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An Ultra Wideband, Novel and Reliable RF MEMS Switch

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This paper presents the design and characterization of wide band ohmic microswitch with an actuation voltage as low as 20~25 V, and a restoring force of 14.1 μN. The design of the proposed switch is primarily composed of an electrostatic actuator, bridge membrane, cantilever (beam) and coplanar waveguide, suspended over the substrate. The analysis shows an insertion loss of -0.002 dB at 1GHz and remains as low as -0.35 dB, even at 100 GHz. The isolation loss of the switch is sustained at -21.09 dB at 100GHz, with a peak value of -99.58 dB at 1 GHz and up-state capacitance of 4 fF. To our knowledge, this is the first demonstration of a series contact switch, which works over a wide bandwidth (DC-100 GHz) and with such a high and sustained isolation, even at high frequencies and with an excellent figure of merit (f_c=1/2.pi.Ron.Cu= 39.7 THz).

Keywords: RF MEMS, Quartz substrate, Figure of merit, High isolation, Wide bandwidth, Low actuation voltage, Broadband antennas

1. INTRODUCTION

The design of the RF MEMS series switch has matured over the years, with many series switches [1-4] available today. RF MEMS switches are an attractive replacement to the existing semiconductor switches, such as PIN diodes and GaAs FETs. Their mechanical switching action and higher cutoff frequency makes them superior to other semiconductor switches. Their salient features include good linearity, very low insertion loss in ON state and high isolation in OFF state [5-8]. RF MEMS switches with good performance have shown anticipated commercial production in specific RF applications. However, limitations including low switching speed, high actuation voltage (voltage required for operation of the switch), reliability issues and low power handling capabilities [9] pose a major bottleneck to the implementation of RF MEMS. Thus, along with RF Response, actuation voltage and reliability also become major concerns to be addressed while designing the switch.

It is believed that RF MEMS switches will be high relevant in the field of satellite communications, test equipment of RF instrumentation, telecom infrastructure in base stations, military tactical radio and phased arrays. They are expected to have great pertinence in mobile phones, consumer electronics and also in IT automotives, such as anti collision radar and roof antennas. MEMS technology is supposed to bring reformation in the field of electronics as it would help to create radical devices and applications that will have notable impact on the performance of communications systems and circuits. RF MEMS switches are mainly an amalgamation of mechanical switching action and electromagnetic actuation.

RF MEMS switches can be broadly classified as: metal-to-metal contact (series) switches and capacitive (shunt) switches. Both of these switches employ varying configuration to be driven either in ON state or OFF state. In a series contact switch, cantilever is fixed at one end while the other end is free to move, whereas the capacitive switches utilize bridge membranes that are fixed at both ends. The operation of a series switch is initiated by applying a bias voltage under the strip which after reaching a certain value (pull in voltage) causes the strip to snap down on the bottom electrode. The opposite tensile force is unable to override the electrostatic force; hence the cantilever bends downward thereby shorting the input and output t-line making the switch conductive. In metal shunt switches, the layer of dielectric between the parallel bridge and t-line forms a capacitor. The switch is driven in OFF state by creating a small resistive

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path between the t-line and the ground. For the switch to be operated in ON state, the applied pull in voltage must be removed, which would in turn tunnel the complete RF signal from source to drain.

This paper presents an unprecedented approach of designing a robust low loss MEMS series switch providing an excellent RF Response. The switch was designed keeping in mind the need for a series switch that can operate over a wideband. Existing MEMS series switches work on 0~60 GHz, [15] but the proposed switch is working efficiently upto 97 GHz, thus making it more suitable for wide band applications and showing an exception from the previously established norms. The proposed switch's novel design gives it the power to route the signal from the signal line to the ground when the beam is in upstate through a bridge (increasing isolation manifolds) and this design alteration makes it superior in performance from earlier series switches. The switch's performance is better than those previously proposed [10-14] and it operates on a wide frequency band.

2. DESIGN APPROACH

The design of the proposed RF MEMS series metal contact switch is very much inspired by the Radant Switch [13]. The switch has been designed with 2 crucial modifications. One being the non-uniform cantilever with low spring constant, which requires lower actuation voltage, and the other being the Bridge Membrane, which is positioned over the cantilever. A non-uniform cantilever improves the insertion of the switch while the bridge guides the signal from the cantilever (in up-state) to the ground, and hence enhances the magnitude of isolation and sustains the same at higher frequencies. When the cantilever is in up-state, it makes contact with the bridge, which improves the isolation manifolds and when the switch is actuated, the cantilever smacks down, creating a connection between the input t-line and output t-line allowing almost the entire of the signal to pass, resulting in a very low insertion loss. Gold (Au) has been used previously due to its anti stiction property to achieve the constraint of low voltage .The switch has been designed over a Silicon (Si) substrate of a thickness of 100 μm with the coplanar waveguide dimensions 55/90/55 μm. Previously series switches operated over the range from DC-60 GHz. Some of the switches in the past, [13,14] have recorded good performance. Comparison between the above mentioned switches and our proposed switch in shown in Table 1.

Table 1. Comparison between the radant, rockwell and proposed switch.

PARAMETER	CONVENTIONAL SWITCH I [13]	CONVENTIONAL SWITCH II [14]	PROPOSED SWITCH
Length (μm)	75	250	110
Width (μm)	30	150	50/90
Height (μm)	1	2.5	3
Spring Constant (N/m)	>100	15	4.7
Actuation Area (sq. μm)	15 × 25	75 × 75	10 × 90
Actuation Voltage (V)	60-80	50-60	20-25
Cu (fF)	4	1.75-2	4
Insertion (dB)	0.15 (0.1-20 GHz)	0.2 (50 GHz)	0.1(0.1-77 GHz) 0.2 (92 GHz)
Isolation (dB)	40 (4 GHz)	50 (4 GHz)	78 (4 GHz)
Isolation (dB)	27 (20 GHz)	30 (40 GHz)	39 (40 GHz)
Isolation (dB)	-	20 (90 GHz)	24 (90 GHz)
Isolation (dB)	-	-	20 (105GHz)

2.1 Design fundamentals

The suggested switch is designed on a 100 μm thick substrate of Quartz (SiO_2). The coplanar waveguide (CPW) line, which is characterized at 50 ohms, is mounted over the switch for the RF signal transmission. Hafnium dioxide (HfO_2) was used as substrate dielectric, because of its high dielectric constant (K = 25). The working principle of the switch is shown in Fig. 1. The operation of the switch is mainly governed by the modifications carried out in the design of the cantilever and the bridge introduced above the cantilever.

Behavior of the presented switch is controlled by the gate voltage. To provide an electrical path between the drain and the source, the gate voltage equivalent to the actuation voltage is applied, while contact between the drain and underside of the beam is made using a platinum-group metal, which helps to obtain a stiction-free performance and improve the lifetime compared to the more commonly used Gold (Au) contacts [13].

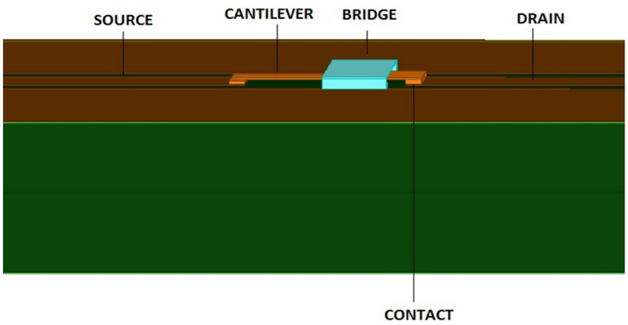

Fig. 1. Top view of the switch demonstrating the source, drain, cantilever & bridge.

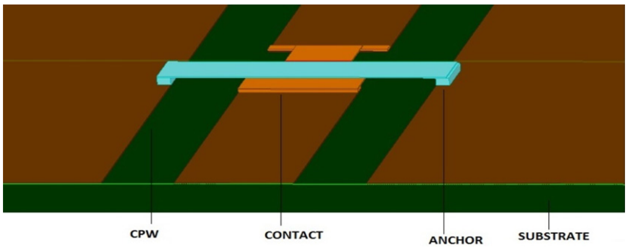

Fig. 2. Front view of the metal contact RF MEMS switch.

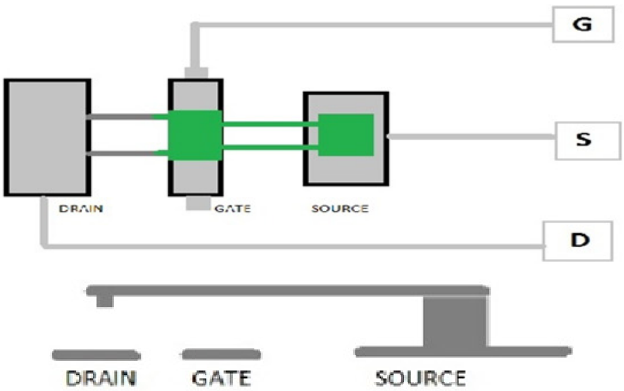

Fig. 3. Schematic representation of the microswitch using FET terminology.

2.2 Selection of material

One of the prime requirements for switch fabrication is a smooth and flat surface of the substrate, undamaged and free from dislocations. Choice of a stable material thus becomes a necessity. Quartz (SiO_2) can serve the purpose, because it possesses uniform electrical properties and chemical resistance, which is mandatory for fabrication. It has a very high melting point (1,670 °C), thus can withstand high temperatures. Bridge and Cantilever have been designed using Gold (Au) due to its high electrical conductivity and anti-stiction tendencies [15]. Platinum (Pt), because of its hardness and high melting point, is used to design contacts as it will protect the contacts from pitting and damage due to overheating. The specifications of various components of the switch are provided in Table 2.

Table 2. Switch specifications.

Component	Length	Width	Depth	Material
Substrate	1,000	600	100	Quartz (SiO_2)
CPW(GSG)	90	600	1	Gold (Au)
Gap	NA	NA	3	NA
Contacts	90	10	3	Platinum (Pt)
Bridge Membrane	214	40	1	Gold (Au)
Anchors	10	40	4	Gold (Au)

2.3 Design of the cantilever

The cantilever is tapered towards the source and broadened towards drain as shown in Fig. 4. Reason for choosing such design of cantilever is because of its superior performance in terms of insertion loss. A comparison describing the effects of two beams (uniform and non-uniform) are depicted in Fig. 5. The

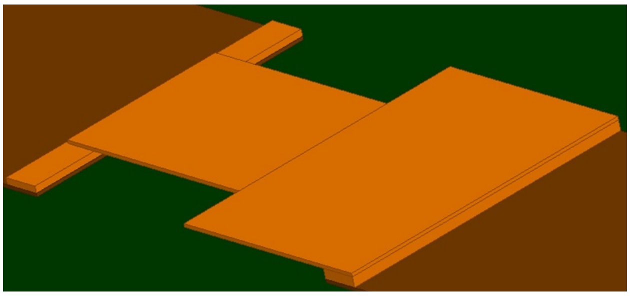

Fig. 4. Structure of the cantilever.

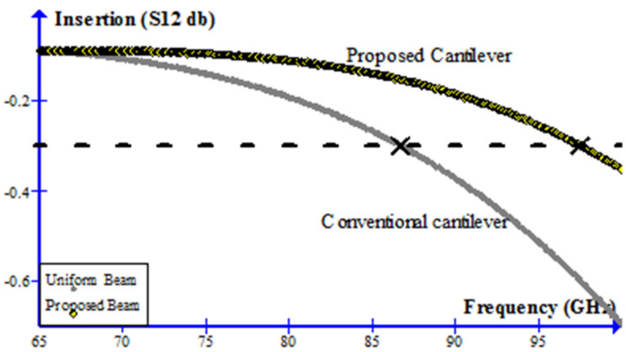

Fig. 5. Insertion loss of simple uniform cantilever vs. proposed cantilever.

geometry of the cantilever highly affects the insertion loss which is well noticeable, in the proposed design.

Repeated hitting of a metal over another causes such as pitting and hardening, thereby reducing the contact area significantly, which further increases the contact resistance of the switch. This is even more predominant in cases of metal contact switches. Contact failure strongly depends upon the selection of the contact metal. The Rockwell Science Center [14] demonstrated that the reliability of electrostatic actuation can be improved by tailoring the actuation voltage waveform, as it helps to diminish the impact energy and the resulting degradation of the contact area. When the gate voltage is applied to actuate the cantilever, it does not touch the pull down electrode placed beneath. Thus, a dielectric layer is not needed to isolate the cantilever from the pull down electrode and hence issues like dielectric charging can be avoided.

2.4 The bridge

Inclusion of the bridge has highly revamped the switch response. This simple adjustment improves the isolation and return loss of switch manifolds. The role of the bridge is to provide passage for the signal from source to the ground when the cantilever is in up-state and touching the bridge, thus, aiding in isolation. The bridge is made of Gold (Au) and is 1 μm thick. A comparison has been drawn in Fig. 6, illustrating the advantages of inculcating the bridge in the design.

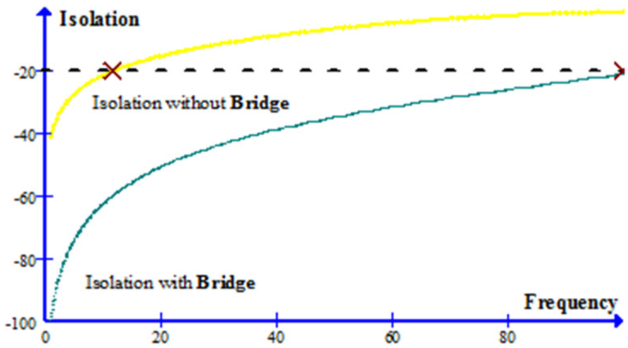

Fig. 6. Isolation with and without using a bridge.

Simulations revealed that the bridge proposed in this paper can improve the performance of the Radant switch [13] (which is considered to be the most mature DC switch as it was demonstrated over more than 10 billion cycles) in terms of the frequency bandwidth of operation and isolation of twice the value can be achieved. The literature demonstrates that the absence of a bridge results in a narrow frequency band. Comparison is shown in Fig. 6 where it can be clearly seen that the bridge brings a great difference in the results.

2.5 Contacts

The contact points are made using a thin layer of Platinum (Pt) to enhance the lifetime of the switch. To increase the power handling capability and decrease insertion loss and resistance, we have to optimize (increase) the contact between the cantilever and the drain.

Contact resistance obtained with Gold (Au) metallization is low in comparison to one using Platinum metal (Pt). This knot of high contact resistance could be released and the overall switch resistance and insertion can be reduced by augmenting the gate area and the contact area. Further reliability enhancement can be achieved by the planting of contact points, called ‘asperities’, on the drain and interior side of the cantilever. These contact points are independent of each other and lead to a fairly low isolation and boost reliability. A tradeoff is required to formulate the number of contact points. With a higher number of contact points, the series capacitance of the open switch increases, resulting in a degradation of the isolation. This degradation becomes more prominent at high frequency [13], but this problem is resolved in the presented design through the use of a bridge that does not allow the increased series capacitance to degrade isolation.

3. ELECTROMAGNETIC CIRCUIT MODELING

Figure 7 shows the equivalent circuit of a series switch. In the down-state, the switch behaves as a simple continuation of the t-line. Because of this behavior, the current distribution of the switch is found to be very similar to that of the CPW t-line. Also, the current is concentrated over the edges of the metal bridge so that holes can be incorporated at the center of the cantilever. This will reduce the air resistance and increase the switching speed of the switch.

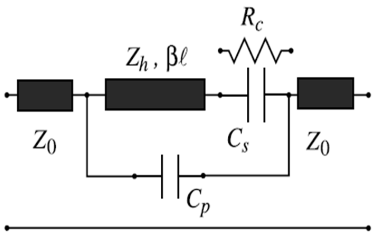

Fig. 7. Equivalent circuit of Inline DC-contact MEMS series switches with one contact area.

3.1 Up-state capacitance

Open ends of the t-line give rise to parasitic capacitance (Cp), electromagnetic software packages can be used for calculations of parasitic capacitance) and series capacitance (Cs) exists between the t-line and the switch metal. Series and parasitic capacitance together constitute the up-state capacitance. The total up-state capacitance of the ohmic switch is the same as that of a shunt switch and is given by:

$$C_u = C_s + C_p \tag{1}$$

The total up-state capacitance of the switch is 4 fF.

3.2 Down-state resistance

At lower frequencies, the down-state resistance can be approximated as the series resistance of the switch and, at higher frequencies, insertion loss is used to represent it. The size of the contact area, the mechanical force applied, and the quality of the metal-to-metal contact affect the contact resistance [13]. The resistance of MEMS series switch is dependent on length and width of the contact area. The measured insertion loss is - 0.1 to - 0.2 dB from 1~95 GHz indicating a total switch resistance of 1~2 ohm.

3.3 Loss

Loss is independent of frequency. A CLR circuit is used for its calculation because of the lower complexity involved in calculation and can be calculated as

$$Loss = 1 - |S_{11}|^2 - |S_{21}|^2 \tag{2}$$

It was found that the loss of the proposed switch is -0.2 dB. This small value of loss indicates the efficiency of the switch to transmit signal with very less loss.

4. RESULTS AND DISCUSSION

Due to the bridge and careful design of the cantilever, the proposed design offers excellent RF characteristics in terms of isolation, insertion loss and return loss. Ansoft HFSS is used for simulation of RF performance characteristics.

Figure 8 shows the insertion loss of the proposed design. As is evident from the figure, the switch has proved its operability over a wide RF spectrum. In line with the knowledge of previous authors, this is the widest RF performance shown by a metal contact switch. Performance of the switch over the RF spectrum is observed between 0~100 GHz.

The isolation loss vs. frequency has been shown in Fig. 9, which demonstrates at peak value of -99.5 dB, which is fairly high in comparison to all other conventional designs. We can consider 3 segments, p, q and r. Bandwidth p includes a narrow frequency range of 0~10 GHz (L, S, C) with isolation above -70

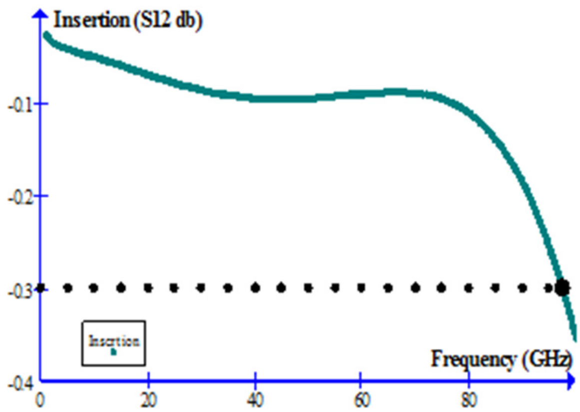

Fig. 8. Insertion loss of the proposed switch.

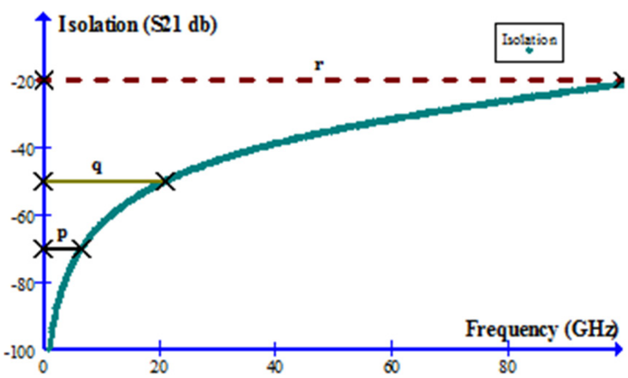

Fig. 9. Isolation loss of the proposed switch.

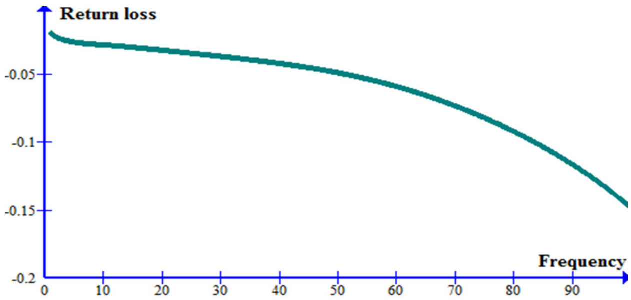

Fig. 10. Return loss of the proposed switch.

Table 3. Improved attributes of the proposed switch.

Frequency (GHz)	Insertion (dB)	Isolation (dB)	Return Loss (dB)
1	- 0.02642	- 99.5812	- 0.02005
10	- 0.05109	- 62.6166	- 0.02880
20	- 0.06993	- 50.7721	- 0.03270
30	- 0.08654	- 43.2854	- 0.03724
40	- 0.09558	- 38.4321	- 0.04235
50	- 0.09575	- 34.9051	- 0.04925
60	- 0.09063	- 31.6194	- 0.05933
70	- 0.08957	- 28.7244	- 0.07354
80	- 0.11119	- 26.0729	- 0.09235
90	- 0.18523	- 23.5606	- 0.11644
100	- 0.35169	- 21.0992	- 0.14855

dB; q includes frequencies from 11~22 GHz where the isolation is above -50 dB, and r includes all the remaining frequency bands where the switch shows isolation above -20 dB.

Discontinuity in a transmission line leads to return loss, which is the loss of the power in the signal returned. Return Loss in OFF state is shown in Fig. 10.

The values of insertion, isolation and return loss at various frequencies are tabulated in the Table 3. It is evident from the table that the switch possesses superior RF performance and is operable over a wide bandwidth.

4.1 Spring constant

The most prominent advantage of the cantilever beam is that it is free at one end and, because of this, any of the residual stress within the beam is released. Moreover, the spring constant does not contain any residual-stress component and, due to the cantilever's free condition at the tip, it does not have any stretching component [15]. The spring constant (k) of the cantilever is much smaller than a fixed-fixed beam with the same (*t/l*) ratio. The calculated value of the spring constant (4.7 N/m) and this low value of spring constant, further lowers the actuation voltage required.

4.2 Actuation voltage

The dimensions of the switch, as mentioned in Table, provide us with an actuation voltage of 22 V, which is indeed very low in comparison with the existing series switches. Since the spring constant (k) and the actuation area (A) are fixed, the value of the actuation voltage completely depends upon the gap in height between the membrane and the signal line (g_o). The actuation voltage (V_p) of the MEMS switch with spring constant (*k*) is given by:

$$V_p = \left(\frac{8kg_0^3}{27\varepsilon_0 A}\right)^{1/2} \quad (3)$$

where ε_0 is the permittivity of free space, g_0 is the gap between the cantilever and signal line, and A is the area of actuation.

4.3 Restoring force

The Restoring Force is the force required to restore the beam to its equilibrium position, as and when the actuation voltage is removed. It is given by:

$$F = -K \times x \quad (4)$$

where K is the spring constant of the beam, and x is the gap between the signal line and the beam. The restoring force of the beam for the proposed design is 14.1 μN.

5. CONCLUSIONS

The proposed series RF MEMS switch results in superior isolation, very low insertion loss and employs a wideband switching circuitry. It has been designed in such a way that it minimizes any stiction problems and reduces contact resistance, promising a greater reliability. The novelty of the proposed switch is the addition of an overhead bridge surpassing the t-line, which exceptionally enhances the RF performance. The bridge proposed is integrated in the design of Radant Switch [10], which showed exceptional reliability. The switch provides excellent isolation of -99.5 dB (peak value) and insertion as low as -0.3 dB up to 100 GHz. The actuation voltage for the switch is 22 V, which is indeed very low in comparison to former series switches. The geometry of the switch is simple, facilitating easy fabrication. Due to its operability over wide range of frequencies, the switch becomes suitable in all wide band and satellite communications.

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