Bi-stable RF MEMS switch with low actuation voltage

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Abstract

Mobile technologies have relied on RF switches for a long time. Though the basic function of the switch has remained the same, the way they have been made has changed in the recent past. In the past few years work has been done to use MEMS technologies in designing and fabricating an RF switch that would in many ways replace the electronic and mechanical switches that have been used for so long. This work describes a design and fabrication process for an RF MEMS switch that can handle higher RF power with CMOS compatible operating voltages.

Keywords**:** RF, MEMS switch, Electrostatic, CMOS, High power

1.0 Introduction

1.1. MEMS

With the ever increasing demand for small and more reliable systems, attention has been focused for some time on exploiting the advances in silicon processing to fabricate some of the commonly used components on silicon. The concept of fabricating micro scale mechanical devices that can function like the ones made using conventional technology has been of interest for some time in the semiconductor industry. It is only in the recent past that this has gained momentum due to the strides made in silicon fabrication technology. Microelectro-mechanical systems or more commonly known as MEMS was the result. MEMS has many applications such as accelerometers, pressure sensors, and optical switches. Though this technology has been used for some time in these fields, it is only recently that work has been done in the field of RF MEMS switches. RF MEMS switches are being used to switch power between the transmitter and the receiver or in antenna arrays to form configurable arrays of antennas.

1.2. Switches

The drive for MEMS switches for RF applications had been mainly due to the highly linear characteristics of the switch over a wide range of frequencies. MEMS RF switches come in two configurations, series and shunt. As the name suggests, a series switch is in series with the power line and either closes or opens the line to turn it ON or OFF (Figure 1). In a shunt switch the power line is sandwiched between

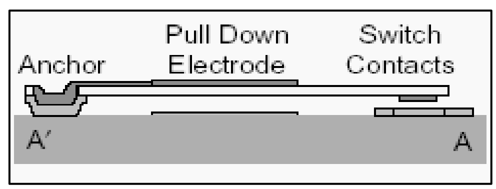

Figure 1 Series switch [1]

two ground lines and the switch turns on to short the power on the signal line to the ground thus preventing the power from going past the switch (Figure 2). In a series switch the contacting surface is usually at the end of a singly supported cantilever beam with a control electrode under the beam. By applying a voltage to the control electrode the beam can be pulled down to

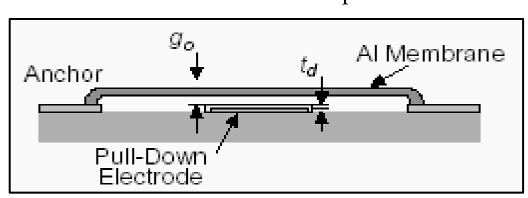

Figure 2. Shunt switch [1]

complete the connection between two conductors. A series switch can be further classified into broad-side or in-line depending on the plane of actuation. In the in-line configuration the actuation plane is co-linear with the transmission line (Figure 3). In an in-line shunt switch the beam is clamped at both the ends and the control plate pulls down the beam when a potential is applied to it. This ensures that the signal finds a shorter path to the ground and does not pass on to the following network.

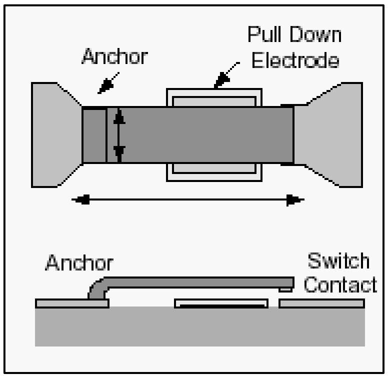

Figure 3. In-line switch [1]

In the broad-side configuration the actuation plane (A-A') is perpendicular to the transmission line (Figure 4).

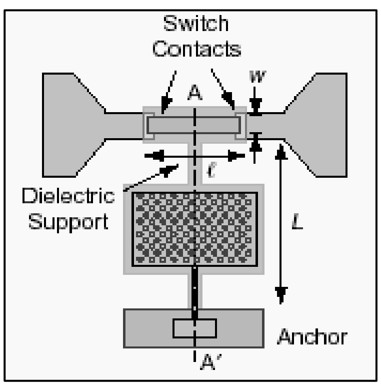

Figure 4. Broadside switch [1]

MEMS switches can also be classified based on the actuation mechanisms into categories such as electrostatic, electromagnetic and thermal. Electrostatic methods rely on the basic columbic force of attraction between two oppositely charged plates. This is the simplest of all the methods as it does not involve any special processing steps that are not supported by normal CMOS processing (Figure 5). Electromagnetic methods of actuation rely on aligning a magnetic material in a magnetic field [2]. By changing the direction of the alignment the switch can be turned ON or OFF. This is a novel method and has some advantages compared to other methods but requires special processing involving magnetic materials (Figure 6). Thermal actuation involves using two materials with different thermal expansion coefficients [3]. When the materials are heated the beam bends away from the material with the higher thermal expansion coefficient. Another thermal method employs shape memory alloys [4]. These thermal methods have not been very popular despite the latching properties due to the required power consumption.

2. Motivation

It has been observed that very few MEMS switches meet the requirements of CMOS compatible operating voltages, high power

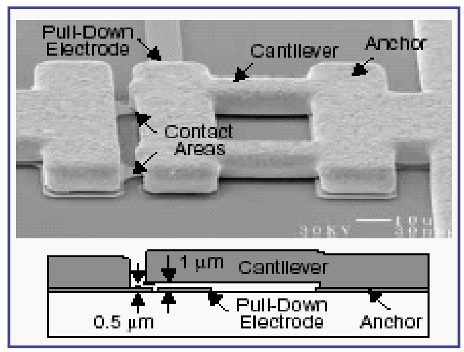

Figure 5. Electrostatic Actuation[1]

handling capabilities, latching properties and low probability of self actuation. It has been observed that electrostatic actuation consumes the least

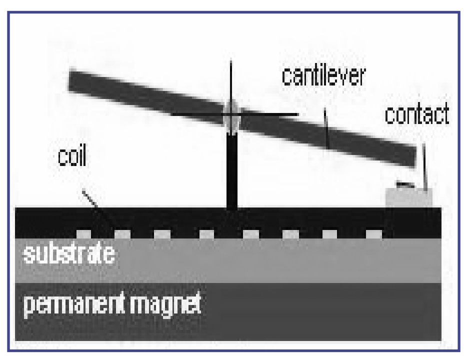

Figure 6. Magnetic Actuation [2]

power while being compatible with CMOS operating levels. A three electrode design significantly reduces the risk of self actuation while providing latching capabilities. Thicker co-planar waveguide helps in carrying higher power RF signals while a stiffer beam between the actuation area and the contact gives lower contact resistance. The switch described here incorporates all of the above mentioned features to some extent.

3.0 Design

3.1 Specifications

3.1.1 Actuation voltage

Actuation voltage is applied to the actuation electrodes of the switch to bring about a change the state of the switch. Typical actuation voltages of high power switches range anywhere between a few tens of volts [5] to nearly a hundred volts. This is an important factor in the design of the switch as this alone decides the compatibility of the switch with other circuitry on the die. In some cases, though the actuation voltage is high, voltage scaling circuitry is used to make the switch compatible with the interface circuitry. This approach consumes precious real estate on the wafer. The main factors influencing the magnitude of the actuation voltage are electrode spacing, area of actuation electrode and dielectric material in between the two electrodes [6].

$$Vp := \sqrt{\frac{\left(8 \cdot K \cdot d^3\right)}{27 \cdot A \cdot \varepsilon}}$$

$$k := 3 \cdot E \cdot \frac{I}{L^3}$$

$$I := w \cdot \frac{t^3}{12}$$

L: Length of the beam
K: Spring Constant
W: width of beam
d: Air gap
t: Thickness of beam
A: Area of membrane
ε: Permitivity of free space

Taking the actuation voltage to be 5 Volts and taking the actuation electrode area to be $300\times300\mu m^2$, the air gap to be 2 micrometers. This is for a structure made with LPCVD silicon nitride (Young's modulus of 290 Gpa) and with a thickness of 4 micrometers and width of 50 micrometers. The length of the beam comes out to be 300 micrometer for the given assumptions.

3.1.2 Power Handling

The power handling [7] capacity of the switch is mainly determined by the properties of the transmission line. We can compute the dimensions of the transmission line that can handle 25 watts of power. Assuming the voltage that is applied on the transmission is 10 volts, the resistance of the line can be at most 4 ohms. Fixing the dimensions of the transmission line to be 20 micrometers wide and 1 micrometer thick, with a resistivity of 221×10^{-10}/ ohm×meter (Gold) we find the resistance to be about 0.55 ohm. The maximum current density that a gold interconnect can handle is 1.8×10^5 A/cm^2 with recovery. The current density of the transmission line is found to be 33.71 A/cm^2, which is well within the tolerance limit.

3.1.3 Insertion Loss

Introduction of additional circuitry into a system leads to losses. Factors contributing to loss in the switch are contact resistance and resistance of the wave guide. Contact resistance is a function of the contact force that is generated when the switch is turned ON which in turn is a function of the actuation voltage, stiffness of the beam and the contact spacing. Insertion loss is a measure of how much loss is being introduced into the system due to the switch. The lower the insertion loss the better. Insertion loss is given as $20\times\log(V_{out}/V_{in})$. Typical insertion losses that have been reported are in the range of –0.1dB to –0.5dB at 40GHz.

3.1.4 Isolation

Isolation determines how well the output is isolated from the input. Higher isolation translates to less coupling between the output and input ports. Isolation of 26dB at 40GHz has been reported [8]. Isolation is dependent on the spacing between the input and output ports or the OFF state capacitance of the switch. The OFF state capacitance can be improved by moving the contact arm as far away from the wave guide as possible when the switch is OFF.

3.2 Process feasibility

Some of the switches that have been proposed have excellent characteristics but cannot be integrated into a typical CMOS process flow. Process compatibility has become a major concern as more and more MEMS technology is being integrated to systems [9]. Some of the major processing steps in the fabrication of the switch are given below. It can be observed from this flow that no special processing steps are required for the fabrication of the switch, apart from a few minor changes in the process. We've used gold in our process only for convenience. More CMOS metals could be substituted. Metal is the material for the coplanar wave guide (CPW). Gold is deposited via electroplating and pattered to form the CPW and the lower electrode of the switch (Figure 8). A thick layer of PECVD oxide to form the spacer between the middle and the lower electrode is deposited and patterned to form the anchor for the structure (Figure 8). The main structure is formed using PECVD nitride. A 2-micron thick nitride is deposited and patterned to form the lower part of the electrode (Figure 9). This also acts as an insulator between the middle and the bottom electrode. A thin layer of gold is patterned to form the middle electrode (Figure 10). A second layer of nitride is deposited to form the top part of the electrode and act as an insulator between the top and the middle electrode. In the same step a trench is formed to make way for the contact of the switch (Figure 11). The contact is formed by electroplating gold (Figure 12). The top electrode is formed by sandwiching a thin layer of gold between a layer of sacrificial oxide and patterned nitride that provides structural support for the top electrode (Figure 13). The structure is released by removing the sacrificial oxide layer that has been deposited. The released structure is shown in Figures 14 and 15.

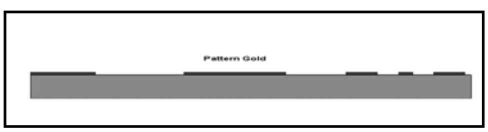

Figure 7. Deposit and pattern Gold

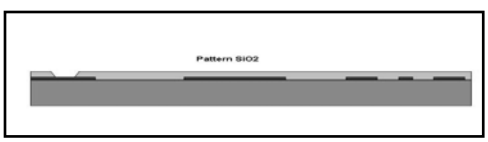

Figure 8. Deposit and pattern oxide

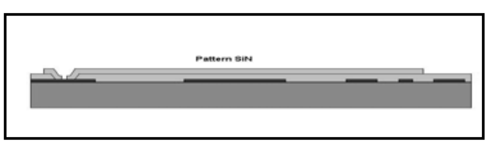

Figure 9. Deposit and pattern Nitride to form anchor

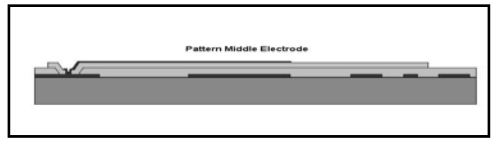

Figure 10. Pattern Gold to form middle electrode

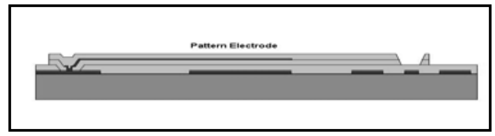

Figure 11. Pattern nitride to form contact area

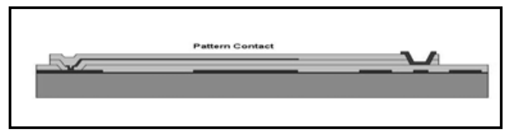

Figure 12. Pattern contact

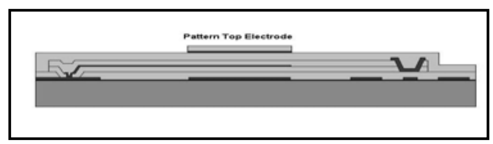

Figure 13. Pattern Top Electrode

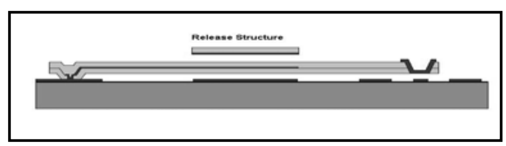

Figure 14. Released structure (profile view)

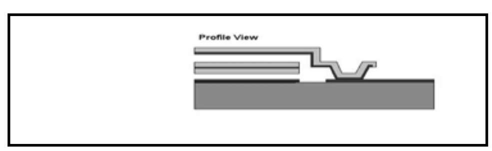

Figure 15. Released structure (Side View)

4.0. Operation

The switch consists of three stacked electrodes. The middle electrode is movable and the top and bottom electrodes work in a push pull manner.

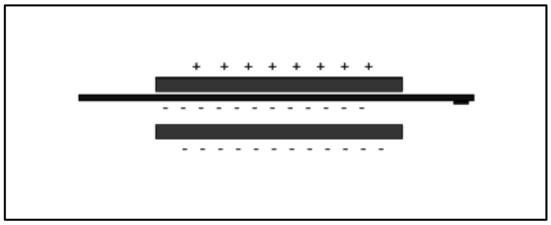

Figure 16. Potentials on the electrodes with switch OFF

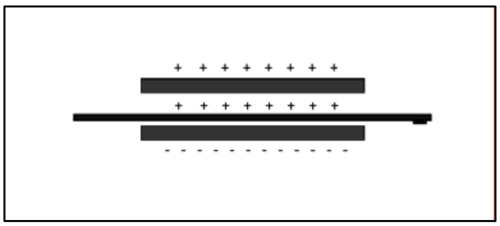

Figure 17. Potentials on the electrodes with switch ON

A simple illustration of the switch is shown in Figure 16. The top and the bottom electrodes are maintained at a constant potential while the middle electrode is charged to a positive or a negative potential to move the beam up or down. Since there are two forces acting on the beam it can be actuated with a lower potential than is normally required to a similar switch. When the switch is turned ON the part of the beam connecting the actuation electrode to the contact area is stiff enough to transfer most of the contact force between the contacts. The interesting thing to be noted is that the switch does not succumb to self actuation as it is latched in the OFF state.

5.0. Simulations

5.1 Introduction

FEA (finite element analysis) consists of a computer model of a material or design that is loaded and analyzed for specific results. Mathematically, the structure to be analyzed is subdivided into a mesh of finite sized elements of simple shape. Within each element, the variation of displacement is assumed to be determined by simple polynomial shape functions and nodal displacements. Equations for the strains and stresses are developed in terms of the unknown nodal displacements. From this, the equations of equilibrium are assembled in a matrix form which can easily be programmed and solved on a computer. After applying the appropriate boundary conditions, the nodal displacements are found by solving the matrix stiffness equation. Once the nodal displacements are known, element stresses and strains can be calculated.

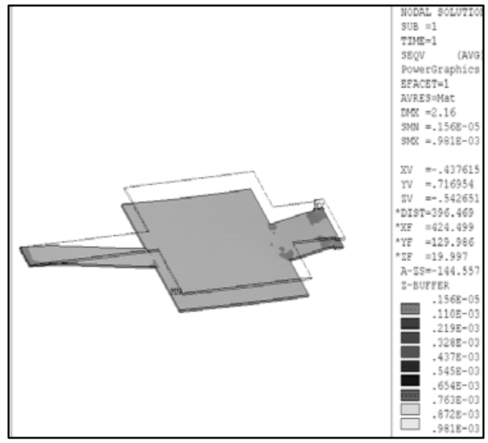

Figure 18. Snapshot of switch showing stresses across it

5.2 Structural

ANSYS® and Coventorware®, two of the leading finite element analysis tools for mechanical simulations, were used to test the structural integrity of the switch.

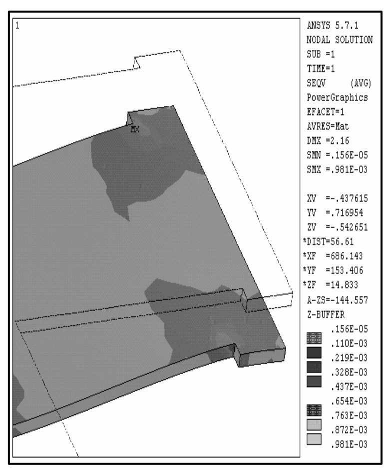

Figure 19. Snapshot of stresses near the contact of the switch

The switch was put through a simulated deflection and the stresses in the beam measured. The stresses in the beam near the contact area are shown in Figure 19. The stress gradients are shown in shades of grey, lighter denoting lower stress and darker being higher stress. The maximum stress in the simulated beam was 0.842×10^{-3} N/μm^2 which is well below the yielding point of the material. The contact force between the CPW and the beam was 95mN. It has been shown that contact force is directly related to the contact resistance [10]. Contact resistance for a contact force of 95mN was determined to be 50 mΩ.

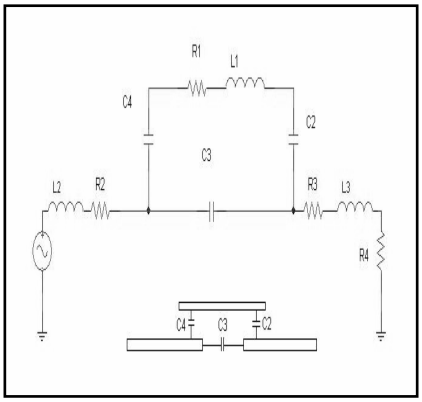

Figure 20. Electrical equivalent of the switch in OFF state

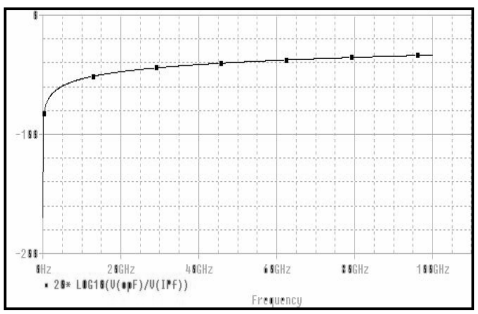

Figure. 21 Frequency response of switch in OFF state, Isolation characteristics

5.3 Electrical

The electrical characteristics of the switch were simulated using PSPICE®. The electrical equivalent of the switch in the OFF state is shown in Figure20. Capacitances C2 and C4 represent the coupling capacitance between the CPW and the contact area of the switch in the OFF state and this is reduced by increasing the spacing between the CPW and the contact in the OFF state. C3 represents the coupling capacitance between the input and the output ports of the CPW. Resistances R1, R2 and R3 are the resistive elements of the CPW and the contact. L1, L2 and L3 are the inductive components of the CPW and the switch. A frequency analysis of the above model gives the effectiveness of the switch in isolating the input and the output ports of the switch. A plot of the isolation is given in Figure 21. As can be observed the switch has very good isolation of 40dB at 50GHz and about 35dB in the 60-100GHz. This is significant as most solid-state switches cannot provide this kind of isolation. Electrical equivalent of the switch in ON state is shown in Figure 22. Capacitances C2 and C4 are no longer present as contact has been made between the CPW and the cantilever.

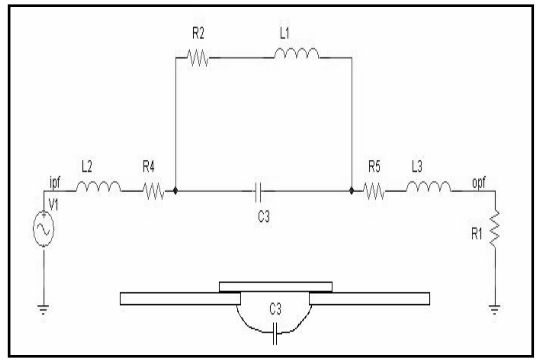

Figure 22. Electrical equivalent of switch in ON state

Coupling capacitance between the input and the output ports of the switch still exist as there still is coupling between the two through the substrate and through the air. Additional factors that come into play are the contact resistance between the contact beam and the CPW.

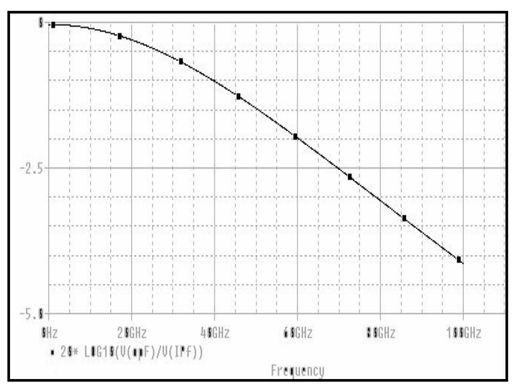

Figure. 23 Frequency response of switch in ON state, Insertion loss characteristics

The contact resistance is determined by the amount of contact force that can be generated by the actuation mechanism. A stiff connecting beam between the actuation area and the contact ensures this is low. A frequency analysis of this model gives the insertion loss of the switch. Results of this simulation are shown in Figure

23. Insertion loss of the switch is below 2.5dB for frequencies below 70Ghz and between 2.5dB and 5 dB for frequencies between 70Ghz and 100Ghz.

6. Fabrication

The switch is being fabricated at Arizona State University's clean room. Some specialized processes were developed for the switch. Non-cyanide based gold plating solution was used to decrease the health risk involved when electroplating gold. CVD recipes had to be enhanced to increase the deposition rates of the oxide and nitride films. Figure 24 shows a picture of the switch before release.

7. Conclusions

All the simulations point to the fact that a RF MEMS switch that can be actuated with a CMOS compatible voltage while handling RF powers in the order of a few watts and having latching properties is feasible. The feasibility of the design is supported by the fact that the

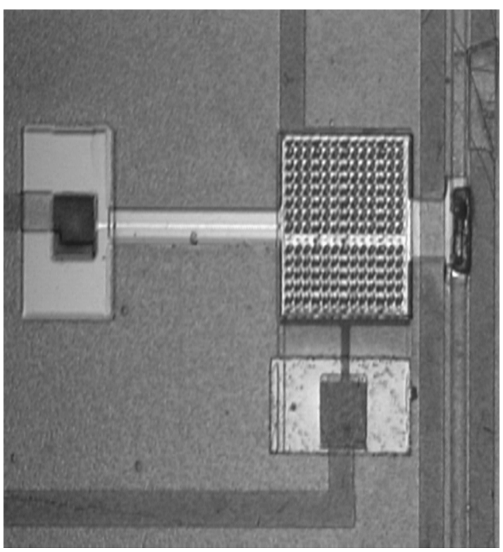

Figure 24. Image of switch before release

fabrication of the switch is near completion. To overcome selectivity issues in the etching of oxide and nitride we are working on using aluminum as the sacrificial layer

Acknowledgement

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