SiO₂ of 2.0 μm deposition on a SOI substrate using plasma-enhanced chemical vapor deposition (PECVD). Upon patterning of SiO₂ by RIE, the HR Si was etched through via DRIE from the backside using 10 μm photoresist as mask material (a). The DRIE process was carried out using STS ICP etcher. After that, another DRIE step was employed to etch the LR Si to buried SiO₂ layer using the top SiO₂ as the hard mask. The exposed SiO₂ was removed by buffered oxide etchant (BOE). After rinsing with deionized water, the wafer was immersed in the isopropyl alcohol (IPA) for 20 min to avoid stiction problem at the narrow cantilever beam. The wafer was then kept dry in room temperature (b). Then the SOI wafer was temporarily bonded to a shadow mask using photoresist as intermediate material. Both wafer-to-wafer alignment and bonding were performed in an Electronic Vision EV Aligner and AB1-PV Bonder. The wafers were bonded under a pressure of 1000 N for 10 min at room temperature. A 1.5 μm thick Al was deposited on the surface and sidewalls of the circuit through the shadow mask (c). Finally, the bonded wafers were heated at 150 °C to soften the photoresist and the shadow mask was separated from the SOI wafer manually. The remaining photoresist was wiped off using acetone (d).

In this process, DRIE was used twice in order to, (1) form the circuit structures and (2) etch through the SOI wafer between the signal line and ground lines to avoid short circuit due to metal deposition. Thanks to the strong high-aspect-ratio Si structures, the stiction phenomenon does not occur even after the wet release. Al was selected as the deposition metal due to the process restriction. The fabricated SPST switch and SPDT switching circuit is shown in Fig. 9(a) and (b), respectively. The size of the SPST switch is 400 μm × 800 μm and that of the SPDT switching circuit is 1.2 mm × 1.5 mm. Due to the nature of the evaporation process, the Al coated at sidewalls is thinner than that coated on the surface. Fig. 10 is SEM micrographs of cross-section view illustrating step coverage of the metal deposition. The thickness of the Al layer at the surface is 1.5 μm, while that on the sidewalls is 6250 Å. It is observed that the metal covers on the sidewalls tightly and uniformly throughout the height of the entire structures. As for the contact part of the switch with gap width of 4 μm, the metal coated on the sidewalls is about 6000 Å which was measured by comparing the optical images of the contact part before and after metal coating. Fig. 11 shows the zoomed view of the contact part of the circuit, in which the contact tip is a semi-round tip with a radius of 3 μm. Due to the 6000 Å metal coated at sidewalls of the structures, the initial distance between the cantilever beam and the contact tip, d₀, had reduced from 4 to about 2.8 μm and the initial
gap between the two electrodes, $g_0$, had reduced from 6 to 4.8 μm.

4. Results and discussions

The RF and mechanical characteristics of both the SPST switch and SPDT switching circuit after fabrication are measured and discussed.

The RF response of the system was measured using the HP 8510C Vector Network Analyzer with tungsten-tip 150 μm-pitch Cascade Microtech ground-signal-ground coplanar probes. The system was calibrated using standard short-open-load-through (SOLT) on-wafer calibration technique. The bias voltage of 30 V was applied via bias-T from the output port to close the corresponding switch.

The measured $S$-parameters of the SPST switch compared with the circuit simulation results and EM simulation results are given in Fig. 12. In Fig. 12(a), the isolation of the switch at the open-state is above 32 dB at low frequencies of below 5 GHz, and decreases with increasing signal frequency to 23 dB at 15 GHz. In Fig. 12(b) the insertion loss of the SPST switch at the closed-state is below 0.08 dB at 5 GHz and increases to 0.2 dB at 15 GHz. The return loss decreases from 32 dB at 5 GHz to 24 dB at 15 GHz. It is found that the simulation results of equivalent circuit using ADS are in good agreement with the measured results up to 15 GHz, which shows the validity of the proposed equivalent circuit. However, the simulated insertion loss using the EM software HFSS do not match well with the measured result. The reason is that the EM simulation using commercial software does not consider the contact resistance of the switch at the closed-state and the real fabrication process is imperfect compared to the simulation condition. The measured dc resistance of the lateral switch is approximately 2 Ω. Generally the hot switching lifetime is shorter than the lifetime of the cold switching due to higher heat dissipation. However, testing on the hot
switching lifetime is currently unavailable due to high cost RF testing equipment. Only testing on the cold switching lifetime was carried out, where the testing result shows the cold switching lifetime of the lateral switch exceeds $10^6$ switching cycles. After $10^6$ switching cycles, the insertion loss of the switch increases by 0.1 dB and the isolation only changes marginally.

The insertion loss and return loss of the SPDT switch are determined by $S_{21}$ and $S_{11}$, respectively, through the input and output branch that contains the actuated switch, while the switch in the other output branch is in the off-state. The isolation of the SPDT switch is characterized by $S_{21}$ along the signal line with the switch in the off-state, while the input signal is routed to the branch containing the actuated switch. Fig. 13 provides the measured $S$-parameters of the fabricated SPDT switching circuit compared with circuit simulation results and EM simulation results. From Fig. 13(a), the measured isolation is higher than 33 dB from dc to 5 GHz, which is in good agreement with the circuit simulation result and EM simulation result. From Fig. 13(b), the measured insertion loss of the SPDT switch is below 0.75 dB and the return loss is above 19 dB from dc to 5 GHz, which are unfavorable compared to the SPST switch. The dominant force of the SPDT switching circuit is the loss in the CPW transmission lines since no air bridges were fabricated at the T-junction to equalize the CPW ground-plane potential. Therefore, power can be converted from the desired CPW mode to the parasitic coupled slotline mode.

Fig. 14 shows the measured pull-in voltage $V_p$ of the switch with various beam length ratio $l_2/(l_1 + l_2)$ with and without the metal deposition. It shows that the pull-in voltage is 20 ± 1 V (without Al deposition) and 24 ± 1 V (with Al deposition) when the ratio $l_2/(l_1 + l_2)$ changes in the range of 30–70%. The measured results are in close agreement with the calculated results. Fig. 15 shows the comparison between the measured, calculated and simulated displacement results of the switches after the deposition of 1.5 μm thick Al. The displacement of the free-end of the cantilever.
beam increases with the increase in the applied dc bias voltage. When the bias voltage increases to 23.3 V, the cantilever beam is attracted to touch the contact tip rapidly from 1.4 \textmu m away. Therefore, the pull-in voltage of the switch is 23.3 V. The measurement result shows a close agreement to the calculation result and the simulation result. The transient response of the lateral switches was characterized by a simple current measuring setup between the two separated parts of the signal line. When the cantilever beam was actuated by a sufficient bias voltage and was in contact with the contact tip, a current of 1 mA was flowing and the resulting voltage could be displayed on the oscilloscope. The switching time was obtained by comparing the resulting voltage and the actuation voltage using the oscilloscope. The measured switching-on (closing) time is 35 \textmu s when applied bias voltage is 30 V. The switching-off (opening) time is 30 \textmu s.

5. Conclusions

In this paper, a dc to 6 GHz SPDT switching circuit using lateral metal-contact MEMS switches is designed and fabricated. The insertion loss and the return loss of the MEMS SPST switch at 5 GHz are 0.08 and 32 dB, respectively. The isolation of the SPST switch is 32 dB at 5 GHz. The SPDT switching circuit has the insertion loss below 0.75 dB and return loss above 19 dB at 5 GHz, respectively. The isolation of the SPDT switching circuit is 33 dB at 5 GHz. The measured pull-in voltage is 23.3 V. The size of the fabricated SPDT switching circuit is 1.2 mm \times 1.5 mm. These results indicate that the SPDT switching circuit is small size and low loss by using the lateral metal-contact MEMS switches. It can be well applied in the true-time-delay phase shifter and tunable filter in wireless communication systems.

References


Biographies

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