Design Optimization for Low Voltage DC Contact RF MEMS Shunt Switch

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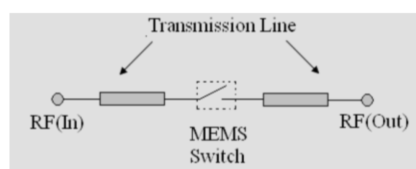
***Abstract-* Radio Frequency switches are widely used in commercial, aerospace and defense applications. These include satellite communication systems, wireless communication and radar systems. In order to select an appropriate RF switch for any application, one must first consider the required performance specifications such as frequency bandwidth, power handling capability, signal level, switching speed, power consumption and tolerable losses. RF MEMS (Micro-Electro-Mechanical-System) technology offers the necessary performance advantages over existing solid-state options. A design of DC contact RF MEMS shunt switch is proposed in this paper. The design is optimized in terms of activation mechanism which includes switch hinge thickness, bridge thickness, air gap height and number of menders. The pull-in voltage is analyzed with commercial CAD finite element analysis software IntelliSuite.**

I. Introduction

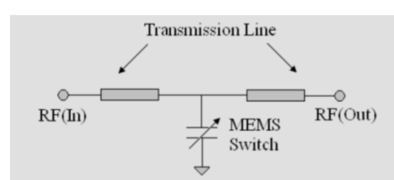
Recent increase in demand for computational circuits in today's rapidly growing information age, the dependence on microelectronics is due to its ability for miniaturization, high volume production and integration. This leads to very economical prices of integrated circuits to be used in devices of our daily use. Conventional solid state switches PIN diodes and MOSFETs are used in telecommunication applications and adjustable gain amplifiers. The disadvantages associated with such solid-state switches is the high insertion loss (1 dB approximately) and poor electrical isolation. The recent advancements in microelectro-mechanical systems (MEMS) have provided new solutions and improved designs to be used in various applications. Microelectro-mechanical systems are integrated devices comprising of electronic components and physical phenomena. This structural property of MEMS provides us with decision making capability in use for microsystems. The fabrication process of MEMS allows batch production resulting in low chip prices [1]. MEMS technology is increasingly involved in RF switches due to its ability to interact with electrical signals at the radio frequency range. The notable components of interest are micromachined switches, mechanically tunable capacitors and three-dimensional inductors which perform better than their conventional solid-state counterparts. "RF MEMS" has a huge budding scope amongst all subfields of MEMS. RF devices based on MEMS have the largest market potential in communication field. Applications such as automated measurement and test equipment, military and space systems are few initial fields of RF MEMS technology [2].

II. MEMS SWITCH TYPES

RF MEMS can be classified into different categories on the basis of circuit configuration, actuation principle, moving structure or desired application. The most common categories of MEMS switches are series and shunt switches. Fig. 1 shows the series and shunt configuration of MEMS switch. On the basis of moving structure, MEMS switches can be of cantilever and suspended bridge types. In this paper, suspended bridge configuration is taken under consideration as actuation voltage issues are more dominant in this type of configuration. Suspended bridge is mostly effective in shunt circuit configuration [3].



(a)



(b)

Fig. 1. (a) Series switch configuration (b) Shunt switch configuration.

III. ELECTROMECHANICAL MODELING OF MEMS SHUNT SWITCH

Radio-frequency microelectro-mechanical system switches (RF MEMS) can be analyzed in terms of their basic equivalent mechanical and electrical models. The operation of RF MEMS capacitive shunt switch can be described in two states. In the "up" state the switch does not affect the signal on the transmission line whereas in "down" state, the switch presents an excellent short circuit due to increase in capacitance to ground. Fig. 2 shows these two switch positions.

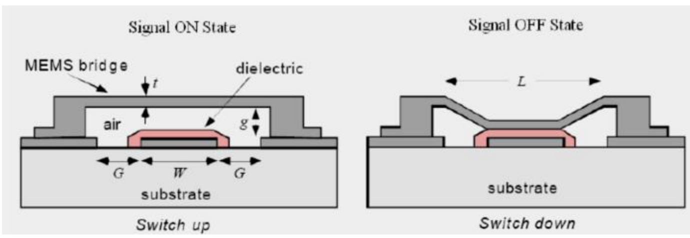


Fig. 2. Operation of RF MEMS switch in "up" and "down" states.

In order to achieve a short circuit or an open circuit in the RF transmission line, the MEMS switches are operated on the basis of mechanical movement. Electrostatic design can be used to obtain the required forces for mechanical movement [3]. A simple 1D lumped model is considered initially which approximates pull-in structure by a single rigid parallel plate capacitor suspended above a fixed ground plane by an ideal linear spring as shown in Fig. 3.

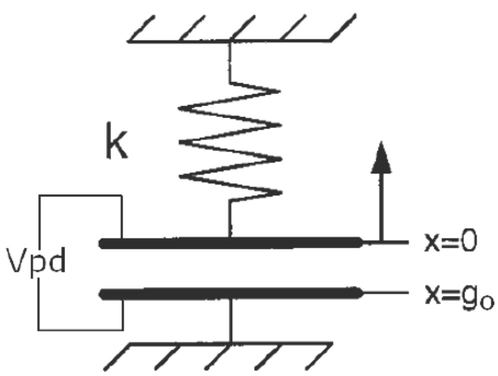


Fig. 3. One-dimensional lumped model for pull-in test of MEMS switch.

When a voltage is applied between a fixed beam and the pull-down electrode, an electrostatic force is induced in the beam as shown in Fig. 4. This is well known electrostatic force which exists on the plates of the capacitor under an applied voltage. In order to approximate this force, the beam over the pull-down electrode is modeled as a parallel plate capacitor. Although the actual capacitance is about 20-40% larger due to fringing fields [4]. Given that the width of the bridge is "w" and the width of the pull-down electrode is "W", then the area A= W x w and the parallel plate capacitance is:

$$C = A\varepsilon_0/g = Ww\varepsilon_0/g \qquad (1)$$

where g = height of the beam above the electrode at particular voltage.

The electrostatic (Fe) applied to the beam is the power delivered to a capacitor as a function of beam height and is given by:

$$Fe = \tfrac{1}{2} V^2 dC(g) / dg \qquad (2)$$

Solving (2) yields:

$$Fe = \tfrac{1}{2} Ww\varepsilon_0 V^2 / g^2 \qquad (3)$$

where "V" is the voltage applied between the beam and the electrode. The electrostatic force is approximated as being evenly distributed across the section of the beam above the electrode. On the other hand there is a pull-up force i.e. restoring force (Fr) of the switch which can be modeled as a spring with a spring constant "k". So this force can be explained using Hook's law as:

$$Fr = -k(g_0 - g) \qquad (4)$$

where "g_0" is the zero bias bridge height.

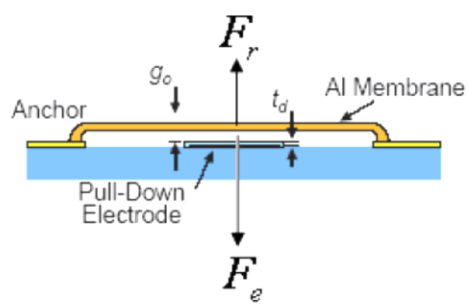


Fig. 4. Electrostatic and restoring forces on the switch.

Equating the applied electrostatic force to the mechanical restoring force due to the stiffness of the beam i.e. Fr = Fe yields:

$$\tfrac{1}{2} Ww\varepsilon_0 V^2 / g^2 = -k(go - g) \qquad (5)$$

Solving (5) for voltage gives:

$$V = \sqrt{\{2k/\varepsilon_0 A\,(go - g)\, g^2\}} \qquad (6)$$

The pull-down (or pull-in) voltage (Vp) is found to be:

$$Vp = V(2go/3) = \sqrt{\{8kgo^3/27\, A\varepsilon_0\}} \qquad (7)$$

The value of applied voltage is 1.2-1.4Vp so as to achieve fast operation of the switch. The pull-down voltage must not exceed the breakdown voltage of the dielectric layer; therefore it puts a constraint on the thickness and type of dielectric material [5].

IV. DESIGN AND OPTIMIZATION OF RF MEMS SHUNT SWITCH FOR LOW ACTUATION VOLTAGE

In order to achieve the better performance of RF MEMS switches, the actuation voltage should be kept as low as possible. When designing switches for low actuation voltage, the choice of the membrane material and the support type is critical [6]. In order to lower the pull-in voltage of the structure, three different ways can be used which are:

i) increasing the area of the membrane.

ii) reducing the air gap between the switch and electrode.

iii) designing the switch for low spring constant.

In the first case, the area cannot be increased beyond a certain limit since the device size becomes a prevailing issue. In the second case, the isolation associated with the RF signal restricts the height of the gap. The third case is the one having most flexibility, since the design of spring does not alter the size of the switch considerably. Optimization parameters taken under consideration in this analysis are:

(a). Hinge thickness

(b). Bridge thickness

(c). Air gap height

(d). Number of menders

In order to observe the effect of variations in each of above parameters on the actuation voltage of the switch, first the switch is modeled in 3D interactive builder module of software IntelliSuite as shown in Fig. 5.

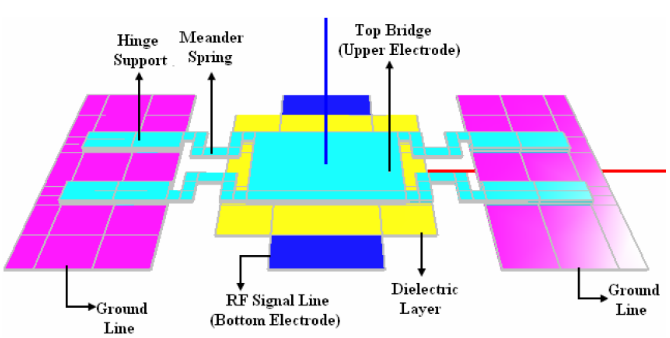
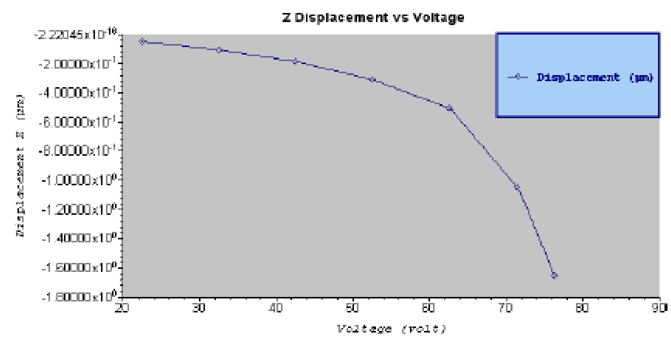


Fig. 5. Three-dimensional model of switch design.

After the construction of 3D structure, it is transferred to "Thermoelectro-mechanical" module for optimization analysis. The device is zoomed 10 times so that the properties of each layer can be defined easily. After the simulation settings; load voltage, boundary conditions and material properties are defined. Meshing is done for finite element analysis (FEA). This analysis is focused on Z-direction movement of the plate when the switch is electrostatically actuated. This includes the maximum Z-displacement of the switch as a function of applied voltage. Now the effect of variation in hinge thickness, bridge thickness and air gap height on the actuation voltage is observed individually by varying one parameter at a time and keeping the other parameters constant.

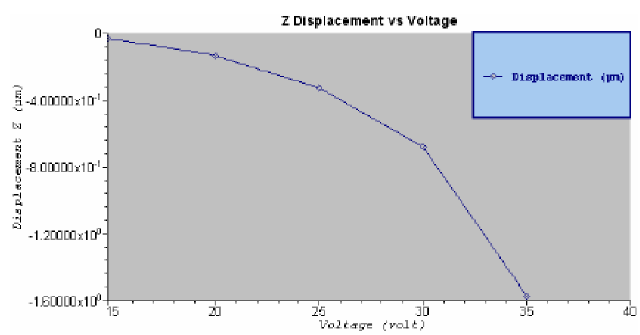
V. SIMULATION RESULTS

Fig. 6 shows the effect of variation in hinge thickness on actuation voltage in terms of Z-displacement while keeping the bridge thickness and air gap height constant.



Hinge thickness 2.5µm

(a)



Hinge thickness 1.0µm

(b)

Fig. 6. Z-displacement as voltage function for (a) hinge thickness=2.5 µm (b) hinge thickness=1.0 µm.

This variation indicates that the pull-down voltage decreases as the hinge thickness reduces. The difference between simulated and calculated results is given in Table I. The difference between the simulated and calculated results is due to the assumptions considered in mathematical modeling.

TABLE I

COMPARISON OF THEORETICAL AND SIMULATED PULL-DOWN VOLATAGES FOR VARIABLE HINGE THICKNESS

Hinge Thickness t (µm)	Simulated Voltage Vp (Volts)	Calculated Voltage Vp (Volts)	Effective Spring Constant Keff (N/m)
2.5	76	98.8166	223.9949
2.0	67	74.4636	127.1940
1.5	49	50.5546	58.6272
1.0	35	28.4678	18.5903

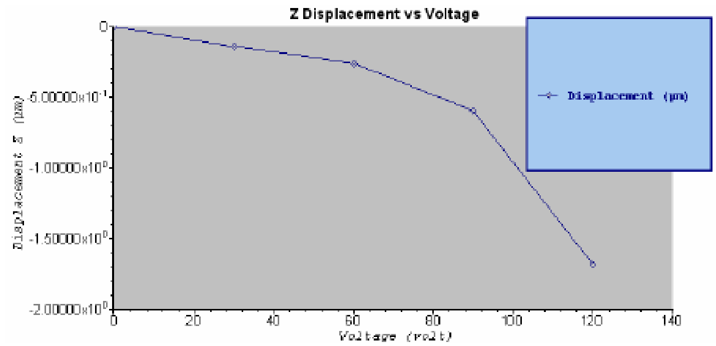
The influence of bridge thickness variations on pull-in voltage is shown in Fig. 7 while keeping the hinge thickness constant. The value of spring constant with 2.0 µm thick bridge is reduced and so is the actuation voltage. Thin membranes are more susceptible towards oscillatory behavior with increased switching time, so the bridge with thickness of 2 µm is a better option. The comparison between simulated and calculated results for variable bridge thickness is given in Table II.

TABLE II

COMPARISON OF THEORETICAL AND SIMULATED PULL-DOWN VOLATAGES FOR VARIABLE BRIDGE THICKNESS

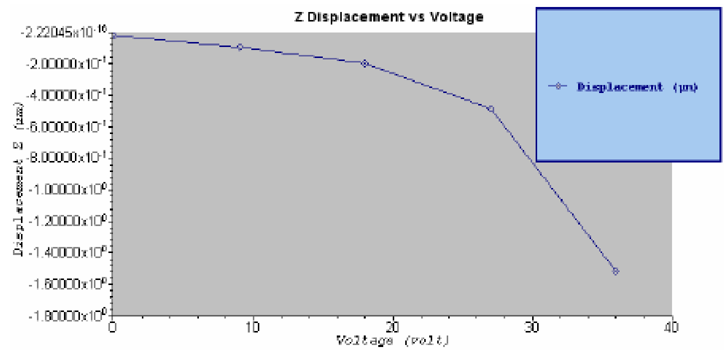
Bridge Thickness t (µm)	Simulated Voltage Vp (Volts)	Calculated Voltage Vp (Volts)	Effective Spring Constant Keff (N/m)
4.0	120	124.5154	355.6512
3.0	67	74.4636	127.1940
2.0	36	28.3802	18.4760
1.5	13.2	10.2680	2.4185

The air gap between the membrane and the lower electrode determines the capacitance of an unactuated RF MEMS switch. This capacitance in turn determines the actuation voltage. Hence the air gap height is one of the key factors in RF MEMS switch design.



Bridge thickness 4.0µm

(a)

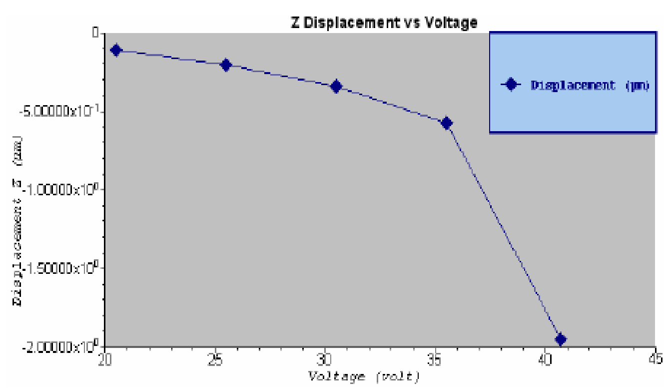


Bridge thickness 2.0µm

(b)

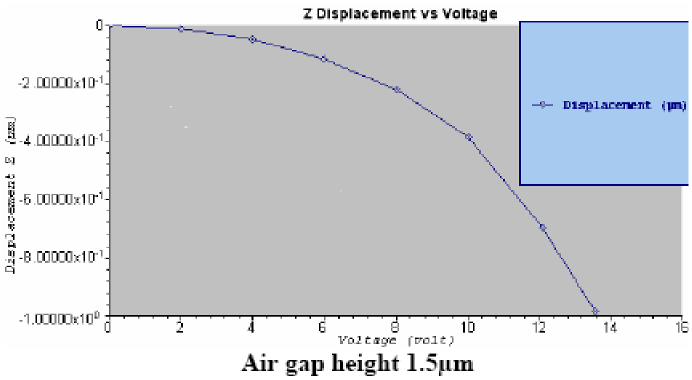
Fig. 7. Z-displacement as voltage function for (a) bridge thickness=4.0µm (b) bridge thickness=2.0 µm.

To observe the affect of variation in air gap height, a 2 µm thick membrane is used. Fig. 8 shows the effect of variation in air gap height on actuation voltage in terms of Z-displacement while keeping the bridge thickness and hinge thickness constant.



Air gap height 3.0 µm

(a)



(b)

Fig. 8. Z-displacement as voltage function for (a) air gap height = 3.0µm (b) air gap height = 1.5 µm.

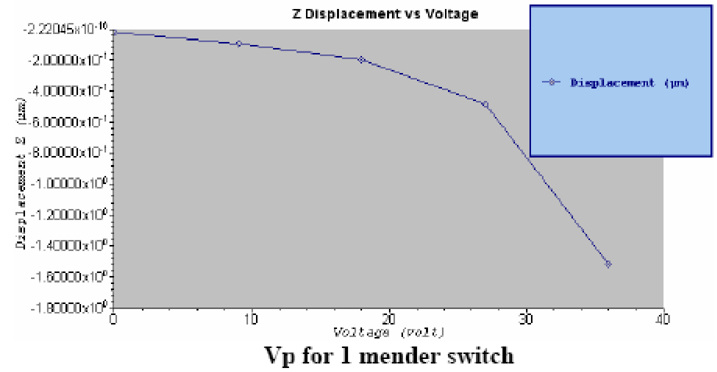
The comparison between simulated and calculated results for variable air gap height is given in Table III. The threshold voltage and gap height data shows that larger the air gap the higher the actuation voltage of the switch.

TABLE III

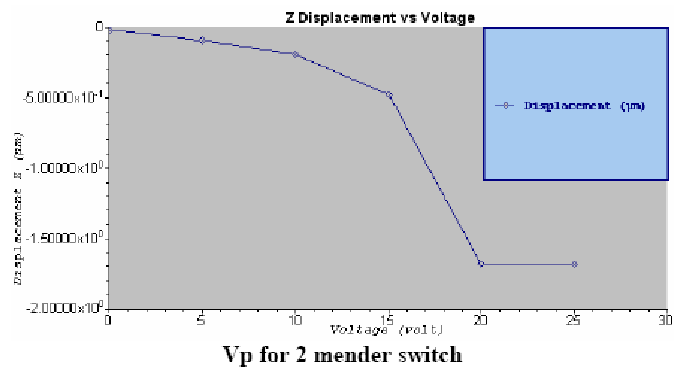
COMPARISON OF THEORETICAL AND SIMULATED PULL-DOWN VOLATAGES FOR VARIABLE AIR GAP HEIGHT

Air Gap Height go (µm)	(2/3) go(µm)	Simulated Voltage Vp (Volts)	Calculated Voltage Vp (Volts)
3.5	2.33	49	47.0118
3.0	2.0	40.6	37.3067
2.5	1.66	36	28.3802
2.0	1.33	23.5	20.3072
1.5	1.0	13.6	13.1899

Capacitive membrane switches generally have meandered line springs which reduce the force required for pull down. Increasing the numbers introduce more flexibility in the hinge by reducing the effective spring constant. The switch design with 1 and 2 menders in the hinges is investigated and the simulation is shown in Fig. 9. The comparison between simulated and calculated results for different number of menders is given in Table IV. These results show that more menders in the beam the lower the actuation voltage and hence the performance of the switch is improved. With 2 menders, the spring constant has a reasonable value comparable to any practical fabricated switch. The calculated value of effective spring constant indicates that the structure is stable and not much oscillatory [7].



(a)



(b)

Fig. 9. Z-displacement as voltage function for (a) 1 mender switch (b) 2 mender switch.

TABLE IV

COMPARISON OF THEORETICAL AND SIMULATED PULL-DOWN VOLATAGES FOR DIFFERENT NUMBER OF MENDERS

Number of Menders N (µm)	Simulated Voltage Vp (Volts)	Calculated Voltage Vp (Volts)	Effective Spring Constant Keff (N/m)
1	36	28.3802	18.4760
2	20	20.1118	9.2785
3	12	16.4332	6.1947

VI. CONCLUSIONS

RF MEMS shunt switch with fixed beam structure was analyzed in this paper. The design was optimized in terms of activation mechanism. The electromechanical analysis found that the pull-in voltage can be tailored by varying hinge thickness, bridge thickness, air gap height and mender structure. Optimization of the switch is done by varying these parameters in turn to observe the effect of each parameter in lowering the actuation voltage. Each parameter is varied within the practical range.

The thinner the hinge and bridge, the lower is the switch pull-in voltage. However, the thinner the membrane the more difficult fabrication becomes and shorter the life of the switch. Therefore, the thickness of the bridge should not be less than 2 μm. The air gap height directly determines the driving voltage. The smaller the air gap height, the lower the pull-down voltage but reducing the air gap below 2 μm may cause stiction and dielectric charging problems. Introducing more bends in the hinge increases the flexibility of the switch.

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