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Design and Simulation of Microelectromechanical System Capacitive Shunt Switches

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Abstract: Problem statement: RF MEMS switch is one of MEMS area that creates devices that have great potential to improve the performance of communication circuits and systems and enables the realization of micro size mechanical switches embedded in electronics devices. The low voltage switches are necessary due to their compatibility of standard IC technology in RF application and microelectronics systems. In realizing MEMS switches with low actuation voltage, spring constant of beam must be reduced. Design and simulation of capacitive RF MEMS shunt switches with regards to the pull in voltage were presented. **Approach:** Design and simulation had been done by using commercial simulation package, CoventorWare 2006. Several switches were designed with different meander spring beams to obtain lower voltage actuations using Architect Module in CoventorWare 2006. **Results:** Results verified with Finite Element Method (FEM) and simple mathematical modeling. Each design gave different voltage actuations. The lowest actuation voltage simulated was 1.9 V. Average difference of simulated and calculated values was about 16%. This is because no fringing field was included in calculation. Finite Element Method (FEM) analysis was done for switch C. Results showed that lower voltage can be obtained by using serpentine spring which lowers the spring constant and pull-in voltage as well. The lower pull-in time was primarily due to its very small dimensions and mass **Conclusion:** Low-voltage capacitive shunt RF MEMS switches were designed and simulated. These switches had actuation voltages of 1.9-7.0 V depending on the serpentine design. The other performance particularly switch C had a pull-in time of 15 µ sec after a voltage of 0-20 V was applied and the resonant frequency is 3153.1 Hz.

Key words: MEMS, RF MEMS, capacitive switches, pull-in voltage, serpentine, meander beams, low voltage

INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) are integrated micro devices or systems that combine electrical and mechanical components and make use of the advantages of both solid-state and electromechanical systems. They are fabricated using Integrated Circuit (IC) batch processing techniques and can range in size from micrometers to millimeters. The electronic parts are fabricated using standard IC processing while the micromechanical components are fabricated using compatible micromachining processes[1]. Many MEMS devices use silicon as their basic material and the technology is derived largely from advances in silicon processing. MEMS is an enabling technology and current applications include accelerometers, pressure, chemical and flow sensors, micro-optics, optical scanners, fluid pumps and RF applications[2].

RF MEMS is one of the MEMS technology areas that have very high demanding applications particularly in wireless and satellite communication systems. MEMS technology enables the realization of RF passive components with the benefits of low loss, small size, low power consumption, high quality factors, high tunable characteristics and high linearity compared with conventional semiconductor based passive. An RF MEMS device includes a MEMS variable capacitor, MEMS tunable inductors, phase shifters, resonators and RF MEMS switches. The most widely investigated RF MEMS device is the electrostatic switch, consisting of a thin metallic cantilever, Air Bridge, diaphragm, or some other

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structure that when pulled down to a bottom electrode shorts, opens or loads an RF transmission line[3].

MEMS switches exhibit better performance compared to conventional semiconductor devices. MEMS switches have low resistive loss, negligible power consumption, good isolation and high power handling capability compared with semiconductor switches. Due to the excellent performance at microwave to mm-wave frequencies compared to other types of switches such as GaAs-based FET, pHEMT or PIN-diode switches[1], MEMS switches have been attracting much interest in research and development. However, one of the major disadvantages is a low switching speed which is much slower than current solid-state switches[4].

Mechanical microwave switches were first demonstrated in 1979 using the bulk-micro machined cantilever[5]. This type of switch is fabricated on silicon with an electrostatic movable cantilever membrane as the switching component. It is also small and consumed low power. Since then, many different types of capacitive MEMS switches have been reported[1-9].

MEMS switches are devices that operate based on mechanical movement to achieve a short circuit or an open circuit in the RF transmission line. The actuation mechanisms to obtain the required forces for the mechanical movement in MEMS switches include electrostatic, electromagnetic, magnetic, piezoelectric and thermal. However, the electrostatic actuation mechanism is the most common method used because of its low consumption[2].

There are two types of MEMS switches that can be developed: The series switch and the shunt switch. Shunt switches are designed for applications at 10-100 GHz. On the other hand, series switches are designed with a low ohmic contact for the lower Gigahertz range. This study will focus on the development of capacitive MEMS shunt switches with low voltage for RF applications. This study will also cover the design, simulations and the characterization of the performances of the devices. Simulation is important to predict the behavior of the devices. The pull-in voltage will be simulated with the CoventorWare 2006 software package using the Architect solver. Other performance characteristics to be simulated will be the switching speed and the resonant frequency. The values of FEM analyses and the analytical method will be compared for verification.

MEMS switches principles: MEMS switches operate based on mechanical movement to achieve on and off states. The shunt switch consists of a thin metal membrane suspended over the center conductor of a Coplanar Waveguide (CPW) and fixed at both ends to the ground conductor by anchors. The center electrode provides electrostatic actuation and RF capacitance between the transmission line and the ground. When the switch is in the up-state, it provides low capacitance and will not affect the signal on the transmission line. However, when a voltage is applied between the beam and the electrode, an electrostatic force will exist on the plates of capacitor. The developed electrostatic force and high capacitance attract the beam toward the fixed ground plane so that the membrane will deflect downwards by decreasing the gap height and increasing the electrostatic pressure on the membrane. The membrane will pull down towards the center conductor with a certain pull-down voltage and will produce short circuit.

The switch is built on 250 μm thick-layer silicon substrates. The transmission line is fabricated on a silicon layer with 1 μm Aluminum. On top of the center electrode is a thin film silicon nitride which is used as the dielectric layer. The metallic switch membrane consists of a thin Gold with 1.5 μm thickness. The membrane is suspended 2.5 μm above the center conductor. The transmission line metal connects to the electrode and the dielectrics materials to form the through path of a shunt switch. Figure 1 shows the side view and the top view of the shunt switch. The transmission gap and width are shown by G and W respectively. The G/W/G of the transmission line is 60/100/60 μm. The suspended metal membrane spans the two coplanar ground lines with perforations of about 4 μm to remove the sacrificial layer from the membrane. This sacrificial layer is removed mechanically so that the membrane suspended and can move up and down onto the lower electrode in response to applied electrostatic forces.

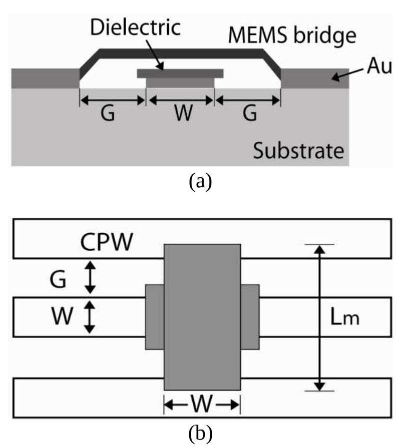


Fig. 1: (a) Side view (b) top view of RF MEMS shunt switch

Low voltage MEMS switches: A low voltage MEMS switch is a desirable switch attribute because it will make it more convenient for a switch to be embedded into real applications[7]. The pull-in voltage depends on the spring constant of the switch in the z-direction K_z, ε_o which is the permittivity of air, the gap between the membrane and the signal line g_o and the actuation area, A, as given in Eq. 1:

$$v_{pull-in} = \sqrt{\frac{8K_z g_o^{\ 3}}{27A\varepsilon_o}} \quad (1)$$

From the pull-in Eq. 1, the actuation voltage can be lowered by reducing the g_o, increasing the actuation area A, or reducing the spring constant, K_z.

MATERIALS AND METHODS

Many researches on MEMS switches have been done to achieve the low actuation voltage for better performances. For instance, the low-voltage MEMS capacitive shunt switch[8] is done by using 1-5 meanders membrane support structures. The MEMS switches have the pull-down voltages as low as 6 V with gap height of 3-5 µm.

In this study, we focus on designing of a low actuation voltage of MEMS switches by reducing the spring constant as the method. Serpentine beam or meander type beam is designed to achieve the lower spring constant. Adding more meanders can significantly lower the spring constant without excessively increasing the required space[8] as miniaturization is necessary for a device to be embedded in RF applications.

Figure 2 shows the design of serpentine spring for the membrane to lower the spring constant. The serpentine beam has a primary meander length of a, secondary meander length of b, width of w and thickness of t.

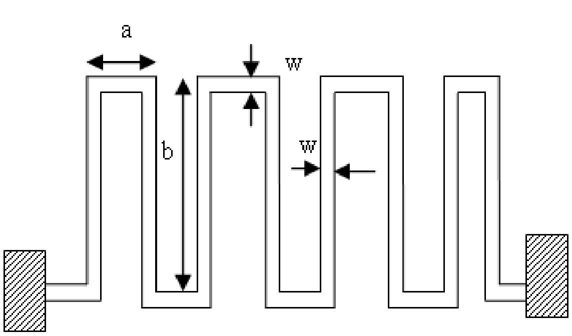


Fig. 2: Serpentine spring design

For these serpentine beam designs, the k_z can be calculated by Eq. 2[8]:

$$k_z = \left[\frac{\left(8N^3a^3\right) + 2Nb^3}{3EI_x} + \frac{abN\left[3b + (2N+1)(4N+1)a\right]}{3GJ} - \frac{Na^2\left[\left(\frac{2Na}{EI_x}\right) + \frac{(2N+1)b}{GJ}\right]^2}{2\left(\frac{a}{EI_x} + \frac{b}{GJ}\right)} - \frac{Nb^2}{2}\left(\frac{a}{GJ} + \frac{b}{EI_x}\right) \right]^{-1} \quad (2)$$

The Eq. 2 shows the k_z as the z-directed spring constant for each one of the springs. Hence, if the switch is connected to the ground through four serpentine springs as shown in Fig. 2, which are used to lower the switch spring constant, the total switch spring constant K_z is given by Eq. 3[8]:

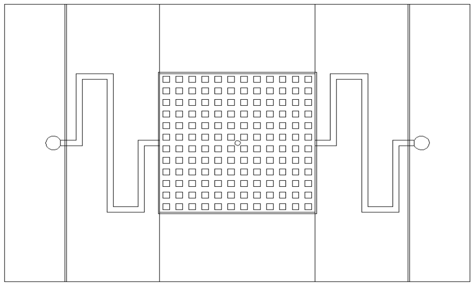
$$K_z = 4k_z \quad (3)$$

In realizing the low actuation RF MEMS switches, four different designs of switches A, B, C and D with different meander types and numbers were built to analyze the performance of each type as shown in Fig. 3a-d.

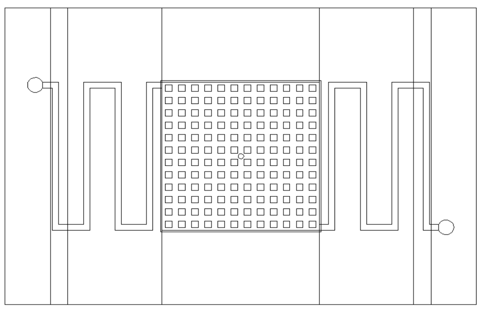
The detailed dimensions and material constants for the design particularly switch C are shown in Table 1. The dimensions are used for most of the switches except dimension of a for switch A and B is 24 µm and b is 25 µm for switch D. Materials such as silicon nitride is used as the dielectric layer as it is widely used as an insulating layer due to its low thermal conductivity while Gold is used as the bridge membrane. Gold is a good material for a membrane layer as it minimizes thermal absorption and can compensate the residual stress to obtain flat suspended structures[6].

Table 1: Physical dimensions and material constant of switch C in Fig. 3

Primary meander length (a)	14 µm
Secondary meander length (b)	96 µm
Switch thickness (t)	1.5 µm
Beam width (both beams) (w)	4 µm
Gold Young's modulus (E)	57 GPa
Gold Poisson's ration (v)	0.35
Sheer modulus (G)	E/{2(1+v)}
x-axis moment of inertia (I_x)	$wt^3/12$
z-axis moment of inertia (I_z)	$tw^3/12$
Polar moment of inertia (I_p)	$I_x + I_z$
Torsion constant (J)	0.413 I_p



(a)



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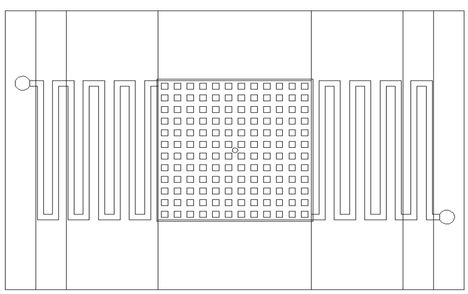

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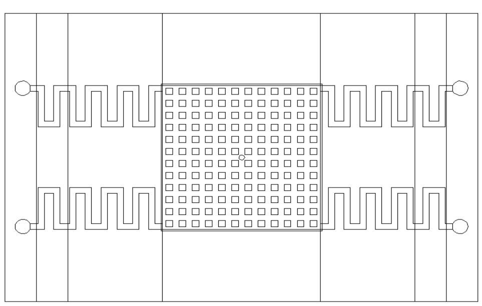
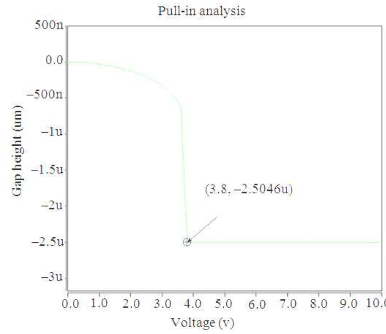


(d)

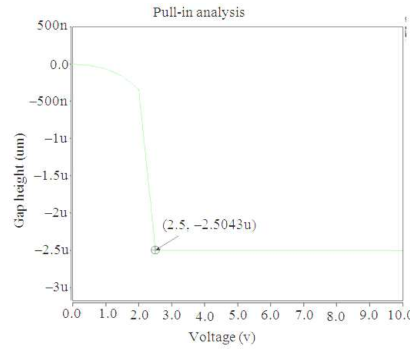
Fig. 3: Layout of RF MEMS switches with different spring/meander types (a) switch A (b) switch B (c) switch C (d) switch D

RESULTS

The simulated pull-in voltage results for all the designs are shown in Fig. 4. The lowest voltage obtained is for Switch C which is 1.9 V. The average different of



(a)



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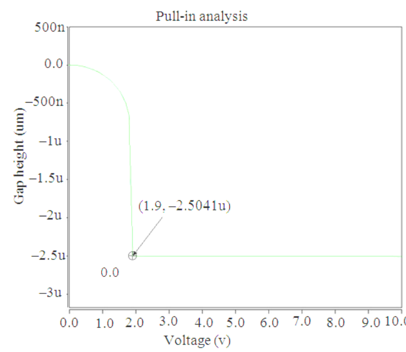

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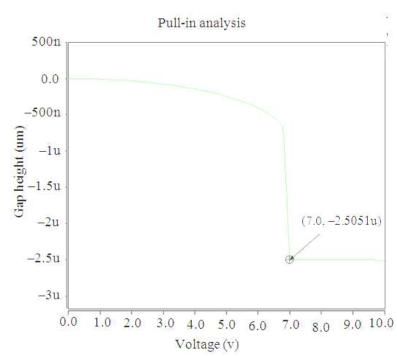

(d)

Fig. 4(a-d): Simulated pull-in voltage for all designs by architect CoventorWare 2006

Table 2: Results of pull-in voltage for all designs

Design	Pull-in voltage (V) (by simulation)	Pull-in voltage (V) (by calculation)
Switch A	3.8	4.954
Switch B	2.5	2.932
Switch C	1.9	2.076
Switch D	7.0	6.572

Table 3: Contact voltage of FEM analysis at range of 2.6-2.8 V of switch C

	Voltage	Pull-in voltage factor high	Pull-in voltage factor low
Pull-in/lift-off	1	2.8E00	2.6E00

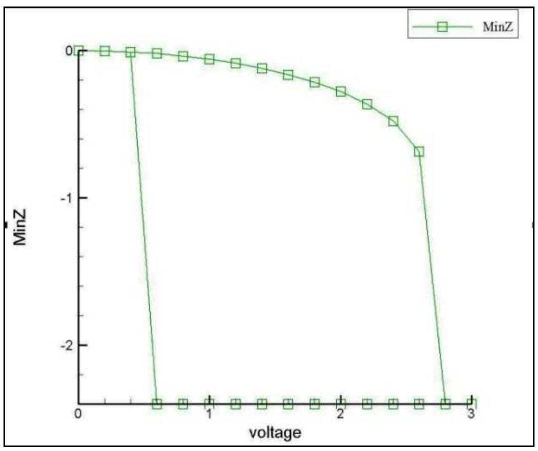

Fig. 5: Result of FEM analysis of pull-in voltage of Switch C

simulated and calculated values is about 16%. This is because no fringing field is included in calculation. The other pull-in voltages which were simulated for all the designs are shown in Table 2.

As verification and for comparison with the Architect results and calculations, FEM analysis using Analyzer's CoSolve was done and Fig. 5 shows the results of the FEM simulation of Switch C. The linearly increasing voltage ramp is applied to observe the effect on the switch while the release voltage is observed by a linearly decreasing voltage ramp. The results showed a slight increase of pull-in voltage which is in the range of 2.6-2.8 V for Switch C. Table 3 described the actuation voltage result for the contact and release voltages. In this case, contact occurs between 2.6 and 2.8 V. Rerunning the simulation with smaller steps and meshes would give more accurate results. For comparison, the Architect predicted a contact voltage of 1.9 V.

The dynamic simulation takes into consideration resonant frequency and switching time. From the harmonic and transient analysis, the switching speed and the resonant frequency results are shown in Fig. 6 and 7

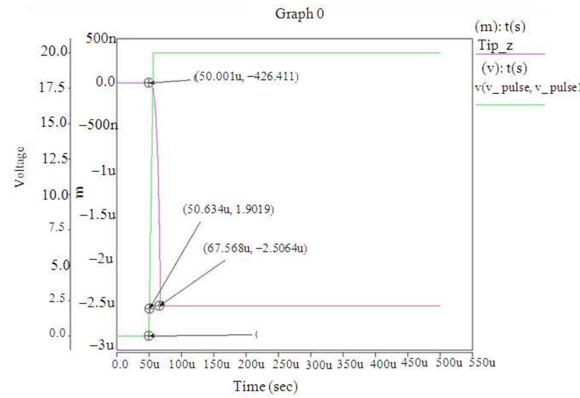

Fig. 6: Pull-in time of the MEMS switch

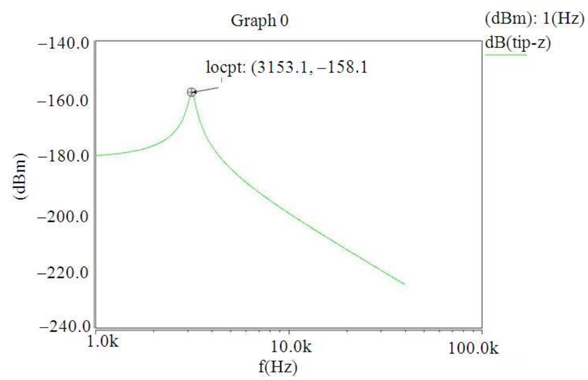

Fig. 7: Resonant frequency of the MEMS switch

respectively. The resonant frequency of Switch C is 3153.1 Hz. The resonant frequency depends inversely on the beam length and can be increased independently by increasing beam thickness[9]. Pull-in time is the time taken to touch the dielectric underneath the bridge. From Fig. 6, the pull-in time is about 15μsec after a voltage of 0-20 V is applied.

DISCUSSION

Four switch designs A, B, C and D with different types and number of meanders were designed and simulated. The results show that the low actuation obtained as low as 1.9 V. The simulation was done using the Architect solver for system-level simulation and compared with the Finite Element Module (FEM) simulation, CoSolve Analyzer and as well as theoretical calculations. The results showed that a lower voltage can be obtained using the serpentine spring which lowers the spring constant and the pull-in voltage as well. The lower actuation voltage is desirable as the lower actuation voltage describes better switch performances. More over, adding more meanders can significantly lower the spring constant as the switch C gave the lowest voltage. For switch A, B, C and D, the simulated results are slightly different with theoretical calculation only with 1.154, 0.432, 0.176 and 0.428 V respectively. The FEM result shows increment of about 0.7 V. Finite Element Method (FEM) simulation can be more accurate if we run with smaller mesh and steps.

The dynamic analyses done were the frequency response and the transient analysis. The 15 μs pull-in time was primarily due to its very small dimensions and mass. The structure does not settle down by the end of the transient simulation since gas damping is not modeled. The maximum switching rate is in fact ideally equal to the resonance frequency for low-amplitude deflections assuming there is no stiction and non-hysteretic behavior[9].

CONCLUSION

A low-voltage capacitive shunt RF MEMS switch were designed and simulated. These switches have actuation voltages of 1.9-7.0 V depending on the serpentine design. The other performance particularly switch C has a pull-in time of 15 μsec after a voltage of 0-20 V is applied and the resonant frequency is 3153.1 Hz.

The development of capacitive MEMS shunt switches is essential in order to solve technical problems in the product development stage as well as to enhance their performance. Development is important in terms of scientific contribution and possibly for commercialization purposes where the latter can be beneficial for local players in the MEMS industry to cater for the demand of MEMS switches in RF applications. Several applications of the switch include switchable routing in RF system front-end, digital capacitor bank and time-delay network[3].

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