Chapter 2
Lateral Series Switches

The objective of this chapter is to study the lateral RF MEMS series switch [1–14]. The switch consists of a silicon-core (Si-core) transmission line and a cantilever beam. The switch connects or disconnects with the RF circuit by the in-plane motion of the cantilever beam. The Si-core coplanar waveguide (CPW) transmission line is used to configure the switch. The Si-core CPW has the same advantage as the normal CPW, that is, it enables series and shunt elements connection without metal coating. The main advantages of the lateral switch are reliable mechanical performance and simple fabrication process.

This chapter is organized as follows. First, the RF design, circuit modeling and simulation of the lateral RF MEMS switch are presented. The RF performance of the switch can be improved by optimizing the electrical parameters of the switch. Second, the mechanical design and optimization of the cantilever beam of the lateral switch are discussed. The dynamic responses such as the switching time and the release time of the switch are studied. Finally, the experimental results of the lateral switch such as its insertion loss, return loss, isolation, threshold voltage, switching speed are discussed. Comprehensive modeling and design of the lateral switch are verified by extensive experiments for both electrical and mechanical characteristics.

2.1 Electrical Design and Simulation

In this section, the RF circuit design and the lumped-element modeling of the lateral switch are discussed. The main purpose is to study the effect of the design parameters and to realize lateral switches with low insertion loss, high return loss, and high isolation. Since the switch is a metal-contact series switch, the on-state and the down-state of the switch and the off-state and the up-state of the switch are used interchangeably.
2.1.1 RF Circuit Design of the Lateral Switch

A lateral switch consists of a Si-core CPW and an electrostatic actuator, as shown in Fig. 2.1a. A cantilever beam is fixed at one port. The free end of the cantilever beam comes into contact with the contact bump at the other port upon turning on the switch. The cantilever beam serves as the signal line alone. The ground lines beside the cantilever beam are extended toward the cantilever beam to avoid drastic increase in the characteristic impedance. The width of the gaps between the cantilever beam and the ground lines is 20–30 μm. The characteristic impedance of the cantilever beam section, \( Z_l \), is about 78 \( \Omega \) simulated by a 3D full-wave finite element method (FEM) analysis tool – Ansoft’s high-frequency structure simulator (HFSS) V8.0 [15]. At the free end of the cantilever beam, one ground line protrudes toward the cantilever beam further to serve as a fixed electrode. Therefore, no additional fixed electrode is required. When sufficient DC bias voltage is applied between the cantilever beam and the ground line, the cantilever beam is pulled toward the fixed electrode by electrostatic force until its free end hits the contact bump, resulting in the on-state of the switch. When DC bias voltage is removed, the mechanical stress of the beam overcomes the stiction forces and pulls the cantilever beam away, resulting in the off-state of the switch. Due to the asymmetrical layout of the two ports, the \( S \)-parameters obtained from the two ports are not reciprocal. The return loss of port 2 is better than that of port 1 at the off-state since the open stub at port 2 is shorter than port 1. Hence, generally port 2 acts as the input port and port 1 acts as the output port to block more RF signal at the off-state of the switch. Figure 2.1 (b) shows the cross sectional view of the lateral switch. The switch is on a SOI wafer.

![Fig. 2.1 Schematics of a lateral switch: (a) top view and (b) cross-sectional view. Copyright/used with permission of/courtesy of Institute of Physics and IOP Publishing Limited](image-url)
The substrate is 500-μm-thick high-resistivity silicon (HRSi). The device layer is 35-μm-thick low-resistivity silicon (LRSi). The switch structures are made of LRSi. A thin layer of metal is coated on the top and sidewalls of the switch structures to propagate RF signal.

### 2.1.2 RF Circuit Model of the Lateral Switch

Figure 2.2 shows the equivalent circuit of the lateral switch. The model consists of a characteristic impedance, $Z_0$, for the input and output sections of the Si-core CPW; a line resistor, $R_l$, of the cantilever beam; a line inductor, $L$, of the cantilever beam; a switch series capacitor, $C_s$ (off-state) or a contact resistor, $R_c$ (on-state); and a shunt coupling capacitor, $C_g$. Except $Z_0$, other parameters are allowed to vary to fit the measurement results or the simulation results. The equivalent circuit is modeled using the design tool of Agilent EESof’s Advanced Design System (ADS).

![Fig. 2.2 The equivalent circuit of the lateral switch. Copyright/used with permission of/courtesy of Institute of Physics and IOP Publishing Limited](image)

According to the $T$-equivalent circuit model, $S_{21}$ of the circuit can be given by [16]

$$S_{21} = \frac{2}{2 + (Z_0 + Z_1 + Z_2)/Z_3 + \left(Z_1 + Z_2 + \frac{Z_1Z_2}{Z_3}\right)/Z_0} \quad (2.1a)$$

where

$$Z_1 = R_l + j\omega L \quad (2.1b)$$

$$Z_2 = \begin{cases} \frac{1}{j\omega C_s} & \text{at the open state} \\ R_c & \text{at the close state} \end{cases} \quad (2.1c)$$

$$Z_3 = \frac{1}{j\omega C_g} \quad (2.1d)$$

$\omega$ is the angular frequency ($\omega = 2\pi f$, $f$ is the signal frequency).
At the off-state of the switch, the switch capacitance, $C_s$, is an important factor that affects the isolation of the switch. When

$$S_{21} \ll -10 \text{ dB and } \omega C_s Z_0 \left[ 2 - \omega^2 C_g L + \frac{C_g}{C_s} + \frac{R_l}{Z_0} \left( 1 + \frac{C_g}{C_s} \right) \right] \ll 1$$

the isolation of switch can be approximately expressed as

$$S_{21} \approx j2\omega C_s Z_0 \quad (2.2)$$

Therefore, the series capacitance, $C_s$, of the off-state switch can be extracted from the simulated or measured isolation of the switch using Eq. (2.2). Figure 2.3 shows the simulated isolation of an off-state switch with various series capacitances of $C_s$. The isolation of the off-state switch increases with the decrease in $C_s$. The equivalent series capacitance $C_s$ of our practical lateral switches is 3–10 fF. Up to 25 GHz, the isolation is higher than 25 dB for $C_s = 3$ fF and 15 dB for $C_s = 10$ fF.

![Fig. 2.3 Simulation results of S-parameters with various capacitances $C_s$ at the off-state of the lateral switch ($R_l = 1 \Omega$, $L = 148 \text{ pH}$, $C_g = 30 \text{ fF}$)](image)

At the on-state of the switch, the insertion loss and the return loss can be expressed as

$$S_{21} = \frac{2}{2 + K_1 + j \cdot K_2} \quad (2.3a)$$

$$S_{11} = \frac{K_1 + j \cdot K_3}{2 + K_1 + j \cdot K_2} \quad (2.3b)$$
where

\[ K_1 = \frac{R_l + R_c}{Z_0} - \omega^2 C_g L \left( 1 + \frac{R_c}{Z_0} \right) \] (2.3c)

\[ K_2 = \omega \left[ C_g \left( R_l + R_c + Z_0 + \frac{R_l R_c}{Z_0} \right) + \frac{L}{Z_0} \right] \] (2.3d)

\[ K_3 = \omega \left[ C_g \left( R_l - R_c - Z_0 + \frac{R_l R_c}{Z_0} \right) + \frac{L}{Z_0} \right] \] (2.3e)

At low frequencies, when \( 2+K_1 \gg 0 \) and \( K_2 \ll 2 + (R_l + R_c)/Z_0 \), the insertion loss and the return loss of the switch can be simplified as

\[ S_{21} \approx 2/\left[ 2 + (R_l + R_c)/Z_0 \right] \] (2.4a)

\[ S_{11} \approx (R_l + R_c)/[2Z_0 + (R_l + R_c)] \] (2.4b)

Figure 2.4 shows the simulated results of the insertion loss and the return loss of the switch at the on-state with various \((R_l + R_c)\). The RF performances of the switch at the on-state deteriorate with the increase in \((R_l + R_c)\). When \( R_l + R_c < 2 \Omega \), the insertion loss is less than 0.2 dB up to 10 GHz. When \((R_l + R_c)\) increases to 10 \( \Omega \), the insertion loss is larger than 0.8 dB at 10 GHz. The return loss decrease with \((R_l + R_c)\). Therefore, the resistance sum \((R_l + R_c)\) should be as small as possible to achieve low insertion loss and high return loss.

![Figure 2.4 Simulation results of S-parameters with various resistance sum at the on-state of the lateral switch \((L = 148 \text{ pH}, C_g = 30 \text{ fF})\)](image)
The resistance sum \((R_l + R_c)\) of the switch at the on-state can also be extracted from the simulated or measured insertion loss of the switch using Eqs. (2.4a) and (2.4b). It is found that the measured resistance sum \((R_l + R_c)\) decreases with the increase in the metal thickness of the coating layer since the cantilever beam resistance, \(R_l\), is determined by the thickness of the coating metal layer and the contact resistance, \(R_c\), is largely affected by it too. The effect of the metal thickness on the beam resistance, \(R_l\), is discussed. Due to the skin effect of the metal layer at high frequencies, the fields decay by an amount of \(1/e\) in a depth of one skin depth. The skin depth, \(\delta_s\), of metal is given by \[\delta_s = \sqrt{\frac{2}{\omega \mu_0 \sigma}}\] (2.5)

where \(\mu_0\) is the permeability of the vacuum \((\mu_0 = 4\pi \times 10^{-7}\) H/m\)) and \(\sigma\) is the conductivity of the metal layer. The conductivity and the skin depth of the metal layer used in our experiments are listed in Table 2.1. The skin depth of aluminum (Al) is 0.83 \(\mu\)m at 10 GHz and 0.53 \(\mu\)m at 25 GHz. The surface resistivity, \(R_s\), of the metal layer is given by

\[
R_s = \begin{cases} 
\frac{1}{\sigma \delta_s} & (t \geq \delta_s) \\
\frac{1}{\sigma t} & (t < \delta_s)
\end{cases}
\] (2.6)

where \(t\) is the metal thickness. Then, the resistance of a cantilever beam, \(R_l\), can be expressed as

\[R_l = R_s \sum_{i} \frac{l_i}{w_i}\] (2.7)

where \(l_i\) and \(w_i\) are the length and the width of different sections of the cantilever beam. Therefore, the resistance of the cantilever beam increases with frequency due to the skin effect. For instance, for a cantilever beam with \(l = 460\) \(\mu\)m, \(w = 3.3\) \(\mu\)m, \(t_1 = 1.2\) \(\mu\)m, and \(t_s = 1.2\) \(\mu\)m, the calculated resistance of the beam \(R_l\) keeps constant of 3 \(\Omega\) from DC to 4.6 GHz, then increases with frequency after 4.6 GHz. The resistance is 7.1 \(\Omega\) at 25 GHz. When the thickness and the conductivity of the metal layer are larger, the beam resistance is smaller. The RF power

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity, (\sigma) (S/m)</th>
<th>Skin depth, (\delta) ((\mu)m)</th>
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</thead>
<tbody>
<tr>
<td>Al</td>
<td>(3.80 \times 10^7)</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Au</td>
<td>(4.55 \times 10^7)</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.37</td>
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<td>Cu</td>
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<td></td>
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<td>0.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.33</td>
</tr>
</tbody>
</table>
dissipation decreases and the insertion loss of the switch is lower. Therefore, the metal layer with high conductivity has to be coated as thickly as possible to achieve good RF performance.

The series inductance $L$ can be calculated by

$$L = \frac{Z_l \beta l}{\omega} = \frac{Z_l l \sqrt{\varepsilon_{\text{eff}}}}{c}$$

(2.8)

where $Z_l$ is the impedance of the cantilever beam, $l$ is the whole length of the cantilever beam, $\beta$ is the phase constant, $\varepsilon_{\text{eff}}$ is the relative effective permittivity, and $c$ is the speed of the light in vacuum ($c = 3.0 \times 10^8$ m/s). In this design, $l = 400–500 \mu$m, $\varepsilon_{\text{eff}} \approx 1.66$, $Z_l = 50–78 \Omega$, and the equivalent series inductance is 86–167 pH. In Fig. 2.5, the simulated results show that the RF performances of the switch at the on-state become better when the inductance increases from 10 to 100 pH. However, the insertion loss and the return loss begin to deteriorate when the inductance $L$ increases further, especially at a high-frequency range.

$C_g$ is the shunt coupling capacitance between the cantilever beam and the fixed electrode, which can be estimated as

$$C_g = \frac{\varepsilon_0 l_2 h}{g_0 - y} + C_f$$

(2.9)
where $\varepsilon_0$ is the permittivity of the air ($8.854 \times 10^{-12}$ F/m), $l_2$ is the length of the fixed electrode, $h$ is the height of the cantilever beam, $g_0$ is the original gap distance between two electrodes, $y$ is the displacement of the electrode part of the cantilever beam, and $C_f$ is the fringing field capacitance which is 20–60% of $C_g$ [17]. This coupling capacitance is fairly large ($C_g \gg C_s$) and affects the loss mechanism at the on-state of the switch. Figure 2.6 shows that the RF performances, including the insertion loss and the return loss of the switch at the on-state, are improved when $C_g$ increases from 10 to 60 fF, whereas the RF performances begin to deteriorate when $C_g$ increases further to 125 fF. It is noted that when the switch is actuated, the gap between the two electrodes, $g = g_0 - y$, decreases. Hence, the coupling capacitance at the on-state, $C_{gc}$, is slightly larger than the one at the off-state, $C_{go}$. On the other hand, the structure design of the cantilever beam and the distance between the cantilever beam and the fixed electrode also determine the mechanical performance of the switch in terms of the threshold voltage and the switching speed. Therefore, it is important to select the proper values of $l_2$ and $g_0$ for the switch design to compromise between electrical and mechanical performances.

### 2.1.3 Double-Beam Lateral Switch

A double-beam lateral switch is designed and shown in Fig. 2.7 to achieve low insertion loss and high power handling. Two cantilever beams are used in the signal route together to propagate RF signal. Both fixed connections of two cantilever
beams are on port 1 and two contact bumps are on port 2. At the free end of two cantilever beams, both ground lines extend toward the nearby cantilever beams to serve as their fixed electrodes, respectively. Therefore, when sufficient DC bias voltage is applied between the signal line and two ground lines at port 1, both cantilever beams are pulled by the electrostatic force and move toward two ground lines, respectively, until they hit two contact bumps at port 2. Generally, port 2 acts as the input port and port 1 acts as the output port for better signal isolation from the source at the off-state of the switch. Similar to the single-beam switch, the two-port S-parameters of the double-beam switch are not reciprocal due to the asymmetrical layout.

Figure 2.8 is the equivalent circuit of the double-beam lateral switch. For the double-beam switch, the resistor $R_1 = R_{l0}/2$, the inductor $L = L_0/2$, the series capacitor of the switch at the off-state $C_s = 2C_{s0}$, the contact resistor of the switch at the on-state $R_c = R_{c0}/2$, and the shunt coupling capacitor $C_g = 2C_{g0}$, assuming that two cantilever beams are identical. Hence, the electrical model of the single-beam switch can also be used for the double-beam switch.
2.2 Mechanical Design and Simulation

The lateral switch is based on an electrostatic actuator as shown in Fig. 2.9. The actuator consists of four components: a suspended cantilever beam serving as a movable electrode, an anchor on the substrate to support the cantilever beam, a fixed electrode opposite to the cantilever beam, and a contact bump.

![Diagram of the top view of an electrostatic actuator](Image)

**Fig. 2.9** The schematic of the top view of an electrostatic actuator. Copyright/used with permission of/courtesy of Institute of Physics and IOP Publishing Limited

The cantilever beam OC is a beam mass structure as shown in Fig 2.9. For the part of the beam OA, the width is \(w_1\) and the length is \(l_1\). For the part of the mass AC, the width is \(w_2\) and the length is \((l_2 + l_3)\) in which \(l_2\) is the length of the electrode section AB and \(l_3\) is the length of the remaining part BC. The mass width, \(w_2\), is designed to be relatively wider than the beam width, \(w_1\), so that low threshold voltage can be maintained and greater deformation of the electrode section may be avoided. Hence, no separate stop bumpers or landing pads are required to avoid short circuit between the two electrodes.

The original distance between the two electrodes is \(g_0\) and the distance between the contact bump and the mass part is \(d_0\). \(d_0\) is relatively smaller than \(g_0\) so that the cantilever beam can touch the contact bump when the switch is actuated. In Fig 2.9, the X- and Z-axes are oriented parallel to the length and the depth of the cantilever beam respectively, while the Y-axis is directed toward the fixed electrode.

For the design of the lateral switch in static behavior, low threshold voltage is always desired. The threshold voltage is determined by two forces – the electrostatic force, \(F_e\), and the restoring force, \(F_r\) – which will be discussed.

### 2.2.1 Static Electrostatic Force

When a DC bias voltage, \(V\), is applied between two electrodes, the electrostatic force, \(F_e\), causes the mass to move toward the fixed electrode and the beam is bent. The bending of the mass part is negligible because it has much higher flexure rigidity than the beam. The displacement of the mass increases with voltage until pull-in occurs. If the displacement of the beam OA and mass AC from its original position
2.2 Mechanical Design and Simulation

are designated as $y_1|_x$ and $y_2|_x$, respectively, the electrostatic force, $F_e$, on the mass can be derived as

$$F_e = \int_{l_1}^{l_1+l_2} \frac{\varepsilon_0 h V^2 dx}{2(g_0 - y_2)^2} = \frac{\varepsilon_0 h l_2 V^2}{2(g_0 - \alpha - \theta l_2)(g_0 - \alpha)} \tag{2.10a}$$

where

$$y_2|_x = \alpha + \theta(x - l_1), \quad l_1 \leq x \leq l_1 + l_2 \tag{2.10b}$$

$$\alpha = y_2|_{x=l_1} = y_1|_{x=l_1} \tag{2.10c}$$

$$\theta = y'_2|_x = y'_1|_{x=l_1} \tag{2.10d}$$

where ('') denotes the derivative with respect to position $x$. When the electrostatic force is not uniform, the bending moment, $M_0$, caused by the electrostatic force can be calculated as

$$M_0 = \int_{l_1}^{l_1+l_2} \frac{\varepsilon_0 h V^2 (x - l_1) dx}{2(g_0 - \alpha + \theta l_2 - \theta x)^2} = \frac{\varepsilon_0 h V^2}{2\theta^2} \left[ \ln \frac{g_0 - \alpha - \theta l_2}{g_0 - \alpha} + \frac{\theta l_2}{g_0 - \alpha - \theta l_2} \right] \tag{2.11a}$$

For small $\theta$, $M_0$ can be approximated as

$$M_0 = \frac{\varepsilon_0 h V^2 l_2^2}{2(g_0 - \alpha)} \left( \frac{1}{g_0 - \alpha - \theta l_2} - \frac{1}{2(g_0 - \alpha)} \right) \tag{2.11b}$$

The equation for the displacement of the beam $y_1|_x$ is determined by [18]

$$E_1 I_1 y''_1|_x = M_0 + F_e (l_1 - x), \quad 0 \leq x \leq l_1 \tag{2.12}$$

where $E_1$ is Young’s modulus of the beam and $I_1$ is the moment of inertia of the cross-sectional area of the beam. At $x = 0$, the boundary conditions are

$$y_1|_{x=0} = y'_1|_{x=0} = 0 \tag{2.13}$$

By solving Eqs. (2.10c), (2.10d), (2.12), and (2.13), $\alpha$ and $\theta$ can be obtained as

$$\alpha = \frac{3M_0 l_1^2 + 2F_e l_1^3}{6E_1 I_1} \tag{2.14a}$$

$$\theta = \frac{2M_0 l_1 + F_e l_1^2}{2E_1 I_1} \tag{2.14b}$$
Therefore, at a specific applied DC bias voltage $V$, $F_e$, and $M_0$ are determined by $\alpha$ and $\theta$ from Eqs. (2.10a), and (2.11a) and (2.11b), whereas $\alpha$ and $\theta$ are determined by $M_0$ and $F_e$ from Eqs. (2.14a) and (2.14b). Thus, $F_e$, $M_0$, $\alpha$ and $\theta$ can be found through numerical iterations. For a voltage equal to or larger than a specific value, the iteration results become divergent. This specific voltage is called threshold voltage. For the threshold voltage, once $\alpha$ and $\theta$ are known, the displacement of the mass is found by Eq. (2.10b). For an actuator with $l_1 = 275 \, \mu\text{m}$, $l_2 = 165 \, \mu\text{m}$, $l_3 = 10 \, \mu\text{m}$, $w_1 = 2.4 \, \mu\text{m}$, $w_2 = 5 \, \mu\text{m}$, $w_{\text{Al}} = 0.45 \, \mu\text{m}$, $g_0 = 4.8 \, \mu\text{m}$, $d_0 = 2.8 \, \mu\text{m}$, the threshold voltage is calculated to be 23.7 V. The maximum stable displacement of the mass center is 1.37 $\mu\text{m}$, which is a little smaller than $1/3g_0$.

### 2.2.2 Static Restoring Force

When the mass part is displaced, an elastic restoring force by the beam tends to pull the mass back toward its original position. At the end of the electrode part AB of the mass, the restoring force, $F_r$, can be written as

$$F_r = -ky_2|_{x=l_1+l_2+l_3} = -k[\alpha + \theta(l_2 + l_3)] \quad (2.15)$$

where $k$ is the equivalent stiffness of the cantilever beam. Suppose that the mass is subject to a concentrated force at the midpoint of the electrode section, the equivalent stiffness, $k$ can be expressed as

$$k = \frac{12E_1I_1E_2I_2}{E_2I_2[4l_1^3 + 9l_1^2l_2 + 6(l_1^2l_3 + l_1l_2^2 + l_1l_2l_3)] + E_1I_1(5l_2^3 + 6l_2^2l_3)/4} \quad (2.16)$$

where $E_2$ is Young’s modulus of the mass and $I_2$ is the moments of inertia of the cross-sectional area of the mass. Before the metal coating, the beam is merely made up of single-crystal silicon. $E_1$, $E_2$, $I_1$, and $I_2$ are given by

$$E_1 = E_2 = E_{\text{Si}} \quad (2.17a)$$

$$I_1 = \frac{1}{12}w_1^3 h \quad (2.17b)$$

$$I_2 = \frac{1}{12}w_2^3 h \quad (2.17c)$$

where $E_{\text{Si}}$ is Young’s modulus of the single-crystal silicon. After the metal coating, the beam is made of single-crystal silicon covered by metal on the top and sidewalls. Therefore, $E_1$, $E_2$, $I_1$, and $I_2$ can be expressed as

$$E_1 = \frac{E_{\text{Si}}w_1 + 2E_mw_m}{w_1 + 2w_m} \quad (2.18a)$$
where $E_m$ is Young’s modulus of the metal, $w_m$ is the thickness of the metal coated at sidewalls of the silicon beam. The material properties of the lateral switches are given in Table 2.2. Typically, $w_1 = 2.5–3 \, \mu m$, $w_2 = 5–15 \, \mu m$, $w_m \leq 1 \, \mu m$. Since $E_{Si}w_1 > 5E_mw_m$, the equivalent stiffness is dominated by silicon structures. After the metal coating, the initial gap distance between two electrodes, $g_0$, and the initial gap distance between the beam end and the contact bump, $d_0$, are expressed as

\begin{equation}
 g_0 = g_{Si} - 2w_m 
\end{equation}

\begin{equation}
 d_0 = d_{Si} - 2w_m 
\end{equation}

where $g_{Si}$ and $d_{Si}$ are the initial gap distance between the two silicon electrodes and the initial gap distance between the silicon beam and the silicon contact bump before metal coating, respectively.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m$^3$)</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>2330</td>
<td>162</td>
<td>0.27</td>
</tr>
<tr>
<td>Al</td>
<td>2700</td>
<td>70</td>
<td>0.35</td>
</tr>
<tr>
<td>Au</td>
<td>19,280</td>
<td>80</td>
<td>0.44</td>
</tr>
<tr>
<td>Cu</td>
<td>8960</td>
<td>128</td>
<td>0.36</td>
</tr>
</tbody>
</table>

### 2.2.3 Static Threshold Voltage

The balanced position of the cantilever beam can be found as the force is balanced

\begin{equation}
 F = F_e + F_r = 0 
\end{equation}

The curves of normalized $F_e$ and $|F_r|$ as functions of the normalized displacement $y/g_0$ are shown in Fig. 2.10. For a specific mechanical structure, $k$ is a constant. Therefore, the curve for the restoring force, $F_r$, is a straight line starting from the origin of the coordinates. The curve for the electrostatic force, $F_e$, is a hyperbola. When the applied bias voltage, $V$, is less than a specific voltage $V_{th}$, the two curves have two intersections. Equation (2.20) has two solutions. When the bias voltage $V$ increases, $F_e$ increases and the two intersections move closer. When $V = V_{th}$, the
intersections coincide. When $V > V_{th}$, the two curves do not intersect since $F_e = -F_r$ at all displacements, that is, the mass part always collapses to touch the contact bump. $V_{th}$ is the threshold voltage, which can be calculated using the iteration method, as discussed in Section 2.2.1.

Figure 2.11 shows the shape of a cantilever beam ($l_1 = 275 \mu m$, $l_2 = 165 \mu m$, $l_3 = 10 \mu m$, $w_1 = 2.4 \mu m$, $w_2 = 5 \mu m$, $w_{Al} = 0.45 \mu m$, $g_0 = 4.8 \mu m$, $d_0 = 2.8 \mu m$) with various bias voltages, which is simulated by commercial 3D simulation software – LS DYNA. The deformation of the beam OA of the cantilever beam.

**Fig. 2.10** Normalized electrostatic force and restoring force on the movable cantilever beam with various applied bias voltages

**Fig. 2.11** The shape of cantilever beam with various applied bias voltages. Copyright/used with permission of/courtesy of Institute of Physics and IOP Publishing Limited
increases with the bias voltage, whereas the mass part AC of the cantilever beam moves almost without deformation. The simulated threshold voltage is 24 V, which is close to the calculated result, 23.7 V, using the iteration method.

The threshold voltage, \( V_{th} \), is determined by the cantilever beam structure and the original gap between two electrodes, \( g_0 \). Figure 2.12 shows that the threshold voltage, \( V_{th} \), decreases when the original gap between the two electrodes \( g_0 \) decreases or the length sum \( (l_1 + l_2) \) increases. When the cantilever beam length ratio, \( l_2 / (l_1 + l_2) \), is within the range of 30 – 75 %, \( V_{th} \) only changes within 10% of the minimum value of \( V_{th} \), which is referred to as \([V_{th}]_{min}\). The corresponding length ratio \( [l_2/(l_1 + l_2)]_{min} \) to \([V_{th}]_{min}\) is 50% when \( w_1 = 2.4 \mu m, w_2 = 5 \mu m, \) and \( w_{Al} = 0 \). It also shows that \( [l_2/(l_1 + l_2)]_{min} \) is almost independent of the initial gap, \( g_0 \), and the length sum \( (l_1 + l_2) \).

Figure 2.13 shows that \( V_{th} \) is more dependent on the beam width, \( w_1 \), than the mass width, \( w_2 \). The effect of the mass width, \( w_2 \), is negligible. \( V_{th} \) increases with beam width, \( w_1 \). The mass structure can be designed as a hole mass structure as shown in Fig. 2.21. The hole mass has three advantages compared to the solid mass. First, the solid-mass with the width of more than 5 \( \mu m \) is not easy for release due to the constriction in the fabrication process. This problem can be solved by hole mass. Second, the etched holes reduce the effective mass of the mass structure and increase the flexibility of the whole cantilever beam structure. Third, the lateral switch with the hole mass structure can provide better RF performance than that with the solid mass structure. Section 2.4 provides a more detailed discussion on the cantilever beam effect on the RF performance of the lateral switch.

The effect of the metal thickness, \( w_{Al} \), of sidewalls on the threshold voltage is more complicated. For further elaboration, aluminum is used as a coating metal. The
The width of the mass section of the cantilever beam, \( w_2 \) (\( \mu m \))

Threshold voltage, \( V_{th} \) (V)

\[ W_1 = 2.0 \]
\[ W_1 = 2.5 \]
\[ W_1 = 3.0 \]
\[ W_1 = 3.5 \]

Fig. 2.13 Calculated threshold voltage \( V_{th} \) with various cantilever beam widths \((w_1, w_2)\) \((l_1 = 275 \mu m, l_2 = 165 \mu m, l_3 = 10 \mu m, g_{Si} = 6 \mu m, w_m = 0)\). Copyright/used with permission of/courtesy of Elsevier B.V

effect of the aluminum (Al) thickness, \( w_{Al} \), is shown in Fig. 2.14. Initially when \( w_{Al} \) increases from zero, the threshold voltage, \( V_{th} \), increases slightly. However, after the threshold voltage, \( V_{th} \), gets to its maximum value, it decreases with increase in \( w_{Al} \). This observation can be explained by two effects that arise from the metal coating at sidewalls. On the one hand, the metal increases the stiffness of the cantilever beam which tends to increase the restoring force, \( F_r \), and the threshold voltage, \( V_{th} \). On the other hand, the metal coating reduces the original gap between the two electrodes from \( g_{Si} \) to \((g_{Si} - 2w_m)\), which tends to increase the electrostatic force, \( F_e \), and reduce the threshold voltage, \( V_{th} \). When \( w_{Al} \) is small, the increase in \( F_r \) dominates the increase in \( F_e \). As a result, \( V_{th} \) increases. However, once \( w_{Al} \) exceeds a specific value, the increase in \( F_e \) dominates the increase in \( F_r \). Therefore, \( V_{th} \) falls. In general, the change of the threshold voltage, \( V_{th} \), due to the metal coating is less than 5 V since \( w_{Al} \) is less than 1 \( \mu m \). The effect of the beam parameters of \( w_1, w_2, \) and \( w_{Al} \) on the threshold voltage, \( V_{th} \), is summarized in Table 2.3 when \( l_1 = 275 \mu m, l_2 = 165 \mu m, l_3 = 10 \mu m, \) and \( g_{Si} = 6 \mu m \).

2.2.4 Dynamic Frequency Response

The frequency response of the cantilever beam is useful to determine the switching time and the mechanical bandwidth of the lateral switch. The frequency response can be determined by d’Alembert’s principle as [19]
Fig. 2.14  Calculated $V_{th}$ versus thicknesses of Al coated at sidewalls $w_{Al}$ ($l_1 = 275 \, \mu m$, $l_2 = 165 \, \mu m$, $l_3 = 10 \, \mu m$, $g_{Si} = 6 \, \mu m$, $w_2 = 5 \, \mu m$)

Table 2.3  The effect of the cantilever beam parameters on the threshold voltage, $V_{th}$

<table>
<thead>
<tr>
<th>Beam width, $w_1 , (\mu m)$</th>
<th>Mass width, $w_2 , (\mu m)$ ($w_{Al} = 0$)</th>
<th>Al thickness at sidewalls, $w_{Al} , (\mu m)$ ($w_2 = 5 , \mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>17.25 17.25 17.25</td>
<td>19.45 22.15 22.45</td>
</tr>
<tr>
<td>2.4</td>
<td>22.65 22.65 22.65</td>
<td>24.7 26.8 26.35</td>
</tr>
<tr>
<td>3.0</td>
<td>31.65 31.65 31.65</td>
<td>33.25 34.35 32.6</td>
</tr>
<tr>
<td>3.5</td>
<td>39.9 39.9 39.9</td>
<td>41.05 41.05 38.1</td>
</tr>
</tbody>
</table>

\[ m y'' + b y' + ky = f_{ext} \] (2.21)

where $'$ denotes the derivative with respect to time $t$, $y$ is the lateral displacement of the cantilever beam relative to the origin of the fixed electrode, $m$ is the effective mass, $k$ and $b$ are the effective stiffness and the damping coefficient of the simplified system, and $f_{ext}(t)$ is the electrostatic force. The electrostatic force, $f_{ext}(t)$, between the two electrodes generated by a bias voltage, $V$, can be simplified as

\[ f_{ext}(t) = \frac{\varepsilon_0 h} {2(g_0 - y)^2} \frac{V^2} {2} \] (2.22)
Based on the Laplace transforms, the frequency response of the cantilever beam with small vibration amplitude can be expressed as

\[
\frac{Y(j\omega)}{F(j\omega)} = \frac{1/k}{1 - (\omega/\omega_0)^2 + j\omega/(Q\omega_0)}\tag{2.23}
\]

where \(\omega\) is the working angular frequency, \(\omega_0\) is the natural resonant angular frequency, and \(Q\) is the quality factor of the cantilever beam. \(\omega_0\) and \(Q\) are expressed as

\[
\omega_0 = \sqrt{\frac{k}{m}}\tag{2.24}
\]

\[
Q = \frac{k}{(\omega_0 b)}\tag{2.25}
\]

The quality factor \(Q\) of the cantilever beam is determined by several different variables, such as the pressure, the temperature, and the intrinsic material dissipation. The quality factor is also an important component for the switching time. For example, a cantilever beam \((l_3 = 10 \mu m, w_1 = 2.4 \mu m, w_2 = 5 \mu m, w_m = 0, g_{Si} = 6 \mu m)\) has the frequency response of \(f = 15\) kHz and \(k = 0.94\). The variation in response amplitude of the cantilever beam is simulated with different quality factors. Figure 2.15 shows that the response amplitude at 15 kHz is increased when the quality factor ranges from 0.2 to 2.0. When \(Q \leq 0.5\), it has a slow switching time; when \(Q \geq 2\), it has a long settling time. In practice, it is beneficial for the switching time that the quality factor of the cantilever beam is designed by \(0.5 \leq Q \leq 2\).

![Figure 2.15 Frequency response of a cantilever beam with resonant frequency \(f = 15\) kHz and \(k = 0.94\)]
Dynamic Effective Mass

It is noted that the effective mass of the cantilever beam is not equal to the actual mass of the cantilever beam since only the end portion of the cantilever beam is moving. The effective mass, $m$, can be estimated by Rayleigh’s energy method [19]. Assume the cantilever beam is subject to a concentrated load, $P$, at the center of the electrode section of the cantilever beam. Referring to Fig. 2.9, we can consider the displacement $y_1$ and kinetic energy $E_k$ of the cantilever beam at three portions, respectively.

The first part is the beam ($0 < x \leq l_1$). Its kinetic energy $E_{k1}$ is given by

$$E_{k1} = \frac{1}{2} (\rho_{Si} w_1 + 2 \rho_{m} w_m) h \int_0^{l_1} y_1'^2 \, dx$$

where

$$y_1 = \frac{P x^2}{6 E_1 I_1} (3 l_1 - x) + \frac{P l_2 x^2}{2 E_1 I_1} = \frac{P x^2}{6 E_1 I_1} (3 l_1 + 3 l_2 - x)$$

$$m_1 = (\rho_{Si} w_1 + 2 \rho_{m} w_m) l_1 h$$

The second part is from the beginning of the electrode to the center of the electrode of the cantilever beam ($l_1 < x \leq l_1 + l_2/2$). The kinetic energy $E_{k2}$ is given by

$$E_{k2} = \frac{1}{2} (\rho_{Si} w_2 + 2 \rho_{m} w_m) h \int_{l_1}^{l_1 + l_2/2} y_2'^2 \, dx$$

where

$$y_2 = \frac{P l_1^2}{3 E_1 I_1} + \frac{P l_2^2}{2 E_1 I_1} + \frac{P(l_1^2 + 2 l_1 l_2)(x - l_1)}{2 E_1 I_1} + \frac{P(x - l_1)^2 [3 l_2 - (x - l_1)]}{6 E_2 I_2}$$

$$m_2 = (\rho_{Si} w_2 + 2 \rho_{m} w_m) l_2 h$$

The third part is from the center of the electrode to the end of the cantilever beam ($l_1 + l_2/2 < x \leq l_1 + l_2 + l_3$). The kinetic energy $E_{k3}$ is given by
\[
E_{k3} = \frac{1}{2}(\rho_{\text{Si}}w_2 + 2\rho_{\text{m}}w_{\text{m}})h \int_{l_1+l_2+3}^{l_1+l_2+3} y_3'^2 \, dx
\]
\[
= \frac{1}{2}m_2 \left[ \frac{P(l_1^2 + l_1l_2)}{2E_1I_1} + \frac{P l_2^2}{8E_2I_2} \right]^2 \left( \frac{1}{2} + \frac{l_3}{l_2} \right)
\]

(2.28a)

where

\[
y_3 = \frac{P(4l_1^2 + 3l_2l_1)}{12E_1I_1} + \frac{P(l_1^2 + l_1l_2)(x - l_1)}{2E_1I_1} + \frac{Pl_2^3}{4E_2I_2} + \frac{P l_2^2}{4} \left( x - l_1 - \frac{l_2}{2} \right)
\]

(2.28b)

Therefore, the total kinetic energy \( E_k \) are given by

\[
E_k = E_{k1} + E_{k2} + E_{k3} = \frac{1}{2}my_{\text{max}}'^2
\]

(2.29a)

where the velocity \( y_{\text{max}}' \) at the end of the cantilever beam is

\[
y_{\text{max}}' = y_3'|_{x=l_1+l_2+3} = \frac{P(l_1^2 + l_1l_2)}{2E_1I_1} + \frac{P l_2^2}{8E_2I_2}
\]

(2.29b)

The effective mass, \( m \), can be obtained by solving Eq. (2.29a). Figure 2.16 shows the portion mass \( m_1, m_2 \) and the effective mass, \( m \), of a cantilever beam changes with the ratio of \( (l_2/(l_1+l_2)) \) when \( l_1 + l_2 = 440 \, \mu m \) and \( l_3 = 10 \, \mu m \). It shows

![Graph showing effective mass and part mass of the cantilever beam versus the ratio of \( l_2/(l_1+l_2) \).](image)

\textbf{Fig. 2.16} Effective mass and part mass of the cantilever beam versus the ratio of \( l_2/(l_1+l_2) \) (\( w_1 = 2.4 \, \mu m, w_2 = 5 \, \mu m, w_{\text{Al}} = 0.6 \, \mu m, l_1+l_2 = 440 \, \mu m, l_3 = 10 \, \mu m, \) and \( h = 35 \, \mu m \))
that the effective mass, \( m \), is mainly determined by the mass of the electrode part, \( m_2 \). The effective mass, \( m \), is 5–85% of the actual total mass of the cantilever beam \([m_1 + m_2(1 + l_3/l_2)]\) when the ratio of \([l_2/(l_1+l_2)]\) is within the range of 30–75%.

Figure 2.17 shows that the natural resonant frequency of the cantilever beam changes with the ratio of \((l_2/(l_1+l_2))\) and the sum of \((l_1+l_2)\). It shows that the natural resonant frequency of the cantilever beam changes slightly when \(l_2/(l_1+l_2)\) is within the range of 30–75%. For example, when \((l_1+l_2) = 440 \mu m\) and \(l_3 = 10 \mu m\), the resonant frequency is \(15 \pm 0.5 \text{ kHz}\) as \(l_2/(l_1+l_2)\) is within the range of 0.3–0.75. The natural resonant frequency of the cantilever beam decreases with the increase of \((l_1+l_2)\) due to the increase of the effective mass and the decrease of the stiffness of the cantilever beam.

2.2.6 Dynamic Switching Time

The switching time is obtained using Eq. (2.21) when \(y = g_0\). Substituting Eqs. (2.22), (2.24), and (2.25) into Eq. (2.21), the dynamic response equation is obtained as

\[
y'' + \frac{\omega_0}{Q}y' + \omega_0^2 y = \frac{e_0 \varepsilon h l_2 V^2}{2(g_0 - y)^3 m} \tag{2.30}
\]

The equation governs the simple 1D nonlinear model and can be solved with a nonlinear simultaneous differential equation solver – Mathematica [20].
Table 2.4 Parameters of the cantilever beam for the dynamics simulations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_1$ ($\mu$m)</td>
<td>275</td>
<td>$\rho_{Si}$ (kg/m$^3$)</td>
<td>2330</td>
</tr>
<tr>
<td>$l_2$ ($\mu$m)</td>
<td>165</td>
<td>$\rho_{Au}$ (kg/m$^3$)</td>
<td>19,320</td>
</tr>
<tr>
<td>$l_3$ ($\mu$m)</td>
<td>10</td>
<td>$\rho_{Al}$(kg/m$^3$)</td>
<td>2700</td>
</tr>
<tr>
<td>$w_1$ ($\mu$m)</td>
<td>2.5</td>
<td>$E_{Si}$ (GPa)</td>
<td>162</td>
</tr>
<tr>
<td>$w_2$ ($\mu$m)</td>
<td>5.0</td>
<td>$E_{Al}$ (GPa)</td>
<td>70</td>
</tr>
<tr>
<td>$w_m$ ($\mu$m)</td>
<td>0.6</td>
<td>$E_{Au}$ (GPa)</td>
<td>80</td>
</tr>
<tr>
<td>$g_{Si}$ ($\mu$m)</td>
<td>6.0</td>
<td>Mass, $m$ (ng)</td>
<td>107 (Al); 264 (Au)</td>
</tr>
<tr>
<td>$d_{Si}$ ($\mu$m)</td>
<td>4.0</td>
<td>Stiffness $k$ (N/m)</td>
<td>0.86 (Al); 0.88 (Au)</td>
</tr>
<tr>
<td>$h$ ($\mu$m)</td>
<td>35</td>
<td>Frequency $\omega_0$ (kHz)</td>
<td>14.3 (Al); 9.2 (Au)</td>
</tr>
</tbody>
</table>

Assume that the cantilever beam has parameter values as shown in Table 2.4. Figure 2.18 presents the time-domain response for the cantilever beam coated with gold (Au) and aluminum (Al) for different $Q$ factors. The applied voltage is 40 V. There is a substantial improvement from $Q = 0.5$ to 2, but little improvement when $Q$ is above 2. The beam coated with Al responds faster than coated with Au since mass of the Al is smaller than the mass of the Au. Figure 2.19 shows the switching time depends significantly on the applied voltage. The calculated switching time is 23 $\mu$s when the applied voltage is 40 V and 43 $\mu$s when the applied voltage is 30 V as $Q = 1$ and the coating metal is Al. The corresponding contact force values are 77.6, 106, and 139 $\mu$N for 30, 35, and 40 V, respectively.

![Figure 2.18](image_url)  
**Fig. 2.18** Time domain response of a cantilever beam with different metal coatings and $Q$-factors ($V_{bias} = 40$ V)
2.2 Mechanical Design and Simulation

Fig. 2.19  Time domain response for the cantilever beam with different applied voltages \((Q = 1)\)

2.2.7 Dynamic Release Time

The nonlinear dynamic analysis equation can also be used to model the release mechanism of the switch when \(f_{\text{ext}}(t) = 0\). The restoring force \((= k_{g0})\) is 3.8–4.6 \(\mu\)N and parameter values of the switch are shown in Table 2.4. Figure 2.20 presents the release response for the cantilever beam coated with Al and \(Q = 0.5, 1, 2,\) and 4, respectively. When \(Q = 2\) and 4, the beam oscillates and takes a longer time to stabilize. When \(Q = 0.5\) and 1, the beam takes a shorter time to stabilize.

Fig. 2.20  Simulation results of release time for different \(Q\)-factors
2.3 Device Fabrication Processes

The lateral switches are fabricated using silicon-on-insulator (SOI) wafers, which include a 35-μm-thick low-resistivity silicon (LRSi) device layer, a 2-μm-thick silicon dioxide (SiO₂) layer and a 500-μm-thick high-resistivity silicon (HRSi) handle layer (>4000 Ω cm). The fabrication process begins with the deposition and patterning of SiO₂ on the device layer. Then, the switch structures are etched in the device layer until the buried oxide using deep reactive ion etching (DRIE) technique. Next, the cantilever beam is released by removing the buried oxide using buffered oxide etchant (BOE). Finally, a thin layer of aluminum is coated on the top and sidewalls of the switch structures using E-beam evaporation [21].

For a typical lateral switch, the signal line width, $S$, the ground line width, $G$, and the space between the signal line and the ground line, $W$, of the Si-core CPW port are 66, 100–300, and 67 μm, respectively. Therefore, the port can accommodate 150 μm-pitch ground–signal–ground coplanar probes; at the same time, the characteristic impedance of the Si-core CPW is 50 Ω. The design dimensions of the electrostatic actuator are $l_1 = 210–275$ μm, $l_2 = 165–220$ μm, $l_3 = 10–30$ μm, $w_1 = 2–3$ μm, $w_2 = 5–15$ μm, $g_{Si} = 4–6$ μm, and $d_{Si} = 3–4$ μm. There are four main concerns in selecting these dimensions for the switch design. First, to keep a small device area, generally <1 mm², a short cantilever beam is required. Second, good RF performance needs a short and wide cantilever beam and a large gap distance between the cantilever beam and the fixed electrode. Third, to obtain low actuation voltage and fast switching speed, a long and narrow cantilever beam and a small gap distance are necessary. Fourth, $w_1$, $w_2$, $g_{Si}$, and $d_{Si}$ should be large enough for easy fabrication. The cantilever beam has a length of 450–500 μm. The entire device including the two ports has a length of 700 μm. The length ratio $[l_2/(l_1+l_2)]_{min}$ is 30–75% for low threshold voltage and low insertion loss.

![Fig. 2.21](image-url)  
*Fig. 2.21* SEM image of a lateral switch with the hole mass (G: ground, S: signal). Copyright/used with permission of/courtesy of Institute of Physics and IOP Publishing Limited
Figure 2.21 shows the SEM image of a lateral switch. The switch has a size of 400 μm × 700 μm in area. The actuator dimensions are \( l_1 = 275 \) μm, \( l_2 = 165 \) μm, \( l_3 = 10 \) μm, \( w_1 = 2.4 \) μm, \( w_2 = 15 \) μm, \( g_{Si} = 6 \) μm, and \( d_{Si} = 4 \) μm. A hole mass structure is employed in the cantilever beam of the switch with the width of 15 μm. Every hole is 10-μm wide and 30-μm long. Figure 2.22 is an AFM micrograph showing the surface roughness of a cantilever beam with Al coating. The surface roughness is 250 Å, which is much smaller than Al skin depth up to 100 GHz. Therefore, only a small percent of the total current sees this roughness. The power
loss due to this roughness is negligible [22]. Figure 2.23 shows the zoomed view of the contact part of the cantilever beam after tens of switching cycles. The small point contact is at the top of the cantilever beam sidewall, instead of the whole depth. That is because the cantilever beam is not absolutely straight due to the limitation of the fabrication process. The metal deposited at the upper side of the cantilever beam is slightly thicker than that at the bottom. Therefore, the gap between the cantilever beam and the contact bump on the upper part is slightly narrower than the bottom. The contact point is about 1 μm × 0.7 μm in area. It is easy to realize effective contact since the contact force focuses on this small contact area.

2.4 Lateral Switch Characterization

The RF responses of lateral switches are measured using HP 8510C Vector Network Analyzer (VNA) with tungsten – tip 150 μm – pitch Cascade Microtech ground–signal–ground coplanar probes. The system is calibrated using short-open-load-through (SOLT) on-wafer calibration technique. All tests are performed in the standard room environment without any device package. Before RF testing, each switch is actuated tens of cycles to make the contact surfaces adapt to each other and to make a constant contact resistance. Table 2.5 lists the actuator dimensions and fitted circuit parameters of all switches discussed in this section. \( g_{Si} = 6 \mu m, d_{Si} = 4 \mu m \). Except switches H and I, the other switches (switches A–G) are coated with 1.2-μm-thick Al. The second column is the key parameter to differentiate each switch. \( R \) is the total resistance (\( R = R_l + R_c \)).

2.4.1 The Single-Beam Switch and the Double-Beam Switch

Figure 2.24 shows measured and fitted S-parameters of a single-beam lateral switch (switch A). The design dimensions of the cantilever beam of the lateral switch are \( l_1 = 275 \mu m, l_2 = 165 \mu m, l_3 = 10 \mu m, w_1 = 2.4 \mu m, w_2 = 5 \mu m \) (solid mass), \( g_{Si} = 6 \mu m, d_{Si} = 4 \mu m \). About 1.2-μm-thick Al is deposited. The insertion loss of the switch is 0.37 dB, the return loss is 23 dB, and the isolation is 27 dB at 10 GHz. The equivalent circuit model values are fitted using the measured S-parameters in ADS. Table 2.6 shows the comparison between the fitted and calculated values of the equivalent circuit models of switch A. The fitted inductance, \( L \), is close to the calculated value. The fitted parasitic capacitance, \( C_{gc} \), at the on-state and \( C_{go} \) at the off-state are 28 and 20 fF, respectively, which are a little larger than the calculated values 22.9 and 15.6 fF due to the fringing field capacitance. Therefore, the fringing field capacitance is about 5.1 fF at the on-state and 4.4 fF at the off-state. The calculated DC resistance of the cantilever beam, \( R_l \), is 0.4 Ω, while the fitted total resistance, \( R \), is 2.6 Ω. Therefore, the contact resistance is about 2.2 Ω. The fitted total resistance increases with frequency, as shown in Fig. 2.25. The resistance is 2.6 Ω at DC and 4.2 Ω at 10 GHz. The contact resistance may also
Table 2.5 Cantilever beam parameters and fitted circuit values of switches at 10 GHz

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameters</th>
<th>$L$ (μm)</th>
<th>$L_1$ (μm)</th>
<th>$L_2$ (μm)</th>
<th>$L_3$ (μm)</th>
<th>$w_1$ (μm)</th>
<th>$w_2$ (μm)</th>
<th>$R$ (Ω)</th>
<th>$L$ (pH)</th>
<th>$C_{\text{gc}}$ (fF)</th>
<th>$C_{\text{go}}$ (fF)</th>
<th>$C_s$ (fF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1-beam</td>
<td>450</td>
<td>275</td>
<td>165</td>
<td>10</td>
<td>2.4</td>
<td>5</td>
<td>4.2</td>
<td>148</td>
<td>28</td>
<td>20</td>
<td>6.5</td>
</tr>
<tr>
<td>B</td>
<td>2-beam</td>
<td>450</td>
<td>275</td>
<td>165</td>
<td>10</td>
<td>2.4</td>
<td>5</td>
<td>2.4</td>
<td>60.4</td>
<td>67</td>
<td>56</td>
<td>7</td>
</tr>
<tr>
<td>C</td>
<td>w$_1$/w$_2$ (μm) (single-beam switch with separated fixed electrode)</td>
<td>447</td>
<td>210</td>
<td>215</td>
<td>22</td>
<td>2.0</td>
<td>5</td>
<td>5.4</td>
<td>149</td>
<td>22.6</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>D</td>
<td>2.0/5.0</td>
<td>447</td>
<td>210</td>
<td>215</td>
<td>22</td>
<td>2.4</td>
<td>5</td>
<td>5.1</td>
<td>140</td>
<td>22.6</td>
<td>16</td>
<td>13.2</td>
</tr>
<tr>
<td>E</td>
<td>2.4/15</td>
<td>447</td>
<td>210</td>
<td>215</td>
<td>22</td>
<td>2.4</td>
<td>15</td>
<td>4.2</td>
<td>130</td>
<td>22.6</td>
<td>16</td>
<td>13.5</td>
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<tr>
<td>F</td>
<td>$L_2$ (μm) (double-beam switch)</td>
<td>235</td>
<td>450</td>
<td>187</td>
<td>235</td>
<td>28</td>
<td>2.4</td>
<td>5</td>
<td>2.8</td>
<td>58</td>
<td>70</td>
<td>63</td>
</tr>
<tr>
<td>G</td>
<td>350</td>
<td>450</td>
<td>72</td>
<td>350</td>
<td>23</td>
<td>2.4</td>
<td>5</td>
<td>3.4</td>
<td>55.6</td>
<td>77</td>
<td>70</td>
<td>7</td>
</tr>
<tr>
<td>H</td>
<td>$t_{\text{Al}}$ (μm) (single-beam switch)</td>
<td>0.8</td>
<td>450</td>
<td>275</td>
<td>165</td>
<td>10</td>
<td>2.4</td>
<td>5</td>
<td>5.0</td>
<td>182</td>
<td>56</td>
<td>50</td>
</tr>
<tr>
<td>I</td>
<td>1.5</td>
<td>450</td>
<td>275</td>
<td>165</td>
<td>10</td>
<td>2.4</td>
<td>5</td>
<td>1.8</td>
<td>147</td>
<td>34</td>
<td>24</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Fig. 2.24 Comparison between measured and fitted $S$-parameters of the single-beam switch (switch A)

Table 2.6 Comparison between fitted and calculated circuit values of switch A

<table>
<thead>
<tr>
<th></th>
<th>$R_{l}+R_{c}$ @ DC (Ω)</th>
<th>$R_{l}+R_{c}$ @ 10 GHz (Ω)</th>
<th>$L$(pH)</th>
<th>$C_{gc}$(fF)</th>
<th>$C_{go}$(fF)</th>
<th>$C_{s}$(fF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted value</td>
<td>2.6</td>
<td>4.2</td>
<td>148</td>
<td>28</td>
<td>20</td>
<td>6.7</td>
</tr>
<tr>
<td>Calculated value</td>
<td>0.5</td>
<td>1.0</td>
<td>150</td>
<td>22.9</td>
<td>15.6</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 2.25 Plot of the fitted resistance, $R_{l}+R_{c}$, of switch A with frequency
increase with frequency. Third, the potential of the two ground lines is not same at the high frequency due to the asymmetrical structure of the switch, which results in more loss at high frequency. In this section, if without specific clarification, the total resistance of the switches is set to increase with frequency in the equivalent circuit model.

Figure 2.26 shows the SEM image of a double-beam switch. The switch has a size of 800 μm × 700 μm. A solid mass structure is employed in the cantilever beam. The actuator design dimensions and fitted circuit elements at 10 GHz are listed in Table 2.5 (switch B). Figure 2.27 shows the comparison between the measured and the fitted S-parameters of the double-beam switch. The fitted S-parameters agree with the measured results well. Figure 2.28 compares measured S-parameters between the single-beam switch (switch A) and the double-beam switch. The double-beam switch has a lower insertion loss than the single-beam switch by 0.1 dB from 0.05 to 25 GHz. The return loss of the double-beam switch is larger than the single-beam switch from 0.05 to 17 GHz and lower than the latter when the frequency is above 17 GHz. The isolation loss of two switches is close to each other. The fitted total resistance, $R$, of the double-beam switch is 2.4 Ω at 10 GHz, which is close to half of the single-beam switch. The fitted inductance, $L$, of the double-beam switch is 60.4 nH, which is also close to half of the single-beam switch. Lower inductance results in lower insertion loss at high frequencies for the double-beam switch. The parasitic capacitance at the on-state, $C_{gc}$, and at the open state, $C_{go}$, of the double beam switch is nearly two times of the single-beam switch, which results in higher return loss at low frequencies for the double-beam switch. The open capacitance, $C_s$, of the double-beam switch is slightly larger than the single-beam switch. Therefore, the equivalent circuit model of the double-beam switch, as shown in Fig. 2.8, is verified to be valid. The double-beam switch can provide lower insertion loss.
Fig. 2.27 Comparison between measured and fitted $S$-parameters of the double-beam switch (switch B)

Fig. 2.28 Comparison of measured $S$-parameters between the single-beam switch (switch A) and the double-beam switch (switch B). Copyright/used with permission of/courtesy of Institute of Physics and IOP Publishing Limited

loss than the single-beam switch. However, when two beams in the double-beam switch are not symmetrical, the double-beam switch performances may deteriorate and become worse than the single-beam switch.
2.4 Lateral Switch Characterization

2.4.2 Cantilever Beam Design Effect

The cantilever beam is the main part of the signal line in the lateral switch. Therefore, the design parameters (beam width, mass shape, and length) of the cantilever beam have a significant role in determining the RF performance of the lateral switch.

Figures 2.29, 2.30, and 2.31 show the comparison between the measured and fitted $S$-parameters of switches C, D, and E, respectively. In switch C, $w_1 = 2.0 \, \mu m$, $w_2 = 5 \, \mu m$; in switch D, $w_1 = 2.4 \, \mu m$, $w_2 = 5 \, \mu m$; and in switch E, $w_1 = 2.4 \, \mu m$, $w_2 = 15 \, \mu m$. Other structure parameters are the same. In these switches, fixed electrode is separated from the ground line, as shown in Fig. 2.38. All switches have insertion loss below 0.8 dB, return loss of above 15 dB, and isolation of above 17 dB up to 20 GHz. The fitted $S$-parameters agree well with the measured results. Table 2.5 shows that both the total resistance, $R$, and the inductance, $L$, decrease with the beam width, either $w_1$ or $w_2$. The parasitic capacitance at the on-state, $C_{go}$, and at the off-state, $C_{go}$, of these three switches are the same. The open capacitance, $C_s$, increases slightly with the beam width. Therefore, the beam width mainly affects the beam resistance and the inductance, as predicted in Section 2.1.2.

![Fig. 2.29 Comparison between measured and fitted $S$-parameters of a single-beam switch with the solid mass (switch C, $w_1 = 2.0 \, \mu m$, $w_2 = 5 \, \mu m$)](image)

Figure 2.32 shows the comparison of the measured results between switch C ($w_1 = 2.0 \, \mu m$) and switch D ($w_1 = 2.4 \, \mu m$). It is found that the switch with $w_1 = 2.4 \, \mu m$ has slightly lower insertion loss and higher return loss than the switch with $w_1 = 2.0 \, \mu m$. This is because narrower cantilever beam results in larger beam resistance, $R_l$, and inductance, $L$, than the wider cantilever beam. The isolations loss of the two switches change marginally.
Figure 2.30 shows the comparison of the measured S-parameters of switch D (solid mass, $w_2 = 5 \mu m$) and switch E (hole mass, $w_2 = 15 \mu m$). The insertion loss of the hole mass switch is lower than the solid mass switch by 0.1 dB. The return loss of the hole mass switch is higher than the solid mass switch by 2.5 dB.
This is because the hole mass offers lower beam resistance $R_l$ and inductance $L$ compared to the solid mass. The isolation of the hole mass switch is slightly lower than the solid mass switch since wider mass structure result in slightly larger open capacitances, $C_s$. 

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Fig. 2.32  Comparison of measured $S$-parameters between switch C ($w_1 = 2.0 \mu m$) and switch D ($w_1 = 2.4 \mu m$)

Fig. 2.33  Comparison of measured $S$-parameters between switch D (solid-mass, $w_2 = 5 \mu m$) and switch E (hole-mass, $w_2 = 15 \mu m$). Copyright/used with permission of/courtesy of Institute of Physics and IOP Publishing Limited
When sum \((l_1 + l_2)\) and \(l_3\) are constant, a change in the length of the fixed electrode, \(l_2\), affects the RF performance due to the effect of the shunt coupling capacitance, \(C_g\). Figures 2.34 and 2.35 shows the comparison between the measured and the fitted \(S\)-parameters of switch F \((l_2 = 235 \mu m)\) and switch G \((l_2 = 350 \mu m)\), respectively. For both switches, sum \((l_1 + l_2)\) and \(l_3\) are 422 and 25 \mu m, respectively. Figure 2.36 compares measured \(S\)-parameters between switch F and switch G. At 10 GHz, the insertion loss increases from 0.37 to 0.41 dB when \(l_2\) increases from 235 to 350 \mu m, whereas the return loss increases from 21 to 22.7 dB. The isolations of two switches change marginally. Theoretically, the resistance, \(R\), should decrease with \(l_2\). However, the resistance of switch G is 4.3 \Omega at 10 GHz, which is larger than switch F of 3.8 \Omega. That is because of larger contact resistance of switch G. The threshold voltage of switch G \((l_2 = 350 \mu m)\) is 30 V and that of switch F \((l_2 = 235 \mu m)\) is 23 V. Therefore, when 40 V bias voltage is applied, the contact force of switch G is smaller than that of switch F, which results in higher contact resistance of switch G. The parasitic capacitance at the on-state, \(C_{gc}\), increases from 70 to 77 fF when \(l_2\) increases from 235 to 350 \mu m. The inductance decreases slightly with \(l_2\).

### 2.4.3 Metal Coating Effect

The thickness of the metal coating affects the RF performance of lateral switches since it determines the switch resistance. Figure 2.37a, b compares the measured \(S\)-parameters of a single-beam switch with various thicknesses of Al coating at the on-state and off-state, respectively. The Al thickness is 0.8 \mu m for switch H, 1.2 \mu m
Fig. 2.35  Comparison between measured and fitted $S$-parameters of switch G ($l_2 = 350 \, \mu m$)

Fig. 2.36  Comparison of measured $S$-parameters between switch F ($l_2 = 235 \, \mu m$) and switch G ($l_2 = 350 \, \mu m$). Copyright/used with permission of/courtesy of Institute of Physics and IOP Publishing Limited
for switch A, and 1.5 μm for switch I. At 10 GHz, the insertion loss decreases from 0.62 to 0.2 dB when the Al thickness increases from 0.8 to 1.5 μm. The main reason is the reduction in the total resistance from 5 to 1.8 Ω due to thicker metal coating. It is noted that the return loss of switch H with 0.8-μm-thick Al coating is larger than the other two switches with thicker metal coating. This is in contrast to the fact that the return loss increases when the metal coating increases from 1.2 to 1.5 μm. It is found that a shunt conductance $G \times 10^{-4}$ S is needed to add in the circuit model of switch H to fit the measured S-parameters, but is unnecessary for the other two switches. This indicates that when 0.8-μm-thick Al is coated, the metal on sidewalls is too thin to isolate the silicon core effect. The device silicon layer works as the substrate of the top metal strips, which causes larger parasitic capacitance $C_g C$ and more dielectric loss. Hence, the metal coating should be larger than 0.8 μm for low loss. The insertion loss of the switch is decreasing with the metal thickness significantly implying that the switch loss is dominated by the conductor loss. The switch RF performance can be improved further by coating a thicker metal layer.

### 2.4.4 The Lateral Switch with a Separate Fixed Electrode

For the lateral switch design, the fixed electrode can be designed either as part of the ground line (combined electrode) or as a separate part of the ground line (separate electrode), as shown in Fig. 2.38. Figure 2.39 compares the measured S-parameters between switch A (combined electrode) and switch D (separate electrode). It shows that the switch with the separate electrode also works at high frequencies. Both switches have an insertion loss of less than 1 dB and a return loss of more than 15 dB up to 25 GHz. However, the isolation of switch D is 14 dB at 25 GHz, whereas the isolation of switch A is 21 dB at 25 GHz. The isolation of switch D is lower than switch A by about 7 dB from 0.05 to 25 GHz. This is because switch D has larger open capacitance, $C_s$, as shown in Table 2.5. The open capacitance of switch

Fig. 2.37  Comparison of measured results of the single-beam switch with various thick Al coating (a) the insertion loss and the return loss, and (b) the isolation. Copyright/used with permission of/courtesy of Institute of Physics and IOP Publishing Limited

2.4.4 The Lateral Switch with a Separate Fixed Electrode

For the lateral switch design, the fixed electrode can be designed either as part of the ground line (combined electrode) or as a separate part of the ground line (separate electrode), as shown in Fig. 2.38. Figure 2.39 compares the measured S-parameters between switch A (combined electrode) and switch D (separate electrode). It shows that the switch with the separate electrode also works at high frequencies. Both switches have an insertion loss of less than 1 dB and a return loss of more than 15 dB up to 25 GHz. However, the isolation of switch D is 14 dB at 25 GHz, whereas the isolation of switch A is 21 dB at 25 GHz. The isolation of switch D is lower than switch A by about 7 dB from 0.05 to 25 GHz. This is because switch D has larger open capacitance, $C_s$, as shown in Table 2.5. The open capacitance of switch
Fig. 2.38 SEM images of a lateral switch with separate fixed electrode. Copyright/used with permission of/courtesy of Springer

D is 13.2 fF, whereas the open capacitance of switch A is 6.5 fF. From Fig. 2.38, it is found that except the end of the cantilever beam, part of the signal line also faces the input port in switch D, which increases the open capacitance. Therefore, the isolation of switch D can be improved by using the cantilever beam alone as the signal line of the switch. It is noted that the parasitic capacitance, $C_{gc}$, of switch D
of 22.6 fF is less than switch A of 28 fF, although switch D has longer electrode than switch A. This is because the parasitic capacitance of switch D is contributed by two capacitors in series. One is between the cantilever beam and the separate electrode. The other is between the separate electrode and the ground line.

2.5 Mechanical Measurements

2.5.1 Static behavior

Since the pull-in of the cantilever beam is sharp and sudden, the measurement of the pull-in voltage can be easily performed at wafer level using the standard electrical test equipment with a microscope.

Figure 2.40 shows the comparison of the measured and calculated threshold voltages, $V_{th}$, of the switch with various original gap distances, $g_0$, where $l_1 = 220 \, \mu m$, $l_2 = 210 \, \mu m$, $l_3 = 10 \, \mu m$, $w_1 = 2.4 \, \mu m$, $w_2 = 5 \, \mu m$, and $w_{Al} = 0 \, \mu m$. The threshold voltage increases with $g_0$. A 0.5-\mu m increase in $g_0$ will increase the threshold voltage by about 2.5 V. The effect of $(l_2/(l_1 + l_2))$ ratio on the threshold voltage, $V_{th}$, is shown in Fig. 2.41. The threshold voltage, $V_{th}$, is $20 \pm 1 \, V$ when the $(l_2/(l_1 + l_2))$ ratio is within the range of 30–75% before metal coating. Figure 2.41 also shows effects of metal coating on the threshold voltage. When a 0.63-\mu m-thick Al is coated on the sidewalls of the lateral switch, the threshold voltage of the switch
increases by about 5 V. However, the measured results of the switch with 0.63-μm-thick Al on the sidewalls do not fit so well to the calculation results compared to the switch without Al coating. This may be because residual stress is introduced by evaporated Al.

Figure 2.42 shows the comparison between the measured, calculated, and simulated displacement results of the free end of a switch with 0.63-μm Al coated on the sidewalls. The measurement procedures of the displacement of the free end of the cantilever beam are as follows: First, the lateral switch is fixed on a probe station, which has a microscope above it. A camera is connected to the microscope. Then, two micro-probes connected to an external power source are put on the two electrodes. After a bias voltage is applied, the camera takes a photo of the contact part once the cantilever beam becomes stable. By comparing the photo at some specified voltage with the photo at 0 V, the displacement of the free end of the cantilever beam is calculated. It can be noted that the displacement of the free end of the cantilever beam increases with the applied bias voltage. When the bias voltage increases to 23.3 V, the cantilever beam is attracted to touch the contact tip rapidly. Therefore, the threshold voltage of this switch is 23.3 V. The measurement result is consistent with the calculated and the simulated results.

### 2.5.2 Dynamic Behavior

A lateral switch with $l_1 = 275 \, \mu m$, $l_2 = 165 \, \mu m$, $l_3 = 10 \, \mu m$, $w_1 = 2.4 \, \mu m$, $w_2 = 5 \, \mu m$, $w_{Al} = 0.63 \, \mu m$, $g_{Si} = 6 \, \mu m$, and $d_{Si} = 4 \, \mu m$ is tested and the results
2.5.3 Reliability of the Lateral Switch

Resistive switches usually fail due to an excessive increase in electrical contact resistance. Generally failure occurs when the contact resistance is greater than 5 \( \Omega \), even though the cantilever beam remains deflecting and making contact. The study includes both cold and hot switching lifetimes. The cold switching refers to opening and closing the switch with zero RF signal level through the contact. The hot switching refers to opening and closing the switch with a specified RF signal level through the contact [23]. It is known that the lifetime of hot switching is shorter compared to the lifetime of cold switching due to larger heat dissipation. The testing results show that the cold switching lifetime of the lateral switch exceeds million switching cycles as shown in Fig. 2.44. The insertion loss and the return loss of a double-beam switch deteriorate by 0.1 and 1.5 dB at 10 GHz, respectively, after 1 million cold switching cycles. The isolation changes marginally. The hot switching lifetimes of these switches are quite poor. Generally, after tens of hot switching cycles, the switch fails due to stiction of the cantilever beam to the contact bump.
2.5 Mechanical Measurements

Fig. 2.43  The experimental results of switching time of a lateral switch: (a) the on-state of the switch and (b) the off-state of the switch.

Fig. 2.44  Measured S-parameters of switch B with different switching cycles. Copyright/used with permission of/courtesy of Institute of Physics and IOP Publishing Limited
This is because the spring constant of these cantilever beam is too low (~1 N/m). To solve this problem, the spring constant of the cantilever beam should be designed to be >10 N/m [16].

2.6 Summary

Different types of lateral switches from 50 MHz to 25 GHz are presented in this chapter. These include single-beam and double-beam switches, switches with part of the ground line as a fixed electrode, and switches with separate fixed electrode. All lateral switches are designed using Si-core CPW and an electrostatic cantilever actuator. A high aspect ratio cantilever beam with beam mass structure is employed as the actuation part of the lateral switch. The electronic design, the mechanical design, and the circuit modeling of the lateral switch are presented. Comprehensive modeling and design of the lateral switches are verified. The measurements show that the optimized lateral switches have low insertion loss (<1 dB), high return loss, and isolation (>20 dB) at 50 MHz to 25 GHz. The threshold voltage is less than 25 V. The switching speed is 35 μs. The RF lifetime is more than 1 million cold switching cycles.

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