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Effect of Air Gap on the Performance of a Capacitive Shunt RF MEMS Switch and a New Design Approach for Improved Performance

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***Abstract*— A Fixed – Fixed RF MEMS switch has been simulated for various air gaps and the variation of the electrical performance in accordance with the air gap has been studied. The switch was simulated and the pulls in voltages for different air gaps were practically determined by electrostatic analysis using IntelliSuite software. Subsequently, the theoretical values were determined analytically and the values were found to be closely matching with less than 2% error. The pull in voltage was found to be 9.78V for an air gap of 1.5 µm and increased to 51.36V for an air gap of 4.5 µm. However, the insertion loss was at –0.5522 dB for an air gap of 1.5µm at 60 GHz and smaller insertion losses was achieved only with larger air gaps. These investigations showed that large compromise on electrical performance is required for lower pull in voltage which is essential for the use of these switches in mobile applications. Considering these difficulties the authors have proposed a varying section fixed – fixed beam switches that can be designed to give lower pull in voltages even for larger air gaps. Therefore these proposed switches can ensure superior electrical performance along with low pull in voltages.**

***Keywords*: RF MEMS capacitive switch, Insertion Loss, Isolation, varying section fixed – fixed beam switches.**

I. INTRODUCTION

Micro Electro Mechanical Systems (MEMS) are the integration of mechanical elements, sensors, actuators and electronics on a common substrate using Integrated Circuits process sequence. In recent years, MEMS based RF circuits have become an area of large interest because of its wide application in the field of wireless communication, phase shifters, receivers and transmitters [1, 3]. Switches play a vital role in the RF MEMS circuits and systems [2]. RF MEMS switches are switches that transmit high frequency (0.1 to 60GHz) signals from one port to another [6]. They are used in application where two or more systems need to be embedded into a single but more complex system. For instance, various systems like Global Positioning System (GPS), Bluetooth and many other applications can be brought together into a single mobile phone. The main idea of the RF MEMS switch is to use miniature mechanical devices and the physical motion of the devices to achieve the function of a microwave switch or a variable capacitor using various principles like the electrostatic, thermal and piezoelectric effect [1, 3]. The reason for the use of RF MEMS switches instead of a conventional electronic switches like the PIN diode or the GaAs based FET switches is because of the advantages like lower insertion losses (loss of voltage at the switch), higher isolation, zero power consumption (very low power consumption), smaller size, lower weight, lower intermodulation losses and good linearity [1, 2]. But, these MEMS switches also suffer disadvantages like low switching speed, high actuation voltage (pull in voltage). This prevents the usage of the RF MEMS switches in miniaturized mobile systems [7]. There are two kinds of switches, the parallel and the series RF switches, the parallel switches use capacitors to switch the RF power to the load. When the switch is actuated electrostatically[8] the air gap reduces resulting in high capacitance that offers low impedance to the RF signal that is to be linked to the load. Therefore, these switches also have insertion losses and isolation like series switches. Hence the designer should focus on designing it in such a way that the actuation voltage is less in addition to small insertion loss and isolation. This paper presents the result of a study that brings out the effect of air gap on the V_{pi} (pull in voltage) and the other electrical performance factors of a RF switch.

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II. STRUCTURE OF THE SWITCH

A typical RF MEMS switch essentially consists of three parts i) CPW(Coplanar Waveguide) ii) dielectric and iii) a membrane. The thin metal membrane is suspended over the center conductor of a CPW which is fixed at both the ends by the insulator silicon nitride or dioxide as shown in Fig 1.The membrane is made of metal deposited by the process of electroplating. The actuating voltage is applied at the top or the bottom of the electrode (mostly at the top). As a voltage is applied to the electrode, the electrode is pulled down due to the electrostatic force which makes it contact with the gate hence allowing the signal to flow from one port to the other. The various geometries considered in the study of the switch are given in Table I.

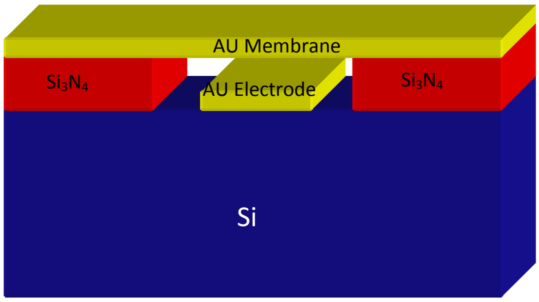

Figure 1.Structure of RF MEMS Switch

Table I. Dimensions of the Switch

Parameter	Dimension (µm)
Si Substrate thickness	500
Si_3N_4 thickness	6
Au electrode thickness	1.5
Au beam thickness	1.5
Air Gap (g_0)	1.5 to 4.5
Oxide thickness	0.2
Length of the Beam (L)	240
Width of the beam (W)	100
Electrode Size	100 × 100

III. SIMULATION STUDIES

The simulation of the RF MEMS switch is carried out with the software "INTELLISUITE", which is primarily meant for designing MEMS application. First, the switch is designed and then the design is realized as a three dimensional structure using 3D Builder module of Intellisuite. The device is constructed first placing the layer or module which forms the lower layer of the switch and this is the silicon substrate of 500µm thickness in the present structure. Then the consecutive layers are placed above the preceding layer till the desired shape of the layer is obtained. The physical dimensions of the material like the height, length and the width is also specified as required by selecting the layer. An obvious question rises that how the layer inhibits the properties of the material to be used. This is done by selecting the layer and specifying the material to be used, then, the software automatically applies the physical properties which are Young's modulus, density, conductivity, Poisson ratio, dielectric constant, resistance, temperature coefficient and specific heat.

A. Deflection Analysis and Estimation of pull-in voltage

Following this the electrostatic analysis is carried out using the Thermo Electro Mechanical (TEM) module. The boundaries are set to the three dimensional structure. Then the actuating voltage is applied to the thin membrane and the amount of deflection is computed by the software. The intensities of deflection on the switch are indicated by differing colors. Pull in voltages are obtained in two ways. First, the central deflection of the beam is obtained for various actuation voltages applied to the beam and the voltage at which the deflection reaches 1/3 of the air gap or the distance to travel is 2/3 of the air gap is considered to be the pull in voltage. It is measured at 1/3 of the air gap because the value of the displacement starts to increase exponentially. This process is repeated for four different air gaps of 1.5, 2.5, 3.5 and 4.5 µm. Fig 2 shows the central deflection versus actuation voltage for the different air gaps ranging from 1.5 ~ 4.5 µm. The least pull in voltage is 9.58V for an air gap of 1.5 µm and it increases to 51.36 V at the air gap of 4.5 µm as shown in Fig 2. Since the distance and the electrostatic force are inversely proportional the actuation voltage increases with increase in the air gap.The second approach is to obtain the spring constant of the hanging beam by thermoelectromechanical analysis and estimate the pull in voltage analytically. The beam is applied a mechanical load and the central deflection (δ) is obtained. Then, the stiffness constant is obtained using the relationship as given in equation 1.

$$k = \frac{F}{\delta} \quad (1)$$

Where k is the spring constant in N/m, F is the force applied to the beam in N and δ is the central deflection in µm. Now, the pull in voltage is estimated using the relation as shown in equation 2.

$$V_{pi} = \sqrt{\frac{8k g_0^3}{27 \varepsilon_0 A}} \quad (2)$$

Where k is the spring constant, g0 is the initial air gap in m, ε_0 is the permittivity in F/m and 'A' is the electrostatic area in µm^2.

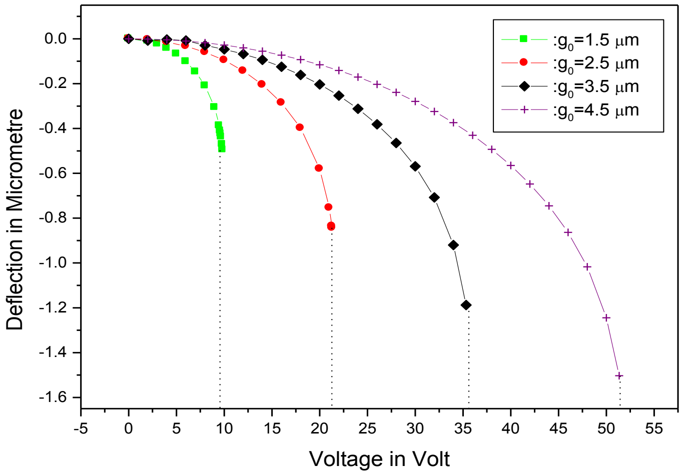

Figure 2. Voltage Vs Central Deflection

Table II. Estimated Pull in Voltage by Simulation

Air Gap in µm	Spring Constant(k) in N/m	V_{pi} (Theoretical) in Volts	V_{pi} (Electrostatic Analysis) in Volts
1.5	7.92	9.46	9.58
2.5	7.92	20.35	21.28
3.5	7.92	33.70	35.39
4.5	7.92	49.13	51.36

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IV. ELECTRICAL PERFORMANCE OF RF SHUNT CAPACITIVE SWITCH

As it is known, the insertion loss and the isolation are the two important parameters that demonstrate the performance of a RF MEMS switches. The electrical equivalent circuits of the switch in ON and OFF states are shown in Fig 3.

The on state (up state) capacitance can be written as

$$C_{on} = \frac{(C_{ox} * C_{air})}{(C_{ox} + C_{air})} \quad (3)$$

Where C_{ox} is the oxide capacitance and C_{air} is the capacitance due to the air gap. Similarly, the off state (off state) capacitance is given by equation 4.

$$C_{off} = C_{ox} \quad (4)$$

These values are calculated and listed in Table 3. The figure of merit C_{off}/C_{on} values are also estimated and given in the Table III.

Table III Capacitance ratio to the corresponding air gap

Air Gap (µm)	C_{on} (pF)	C_{off} (pF)	Figure of Merit
1.5	0.0512	1.7708	31
2.5	0.0347	1.7708	51
3.5	0.0249	1.7708	71
4.5	0.0194	1.7708	91

Assuming that the switch to be a two port network and the value of L_s and R_s are negligible the insertion loss and the isolation can be determined by calculating the s – parameters of the two port network. The parameter s_{21} is the insertion loss and the parameter s_{11} is the isolation. These parameters are given by the equations 5 and 6. Before calculating the insertions loss and the isolation it must be bore in mind that both parameters exists when the actuation voltage is not applied (up state) and also when the actuation voltage is applied (down state). So the insertion loss and insolation are to be determined for the up state and the down state respectively. For an ideal switch the isolation is infinite in the down state and the insertion is zero in the up state. So the isolation is calculated for the down state and insertion loss for up state using the following expressions [9] given in equation 5 and 6.

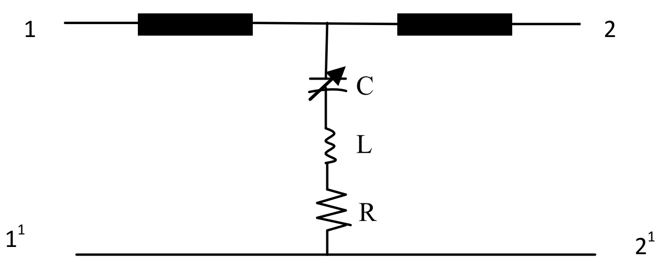

Figure3. Electrical Equivalent Circuit of A Shunt Capacitive Switch

$$S_{21} = \frac{1}{(1 + j\omega C_{on} Z_0 / 2)} \quad (5)$$

$$S_{11} = \frac{- j\omega C_{off} Z_0}{(2 + j\omega C_{off} Z_0)} \quad (6)$$

The insertion losses are calculated for the frequencies in the range of 0.1 GHz to 60 GHz and are plotted in Fig 4 and the Fig 5 gives the plot for isolation in the same range of frequencies. The insertion loss varies approximately from -0.5522 dB to -0.0718 dB and the insertion losses of the switches at 60GHz are -0.5522 dB, -0.2207 dB, -0.1167 dB, -0.0718 dB for the air gaps 1.5, 2.5, 3.5 and 4.5 µm respectively. It is also true from the results the insertion loss also increases as the air gap decreases. Further, it is observed from Fig 5 that the isolation of the switch for the varying thickness of the oxide layer. The switch has a better isolation for higher thickness of the oxide layer and at lower frequencies however, the isolation is almost the same for higher frequencies.

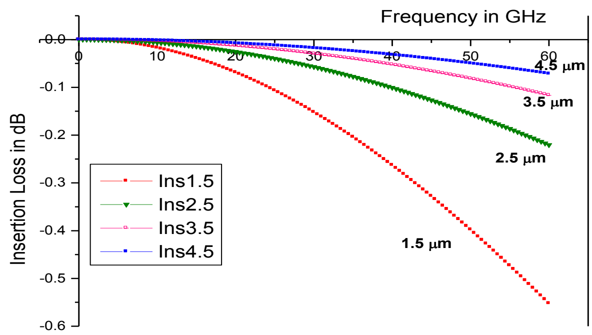

Figure4. Frequency Vs Insertion Loss (Up State)

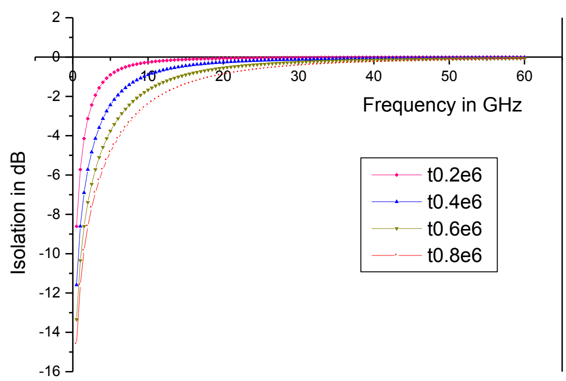

Figure5. Frequency Vs. Isolation (Down State)

The isolations are measured as -8.6112 dB, -11.59 dB, -13.45 dB and -14.59 dB at 0.5 GHz for the oxide thickness of 0.2, 0.4, 0.6 and 0.8µm respectively. Unlike the insertion loss the isolation does not vary with the air gap since it only depends on the down state capacitance of the switch or oxide thickness. Even though an ideal switch cannot be constructed, it is important that the insertion loss is low. This is possible only if the air gap is set high. But, if the air gap is increased then the pull in voltage also increases which prevents the device to be used in mobile application as said earlier. Therefore, it becomes essential to keep the air gap (g_0) larger for better electrical performance of the switch which increases the pull in voltage. Hence, alternative approach must be sought to reduce the pull in voltage without manipulating the air gap. The authors present in the next section a new design approach that would pave the way for decreasing the pull in voltage without manipulating the device geometries.

V. NEW DESIGN APPROACH

The top view of the proposed RF MEMS switch employing varying section beam is shown in Fig.6. As it is seen in the figure, the constant width fixed-fixed beam is replaced by a varying section fixed-fixed aluminium beam with its wider section at the anchored ends and its narrowest section at point of contact with the contact electrode.

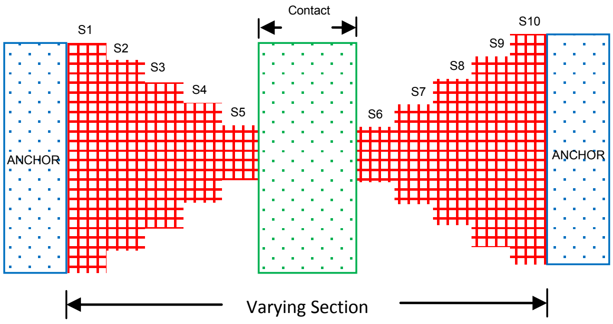

Fig 6. Top View of the proposed structure of Fixed – Fixed Beam (n=5)

The section closer to the anchor is of width W_1 and width of the subsequent section towards the pull-in pad assumes varying widths W_2, W_3 and so on depending on the number of sections. The length of each section is kept the same. Here 'L' is the length of the beam and 'n' is the number of sections on either sides of the contact area.

Four different devices namely FF21, FF22, FF25 and FF210 were considered and all of them had the same beam length of 150μm, thickness of 2 μm with an air gap of 2 μm but contains 1, 2, 5 and 10 number of sections respectively. The deflection response at various actuation voltages is obtained by measuring the mid-point movement (g) towards the contact pad on application of the voltage. Thermoelectromechanical relaxation type analysis was used to achieve the goal. The deflection response of devices under consideration is shown in Fig 7. In this graph the y-axis represents the remaining distance to be travelled (g_0-g), where 'g' is the distance travelled by the beam tip. The V_{pi} is extracted by finding the voltage at which the distance to travel (g_0-g) is two third of the initial gap g_0 as indicated in Figure 7.

The pulls in voltages thus measured are given in the Table 4. It is obvious from the Table 4 that the V_{pi} is reduced by 22.74% when the number of sections is increased from 1 to 10 but still maintain the same air gap.

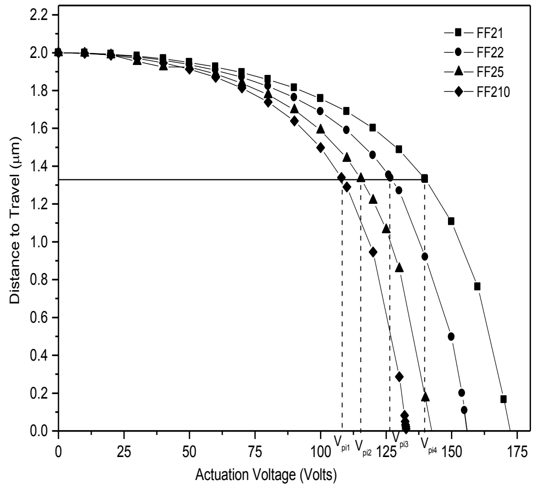

Figure7. Voltage Vs Deflection response of the switches

Table4. Dimension of the switch and the corresponding pull in Voltages

Device ID	No. of Sections (n)	Thickness (t)	V_{pi} (Measured)	% drop in Pull-in Voltage
FF21	1	2	139.75	-
FF22	2	2	126.75	9.30
FF25	5	2	115.4	17.42
FF210	10	2	107.97	22.74

Therefore it is a promising design approach since this approach enables one to achieve low pull in voltage still maintaining the air gap high thus assuring high degree of isolation.

VI. CONCLUSION

The effect of air gap on the insertion and isolation performance of capacitive shunt type RF MEMS switches has been investigated. The fixed- fixed beam configuration has been considered in this study. Intellisuite MEMS CAD tools have been used for creating the device structure and evaluate the performance. It has been found that the insertion loss increases to -0.5522 dB at 60 GHz from -0.0718 dB when the air gap is reduced to 1.5 μm from 4.5 μm. Similarly these devices show poor isolation at large frequencies. These results clearly show that alternative approach must be identified to reduce the pull in voltage without manipulating the air gap. Subsequently the authors conducted experiments on a varying section fixed- fixed beam RF MEMS switches and showed that it is possible to achieve small pull in voltages still maintaining the air gap high with the proposed structure.

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