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Ultra low actuation voltage RF MEMS switch

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Abstract

In this brief a new low actuation voltage RF MEMS switch is presented which can be integrated and controlled with available CMOS technologies. Despite the advantages in the design of RF MEMS switches designing a low actuation voltage RF MEMS switch is still a challenging task. To overcome this problem, a small size RF MEMS switch utilizing a moving plate with multiple holes supported by a low spring constant beam is presented in this work. Experimental measurement results indicate pull-in voltage of 0.5 V and lift-off voltage of 0.3 V for 1.5 μm displacement. The measured return loss and insertion loss are better than −20 dB and −0.1 dB respectively for a frequency range extending from 3 kHz to 3GHz. The switching time is less than 0.22 ms when the switch is turned on with a CMOS buffer from TSMC-65 nm technology with 1.00 V supply voltage.

Keywords: Radio frequency micro-electro-mechanical-system (RF MEMS) switch; Low actuation voltage; Microfabrication

Introduction

Micro-Electro-Mechanical Systems (MEMS) devices have been vastly employed for many applications including Radio-Frequency (RF) components such as RF switches, variable capacitors and inductors [1–4]. RF and microwave MEMS switches have been subject of many research studies due to their superior performance such as high isolation, low insertion loss, good linearity and low power consumption. MEMS switches are either direct-contact style or capacitive type. Direct-contact MEMS switches are commonly used for application where the frequency of operation is limited to a few gigahertz. Capacitive switches are preferred for higher frequencies. To close or open MEMS switches the force is applied through electrostatic, magnetic fields or thermally induced forces [3]. RF MEMS switches mostly employ electrostatic actuation due to low power consumption and short switching time as well as compatibility with electrical circuits and components. Electrostatic MEMS switches require a relatively high actuation voltage to drive the movable part. For the purpose of wireless communication or integrated circuit design, it is highly desired to reduce the pull-in voltage of MEMS switches. Various design techniques are proposed in the literature

to reduce the actuation voltage. In [5] a pull-up type RF MEMS switch with low actuation voltage of 4.5 V is presented. In [6], a mechanically coupled low-voltage electrostatic resistive RF multithrow switch with 15 V is proposed.

In general, low actuation MEMS switches suffer from a range of problem including stiction, dielectric charging, hot switching life time and low power handling. In the proposed application in this work, a minute amount of power passes through the MEMS switch and thus the power handling and hot switching life time are not important issues. However, stiction and holding can affect the tag operation. The design of the MEMS switch has to be optimized to reduce these undesired effects.

In this work, a helix restoring spring is utilized to implement a low actuation voltage RF MEMS. The implemented switch includes a moving plate with multiple square holes that contribute to the faster operation of the switch by reducing the air damping factor under the moving plate. The dimple is added to reduce the gap between the movable plate and the output transition line to lowers the actuation voltage. A low-cost MEMS microfabrication process has been used to fabricate the MEMS switch. The implemented switch can be integrated with available 1.00 V supply CMOS technologies.

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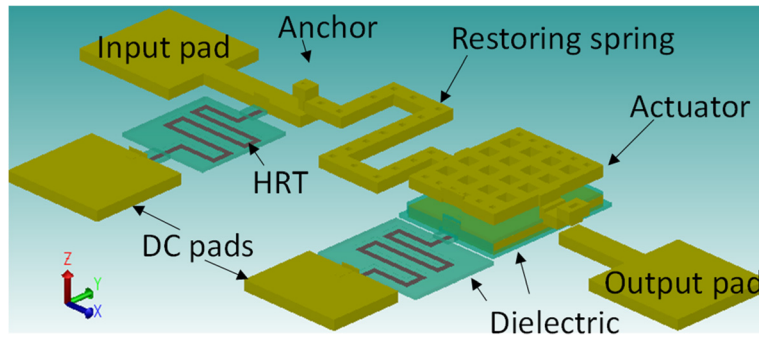Electrical and Computer Engineering Department, University of Windsor, Windsor, Ontario, Canada

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Fig. 1 3D view of the implemented low actuation voltage MEMS switch using Coventorware

Mechanical and RF design principles

There are different structures to implement a MEMS switch; among them cantilever switch supports a relatively low pull-in voltage [3, 4]. The pull-in voltage, $V_{pull-in}$, of a MEMS switch can be calculated from Eq. (1) [4],

$$V_{pull-in} = \sqrt{\frac{8K_Z g_0^3}{27 W \varepsilon_0}} \qquad (1)$$

where K_Z is the spring constant, g_0 is the gap between metal plates, W is the area of the pads and ε_0 is the air permittivity. The pull-in voltage, $V_{pull-in}$ can be reduced by (a) increasing the area of the pads, W. (b) reducing the gap between metal plates, g_0, and (c) reducing the spring constant K_Z. There is a trade-off between the size of the

MEMS switch and its pull-in voltage. To lower the pull-in voltage, the size of the MEMS has to be increased.

A MEMS switch are mainly implemented using either a fixed to fixed beam structure [3], or a cantilever beam actuator. Fixed to fixed MEMS switches as compared to cantilever switches support larger electrode areas and therefore larger actuation capacitances; whereas cantilever structures support lower pull-in voltages. The spring constant K_Z in the z-direction can be determined from Eq. (2) [3, 4].

$$K_z = EW\left(\frac{t}{L_c}\right)^3 \left\langle 1 + \frac{L_s}{L_c}\left\{\left(\frac{L_s}{L_c}\right)^2 + 12(1+v)\left[1+\left(\frac{W}{t}\right)^2\right]^{-1}\right\}\right\rangle^{-1} \qquad (2)$$

where E is Young's modulus, v is Poisson's ratio of the metal. The lengths of the cantilever and spring are L_c
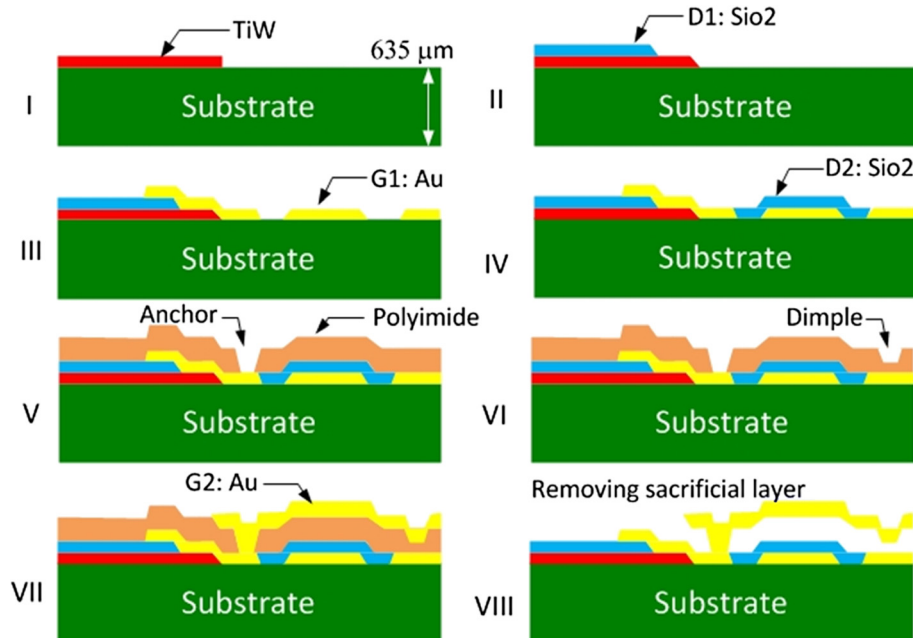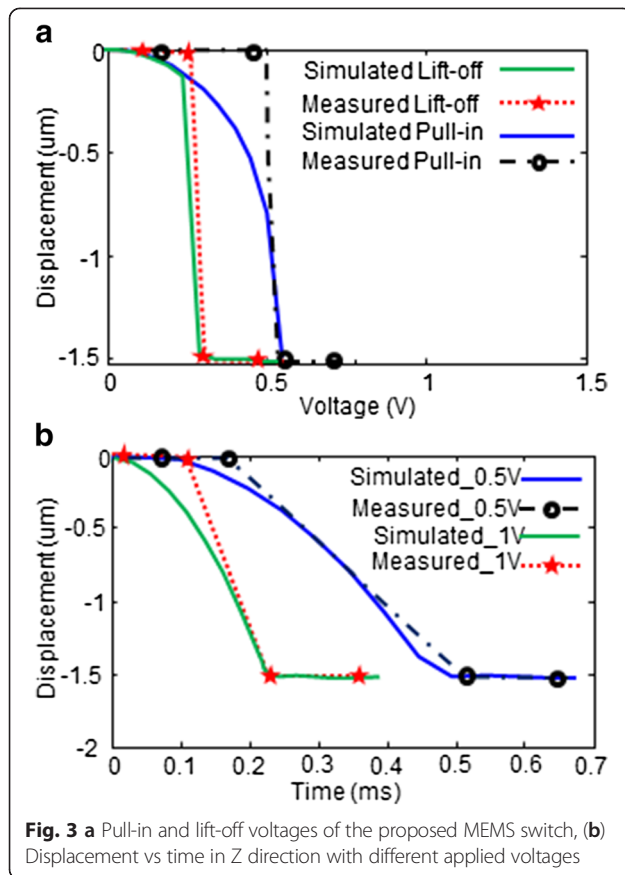

Fig. 2 Microfabrication process

Fig. 3 a Pull-in and lift-off voltages of the proposed MEMS switch, (**b**) Displacement vs time in Z direction with different applied voltages

Fig. 4 a Prototype under test using Agilent E5061B network analyzer and MA-8100 RF probes from SEMIPROBE™, (**b**) Return loss, insertion loss and isolation versus frequency

and L_s, respectively. W and t are width and thickness of the cantilever.

Current distribution is high on the edges of the cantilever beam. In the proposed design, some small holes are made in the beam to increase the effective area of the edges to increase the speed of the switching. Helix restoring spring with length and width of 700 μm and 30 μm are chosen to support the low actuation voltage with a small area. Actuation pad length and width are designed to be 190 μm and 220 μm. The Helix high resistivity traces (HRT) provides enough resistivity to isolate the input signal from the DC supply. The gap between dimple and transmission line is optimized to provide enough isolation in the OFF state mode. A 12.5 μm × 25 μm dimple is chosen to meet enough isolation in the OFF state and low contact resistance in the ON state for RF applications. The fabrication process allows the reduction of the gap between metal plates, g_0, down to 1.5 μm. A thinner cantilever beam reduces the spring constant and consequently lowers the actuation voltage but it also reduces the weight which is inversely proportional to the actuation voltage. It will also increase the pull-in switching speed since the pull-in acceleration of the movable actuator is inversely proportional to its mass. The transient time for lift-off increases with the
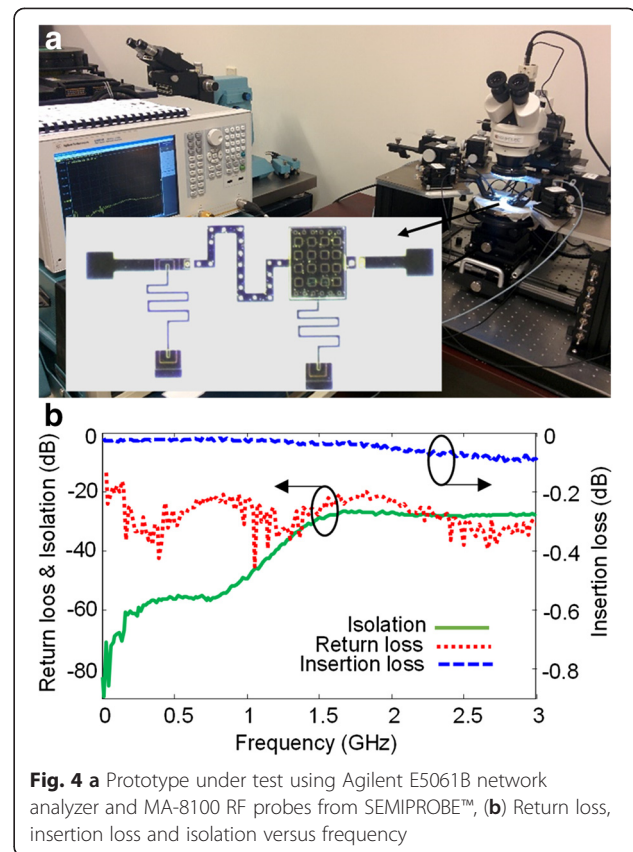
reduction of the movable actuator thickness due to the electrostatic capacitor hysteresis. An optimization for pull-in and lift-off voltages, resulted in a 2 μm thick movable actuator. Figure 1, presents 3D view of the implemented low actuation voltage using Coventorware™. The total fabrication area of the switch is 1264 μm × 635 μm, including input and output transmission lines, DC bias lines and pads.

Table 1 Comparison of key features

Parameter	Ref. [5]	Ref. [6]	This paper
Frequency (GHz)	50	2	0–3
Pull-in Voltage	4.5	15	**0.5**
Displacement (μm)	1.5	1.3	1.5
Transition Time	120 ns	7.4 μs	0.5 ms
Isolation (dB)	55	45.7	27
Insertion loss (dB)	0.5	0.25	**0.1**
Return loss (dB)	12.4	NA	**20**
1 V CMOS technology	No	No	Yes
Life Cycle	8×10^8	1×10^7	1×10^4
Size	$400 \times 100 \ \mu m^2$	$2000 \times 1000 \ \mu m^2$	$1264 \times 635 \ \mu m^2$
	(Lower contact pad)	(SPDT)	(Including biasing pads)

Fabrication process

A prototypes is fabricated using a cost effective micro-fabrication process as a proof of concept. The fabrication process employs eight steps, as shown in Fig. 2. The substrate is a 635 μm thick Alumina with loss tangent of 0.0001 at 1 MHz and relative permittivity of 9.9. Electron beam-write chromium masks are used during the fabrication process. At the first step, a 50 nm Titanium tungsten (TiW) is sputtered and patterned. This creates HRT to connect the DC bias pads to the actuation pad and input signal line. The first step is followed by deposition of 0.7 μm SiO_2 at 250° C by a plasma enhanced chemical vapor deposition (PECVD) and patterned using reactive ion etching (RIE). Then a seed layer is deposited by evaporation of 40 nm Cr/70 nm Au bilayer. G1 is patterned using a negative photoresist mold by photolithography process. This is followed by electroplating 1 μm Au within the mold.

The Cr layer is used as an adhesion layer for Au which is washed out later. The fabrication process is followed by 0.7 μm SiO_2 PECVD deposition at 250 ° C as dielectric. A 30 nm TiW is used at this step as an adhesion layer between D2 and G1. In step five a 2.5 μm thick spin coated polyimide layer is used as a sacrificial layer. To create the anchor and the dimple holes, polyimide is patterned using RIE. Then the fabrication process is completed by sputtering the 70 nm Au as a seed layer and an electroplated Au layer with total thickness of 2 μm and removing the sacrificial layer using O_2 plasma dry etching in RIE.

Simulation and measurement results

Figure 3a shows the pull-in and lift-off voltages of 0.5 V and 0.3 V with 1.5 μm displacement using the finite element analysis (FEA) tools in Coventorware™ and they are in agreement with measurement results. The transient response in Fig. 3b, indicates that 0.5 ms is required for switching at the pull-in voltage of 0.5 V. It can be seen that by increasing the applied voltage, the switching time reduces. The number of switching cycles of this switch has reached 1×10^4 cycles at 0.5v. Figure 4a shows the fabricated MEMS switch under test using MA-8100 RF probes from Semiprobe™ and an Agilent E5061B 3 kHz to 3 GHz ENA network analyzer. Figure 4b shows S-parameter measurement results for the MEMS switch at the ON and OFF states. An insertion loss of less than −0.1 dB and return loss of better than −20 dB were measured over the entire frequency range of 100 kHz to 3 GHz. The switch also shows an isolation of higher than −27 dB over the measured frequency range as shown in Fig. 3b. Table 1 presents a comparison between the key features of the designed MEMS switch with reported works in the literature [5, 6].

Conclusion

This paper presents a new low actuation voltage RF MEMS switch. A helix restoring spring together with a moving plate containing square holes are used to lower the pull-in voltage. A prototype is fabricated as a proof of concept using a fabrication process with seven electron-beam-write chromium masks. The switch is designed and optimized using Coventorware™. Measurement results indicate a pull-in voltage of 0.5 V which makes the switch ideal for integration with available low voltage CMOS technologies. It also presents −0.1 dB insertion loss and less than −20 dB return loss over a frequency range extending from 3 kHz to 3 GHz.

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