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A LOW VOLTAGE MEMS STRUCTURE FOR RF CAPACITIVE SWITCHES

E. Abbaspour-Sani and S. Afrang

Electrical Engineering Department
Urmia MEMS Lab
Urmia University
Urmia, Iran

Abstract—A novel structure for the capacitive micromachined switches with low actuation voltage is proposed. In this structure both contact plates of the switch are designed as displaceable membranes. Two structures with similar dimensions and conditions, differing on only the number of the displaceable beams are analytically investigated as well as simulated using ANSYS software. The obtained results indicate about 30% reduction in actuation voltage from the conventional single beam to our proposed double beam structure. The stress on the beam due to the actuation voltage is also reduced increasing the switching life time. The dynamic simulation results in switching time of 6.5 μsec compared to the 8.9 μsec of the analytical results. It can be implemented by the well established surface micromachining for RF applications.

1. INTRODUCTION

Miniaturization has been one of the most important technological trends in the last decades [1]. Microelectronic has paved this way during the past 40 years. In recent years the micro-miniaturization of the electromechanically Systems (MEMS) and integration of these systems and microelectronics into Microsystems has become one of the most prominent research areas all over the world [2]. The switch is one of the devices that are interested to be compatible with integrated circuits. The RF mobile switches to be compatible with integrated circuits (IC) must fulfill the three following conditions [3–5]:

1. Very small size,
2. Low actuation voltage,
3. Low power consuming.

MEMS switches were first demonstrated in 1979 as electro-statically actuated cantilever switches [1]. This type of switch was small in size and consumed low power. The main disadvantage of this type of the switch was high actuation voltage [6, 7]. The actuation mechanisms of other types are based on electromagnetic [8, 9] and thermal principles. The micro-switches based on electromagnetic actuation have low actuation voltage but consume high power and have complex fabrication process. On the other hand, thermal actuated micro-switches have high power consumption. If the actuation voltage of the electro-statically switches is lowered, then this type of switches will be the best candidate for RF applications. In recent years so many efforts have been put on to decrease the actuation voltage of the electrostatic type of micro-switches. These include using a variety of hinges and materials to decrease the spring constant of the beam, increase area of the electrostatic field, decrease the gap and increase the dielectric constant between two plates of the switch. Any variation in most of these parameters causes a loss on the other parameters of micro-switch. As an example, if we decrease the gap or increase the area of the electrostatic field, this results in increase of off-capacitance, leading to a poor isolation.

The reduced actuation voltage of our proposed structure is due to the decreased equivalent spring constant of the system. Therefore, not only we do not loss any other parameters but also the lifetime of the micro-switch is increased.

2. DEVICE STRUCTURE

The schematic diagram of the proposed switch is shown in Figure 1. Among the various feeds, the CPW feed is very suitable for the design of the active integrated circuits due to its co-planar configuration [10]. Therefore to design a specific structure for RF application of the switch, coplanar wave-guide (CPW) transmission line is chosen. The proposed dimensions of the CPW lines are G/W/G = 60/104/60 μm (50 Ω). It consists of two membranes namely lower and upper membranes. Lower membrane act as the signal line and upper membrane is considered to be connected to the ground line. The lower beam is suspended on a cavity that can be fabricated by a sacrificial layer and the upper membrane separated from the lower membrane by the second sacrificial layer. The membranes are assumed to be fabricated by gold electro-plating to the thickness of the 1.5 μm. The gap between the two membranes is taken 1.5 μm.

The actuation voltage is applied between the membranes and the resultant electrostatic field causes the deflection of both beams. It

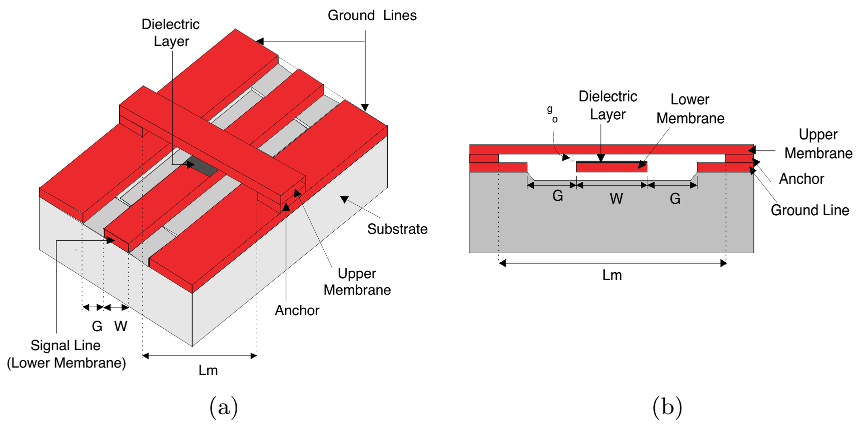

Figure 1. Schematic diagram of our Proposed Switch: (a) a 3D isometric view of the switch; (b) the cross-sectional view of the switch $Lm = 280\,\mu$m.

bends both of the membranes providing the ON state of the switch, while absence of this voltage realizes the membranes making the OFF state of the switch.

3. MODELING AND ANALYSIS

The presented general Mechanical model is based on the double membranes structure with each membrane having different spring constant as shown in Fig. 2b. The spring constant of the upper membrane is K_1 and the lower membrane is K_2. The displacement of the upper and lower membranes is assumed X_1 and X_2 respectively. Fig. 2a shows the displacement of each membrane after the applied actuation voltage.

The relationship between the electrostatic pull-up and pull-down forces are as below:

$$F = K_1 \cdot X_1 \tag{1}$$
$$F = K_2 \cdot X_2 \tag{2}$$

The total displacements of the membranes are:

$$X_1 + X_2 = X(3) \tag{3}$$

Relating the total membrane displacement to the applied electrostatic force we may write:

$$F = K_{eq} \cdot X \tag{4}$$

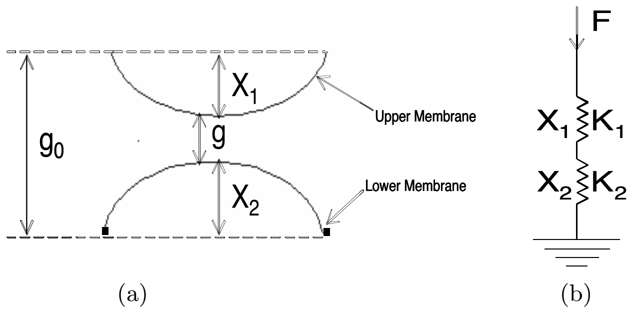

Figure 2. The displacement of the membranes.

Substituting X_1, X_2 and X from equations (1), (2) and (4) in equation (3) we will have:

$$\frac{F}{K_1} + \frac{F}{K_2} = \frac{F}{K_{eq}} \tag{5}$$

Therefore, we can conclude from equation (5) that:

$$K_{eq} = K_1 || K_2 \tag{6}$$

As indicated in equation (6), by using two membranes, the equivalent spring constant of the device can be reduced. For the special case of $K_1 = K_2$ we will have the lowest spring constant, which is half of each.

When the actuation voltage is applied between the membranes, the electrostatic force attracts them towards each other. However, the pull up and pull down forces due to the spring constant of the membranes resist the electrostatic attraction force. The equilibrium is achieved when both forces are equal and is given by:

$$F = \frac{\varepsilon A V^2}{2\left(g + \dfrac{t_d}{\varepsilon_r}\right)^2} = K_{eq}(g_0 - g) \tag{7}$$

Where, g_0 is the initial separation of the membranes, V is the applied actuation voltage and A is the area of each membrane. The bottom electrode is often covered by a dielectric layer with a thickness (t_d) of 100–200 nm and a relative dielectric constant (ε_r) between 3 and 8 to prevent a short circuit between the top and bottom plates.

Solving this equation in g results in a stable position of approximately $X_1 + X_2 = g_0/3$ and then a complete collapse of the membranes to the contact position. The voltage that causes this collapse is called the threshold voltage and is given by [15]:

$$V_{th} = \sqrt{\frac{8K_{eq}g_0^3}{27\varepsilon A}} \tag{8}$$

As it is clear from equation (8), the spring constant of the switch affects the threshold voltage. The spring constant of a membrane depends on the geometry, material, residual stress and degrees of its freedom. The only difference between the conventional single beam and our double beam switch is the reduction of the equivalent spring constant. In other words we would expect an improvement on threshold voltage in our case.

For a fixed-fixed beam (as is the case with our membranes) with a force distributed on the overlapping area of the beam, K is given by:

$$K = \frac{16Ewt^3}{l^3} + \frac{4\sigma(1-\nu)wt}{l} \tag{9}$$

Where E is the Young's modulus of the membrane, ν is Poisson's ratio, σ is the residual stress in the membrane, l, w and t are the length, width and thickness of the membrane, respectively.

For the static analysis of the single and double membrane structures equations (8) and (9) are employed. The assumed mechanical dimensions and parameters of structures are shown in Table 1.

Table 1. Material and geometrical parameters of the proposed switch.

parameter	Value
Young's modulus E_{au} (GPa)	76.52
Poisson's ratio ν_{au}	0.41
Density (Kg/m³)	19300
Permittivity of air (F/m)	8.854e-12
Relative permittivity of dielectric layer	7.6
Length of the beams (μm)	280
Width of the beams (μm)	104
Thickness of the beams (μm)	1.5
Initial gap (μm)	1.5
Thickness of the Dielectric layer (μm)	0.1

The computed threshold voltage for the single beam was 14.2 V, and for our proposed double beam structure was reduced to 10.1 V. In other words, we can see an improvement of about 30% on the actuation voltage. The possible residual stresses on the beams were assumed zero for both cases.

For dynamic analysis we evaluate the switching time. The governing equation for the dynamic response of the device is:

$$m = \frac{2\rho A}{y_{\max}} \int_0^{l/2} [y(x)]^2 dx \tag{10}$$

Where $y_{\max} = \frac{-Fl^3}{192EI}$ and $y(x) = \frac{Fx^2}{48EI}(4x - 3l)$.

The resonance frequency of the membrane is given by:

$$\omega_0 = \sqrt{\frac{K}{m}}$$

The switching time of the structure can be derived from [15]:

$$t = 3.67 \frac{V_{th}}{V_s \omega_0} \tag{11}$$

Since the spring constant for structures of single and double membranes are equal, thus the switching time for both structures will be the same. The computed switching time for the case of zero residual stress is 8.9 μsec. The computed resonant frequency was 45742 Hz.

4. SIMULATION RESULTS

The proposed structure is simulated by the finite element analysis using ANSYS 5.7 software. This software uses electrostatic/structural analysis directly. Two types of micro-switches, namely single beam (only one beam displaces) and double beam (both beams are displaceable) are simulated. Material and geometrical parameters for both types are identical and are indicated in Table 1. Static simulation for evaluating the threshold voltage and dynamic simulation for the switching time of the device are accomplished.

According to the static simulation results the required threshold voltage for the single membrane type is 17.5 V while it is reduced to 12.5 V for the double membrane type. The affect of residual stress on the beams due to the fabrication processes is omitted. Fig. 3 shows the stress distribution on the membranes due to the displacement of upper and lower membranes for the double membrane type switch. As it is indicated in Fig. 3, the maximum stress on each beam is 0.16×10^8

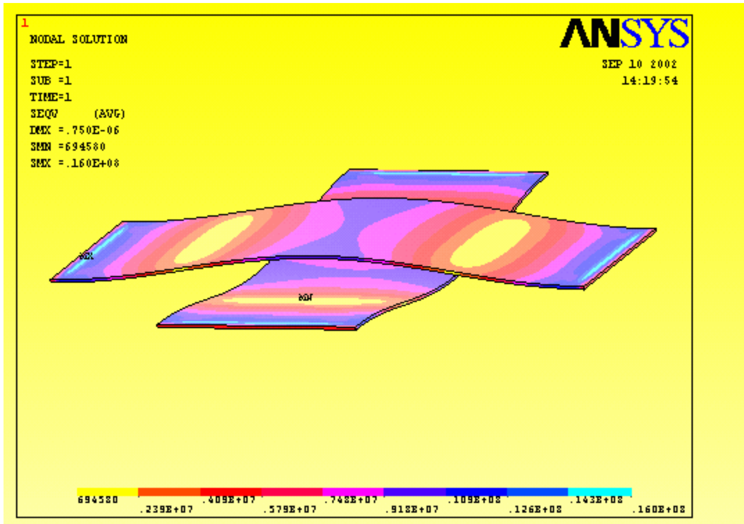

Figure 3. Stress distribution on the double membranes structure.

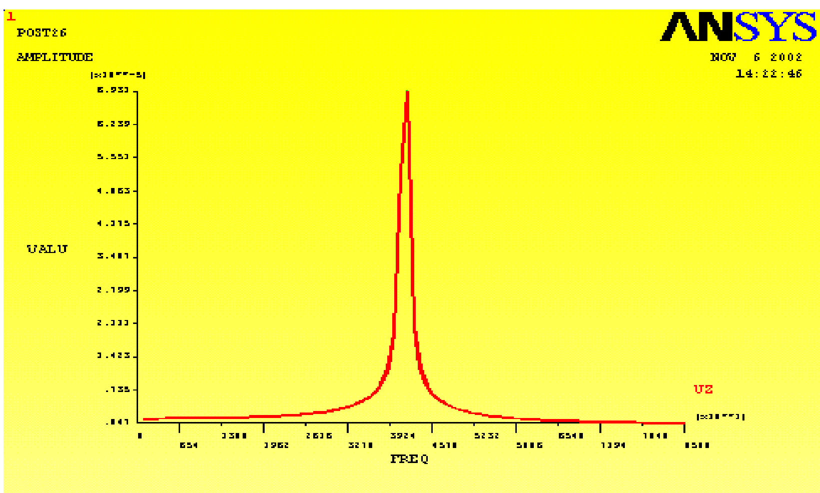

Figure 4. The resonant frequency of the membrane [$f_{res} = 42.5\,\text{KHz}$].

Pascal, while for the case of single beam switch it comes out to be 0.319×10^8 Pascal. The reduced stress on the double beam structure can increase the life time of the switch.

The dynamic simulation, considers resonant frequency and

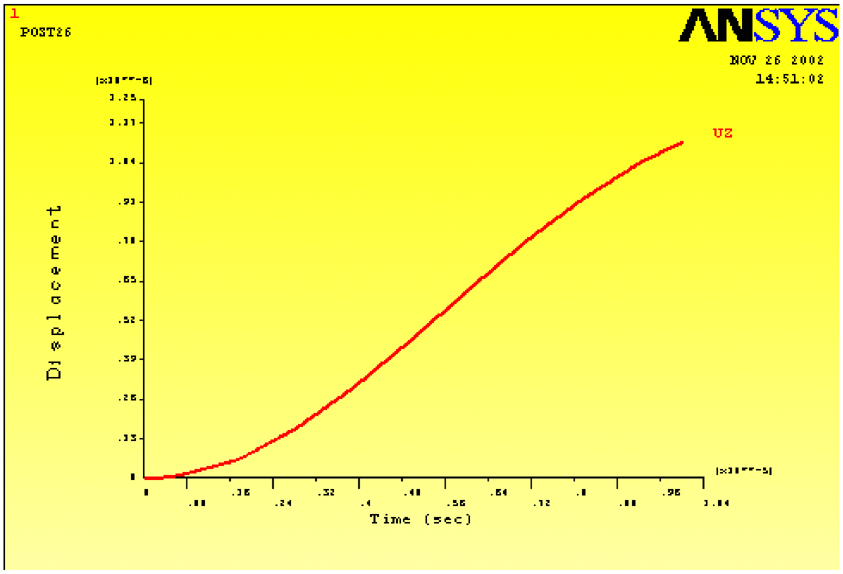

Figure 5. Device switching time diagram. The required time for a membrane to displace half the initial separation between the membranes (0.75 μm) is 6.5 μsec.

switching time. This is done by the harmonic and transient analysis. The simulation is accomplished for double membranes type, with considering identical material and geometrical parameters for both membranes. We have assumed negligible squeeze film damping for the structure during the simulation. The simulated result of resonant frequency for a beam is shown in Fig. 4 witch is 42500 hertz. Figure 5 shows the simulated switching time diagram by using transient analysis. As indicated in this figure, the switching time is 6.5 μsec.

5. CONCLUSION AND COMPARISON

A novel double membrane micromachined microwave switch is proposed. The static and dynamic behavior of the single and double membrane structures are calculated, simulated and compared. The static analytical results indicate an improvement in the actuation voltage for double membrane structures. The calculated threshold voltage for the single membrane is 14.25 V and for the double membrane is 10.1 V. The calculated switching time is 8.9 μsec.

The simulated threshold voltages are 17.5 V for a single membrane and 12.5 V for the double membrane structure. Similar assumptions of the analytical case are also considered for the residual stress and spring constant. The higher threshold voltages of the simulation results compared to the analytical values are due to the spring constant. Where, for the analytical case, K is taken as an approximated average value, while computer simulation takes the exact value of the spring constant.

The dynamic simulation results in switching time of 6.5 μsec compared to the 8.9 μsec of the analytical results. The difference between the analytical and simulation results is again due to the spring constant as mentioned for the static case.

To compare our proposed structure with the other switches, Table 2 is arranged. Since, our device is not fabricated and to have a fare comparison with the fabricated devices, our calculated results are shown with three different residual stresses (0, 8 and 120 Mpa). Even at the worst case of 120 Mpa the actuation voltage of our design is about 30 V which is less than other simple fixed-fixed structures. As it is shown in Table 2, reduction of the actuation voltage in our case has not affected the switching time compared to the other works.

Table 2. Comparison of our proposed device with other works.

Paper	Switch type	Fabrication Calculation simulation	Actuation voltage (V)	Switching time (μs)
D. Peroulis et al.[11]	Meander type hinge	Fab.	6	50
R. Chan et al.[12]	Meander type hinge	Fab.	15	22
S. Duffy et al.[13]	Cantilever type	Fab.	50-60	1
Z. Jamie et al.[3]	Simple fixed-fixed type	Fab.	50 (σ=120 Mpa)	6
Markus Ulm et al.[14]	Simple fixed-fixed type	Fab	Smaller than 42	10
J_0-M_0 Huang et al.[7]	Simple fixed-fixed type	Sim.	16	9
Proposed Structure	Simple fixed-fixed type	Sim.	12.5(σ=0)	9.5
		Cal.	10(σ=0)	9
			25(σ=80Mpa)	3.5
			30(σ=120Mpa)	3

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