Chapter 3

Design and simulation of Two Movable Plate Switch (TMPS): Static and Dynamic Analysis

3.1 Introduction

This chapter details the static and dynamic analysis of MEMS capacitive shunt switches under electrostatic force. The stiffness of the MEMS switch mostly governs the static and dynamic behavior of the system, playing a major role in determining the pull-down voltage and switching time of the RF MEMS switch. In order to overcome the major limitation of high actuation voltage in conventional RF MEMS switch, low spring constant designs having meander suspensions are generally used. But such designs severely affect the dynamics of the system and also the reliability of the switch. Further a faster switching is obtained with the use of a stiffer membrane. This contradiction between the lowering of actuation voltage and improvement of switching time has been the motivation for this work. A novel design namely Two Movable Plate Switch (TMPS) has been presented which shows simultaneous lowering of the actuation voltage and improvement in the switching time. A one dimensional (1-D) analytical model has been proposed for the TMPS to gain an insight into the behavior of the TMPS and for laying down the basic design guidelines. Subsequently, three dimensional (3-D) Finite Element Method (FEM) simulations have been carried out in Intellisuite® (for static analysis) and Ansys® (for dynamic analysis).
3.2 Review of some key parameters of MEMS shunt switch for static and dynamic analysis

3.2.1 Spring constant

The mechanical operation of RF MEMS switches depends on the spring constant of the beam. If the operation of the structure is limited to small deflection, as in the case for most RF MEMS switches, the mechanical behavior can be modeled using a spring constant having a linear behavior. The spring constant for the fixed-fixed beam can be modeled in two parts. One part is due to the stiffness of the bridge which accounts for the mechanical characteristics such as Young’s modulus. The other part of the spring constant is due to the biaxial residual stress within the beam and is a result of fabrication process [1]. The spring constant is the most critical parameter for RF MEMS switches and governs both the static and dynamic performance of the system.

a) Spring constant due to elasticity

For RF MEMS switches, the force by which the MEMS bridge is pulled downward is normally distributed over its central portion. The general expression for this spring constant is given by

$$k' = 32Ew\left(\frac{t}{l}\right)^3\left(\frac{1}{8(x/l)^3 - 20(x/l)^2 + 14(x/l) - 1}\right)$$

(3.1)

where E is the Young’s modulus, w, t and l are the width, thickness and length of the MEMS bridge respectively. Here x denotes the extent up to which the force is evenly distributed [Figure 3.1].
Figure 3.1: Fixed fixed bridge with a force $P=2\xi(x-l/2)$ evenly distributed about the centre of the beam

**b) Spring constant due to residual stress**

The part of the spring constant that is due to the biaxial residual stress within the beam is derived from modeling of the beam as a stretched wire. It should be noted that this model only applies for tensile stress. For the case when the force is distributed over the central portion of the beam, the spring constant is given by

$$k' = 8\sigma(1-\nu)w\frac{t}{l}\left(\frac{1}{3-2(x/l)}\right)$$

where $\sigma$ is the biaxial tensile residual stress, $\nu$ is the Poisson’s ratio, $w$, $t$ and $l$ are the width, thickness and length of the MEMS bridge respectively [Figure 3.1].

**3.2.2 Actuation voltage**

For RF MEMS switches with electrostatic actuation, the voltage at which the MEMS bridge makes contact with the pull down electrode is given by
Design and simulation of Two Movable Plate Switch (TMPS): Static and Dynamic Analysis

\[ V_p = \sqrt{\frac{8k}{27\varepsilon_0 A} g_0^3} \]  \hspace{1cm} (3.3)

where \( k = k' + k'' \), \( A \) is the actuation area and \( g_0 \) is the height of the MEMS bridge from the pull down electrode.

### 3.2.3 Damping coefficient/ Quality factor

The energy dissipation mechanism that causes vibrations to diminish over time and eventually stop is known as damping. The damping coefficient plays an important role in determining the dynamic performance of the device. Further, the quality factor of a bridge, a figure of merit for a bridge, is determined by several different variables such as the pressure, temperature, and intrinsic material dissipation. Because most RF MEMS devices are operated at atmospheric pressure, the quality factor is dominated by squeeze-film damping [1]. According to squeeze film damping, the fluid can add stiffening and/or damping to the system depending on the operating frequencies. At low frequencies, the fluid can escape before it compresses. Therefore, the fluid only adds damping to the system. At high frequencies, the fluid compresses before it can escape. Therefore, the fluid adds both stiffening and damping to the system. Amount of damping mainly depends on the material, velocity of motion, and frequency of vibration.

The damping of rectangular parallel-plate geometries has been derived from a linearized form of the compressible Reynolds gas-film equation [1] and is given by

\[ b = \frac{3}{2\pi} \frac{\mu A^2}{g_0^3} \]  \hspace{1cm} (3.4)

where \( A \) is the area of the device and \( \mu \) is the coefficient of viscosity.
An approximate formula for the quality factor of a fixed-fixed bridge is given by [1],

\[ Q = \frac{\sqrt{E \rho r^2}}{\mu \left( \frac{wl}{2} \right)^2 g_0^3} \]  

(3.5)

where \( \rho \) is the density of the bridge material.

### 3.2.4 Resonant frequency/switching time

The switching time is more difficult to predict because it pertains to the time required for the air bridge to drop from threshold state to the bottom contact under the effect of electrostatic force. Since this force increases as the gap reduces, the switch down-time is substantially shorter. Practically the turn off time might be higher than turn on time, due to “stiction”. Stiction is a phenomenon by which parts of the MEMS device can bond together upon physical contact. When actuating switches on and off, it is possible for the high electric field across the thin dielectric to cause charges to tunnel into the dielectric and become trapped. These charges screen the applied electric field, causing the switches to need higher switching voltages. Further, they are difficult to switch using unipolar dc control voltages [1]. To accurately estimate the switching time, the dynamic response of the MEMS bridge is evaluated from d’Alembert’s principle taking into account the non-linearity of the system as well as the damping factor of the air layer underneath the MEMS bridge.

A rough estimate of the switching time may also be obtained by simply evaluating the resonant frequency of the bridge. It is seen that the resonant angular frequency of the MEMS bridge is given by
where \( m \) is the mass of the MEMS bridge. A rule of thumb for switching speed is that the switches will change state (between up and down) in \( 1/2 \) to \( 1/3 \) times of a cycle of the fundamental frequency.

### 3.3 Physical description of MEMS capacitive shunt switches

#### 3.3.1 Single Movable Plate Switch (SMPS)

The MEMS shunt switch can be integrated in a Co-Planar Waveguide (CPW) or in microstrip topology. In a CPW configuration, the anchors of the MEMS switch are connected to the CPW ground planes.

A conventional SMPS on a CPW is shown in figure 3.2(a) and (b). The switch is suspended at a height \( g_0 \) above the dielectric layer on the CPW and the dielectric thickness is \( t_d \) with a dielectric constant \( \varepsilon_{rd} \). The MEMS bridge has a length \( l_1 \), width \( w_1 \) and thickness \( t_1 \). The CPW has a configuration of W/S/W on silicon substrate.
Typical values of the switch geometry are a dielectric thickness of 1000-1500Å, a relative dielectric constant of 5.0-7.6 depending on the dielectric material used, a bridge height of 2.5-5µm, a length around 250-400µm, and a width between 25-180µm depending on the switch capacitance required. The length is
rarely shorter than 200μm due to the sharp increase of the actuation voltage with decreasing bridge length. The width is practically limited to 200μm so as to result in a flat contact area between the MEMS bridge and the t-line. The thickness of the bridge is generally between 0.5-2μm depending upon the required stiffness [1].

To design a MEMS switch a standard CPW configuration having central conductor width of 90μm and a gap of 77.5μm is chosen to have 55Ω characteristic impedance. A bridge having length 245μm, width 80μm and thickness of 0.9μm is chosen which is a tradeoff between the actuation voltage, switching time and reliability of the device. An optimum height of 2.5μm is chosen and is a tradeoff between capacitance ratio and actuation voltage. The selection of an optimum material for RF MEMS capacitive shunt switch and the CPW transmission line has been of much research interest. As a variety of materials are available to the design engineer, a proper way to select the best possible material is needed. The primary performance indices for the RF MEMS switch is the pull in voltage and switching time and that for the CPW transmission line is the RF loss. Recent work by Sharma et al. [2] shows that gold and aluminium are the appropriate materials for the RF MEMS switch. Gold however will have a better RF performance as compared to aluminium when used to the CPW configuration. Although gold is costlier than aluminium, a mass production of the switch will bring down the production cost. The thesis will, therefore, entirely focus on the use of gold (E=75GPa, ν=0.4) as the material for realizing RF MEMS switch and CPW configuration. A Si₃N₄ dielectric having a thickness of 0.15μm & permittivity of 7.5 is considered for the SMPS. This specific SMPS has been considered over which an enhancement in performance is achieved. One may however note that the enhancement in performance is applicable to any SMPS with a slight mechanical modification in the CPW configuration.
3.3.2 *Two Movable Plate Switch (TMPS)*

The structure of the proposed MEMS shunt switch (TMPS) is same as that of the SMPS but only some amount of silicon is scooped out from underneath the CPW central line having a configuration $W/S/W$ to make two movable plates. The MEMS bridge (*top plate*) has a length $l_1$, width $w_1$ and thickness $t_1$ as that of SMPS while the movable CPW central line (*bottom plate*) has a length $l_2$, width $w_2$ and thickness $t_2$. Figure 3.3(a) and 3.3(b) shows the top view and cross sectional views of the proposed structure.

![3.3(a) Top view of TMPS](image)

![3.3(b) Cross sectional view of TMPS with reference to A-A’](image)
3.4 **Static Analysis of SMPS and TMPS: Analytical Modeling**

![Figure 3.4(a): 1-D MEMS beam model](image)

![Figure 3.4(b): 3-D view of the TMPS prior to bonding](image)
Figure 3.4(c): Cross sectional view of the TMPS along B-B’ after bonding

Figure 3.4(a) shows the one-dimensional (1-D) MEMS beam model of the proposed TMPS. $x_1$ and $x_2$ represent the actual displacements of the top and bottom plate respectively, while $x_3$ is the position of the CPW as measured from the origin ($x=0$) of the reference axes, as indicated in the diagram, when a voltage $V$ is applied between the plates. Figure 3.4 (b) shows the 3-D view of the proposed TMPS structure fabricated by bulk micromachining and bonding, prior to bonding. The fabrication of the device is discussed in chapter 5. Figure 3.4(c) shows the cross sectional view of the TMPS along B-B’ [Figure 3.4(b)] after the two wafers are bonded together.

The parallel plate capacitance at any instant of time $t$ is given by [1]

$$ C(t) = \frac{\varepsilon_0 (w_1 X w_2)}{g(t)} $$

(3.7)

assuming $t_d / \varepsilon_r < g(t)$, which is valid in practical situation.
In Equation (3.7), the instantaneous gap between the plates under displaced condition is

\[ g(t) = g_0 - x_1(t) - x_2(t) \]  

(3.8)

For an applied voltage \( V \) the electrostatic force applied to both the plates is given by [1]

\[ F_e(t) = \frac{1}{2} V^2 \frac{dC(g)}{dg} = -\frac{1}{2} \frac{\varepsilon_0 w_1 w_2 V^2}{g(t)} \]  

(3.9)

On application of a voltage \( V \) each of the movable plates is brought to equilibrium by electrostatic deflection force \( F_e \) and by an equal and opposite restoring force \( F_r \) which leads to

\[ k_1 x_{1e} = k_2 x_{2e} = \frac{1}{2} \frac{\varepsilon_0 A V^2}{g_e^2} \]  

(3.10)

where

\[ k_i = 32Ew_i \left( \frac{t_i}{l_i} \right)^3 \frac{1}{8(p_1/l_1)^3 - 20(p_1/l_1)^2 + 14(p_1/l_1) - 1} + 8\sigma(1-\nu)w_i \left( \frac{t_i}{l_i} \right)^3 \frac{1}{3 - 2(p_1/l_1)} \]

and

\[ k_2 = 32Ew_2 \left( \frac{t_2}{l_2} \right)^3 \frac{1}{8(p_2/l_2)^3 - 20(p_2/l_2)^2 + 14(p_2/l_2) - 1} + 8\sigma(1-\nu)w_2 \left( \frac{t_2}{l_2} \right)^3 \frac{1}{3 - 2(p_2/l_2)} \]

are the spring constant of the two plates, \( x_{1e} \) and \( x_{2e} \) are the displacement of the two plates under equilibrium, \( g_e = g_o - x_{1e} - x_{2e} \) is the effective gap between the two plates, \( p_1 = (l_1/2) + (w_2/2), \ p_2 = (l_2/2) + (w_1/2), \ A \) is the intersection area of the plates forming the switch, \( \sigma \) is the biaxial tensile residual stress and \( \nu \) is
the Poisson’s ratio. The force is taken to be distributed along the overlap of the two plates [1].

Solving for voltage one gets

$$V = \sqrt{\frac{2k_1x_{1e}}{\varepsilon_0 w_1 w_2} \left( g_0 - x_{1e} - \frac{k_1}{k_2} x_{1e} \right)^2}$$  \hspace{1cm} (3.11)

Under pull down conditions \( \frac{dV}{dx_{1e}} = 0 \) so that

$$x_{1PD} = \frac{g_0 k_2}{3 k_1 + k_2} \quad \text{and hence} \quad x_{2PD} = \frac{g_0 k_1}{3 k_1 + k_2}$$

At pull down

$$g = g_0 - x_{1PD} - x_{2PD} = \frac{2}{3} g_0$$  \hspace{1cm} (3.12)

As the point of instability occurs at a distance of one third of the gap from the original position, the pull down voltage for the two-movable plate switch is

$$V_{TMPS} = \sqrt{\frac{8k_1 k_2 g_0^3}{27\varepsilon_0 w_1 w_2 (k_1 + k_2)}} = \sqrt{\frac{8k_{eff} g_0^3}{27\varepsilon_0 w_1 w_2}}$$  \hspace{1cm} (3.13)

where

$$k_{eff} = \frac{k_1 k_2}{k_1 + k_2}$$  \hspace{1cm} (3.14)

It may be noted that the pull-down voltage of the SMPS is given by [1]
Design and simulation of Two Movable Plate Switch (TMPS): Static and Dynamic Analysis

\[ V_{SMPS} = \sqrt[3]{\frac{8k_1g_0^3}{27\varepsilon_0w_1w_2}} \]  

(3.15)

where \( k_1 \) is the spring constant of the membrane and the central line of CPW is rigid (\( k_2 \rightarrow \infty \)). Comparison of equations (3.13) and (3.15) shows that the TMPS behaves like the SMPS with a spring constant given by equation (3.14). This is the case when two springs are in series.

3.4.1 Static Analysis ignoring residual stress

For the sake of simplicity, the residual stresses in the plates which correspond to the second term in the expression for spring constant are neglected. For choosing an optimum bottom plate the effect of its physical dimensions on the actuation voltage has been studied.

(a) Variation of actuation voltage with width of bottom plate

Figure 3.5(a) shows the effect of width of the bottom plate on the actuation voltage on different values of \( t_2/l_2 \). It is seen that as the width is increased the actuation voltage decreases owing to a higher actuation area and vice-versa. A higher ratio of \( t_2/l_2 \) is indicative of a stiffer bottom plate which results in a higher actuation voltage whereas a lower ratio is indicative of a fragile bottom plate with very low actuation voltage. It is seen that a \( t_2/l_2 \) ratio of 0.003-0.005 for \( w_2 \) in the range of 80-100µm results in optimum actuation voltages with reliable operation. The width of the bottom plate is chosen as 90µm with suitable gap of 77.5µm in the CPW configuration will give 55Ω characteristic impedance.
Figure 3.5(a): Variation of actuation voltage with the width of bottom plate

(b) Variation of actuation voltage with thickness of bottom plate

Figure 3.5(b) shows the effect of the bottom plate thickness on the actuation voltage with different bottom plate lengths keeping the width of the plate constant at 90µm. It is seen that as the thickness of the bottom plate is increased to about 2µm, the actuation voltage tends to the actuation voltage of the SMPS. For lower values of thickness the actuation voltage would be less at the cost of a very fragile bottom plate. A $t_2/l_2$ ratio of around 0.003-0.005 will provide optimum results.
Figure 3.5(b): Variation of actuation voltage with the thickness of bottom plate

(c) Variation of actuation voltage with length of bottom plate

Figure 3.5(c) shows the effect of the bottom plate length on the actuation voltage with different thickness of the bottom plate keeping the width of the plate constant at 90µm. As the length increases, the stiffness of the bottom plate decreases, leading to a lower actuation voltage. On the other hand if the length of the bottom plate reduces, a point is reached when the plate becomes stiff enough for the TMPS to resemble the SMPS performance. Again a $t_2/l_2$ ratio of around 0.003-0.005 is seen to provide optimum results.
Figure 3.5 (c): Variation of actuation voltage with the length of bottom plate

(d) Optimization

Table 3.1 shows typical dimensions of top and bottom plates for t/l ratios in the range of 0.003-0.005. The top plate has been kept unchanged as discussed earlier. TMPS I, II and III with various bottom plates is analyzed for fine tuning the performance.

Table 3.1: Typical dimensions of Two Movable Plate RF MEMS shunt switch

<table>
<thead>
<tr>
<th>SMPS/TMPS</th>
<th>Plate(s)</th>
<th>Length (µm)</th>
<th>Width (µm)</th>
<th>Thickness (µm)</th>
<th>Thickness/Length of plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMPS</td>
<td>Top plate</td>
<td>245</td>
<td>80</td>
<td>0.9</td>
<td>0.00367</td>
</tr>
<tr>
<td>TMPS I</td>
<td>Top plate</td>
<td>245</td>
<td>80</td>
<td>0.9</td>
<td>0.00367</td>
</tr>
<tr>
<td></td>
<td>Bottom plate</td>
<td>235</td>
<td>90</td>
<td>1.1</td>
<td>0.00468</td>
</tr>
<tr>
<td>TMPS II</td>
<td>Top plate</td>
<td>245</td>
<td>80</td>
<td>0.9</td>
<td>0.00367</td>
</tr>
<tr>
<td></td>
<td>Bottom plate</td>
<td>240</td>
<td>90</td>
<td>1.0</td>
<td>0.00416</td>
</tr>
<tr>
<td>TMPS III</td>
<td>Top plate</td>
<td>245</td>
<td>80</td>
<td>0.9</td>
<td>0.00367</td>
</tr>
<tr>
<td></td>
<td>Bottom plate</td>
<td>245</td>
<td>90</td>
<td>0.9</td>
<td>0.00367</td>
</tr>
</tbody>
</table>
Figure 3.6 shows the variation of gap height with applied voltage as obtained from equation (3.11) for typical dimensions of top plate \((l_1, w_1, t_1)\) and bottom plate \((l_2, w_2, t_2)\) as given in Table 3.1. An actuation voltage of 20V corresponding to a fixed bottom plate, which is a Single Movable Plate System (SMPS), and an actuation voltage of 16.4V (TMPS I), 15.4V (TMPS II) & 14.2V (TMPS III) corresponding to a movable bottom plate is obtained as in figure 3.6. It is seen that an improvement of around 16%, 21% and 28% in the actuation voltage is obtained over the SMPS in TMPS I, II and III respectively, since \(k_{\text{eff}}\) is always less than either \(k_1\) or \(k_2\).

![Figure 3.6](image_url)

Figure 3.6: Plot of gap height vs. voltage for TMPS and SMPS

Careful selection of the bottom plate must be done to get an improvement in the actuation voltage with a simultaneous increase in switching speed. TMPS I is seen to provide such an optimum improvement in both.
3.4.2 Effect of residual stress in the two movable plates

In the previous Section the effect of the total intrinsic stress was not considered. The total intrinsic stress in a thin film deposited on a substrate may be approximated by a biaxial homogeneous stress superimposed on a linear biaxial stress gradient, which varies linearly from the top surface to the bottom surface [3]. The residual stress in thin film structures may result in undesirable buckling, curling or warping and deteriorate the performance of the switch or lead to its failure. Assuming a linear stress profile within the beam, the intrinsic stress may be expressed as [3]

\[ \sigma(x) = \sum_{k=0}^{\infty} \sigma_k \left( \frac{x}{t/2} \right)^k \] \hspace{1cm} (3.16)

where ‘t’ is the film thickness and \( x \in (-t/2, t/2) \) is the coordinate across the film thickness, with its origin at the mid-plane of the film. For a first order approximation, the total stress can be calculated as

\[ \sigma(x) \approx \sigma_0 + \sigma_1 \left( \frac{2x}{t} \right) \] \hspace{1cm} (3.17)

Thus it is seen that the total stress is the superposition of a constant mean stress (\( \sigma_0 \)) and a gradient stress about the mid-plane. Typical values reported for the mean stress range between 0-150MPa and that of the gradient stress between 5-20MPa [4]. It is this stress gradient which creates a moment that bends the beam. This intrinsic stress may be tensile or compressive in nature. Their effects of the TMPS are discussed in the following cases.
Case I: Effect of tensile stress

The process usually followed to fabricate the MEMS bridges involves the vacuum evaporation of a seed layer (Cr/Au, Ti/Au, Pt/Au) followed by electroplating of gold (in a cyanide/ cyanide-free bath) to obtain the desired thickness. It is experimentally found that the average residual stress in the thin film, if processed as above, is tensile (\(\sigma_0\) positive) in nature. The tensile stress results from micro-voids in the thin film, because of the attractive interaction of atoms across the voids [3]. The values of the tensile stress and the stress gradient depend on a variety of factors ranging from seed layer material, vacuum deposition conditions, anode size, temperature of bath, current density during electroplating, nature of sacrificial layer, removal method of the sacrificial layer. An average tensile residual stress not more than 50MPa is desired and the fabrication should be carried out in a manner so that initial warping of the beam does not occur. Low values of gradient stress have been found to produce negligibly small deflection of a fixed-fixed beam [5]. Figure 3.7 shows the variation in the actuation voltage of SMPS and TMPS I for mean biaxial tensile residual stresses of 50MPa and 100MPa using equation (3.11). It is seen that the tensile residual stress increases the beam stiffness leading to an increase in the actuation voltage. Further, it is observed that the improvement in the actuation voltage increases from 16% to 23% for TMPS I with 100MPa residual stress.
Figure 3.7: Plot of gap height vs. voltage for TMPS I and SMPS for different values of tensile residual stress

**Case II: Effect of compressive stress**

With the application of RF power the electrons will crowd at the edges of the plates due to skin effect. As the thickness of the metal layer is comparable to the skin depth (0.64µm at 15GHz) the plates may be assumed to be heated uniformly to cause an induced stress, which is compressive in nature, given by [6]

\[
\sigma_{THERMAL} = -E\alpha_T \Delta T
\]

(3.18)

where \(\Delta T\) is the rise in temperature, \(E\) is the Young’s modulus and \(\alpha_T\) is the coefficient of thermal expansion. This compressive stress will cause the plates to bend out of plane. Contrary to the effect of the tensile residual stress, which causes an increase in the stiffness of the plates, thermally induced compressive stress lowers the stiffness of the plates. At a critical value of compressive stress known
as Euler buckling limit, the lateral stiffness of the plates becomes zero and the plates spontaneously assume an approximate cosine shape due to a deflection in the central region. Depending on the nature of the load, higher order buckling may also be observed. The critical value of stress is given by [1]

\[ \sigma_{cr} = \frac{\pi^2 E t^2}{3l^2 (1-\nu)} \]  

(3.19)

where ‘\(E\)’ is the Young’s modulus, ‘\(l\)’ is the length of the membrane, ‘\(t\)’ is the thickness of the membrane and ‘\(\nu\)’ is the Poisson’s ratio. The buckling limit is found around 6MPa for the top plate and 10MPa for the bottom plate in TMPS I from Equation 3.19. A simple analytical estimate of the post-buckling deflection can be given by [7]

\[ d = \pm \frac{t}{\left[ \frac{1}{2} \sqrt{3} \left( -\frac{\sigma_0}{E(1-\nu)} \right) \right]} \left\{ \frac{\pi^2 E'}{3} \frac{E'(t^2)}{E(l)} \right\}^{-1} \left( \frac{E'}{E} \right) \]  

(3.20)

where \(E'\)=E for \(w/t<1\) and \(E'=E/\left(1-\nu^2\right)\) for \(w/t>5\). \(w\) is the width of the film.

3.5 Static Analysis: Simulations

3.5.1 Simulations ignoring residual stress

SMPS and TMPS are modeled to compute the central deflection of the plate(s) for an applied voltage. From optimized device dimension, the SMPS and TMPS I have been modeled and simulated from Intellisuite.

The simulated results of SMPS and TMPS obtained from Intellisuite are listed below. In all the cases material used is gold\((E=75\text{GPa})\) and dimensions of the top and bottom plates are \((l_1,t_1,w_1)=(245,0.9,80)\) and \((l_2,t_2,w_2)=(235,1.1,90)\) respectively.
Figure 3.8(a): SMPS for gap height 2.0um, applied voltage 12.97V and displacement obtained is 0.66 um

Figure 3.8(b): TMPS for gap height 2.0 um, applied voltage 11.52V and displacement obtained is 0.66um
Figure 3.9(a): SMPS for gap height 2.5µm, applied voltage 18.32V and displacement obtained is 0.84 µm

Figure 3.9(b): TMPS for gap height 2.5µm, applied voltage 15.45V and displacement obtained is 0.84 µm
Figure 3.10(a): SMPS for gap height 3.0 um, applied voltage 23.82V and displacement obtained is 1.0 um

Figure 3.10(b): TMPS for gap height 3.0 um, applied voltage 19.66V and displacement obtained is 1.0 um
The results obtained from Intellisuite are summarized below.

Table 3.2: Actuation voltage of SMPS and TMPS switch with different gap height

<table>
<thead>
<tr>
<th>Types of switch</th>
<th>Gap ht. (um)</th>
<th>Effective spring constant (N/m)</th>
<th>Actuation voltage in volts</th>
<th>% of improvement in actuation voltage of TMPS over SMPS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>calculated</td>
<td>Intellisuite</td>
<td>ratio</td>
</tr>
<tr>
<td>SMPS</td>
<td>2.0</td>
<td>5.34</td>
<td>14.10</td>
<td>12.97</td>
</tr>
<tr>
<td>TMPS I</td>
<td>2.0</td>
<td>3.72</td>
<td>11.76</td>
<td>11.52</td>
</tr>
<tr>
<td>SMPS</td>
<td>2.5</td>
<td>5.34</td>
<td>19.70</td>
<td>18.32</td>
</tr>
<tr>
<td>TMPS I</td>
<td>2.5</td>
<td>3.72</td>
<td>16.44</td>
<td>15.45</td>
</tr>
<tr>
<td>SMPS</td>
<td>3.0</td>
<td>5.34</td>
<td>25.90</td>
<td>23.82</td>
</tr>
<tr>
<td>TMPS I</td>
<td>3.0</td>
<td>3.72</td>
<td>21.61</td>
<td>19.66</td>
</tr>
</tbody>
</table>

The gap height 2.0 um and 3.0 um are chosen to achieve a low capacitance ratio and high actuation voltage respectively where as the gap height 2.5 um is the optimum choice of the device performance.

3.5.2 Effect of residual stress in the two movable plates

Coventorware® was used to evaluate the critical stress, and a result of 7MPa and 11MPa was obtained for the top and bottom plate respectively. They are in close agreement with the values of 6MPa and 10MPa obtained analytically. Simulation results also indicate that uniform stress causes larger transverse deflections when compared to that of gradient stress. So, uniform compressive stress was applied in simulations for buckling to occur. The central deflection of the plates in the post-buckling regime is important as it will affect the actuation voltage of the system [8]. If the top and bottom plate were assumed to be having a perfect boundary (idealization of geometry and loading), there would be an equal chance of buckling upward or downward [9]. The beam imperfections cause
buckling to occur in a specified direction. There is a potential advantage of the TMPS design in the post-buckling regime if both the plates move in the same direction, which causes the effective gap between the plates to remain same, and there is no drastic increase in the actuation voltage. In the other two cases, the two plates may move towards each other or move apart. To favor the deflection of both the plates in the same direction, the bulk micromachining of the top substrate is such that the silicon is also removed from an additional section ‘A’ as indicated in figure 3.4(c). This causes an imperfect boundary condition of the top plate in which the upper surface of the plate has no anchorage. It should be noted that the movable bottom plate by default has a similar boundary condition. Simulation was carried out using Coventorware® for a uniform compressive stress in both the plates which are found to buckle upward for a value of $\sigma_0=-100$MPa as shown in figure 3.11.

![Deflection of the plates for a uniform compressive stress of $\sigma_0=-100$MPa using Coventorware®.](image)

Figure 3.11: Deflection of the plates for a uniform compressive stress of $\sigma_0=-100$MPa using Coventorware®.
3.6 Dynamic Analysis of SMPS and TMPS: Analytical Modeling

The dynamic response is given by d’Alembert’s principle and an accurate mechanical analysis takes into account the non-linearity of the system as well as the damping factor of the air layer underneath the MEMS bridge. The equations of motion of the TMPS are [1]

\[ m_1 \frac{d^2 x_1}{dt^2} + b_1 \frac{dx_1}{dt} + k_1 x_1 = F_e = \frac{1}{2} \frac{\varepsilon_0 AV^2}{(x_3 - x_1)^2} \] (3.21a)

for the top plate and

\[ m_2 \frac{d^2 x_3}{dt^2} + b_2 \frac{dx_3}{dt} - k_2 (g_0 - x_3) = -F_e = -\frac{1}{2} \frac{\varepsilon_0 AV^2}{(x_3 - x_1)^2} \] (3.21b)

for the bottom plate.

Here \( m_1, b_1, k_1 \) and \( m_2, b_2, k_2 \) are the mass, damping coefficient and spring constant of the top and bottom plate respectively. The damping coefficients \( b_1 \) and \( b_2 \) are assumed to be constant for the very small volume of trapped air between the plates. Further, \( b_1 \) and \( b_2 \) are given by [1]

\[ b_1 = \frac{3}{2\pi} \frac{\mu_e A_1^2}{g_0^3} \] (3.22a)

\[ b_2 = \frac{3}{2\pi} \frac{\mu_e A_2^2}{g_0^3} \] (3.22b)

where \( A_1 \) and \( A_2 \) are the areas of the top and bottom plates respectively and \( \mu_e \) is the effective viscosity of trapped air between the plates. Equations (3.21a) &
(3.21b) are non-linear differential equations which can be solved numerically under the boundary condition:

at t=0,

\[ x_1 = 0; x_3 = g_0 \text{and} \frac{dx_1}{dt} = 0; \frac{dx_3}{dt} = 0 \]  

(3.23)

The above equations are valid till the two plates come in contact.

As evident from the above equations the switching time can be reduced by applying a voltage higher than \( V_P \). Very high switching voltage will, however, limit the application of the switch. For practical reasons, a switching voltage which is 1.4 times \( V_P \) is applied which not only reduces switching time but also ensures reliability of switching.

**Case I: Dynamic analysis ignoring damping**

The switching time is mainly determined by the time taken by the two plates to move towards each other from an initial gap of \( g_0 \) to a gap of \( (2/3) g_0 \), when pull-down occurs. For the sake of simplicity if we take the gap to be constant at \( g_0' = 0.83 g_0 \) and solve equations (3.21a) & (3.21b) with this simplification and ignore the effect of damping [1], the solution leads to

\[ x_1 \frac{t}{2} = \frac{1}{2} \frac{\varepsilon_0 A V^2}{k_1 g_0^2} 1 - \cos \omega_1 t \]  

(3.24a)

and

\[ x_3 \frac{t}{2} = g_0 - \frac{1}{2} \frac{\varepsilon_0 A V^2}{k_2 g_0^2} 1 - \cos \omega_2 t \]  

(3.24b)

where \( \omega_1 \) and \( \omega_2 \) are the resonant frequencies of the top and bottom plates respectively. Using the Taylor series expansion for the cosine terms and neglecting the terms higher than second order and equating \( x_1(t_s) = x_3(t_s) \) at \( t = t_s \) when the two plates meet, one gets an approximate expression of switching time as:
Comparing Equation (3.25) with standard SMPS switch [1], the effective mass of the TMPS is

\[ m_{\text{eff}} = \frac{m_1 m_2}{m_1 + m_2} \]  

(3.26)

(which is actually the same as in the case of two bodies approaching each other with linear motion), leading to resonant frequency

\[ \omega_{\text{TMPS}} = \sqrt{k_{\text{eff}} / m_{\text{eff}}} \]  

(3.27)

This indicates that the TMPS can be regarded as an equivalent SMPS with effective mass \( m_{\text{eff}} \) and effective spring constant \( k_{\text{eff}} \) in absence of damping. For \( k_1 = k_2 \), and \( m_1 = m_2 \), resonant frequency is unchanged and same switching time is obtained with a 30% lower actuation voltage. But when \( k_1 \neq k_2 \), the effective resonant frequency of the TMPS can be made higher than SMPS resonant frequency if \( \left( \frac{l_1}{l_2} \right)^2 < \left( \frac{l_1}{l_2} \right)^2 \) as obtained by putting the values of \( k_{\text{eff}} \) and \( m_{\text{eff}} \). The condition implies that for achieving a higher resonant frequency \( (\omega_{\text{TMPS}} > \omega_{\text{SMPS}}) \) one must have \( l_2 < l_1 \) so that \( k_2 > k_1 \). In other words the bottom plate should be stiffer than the top plate. Under this condition the switching time of TMPS is less than that of SMPS. It should be pointed out here that the mismatching of the two plates for improving the switching time is somewhat limited. This is because if the bottom plate becomes excessively stiff the TMPS behaves like the SMPS.
Design and simulation of Two Movable Plate Switch (TMPS):
Static and Dynamic Analysis

For a better expression of the switching time one has to consider the time required by the less stiff plate to reach the maximum displacement of the stiffer plate resulting in

$$t_{\text{TMPS}} = \frac{1}{\omega_{\text{LOW}}} \cos^{-1} \left( \frac{\varepsilon_0 A V^2}{k_{\text{HIGH}} g_0^2} + \frac{\varepsilon_0 A V^2}{2 k_{\text{LOW}} g_0^2} - g_0 \right) \left( \frac{\varepsilon_0 A V^2}{2 k_{\text{LOW}} g_0^2} \right)$$ (3.28)

where $k_{\text{HIGH}}$ and $k_{\text{LOW}}$ are the spring constants of the stiffer plate and less stiff plate respectively. It is interesting to note that for matched pairs equations (3.25) & (3.28) lead to same values of switching time.

**Case II: Dynamic analysis considering only damping**

Another approximation can be obtained if the mass and spring constants are assumed to be negligible in comparison to the damping coefficient [1]. In this case the equations of the TMPS are given by

$$b_1 \frac{dx_1}{dt} = \frac{1}{2} \frac{\varepsilon_0 A V^2}{g_0^2}$$ (3.29a)

and

$$b_2 \frac{dx_2}{dt} = -\frac{1}{2} \frac{\varepsilon_0 A V^2}{g_0^2}$$ (3.29b)

On solving the above equations and comparing above equation with that of SMPS we see that the effective damping coefficient of the TMPS can be given by

$$b_{\text{eff}} = \frac{b_1 b_2}{b_1 + b_2}$$ (3.30)
Design and simulation of Two Movable Plate Switch (TMPS): Static and Dynamic Analysis

Therefore for matched pairs using equations (3.14), (3.26) & (3.30) we can represent the TMPS with a single expression given by

\[
m_{eff} \frac{d^2 x}{dt^2} + b_{eff} \frac{dx}{dt} + k_{eff} x = F_e
\]  
(3.31)

3.7 Alternative dynamic analysis of TMPS

An alternative analysis of TMPS switching time may be done from energy consideration following Kaajakari \[10\] and using equation (3.31).

The work done by the TMPS in moving from open position to a position \(x_a\) is given by

\[
W = \int_{0}^{x_a} F dx = \frac{1}{2} \frac{dC}{dx} = \frac{\varepsilon_0 A x_a^2 V^2}{2(g_0 - x_a)g_0}
\]  
(3.32)

This work is done against the movement of switch mass only if the spring and damping forces are ignored. The switch mass will thus gain kinetic energy

\[
\frac{1}{2} m_{eff} x^2 = W
\]  
(3.33)

Solving for the switch velocity we have

\[
x = \sqrt{\frac{\varepsilon_0 A x_a V^2}{m_{eff} (g_0 - x_a)g_0}}
\]  
(3.34)

Using equation (3.34) the inertia limited switch actuation is

\[
t_m = \int_{0}^{x_a} \frac{dx_a}{\dot{x}} = \frac{\pi}{2V} \sqrt{\frac{g_0^3 m_{eff}}{\varepsilon_0 A}}
\]  
(3.35)
Another limiting case for the switch closing time is obtained by ignoring the switch inertia.

By setting \( m = 0 \) and solving for the velocity for the TMPS we get

\[
\frac{dx}{dt} = \frac{1}{b_{\text{eff}}} \left( \frac{\varepsilon_0 A V^2}{2(g_0 - x)^2} - k_{\text{eff}} x \right)
\]  

(3.36)

Using the Taylor series to simplify the integrand we obtain

\[
t_b = \int_0^{g_0} \frac{dx}{x} = \frac{2b_{\text{eff}} g_0^3}{315} \left( 5g_0^6 k_{\text{eff}}^2 + 21g_0^3 k_{\text{eff}} \varepsilon_0 A V^2 + 105 \varepsilon_0^2 A^2 V^4 \right) \varepsilon_0^3 A^3 V^6
\]

(3.37)

A good approximation for the switch actuation time obtained by summing the inertial and damping limited switching times is given by equations (3.35) & (3.37) leading to

\[
t_s = t_m + t_b
\]

(3.38)

3.8 Dynamic Analysis of SMPS and TMPS: Numerical Study

In this section, equations (3.21a) and (3.21b) are solved numerically subject to the appropriate boundary conditions. The effects of the bottom plate on the dynamic analysis of the TMPS are studied for choosing an optimum bottom plate for enhanced performance over the SMPS.

3.8.1 Switching Time

(a) Effect of thickness of bottom plate on switching time

Figure 3.12 gives us the variation of the switching time with the thickness of the bottom plate for different plate lengths keeping the width of the plate
constant at 90µm. It is seen that an improvement in the switching time is obtained when the bottom plate thickness is close to the thickness of the top plate or is slightly greater than it. This also validates the analytical estimate of having $t_2 > t_1$ for achieving $k_2 > k_1$. A much thicker bottom plate would cause the TMPS to resemble the SMPS so an optimum choice for the bottom plate thickness is to be made. It should be noted here that an improvement in the switching time is obtained for a lower value of switching voltage than in the SMPS as $V_s = 1.4V_p$.

![Figure 3.12: Variation of the switching time with the thickness of the bottom plate](image)

**Figure 3.12**: Variation of the switching time with the thickness of the bottom plate

**(b) Effect of length of bottom plate on switching time**

Figure 3.13 gives us the variation of the switching time with the length of the bottom plate for different bottom plate thickness keeping the width of the plate constant at 90µm. It is seen that an improvement in the switching time is obtained
when the bottom plate length is close to the length of the top plate or is slightly less than it. This also validates the analytical estimate of having \( l_2 < l_1 \) for achieving \( k_2 > k_1 \). But it is seen that for much shorter bottom plate the switching time does not keep improving. This is due to the fact that for shorter bottom plate the stiffness is much more causing the bottom plate to have a minimal displacement leading to degradation in the switching time.

![Graph](image)

**Figure 3.13**: Variation of the switching time with the length of the bottom plate

(c) **Effect of stiffness of bottom plate on switching time**

Four different TMPS structures namely TMPS A, B, C and D are used to numerically estimate the effect of the length and thickness of the bottom plate on the stiffness of the TMPS [Table 3.2]. In TMPS A and B, the thicknesses of the bottom plate are different but the lengths and widths are the same while in TMPS C and D, the lengths of the bottom plate are different with same thickness and width.
Table 3.3: Dimensions of four different TMPS structures and computed switching times

<table>
<thead>
<tr>
<th>Parameters</th>
<th>TMPS A</th>
<th>TMPS B</th>
<th>TMPS C</th>
<th>TMPS D</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_1(\mu m) )</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>( w_1(\mu m) )</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>( t_1(\mu m) )</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>( l_2(\mu m) )</td>
<td>235</td>
<td>235</td>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>( w_2(\mu m) )</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>( t_2(\mu m) )</td>
<td>0.5</td>
<td>2.0</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>( V_p(\text{Volts}) )</td>
<td>8.29</td>
<td>19.02</td>
<td>18.79</td>
<td>14.13</td>
</tr>
<tr>
<td>( t_s(\mu s) )</td>
<td>184.89</td>
<td>42.58</td>
<td>39.67</td>
<td>62.41</td>
</tr>
</tbody>
</table>

Figures 3.14 and 3.15 represent the time-displacement characteristics of TMPS as per Table 3.3. The dashed lines represent the displacement of the top plate and the solid lines represent the displacement of the bottom plate. The switching times are obtained when the two lines meet. As expected physically, the switching time is reduced with increasing stiffness, either by increasing thickness or by decreasing length. The thickness and width of the bottom plate are determined by the signal power, attenuation and matching requirements. The thickness of the bottom plate is therefore kept in between 0.9-1.1\( \mu m \) considering the skin depth at the operating frequency. It may be noted here that sometimes in monolithic microwave integrated circuits, the bottom plate thickness \( (t_2) \) is less than or equal to the skin depth at the operating frequency [11]. The length of the released portion of the bottom plate is a more flexible design parameter which can be controlled to adjust switching time without much affecting signal transmission characteristics.
Design and simulation of Two Movable Plate Switch (TMPS):
Static and Dynamic Analysis

Figure 3.14: Time-displacement characteristics of TMPS A and TMPS B

Figure 3.15: Time-displacement characteristics of TMPS C and TMPS D
(d) Optimization

In Figure 3.16, the gap between the plates is plotted against time for TMPS as defined in Table 3.1 and also for SMPS having the same dimensions but with the bottom plate fixed. In this case, the actuation voltages are $V_{P \text{SMPS}} = 20V$, $V_{P \text{TMPS I}} = 16.4V$, $V_{P \text{TMPS II}} = 15.4V$, $V_{P \text{TMPS III}} = 14.2V$. The applied switching voltages are $V_{S \text{SMPS}} = 28V$, $V_{S \text{TMPS I}} = 22.9V$, $V_{S \text{TMPS II}} = 21.5V$, $V_{S \text{TMPS III}} = 19.8V$. Figure 3.16 shows that the switching time for SMPS is 48$\mu$s as compared to the switching time of 39.68$\mu$s for TMPS I, 43.48$\mu$s for TMPS II and 51.15$\mu$s for TMPS III. The results are summarized in Table 3.4. It is seen that a degradation in switching time is obtained for TMPS III although $k_2 > k_1$. It is so because the condition $\left(\frac{t_1}{t_2}\right) < \left(\frac{t_1}{t_2}\right)^2$ is not satisfied. TMPS I therefore emerges an optimum choice where simultaneous improvement in actuation voltage and switching time is obtained over the SMPS.

Table 3.4: Dimensions of SMPS and TMPS used for calculating the switching time

<table>
<thead>
<tr>
<th>Plate</th>
<th>$m$(pg)</th>
<th>$b$(Ns$^2$m$^{-1}$)</th>
<th>$k$(N/m)</th>
<th>$V_p$(Volts)</th>
<th>$t_s$ ($\mu$s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Plate (SMPS)</td>
<td>136.3</td>
<td>1.29 X 10$^{-4}$</td>
<td>5.34</td>
<td>19.7</td>
<td>48.17</td>
</tr>
<tr>
<td>Bottom Plate (TMPS I)</td>
<td>179.7</td>
<td>1.51 X 10$^{-4}$</td>
<td>12.25</td>
<td>16.4</td>
<td>39.68</td>
</tr>
<tr>
<td>Bottom Plate (TMPS II)</td>
<td>166.9</td>
<td>1.57 X 10$^{-4}$</td>
<td>8.60</td>
<td>15.4</td>
<td>43.48</td>
</tr>
<tr>
<td>Bottom Plate (TMPS III)</td>
<td>153.3</td>
<td>1.64 X 10$^{-4}$</td>
<td>5.87</td>
<td>14.2</td>
<td>51.15</td>
</tr>
</tbody>
</table>

Further, the switching time of TMPS I can be further lowered to 24 $\mu$s by applying a slightly higher voltage of 28V which corresponds to that of SMPS [Figure 3.17]. With the same applied voltage, TMPS switches two times faster than SMPS, which is a significant improvement of performance. As already pointed out, the effect of the tensile residual stress causes a further improvement in the actuation
voltage for a given TMPS. However, this improvement comes at the expense of the improvement in switching speed. Figure 3.18 shows the switching speed of TMPS I for a residual stress of 50MPa and 100MPa, with the TMPS being switched at the reduced TMPS voltage and the voltage corresponding to that of SMPS. It is seen that the improvement in the switching time drops to around 10% from 20% for a switching voltage corresponding to the TMPS. Thus it is seen that careful optimization of the structure is needed if simultaneous improvement in actuation voltage and switching speed is desired and TMPS I emerges as the optimum for the same.

![Time-displacement characteristics of TMPS as per Table 3.1](image)

Figure 3.16: Time-displacement characteristics of TMPS as per Table 3.1
Figure 3.17: Switching characteristics of the TMPS I and the SMPS counterpart for different switching voltages.

Figure 3.18: Switching characteristics of the TMPS I and the SMPS counterpart for different values of residual stress.
The numerical analysis has finally been compared with the results obtained analytically. Figure 3.19 and 3.20 show the comparison between the numerical result and the obtained analytical result. It is interesting to note that the exact numerical solution for the switching time as obtained from equations (3.21a) & (3.21b) match very well for an equivalent SMPS having equivalent parameters $m_{eff}$, $k_{eff}$ and $b_{eff}$ for a wide range of length and thickness of the bottom plate. The matching with the equivalent SMPS from energy considerations [10] are also within reasonable limits. Thus for all practical purposes the two movable plates of a RF switch may be considered as an equivalent single movable plate having equivalent parameters for analysis of their static and dynamic performance.

Figure 3.19: Comparison between numerical result and analytical result for variation in length of bottom plate for TMPS I
3.8.2 Release Time

The nonlinear dynamic analysis can also be used to model the release time simulation of the switch and is done by setting $F_e = 0$ [1] in equations (3.21a) & (3.21b). The restoring force is given by $kg_0 + k_s g_0^3$ for the plates both in case of SMPS and TMPS [1] where

$$k_s = \pi^4 Ewt / 8t^3$$  \hspace{1cm} (3.39)

Solving the equations using Mathematica® gives the release times for the SMPS and TMPS. Figure 3.21 shows the time-displacement characteristics of TMPS I during release. It is seen that the time needed for proper release of the plates is greater than 60µs for the SMPS and 50µs for the TMPS. It should however be noted that the bottom plate with a higher stiffness reaches its initial state faster.
than the less stiff top plate. Further, it should also be pointed out that for release time calculations the slower of the two plates will dominate the release response. As seen from figure 3.21 since both the plates are movable the individual displacement is less compared to that of the SMPS. As the displacement is less, the restoring force acting on each plate is also less leading to a lower stress which in turn may result in a higher reliability.

![Time-displacement characteristics of SMPS and TMPS](image)

Figure 3.21: Time-displacement characteristics of SMPS and TMPS I upon release

### 3.9 Dynamic Analysis: Simulations

(a) **SMPS**

SMPS is modeled using ANSYS Multiphysics to compute the natural frequency of the device. The mode shapes of the first two fundamental modes of the SMPS structures are shown in figure 3.22(a) and 3.22(b) respectively. From
the simulated result it is observed that the obtained natural frequency of the SMPS is 201 KHz which matches 98% with the calculated value 197.9 KHz using equation (3.27) for SMPS. Simulated values of switching time (52µs) for the SMPS also matched closely with the results obtained analytically (50µs).

Figure 3.22(a): First mode of SMPS

Figure 3.22(b): Second mode of SMPS


(b) TMPS

Similarly, the mode shapes of the first two fundamental modes of TMPS I are shown in Figure 3.23(a) and 3.23(b) respectively.

Figure 3.23(a): First mode of TMPS

Figure 3.23(b): Second mode of TMPS
From the simulation it is noted that the frequency of 201 KHz corresponding to first mode and a frequency of 268 KHz corresponding to second mode of TMPS is obtained. Hence it is concluded that the different modes of the TMPS is nothing but the modes of two individual plates. One may note here that although the switching time simulations of the SMPS matches well with the analytical results, FEM tools like Intellisuite® were unable to simulate the TMPS structure. This was due to the unavailability of the option to make both the plates movable while performing the simulations.

3.10 Pull up force and Reliability

The reliability of RF MEMS switches is one of the major limitations. Dielectric charging still remains an issue which demands serious attention as it is by far the most common reason of failure of MEMS switches. The pull-up force is responsible for restoring the switch to its original position and many techniques have been devised to increase the same. The pull-up force for the TMPS is calculated by summing up the restoring forces of the two plates as it is the total force that acts at the interface before the plates are separated from each other. The forces are given by:

\[
F_{\text{PULL-UP}1} = k_1x_1 + k_{S1}x_1^3
\]

\[
F_{\text{PULL-UP}2} = k_2x_2 + k_{S2}x_2^3
\]

where \( F_{\text{PULL-UP}1} \) is the total restoring force of the top plate and \( F_{\text{PULL-UP}2} \) is the total restoring force of the bottom plate. \( x_1 \) and \( x_2 \) are calculated from equations 3.21a and 3.21b respectively.

Figure 3.24 shows the pull-up force for TMPS as per table 3.3. It is seen that for thinner and longer bottom plate, the pull-up force is less [TMPS A and
TMPS D] than that of SMPS (50\textmu N). However, if the stiffness of the bottom plate is increased as in TMPS B and C, a pull-up force much higher than the SMPS is obtained. But in such cases there would be little or no improvement in the actuation voltage. However the TMPS will switch at a faster speed than the SMPS. Further, figure 3.25 shows the pull-up force for TMPS as per Table 3.1. It is seen that TMPS I has the highest pull up force when compared to others making it an optimum choice. One may note that the TMPS design still has a pull-up force much greater than any low spring constant designs and the pull-up force obtained is acceptable for reliable operation (30-120\textmu N) [1]. By far the most common technique used in MEMS switches for successful pull-up is the concept of the pull-up electrode and if that design modification is incorporated in the TMPS design it not only switches faster at a lower switching voltage but also maintains the same reliability.

Figure 3.24: Pull-up force of TMPS as per Table 3.3
It should be noted here that the pull-up force has been calculated by neglecting the effect of the residual stress. As discussed earlier and evident from section 3.2.1, the residual stress can be used to increase the spring constant and hence the pull-up force. With the use of residual stress and pull-up electrodes as in conventional designs, the TMPS design will also operate reliably but at a much lower switching voltage and a faster switching time.

### 3.11 Miniaturized Switched capacitors: A paradigm shift

A paradigm shift in RF MEMS shows the development of miniature switched capacitors for RF applications [12]. They are not sensitive to charging in the dielectric layer and also, are not sensitive to temperature variation. A major advantage of the miniature design is the pull-up force per unit contact area with the dielectric layer. As already discussed the predominant failure mechanism of
capacitive switches is charging in the dielectric layer and the miniature design has a much higher pull-up force per unit contact area as compared to the conventional RF MEMS switches.

For typical dimensions of RF MEMS switched capacitors as shown in Table 3.5 the TMPS has an actuation voltage of 16V as compared to 20V for the SMPS. Further it is noticed that an improvement of 44% (from 625ns to 350ns) in switching time is obtained when the TMPS is actuated at the voltage corresponding to that of the SMPS [Figure 3.27]. Thus it is seen that the TMPS design can successfully lower the switching time in the range of 300-600ns without affecting the reliability as the miniature designs have a higher amount of pull-up force [Figure 3.27].

Table 3.5: Typical dimension of Two Movable Plate RF MEMS switched capacitor

<table>
<thead>
<tr>
<th>Plate(s)</th>
<th>Length (µm)</th>
<th>Width (µm)</th>
<th>Thickness (µm)</th>
<th>Mass (µg)</th>
<th>Spring Constant (N/m)</th>
<th>Damping (Ns/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Plate</td>
<td>28</td>
<td>8</td>
<td>0.5</td>
<td>0.8655</td>
<td>61.06</td>
<td>1.69e-5</td>
</tr>
<tr>
<td>Bottom Plate</td>
<td>27</td>
<td>10</td>
<td>0.55</td>
<td>1.1476</td>
<td>109.63</td>
<td>2.46e-5</td>
</tr>
</tbody>
</table>
Design and simulation of Two Movable Plate Switch (TMPS):
Static and Dynamic Analysis

Figure 3.26: Actuation voltage of miniaturized SMPS and TMPS as per Table 3.5

Figure 3.27: Time-displacement characteristics of SMPS and TMPS as per table 3.5
3.12 Summary

In this chapter the analytical expressions for actuation voltage and switching time of a TMPS structure has been derived and the optimized structure is simulated with Intellisuite®/ Coventorware®/ Ansys®. From the analytical expressions/simulations it is seen that TMPS I gives us an optimum performance and a simultaneous improvement in the actuation voltage and switching time with a pull-up force similar to that of the SMPS is obtained. Thus, TMPS I has been taken forward for evaluating its electromagnetic performance and subsequently fabricated.

References

Design and simulation of Two Movable Plate Switch (TMPS):
Static and Dynamic Analysis
