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Design and Simulation of Radio Frequency Micro Electro Mechanical Capacitive Shunt Switches

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Abstract

Radio Frequency Micro ElectroMechanical (RFMEM) switches play an important role in microwave switching. The demand for low voltage, low insertion loss, high Isolation RF MEMS capacitive switches for high frequency (10-40 GHz) applications has led to the development of MEMS based switching devices in the RF domain. This work reports the design and simulation of RF MEMS capacitive shunt switches for K and Ka bands. The switching element consists of a thin gold membrane which gets actuated over a transmission line under an applied bias. The dc simulation is carried out in CoventorWare and the designed switch is found to actuate at 18.75 volts. HFSS simulation results demonstrate an acceptable RF performance with an insertion loss of 0.25 dB in the range 20-35 GHz and an isolation better than 20 dB beyond 20GHz.

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Keywords: RF MEM; insertion loss; isolation; capacitive; actuation

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1. Introduction

RF MEMS switches are one of the most fundamental structures of MEMS technology. RF MEMS switch technology has been under intense research for the last 10-15 years and is being touted as a viable alternative with superior RF performance over traditional solid state switches. RF MEMS switches are prime candidates to replace conventional GaAs field effect transistor (FET) and p-i-n diode switches, mainly due to their ultra low insertion loss, high isolation, excellent linear characteristics and miniscule power consumption. These capacitive shunt switches are electrostatically operated, consuming essentially no DC power. This makes RF MEMS switches suitable for hand-held devices, satellite and space systems.

Since these devices are highly linear, they offer an excellent choice for broadband communication with high dynamic range. Various designs of capacitive MEMS shunt switches with membranes made out of nickel[2], aluminum[1], gold[5], and copper[1] have been reported in literature for a variety of applications such as phase shifters, reconfigurable filters and tuners. The structure of all these reported designs consists of a lower electrode (transmission line), a thin

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dielectric layer deposited over the transmission line and a movable thin membrane hanging over the dielectric shunting the transmission line.

1.1. RF MEMS Capacitive Shunt Switches

In capacitive switches (actuating membrane is in shunt with the Coplanar waveguide transmission line), a metal membrane is pulled down onto a dielectric layer, usually by electrostatic means, to form a capacitive sandwich. At high frequencies, this capcitive sandwich acts like a shunt capacitor with a 100:1 ratio (actuated:unactuated). Thus the mechanical deformation of the metal membrane causes the switch to efficiently change from a high impedance to a low impedance. However this performance of the RF MEMS switches comes with some trade-offs as well compared to their solid-state counterparts. These include dielectric charging[3], high pull-down voltage and slow switching speed. The pull-down voltage is very decisive for commercial applications. There exists great challenges to lower the actuation voltage using different methods including electromagnetic and thermal actuation[4], lowering the spring constant of the membrane and gap height. Several methods have been proposed to improve the performance characteristics of RF MEMS switches with primary focus on lowering actuation or pull-down voltage. Although there is currently tremendous amount of research in RF MEMS devices, reliability and packaging of the switches continue to be problematic.The switches are limited in their power handling capability as well.

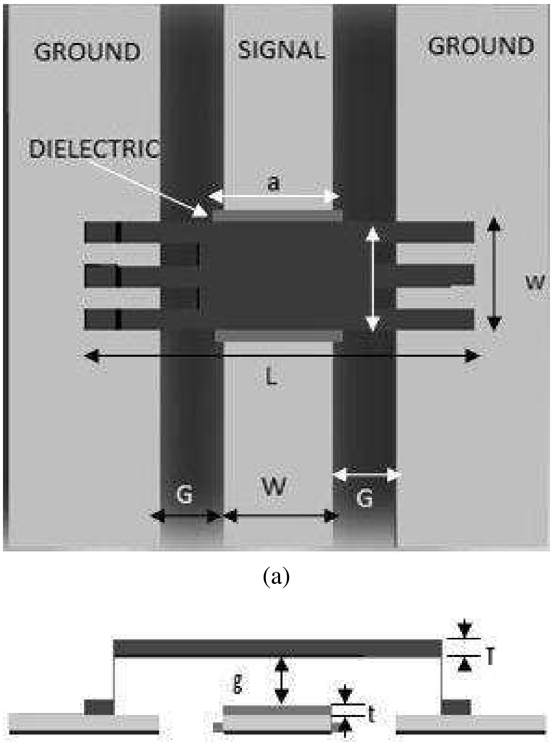
1.2. Proposed Shunt switch

The single MEMS switch is fabricated on a CPW transmission line with dimensions of G/W/G = 60/100/60 (all in μm).The selected CPW dimensions corresponds to a characteristic impedance (Z0) of 50 Ω. A coplanar waveguide (CPW) consists of a centre conductor with semi-infinite ground planes on either side. Principal advantage of CPW at millimeter wave frequencies is that the signal grounds as well as signal line are on the on the same plane. This simplifies the fabrication process and allows easy integration of shunt and series circuit elements.The substrate used is high resistivity silicon (4000 Ω-cm) of 500 μm thick and relative dielectric constant of 11.7. The beam length (L) shunting the trans- mission line, beam width (w), beam thickness (T) and the air gap between the beam and transmission line (g) are shown in Figure 1(a) and (b). A DC control voltage actuates the membrane for switching action. During unactuated state, the RF signal travels down the transmission line unaffected from input port to output port. This is ON sate of the shunt switch.

When a control voltage is applied between the beam and the transmission line, the electrostatic field forces the membrane to deform downwards. The elastic force due to the membrane stiffness balances the electrostatic force until the threshold voltage is reached. When the control voltage exceeds the threshold voltage (also called actuation voltage or pull-down voltage), the field overcomes the elastic force and pulls the membrane down on to the transmission line, presenting an RF short. This is OFF state. On removal of control voltage, the elastic force brings the membrane back to the original position.

1.3. Pull-in voltage

Most RF MEMS switches generally employ electrostatic actuation to overcome the spring force leading to relatively high dc voltage of the order of 20-60 V for switching heights of 2-2.5 μm. This brings up the issue of additional CMOS integrated up converter to raise the usually used 5 Volts control voltage to the required level. The actuation voltage is an important index of RF MEM switch function. This will directly impact the circuit design and performance of the whole system such as the system size, power consumption etc. Simple beam theory gives a relation between the flexibility degree of the beam and pull-in voltage. Thus Pull-in voltage V_p and switching time t_s are given by equation 1 and 2.[6].



(a)

(b)

Fig. 1. RF MEMS switch (a) Top View (b) Side View

Equation 1 shows the impact of beam geometry on pull-in voltage. Membrane length exhibits strong inverse relation with the pull-in voltage where as beam thickness shows strong direct relation. Pull-in (V_p) is directly proportional to the airgap $g^{\frac{3}{2}}$

$$V_p = \sqrt{\frac{8\,k\,g^3}{27\,W\,w\,\epsilon_0}} \tag{1}$$

$$t_s = 3.67\frac{V_p}{V_s\sqrt{\frac{k}{m}}} \tag{2}$$

Where k is the spring constant of the membrane, m is the effective mass, V_s is the switching voltage, g is the air gap between the beam and the transmission line, W is the width of the CPW signal line, w is the width of the beam.

1.4. DC Analysis

Design and detailed DC analysis of RF MEMS switches with respect to beam geometry is carried out in FEM based commercial software CoventorWare. Fig.2 illustrates the dependence of pull-in voltage on the membrane material properties. It has been observed intuitively from simulation that, for the same beam geometry, switch with aluminum membrane has the lowest pull-in voltage since aluminum has the lowest Young's modulus (70x10^9 N/m^2). Simulation results show that the switch with aluminium membrane actuated at 18.75 V where as with gold membrane (Y=78x10^9 N/m^2) the pull-in occurs at 20.625 V. The flipside is that high conductivity metals such as gold and aluminum have low melting point and thus low thermal stability resulting in plastic deformation of the membranes at relatively low temperature ($< 200^0C$). High melting point metals such as Platinum show plastic deformation only at

Table 1. Geometrical dimensions and material property of the Proposed Capacitive shunt Switch

Geometry and Material parameter	Dimension in (μm) and parameter values
CPW configuration (G/W/G)	60/100/60
Length of the membrane (L)	300
Width of the membrane (w)	100
Thickness of the membrane (T)	1
Gap between the transmission line and membrane (g)	3
Dimension of dielectric layer (a*a*t)	120*120*0.2
Dielectric Constant of (Si_3N_4)	$\epsilon_r = 7.4$
Dielectric constant of Si	$\epsilon_r = 11.7$

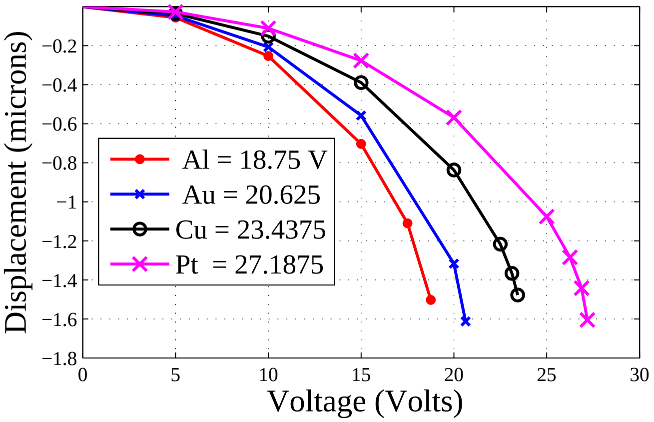


Fig. 2. Pull in voltage for various materials

high temperatures which makes them attractive for use as membrane material in RF MEM switches.[7]

1.5. S-Parameter Analysis

The RF performance of the switch is quantified by its insertion loss, return loss and isolation. Basically, it is desirable to have low insertion loss and high isolation. RF performance can be improved by modifying the beam geometry. When the switch is unactuated, up state capacitance, C_u, will be very small and bridge inductance and resistance can be neglected. Insertion loss include substrate loss, conductor loss due to skin effect and reflection due to impedance mismatch.

It has been observed from RF simulation results that insertion loss of the switch when it is in the ON state is observed to be better than 0.25 dB from 10 to 35 GHz.The radiation and conductor losses can be minimized by using highly conducting materials such as gold for membrane. The return loss (S11-ON state) is due to reflection of the RF energy by the parasitics present because of the proximity of the actuating membrane to the transmission line below. The return loss is found to be better than 25 dB in the range 10 to 35 GHz. The magnitude of insertion loss and return loss are presented in Fig. 3. The key RF characteristic, isolation offered between the input and output (S12-OFF state) is found to be better than 20 dB beyond 20 GHz. The OFF state return loss is less than 0.5 dB in the range 20-35 GHz and are presented in Fig. 4

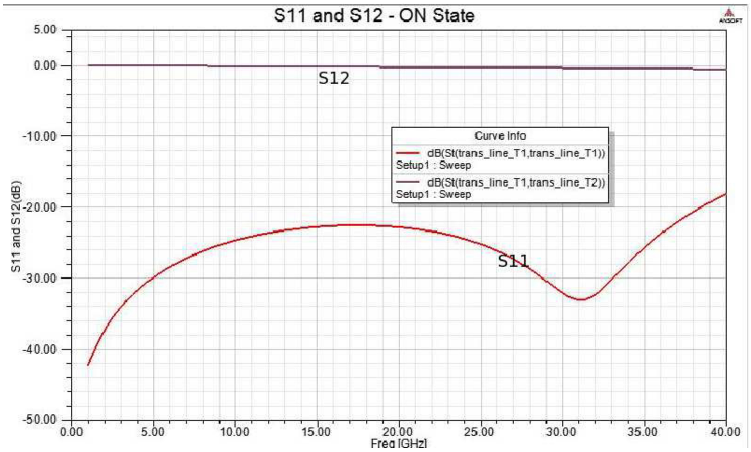


Fig. 3. Insertion loss and Return loss

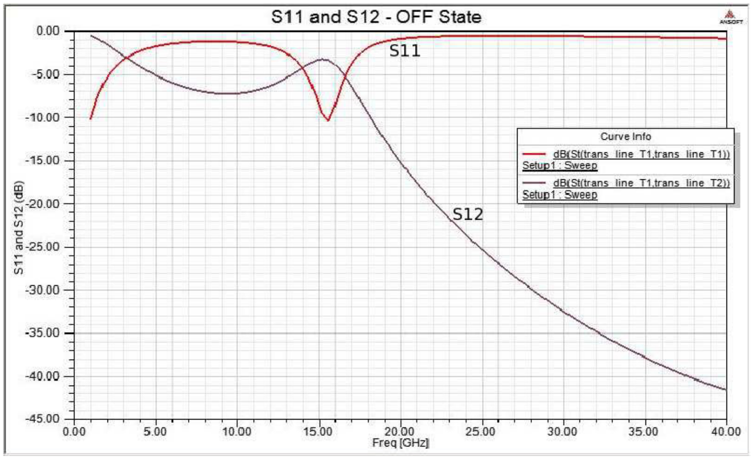


Fig. 4. Isolation and Return loss

2. Conclusion

Low voltage capacitive MEMS switch is designed and simulated in CoventorWare. The switch using gold membrane is actuated at 18.75 volts. RF analysis of the device is performed in Ansoft HFSS. The insertion loss of the switch is observed to be better than 0.25 dB in the frequency range 10-35 GHz. The ON state return loss is found to be better than 25 dB in the same range. Isolation of the switch is better than 20 dB beyong 20 GHz and the OFF state return loss is 0.5 dB in the same range. The results show that the device can be operated in K and ka bands with satisfactory performance.

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