Design And Analysis of Various SU 8 Structures for On/Off Mems Switch in RF Applications

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Abstract : This paper presents new design techniques of SU-8 RF MEMS switches for low voltage applications. Three different configurations, namely cantilever based, clamped-clamped and meandered, has been proposed to SU-8 2005 (5 μm) beam structure driven by electrostatic force. Proposed structure has been designed and simulated using Coventorware software. Pull-in voltage for clamped-clamped beam configuration varies within 4 – 7 V for various widths, where as for other two configurations pull-in voltage is 2.5 V. The pull-in voltage analysis has also been carried out for different beam materials to choose the optimum one for fabrication. It is revealed that beam with SU-8 materials presents the lower pull-in and is most suitable for practical use. The proposed switch is simulated for RF analysis using Agillent ADS and HFSS and Simulation results shown that the switch exhibits insertion loss of 0.37 dB at 6 GHz and 1 dB up to 10 GHz and isolation of 20 dB at 6 GHz and 15 dB up to 10 GHz. Proposed switches are highly compact, low profile with less operating voltage and can be easily integrated into planar passive microwave components for reconfigurable applications requiring compatible switches.

Keywords : RF MEMS, Switches, SU-8, pull-in voltage, fabrication

I. Introduction

The research in the field Micro-electro Mechanical systems (MEMS) has grown up exponentially during the last two decades due to their diversified applications in various branches of engineering. In the MEMS field devices are conventionally fabricated using Si-based materials. However, polymer, especially SU-8 has recently become one of the promising materials [1] due to various practical advantages. SU-8 has several interesting and useful material characteristics, including photosensitivity, transparency to visible light, low Young's modulus, chemical resistance and biocompatibility. The fact is that SU-8 has about 30 times smaller Young's modulus than Silicon ($E_{SU-8} = 2 - 4$ GPa [2] and $E_{si} = 164$ GPa [3]).

The SU-8 polymer, epoxy based negative photoresist material invented by IBM, which is widely used in RF MEMS switching devices as structural and sacrificial material. SU-8 has various groups based on the polymerization process like SU-8 2000 and SU-8 3000. SU-8 2000 series are available in twelve standard viscosities [4]. Design of SU-8 based switches has emerged as one of the most enthralling work to the MEMS community over last few years. Andrea Lucibello *et.al* has designed a double clamped RF MEMS capacitive switch in the coplanar configuration with SU-8 as sacrificial material for lateral supports [5]. A clamped-clamped beam switch was developed by Chao *et.al* with SU-8/Cu/SU-8 sandwich layer as a structural material [6]. The process might be good for RF switch. However, the stacked layer with comparable thickness of Cu with SU-8 increases the spring constant of structural beam and results in higher pull-in voltage. After that K.S. Ramadan *et.al* developed a switch with two metal electrodes using amorphous silicon as a sacrificial material [7].
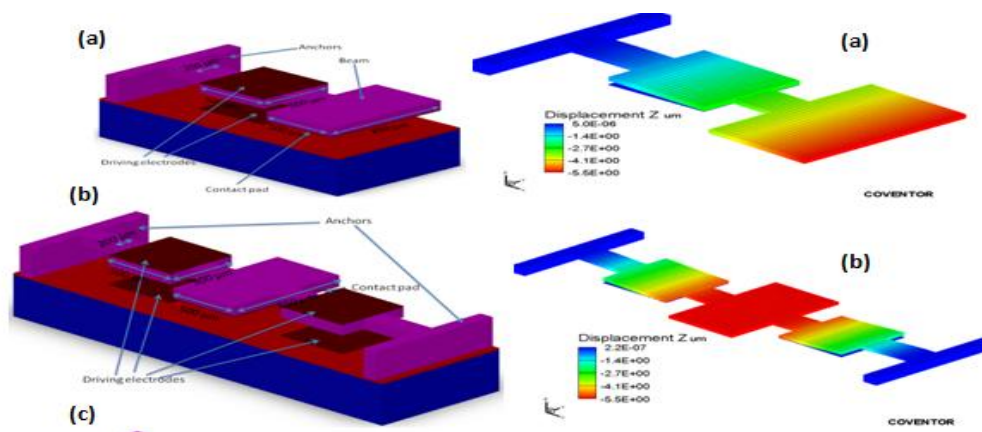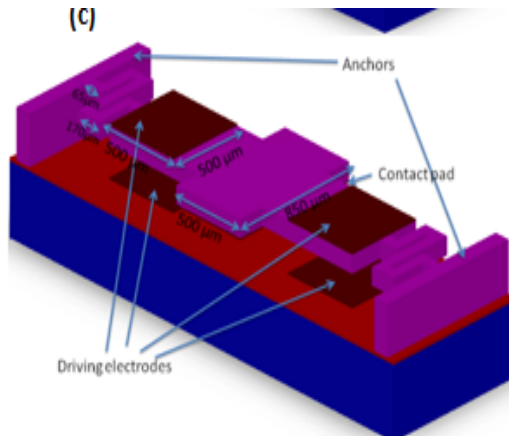

Fig.1. 3D structure for (a) Cantilever beam (b) Clamped-Clamped beam (c) Meander beam
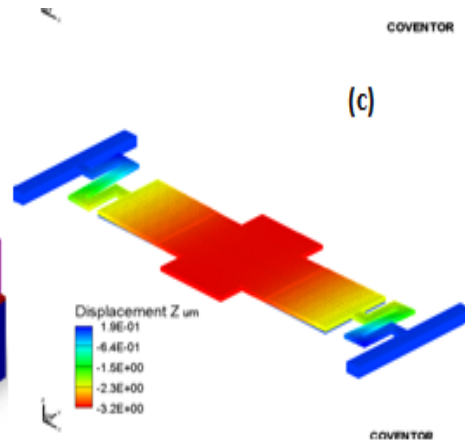
Fig.2. Z-Displacement (a) Cantilever (b) Clamped-Clamped (c) Meander Structure

This paper presents three different implementations of RF MEMS switches on SU-8 material. Physical dimension and configuration of the switches ensures their compatibility in using in planar transmission line to achieve electrical short/open condition. Such reconfigurable transmission line can drastically change the operation of various microwave components, waveguides [8], antennas [9-17] and circuits [18-24] providing a switchable control over the performance of the RF circuits and radiators [25]-[26]. However, performance of such reconfigurable RF circuits and/or antennas is predominantly dependent on the characteristics of the switch embedded in the module. MEMS switch in RF applications is an appealing choice thanks to its low insertion loss, virtually no energy consumption, excellent quality factor (Q), RF isolation and less expensive as compared to

conventional solid state switches. The design of RF MEMS switches can be varied according to their uses, either series or shunt configuration and can move vertically or laterally. The MEMS switches can provide both capacitive and metal-to-metal connection. Their movement can be carried out via electrostatic, magnetostatic, piezoelectric or thermal actuation. Various types of MEMS switches include cantilever, clamped-clamped, meander and other structures electronically arranged in series or parallel with the RF transmission line. Cantilever beams are useful in many situations where it is inconvenient to fix both ends of the beam. Since it is not fixed at   one end, any residual stress within the film is released and the spring constant does not contain any residual component which results low pull-in voltage. However, if there is a stress gradient over the cross section of the cantilever, then the beam deflects up/down side on release and it is undesirable [28]. On the other hand clamped-clamped beam doesn't have any deflection problem but exhibits higher pull-in voltage.

In this paper, three different configurations of RF MEMS switches, cantilever type, clamped-clamped beam type and a meander type is designed and simulated using proposed SU-8 micromachining technique for reconfigurable applications in RF circuits/antennas. The switch geometry and dimensions are properly optimized to achieve targeted pull-in voltage, $V_p <= 5$V and proper operational frequency.

II.   Desig

In general, to design a RF MEMS electrostatic actuated switch, the structure of the switch beam must be chosen so as to produce the lowest possible insertion loss, the highest possible isolation, the highest possible switching frequency, and lowest possible actuation voltage. The SU-8 polymer has Young's modulus of 2 to 4 GPa, much lower than poly-The RF switch is fabricated on a silicon wafer with 1 μm thermally grown silicon dioxide considered as a substrate. The beam is assumed to be SU-8 2005 material of thickness 5 μm. The electrodes are of Cu material of thickness 0.5 μm on both top and bottom of the beam using POLYIMIDE as sacrificial material and patterned to realize cantilever, clamped-clamped and meander structures. Fig.1 shows 3D view of three types of structures.
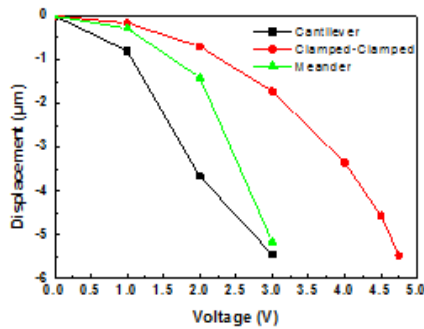
Fig.3. Z-Displacement versus applied voltage of switch

TABLE 1 Influence of beam materials on Pullin voltage

Beam material	Pullin voltage (V)
Cu	26
Al	20.5
Cr	27.5
Poly-Si	28
SU-8	4.5

TABLE 2 Frequency at various beam widths and modes

Width of the beam, w (μm)	Mode 1 (Hz)	Mode 2 (Hz)	Mode 3 (Hz)
150	476	1174	1744
200	541	1377	1952
250	596	1563	2124
300	644	1738	2270
500	792	2304	2680

TABLE 3 Pull-in voltage at various beam widths

Beam width, w (μm)	Pullin voltage (V)
150	4.5
200	4.75
250	5.5
300	5.75
500	7

The mechanical design of electrostatically actuated switches is dictated by the required actuation voltage. When designing a switch with low actuation voltage, the choice of membrane material and the support beam design are critical. Equation (1) is the governing equation for calculating pull-in voltage of electrostatically actuated MEMS switches [19] given by equation 1.

$$V_p = \sqrt{\frac{8k \left(g_0 + \frac{t_d}{\varepsilon_r} \right)^3}{27 \varepsilon A}} \qquad (1)$$

Where g_0 is the initial gap between electrodes, ε is the permittivity of the medium between electrodes, t_d is thickness of SU-8 membrane, ε_r is the dielectric constant of SU-8 and A is the area of the electrodes. The spring constant k, depends on the type and dimensions of membrane. The design formulae for k were discussed in [18, 19]. The necessary parameters for cantilever, clamped-clamped and meander structures are shown in Fig.1.

III. Simulation results

The designed switches have been actuated with a voltage ramp, 0 to 10 V to upper electrodes and lower electrodes were grounded. Three different switch configurations conceived in this paper is simulated in Coventorware, providing a pull-in voltage of 2.5 V, 5 V and 2.5 V for cantilever, clamped-clamped and meander beam switch configurations respectively. Fig.2 shows the vertical ('z' direction) displacement for various switch configurations at pull-in voltage. It can be observed that the maximum deflection takes place at the free end of beam for cantilever configuration, and centre of the beam for both clamped-clamped and meander configuration as expected. The displacement as a function of applied voltage for all three beams is shown in Fig. 3. It can be shown that the negative z-displacement of the beam for various voltages ensuring the anticipated downward movement.
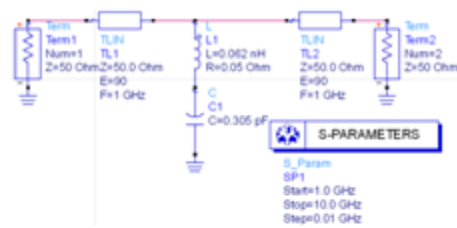
Fig. 4(a) Lumped equivalent circuit of the switch in the up-state position
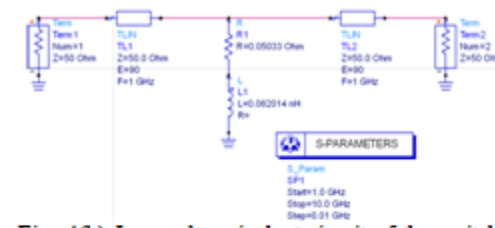

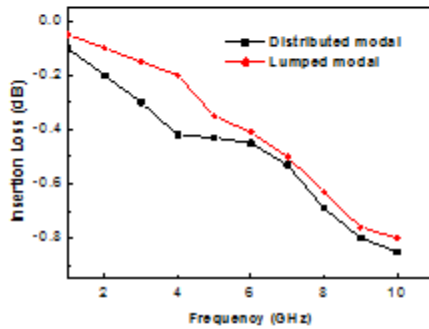Fig. 4(b) Lumped equivalent circuit of the switch in the down-state position

Fig. 5(a) Insertion (*S21*) losses for a DC contact MEMS switch in the upstate with both lumped and distributed modal
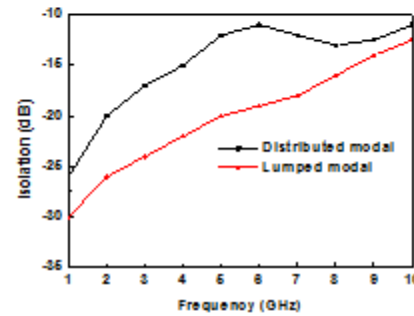

Fig. 5(b) Isolation (S21) for a DC contact MEMS switch in the upstate with both lumped and distributed modal
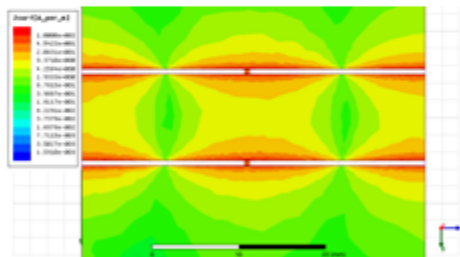

Fig. 6(a) Simulated current distribution of the DC contact MEMS switch at the up-state for the dimensions given in table 5.1.
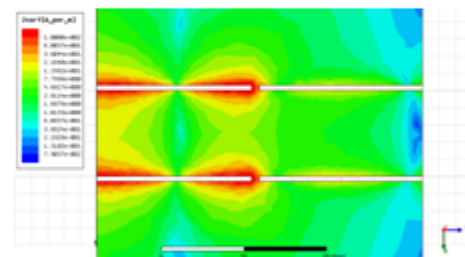

Fig. 6(b) Simulated current distribution of the DC contact MEMS switch at the down

A. Material Selection

We have used some standard materials of same dimensions to compare the pull-in voltage with SU-8 structure for MEMS switch. As shown in Table 1, different materials were used for clamped-clamped beam MEMS switch at beam width 200 μm and pull-in voltage was obtained. Simulation results showed that SU-8 material gives lowest pull-in voltage compared with other materials. So SU-8 was selected for lower actuation voltage applications

B. Relationship Between Pull-In Voltage And Width Of The Beam

Table 2 illustrates the relationship between pull-in voltage and width of the beam with thickness 5 μm. When width of the beam is decreased from 500 μm to 150 μm, the pull-in voltage is reduced from 7V to 4.5V.

C. Relationship between Resonant frequency and the width of the beam

Table 3 shows the resonant (modal) frequency at various beam widths for the first three modes of the clamped-clamped beam switch. When width is increased from 150 μm to 500 μm, the resonant frequency is increased for all modes.

The designed switch is simulated for insertion loss and Isolation in Agilent ADS software with the lumped equivalent model shown in Fig. 4(a) & 4(b). Simulation results from shown that the switch exhibits insertion loss of 0.37 dB at 6 GHz and 1 dB up to 10 GHz in Fig. 5(a) and Isolation of 20 dB at 6 GHz and 15 dB up to 10 GHz in Fig. 5(b). There is a variation in lumped modal results from HFSS simulation results due to fringing effect. Fig. 6(a) & 6(b) shows the simulated current distribution of CPW transmission line when the

switch in the upstate and downstate condition from high-frequency structure simulator (HFSS) software from Ansoft. As shown in Fig. 6(a), when the switch is in the upstate, the total amount current is flowing from input port to the output port and very low current is passing to the ground. From Fig. 6(b), when the switch is in the down-state, the front edges of the contact pad that are over the CPW slot act as short paths from the centre conductor to the ground. Therefore, the current in the metal bridge is mainly concentrated on the front edges of the metal bridge that are over the CPW slot. This implies that for the DC contact MEMS switch, the down-state inductance is also mainly determined by the portion of the metal bridge over the CPW slots. Therefore, when the dimensions of the CPW slot are reduced, the inductance of the switch can also be reduced.

IV.   Conclusion

RF industry demands for low voltage operated switch. Polymer based switches have the potential to fulfill the requirements. The switch structures discussed in this paper have all of the characteristics which make them ideal for RF application. In addition, those switches ideally consume no power. This work is mainly motivated by low operation voltage demand. Choice of membrane material is also an important object for this work. SU-8 is chosen among the materials like Cu, Al, Cr, and Poly-Si. Three designs, cantilever, clamped-clamped and meander structure are considered for the analyses of low voltage operation and meander structure shows lowest among them for the same dimensions.

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