Analysis and design of an all metal in line series ohmic RF MEMS switch for microwave applications

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Abstract: - **This paper presents the analysis, design and simulation of an all metal in line series ohmic RF MEMS switch. The proposed switch is indented to be used in the frequency range between DC and 10GHz. The switching characteristics of the proposed switch fulfill all the requirements as concerns loss, isolation, linearity, power handling and small size/power consumption. The specific design of the cantilever (hammerhead) and the distributed actuation force ensure the reliability and the controllability of the switch and the relatively simple design (all metal) the robustness and high fabrication yield.**

Index Terms: - **All metal in line series ohmic RF MEMS switch, hammerhead, distributed actuation force**

I. INTRODUCTION

The exponential growth of wireless communications requires more sophisticated system design to achieve higher integration, power saving and robustness. System design concentrates in developing high frequency, low scale configurations to follow the trends of the market for smaller, technologically more advanced applications. In the same manner, technological advances in radio-frequency (RF) front-ends, such as reconfigurable antennas, tunable filters, phase sifters, switching networks etc require state of the art switches to allow operation in cognitive wireless networks [1,2,3].

Ohmic RF MEMS switches utilize physical contact of metal with low contact resistance to achieve low insertion loss when actuated. Their isolation is defined by the coupling capacitance of the electrodes when the switch is open. Thus, the ohmic MEMS switches are used where low loss devices are necessary, capable of reliably handling a few watts of RF power and operate in the frequency band from DC to 10GHz [4,5].

The design approach followed in this work was mainly towards the simplicity, the reliability, the controllability and the power handling of the RF MEMS switch, while great effort has been paid in analyzing all possible failure mechanisms, too. The investigation of the proposed design has been carried out using Coventorware 2008 [6], for electromechanical and electromagnetic analysis.

II. DESIGN CONSIDERATIONS AND RELIABILITY ISSUES

The proposed all metal in line series ohmic RF MEMS switch is shown in Fig. 1 & 2. The materials, the shape, the dimensions of the cantilever, the contact area, the gaps between the contacts, the gap between the cantilever and the electrode, the dimensions and distribution of electrodes have been chosen such to fulfill the constraints and reliability issues.

The material chosen to design the proposed switch is gold (Au) due to its exceptional electrical, mechanical and chemical characteristics [7].

To avoid stiction phenomena high restoring force is necessary. Restoring force mainly depends of the stiffness of the cantilever which is determined by the width, the thickness and the Young Modulus of the material and affects significantly the magnitude of the pull down voltage of the cantilever [8].

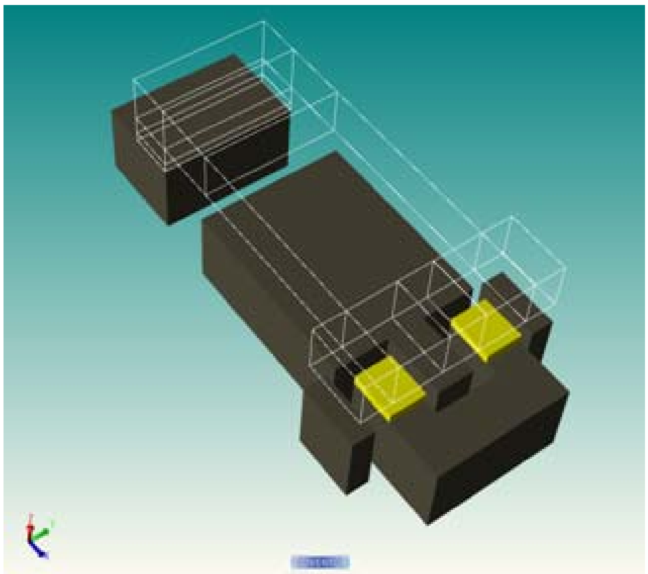

Fig.1. The electrode area

Additionally another way of increasing restoring force is the s-shaped deformation of the cantilever. Initially by applying a pull-in voltage *Vp*, the edge of the upper contact area can be brought down into contact with the bottom contact area. However, in this case, the contact area is small; the resulted contact material deformation also is too small to generate a low contact resistance and the restoring force of the cantilever is not enough to prevent the switch from stiction. The solution is to increase the actuation voltage well above the pull-in voltage *Vp*. Thus, the upper cantilever begins to bend after pull-in, so that additional force is supplied to the contact area.

On the other hand, the contact resistance of the switch depends on many parameters such as the contact materials, the effective contact area, the contact force, the metal deposition process, the surface roughness, the contact cleaning procedure, the surface contamination, the atmospheric environment, the measurement current, and the switching history. Additionally, friction between the contacts caused by cantilever bending may also help to mechanically wipe contaminant films from the contact area maintaining low contact resistance [9,10].

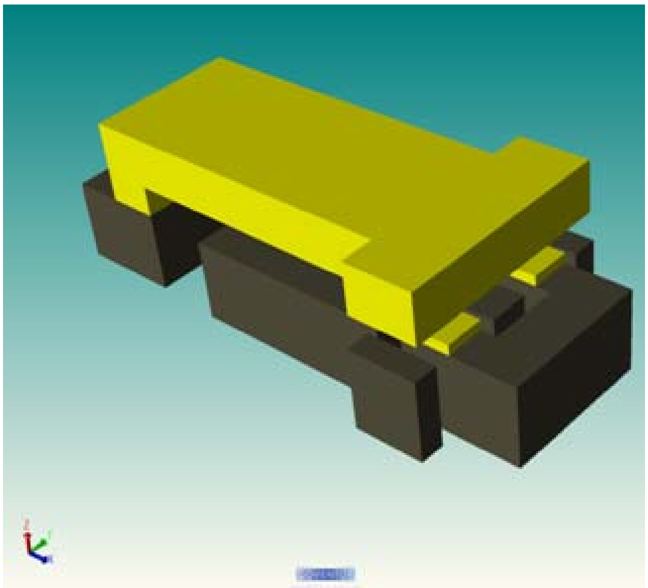

Fig.2. The proposed Ohmic RF MEMS Switch

Besides, a non-uniformed shaped cantilever (hammerhead) and a sophisticated contributed electrode area can keep low the actuation voltage while simultaneously improve the switching control.

Finally, the size and the hardness of the contact area of the switch must be taken into consideration in order to maintain high isolation in the desired frequency range, low contact resistance, high power handling capability, linearity, and a minimum of surface adhesion wear. To meet the above requirements a relatively large contact area has been chosen, which consists of two relative big contact areas 2000um^2 each.

Large nominal contact areas do not directly lower the contact resistance if the contact force is not increased. However, they provide a better heat distribution from the effective contact spots; heated by the dissipated power of the signal current flowing over the contact interface and nonlinearities are avoided [11,12].

III. CONTROLLING THE SWITCH

Under nominal fast pulse switching conditions, when contact is achieved, the contact force is very high due to the high impact velocity of the collapsed cantilever. Instantly, the conductance becomes very high but unstable, due to the bouncing of the cantilever which follows the first contact. Consequently, additional time is necessary for a stable contact force and thereof a stable conductance to be achieved. This bouncing behavior increases the effective closing time of the switch.

Instead of using a continuous step command or a series of square waves to control the electrode, the proposed command uses a series of pulse trains with precisely calculated applied voltages and time intervals, schematically shown in Fig.3. [13].

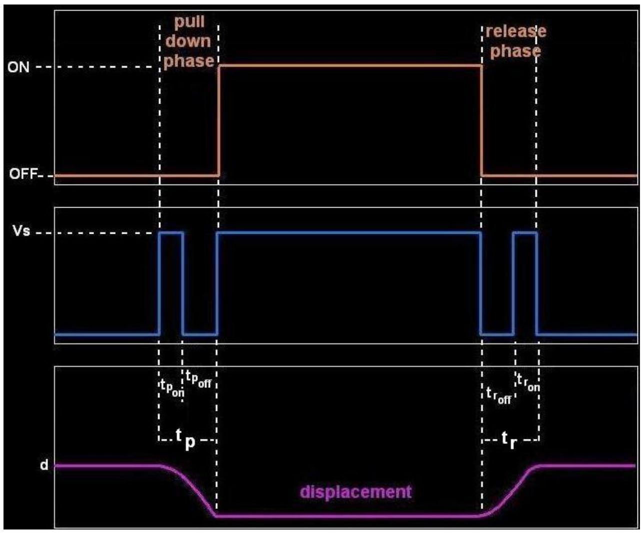

Fig.3. The phases of the tailored actuation pulse

The entire operation can be classified into two phases, the “pull-down” phase and the “release phase”. The pull-in phase mainly concerns the actuation of a contact switch from its original null position to the final contact position. A proper design must achieve a rapid and low impact response (ideally zero velocity) at the time of contact and a fast settling once the switch is released from its contact position back to the null position. Special effort must be paid in the release phase due to the fact that considerable residual vibration at the null position could be generated before settling, reducing the switching rate during a repeating operation and producing undesirable noise, as the isolation of the switch is unstable, during hot switching operation.

IV. SIMULATION RESULTS

The design and evaluation of the proposed ohmic RF MEMS switch has been carried out using the module Architect of the Coventoreware 2008 software package. The simulation results have been extracted under the following environmental conditions: Temperature: 293°K (20°C), Pressure: 730mTorr (1Atm) and Gas type: Nitrogen.

Under fast pulse implementation, undesirable conditions such as great impact forces and bouncing phenomena appeared to the switch, which render its operation problematic, see Fig. 4.

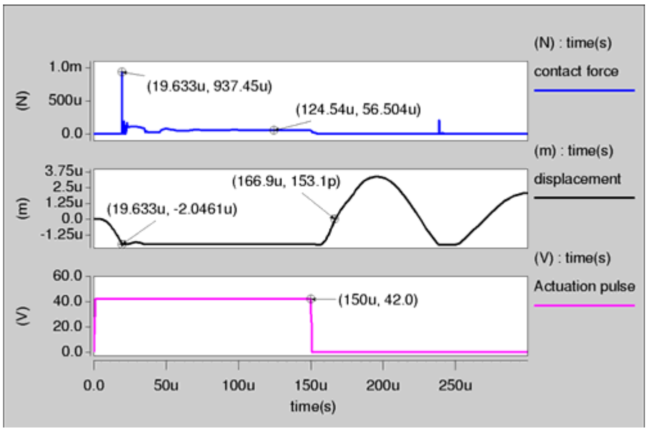

Fig. 4. Switch's behavior under fast pulse

Thus a tailored actuation pulse was implemented to control the switch and its electromechanical characteristics have been obtained via transient analysis.

The tailored actuation pulse is illustrated in Fig.6 and is divided into four sections.

1. The pull down section 0 to 26uSec which is modified to minimize the velocity and consequently the impact force of the switch.
2. The ON state section of the switch, between 26 and 150uSec.
3. The release time section of the switch 150 to 176uSec which is modified to minimize the residual vibration at the null position before settling.
4. The OFF state section of the switch between 176 and 500uSec

The results of the tailored actuation pulse as concerns displacement, conductance, contact area and contact force are illustrated in Fig. 5.

By applying the tailored actuation pulse, high impact force and bouncing phenomena, shown in Fig. 5, have been almost eliminated. Under these conditions:

- The switching time is 26uSec for the ON state transition, 6uSec slower compared to the sharp-pulse implementation. The switching time for the OFF state transition remains at 18uSec but the maximum variation of the cantilever over the null position during the settling time is reduced from 1.66μm to 67nm. The impact velocity is reduced from 23 to 5.4cm/sec resulting degradation in the initial impact force from 917 to 176μN.
- The conductance under stable conditions is 2.6S which corresponds to a resistance of 0.38Ω, and the settling time for that is about 35uSec.
- The contact area graph, shown in the same figure, indicates that full contact 2000μm^2 is obtained at about 35μSec.
- The stable value of the contact force is 56.5μN although that is after a settling time of 35μSec.

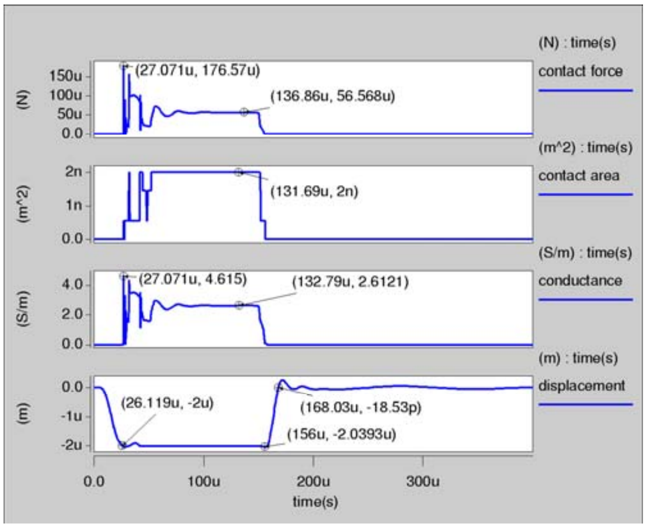

Fig. 5. Switch's behavior under tailored actuation pulse

In RF MEMS it is often supposed that there is no current consumption as there isn't any ohmic contact between the cantilever and the electrode, but this quick movement of the cantilever during the pull down phase and release up phase changes rapidly the capacitance and creates a transient phenomenon. Thus for this small time periods there is an instantaneous current request which can arise up to 4.9μA, as illustrated in Fig.6.

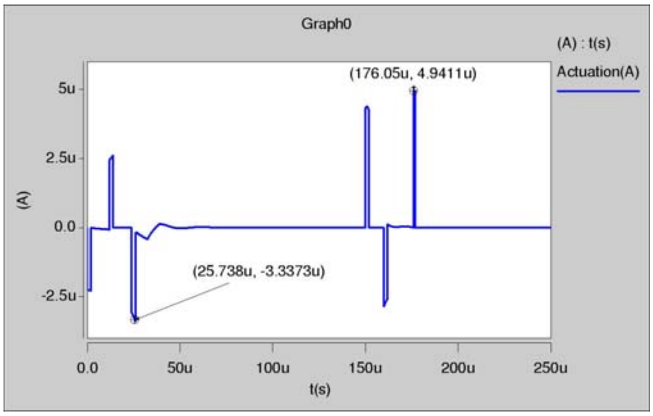

Fig. 6. Bias current demand during switching operation

Last but not least, Fig.7 presents the gas damping influence under nitrogen conditions at 760mtorr. The simulation took into account switch geometry, a non-linear spring model used to model the interaction between the contact and cantilever and a two-dimensional non-uniform squeeze damping effect. The damping force changes as a function of cantilever position and speed and opposes to the electrostatic force. It reaches its maximum just before the switch contacts meet the lower electrodes. At this point the switch is traveling at a maximum speed while the gap distance is reaching a minimum.

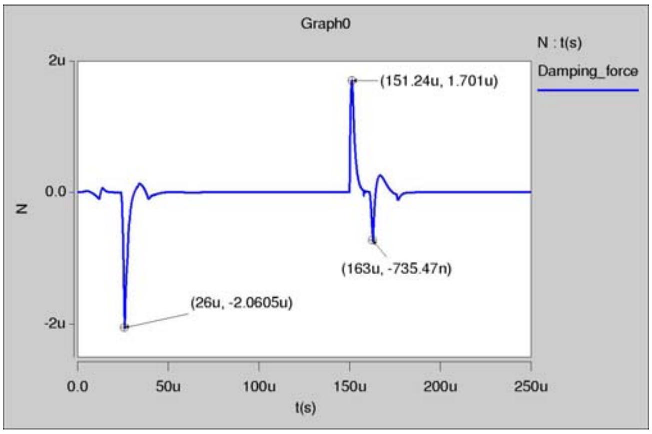

Fig. 7. Damping force graph during switching operation

A. *Hot switching mode of operation*

Below are the results after simulating the new switch under hot cycling mode operation.

The conductance, the contact area and the contact force has been investigated when 1V RF input signal has been applied and are shown in the Fig.8 below. Comparing the results with those without input signal (Fig 5), as concerns their maximum values, it is clear that there is an increment due to added amplitude of the RF signal.

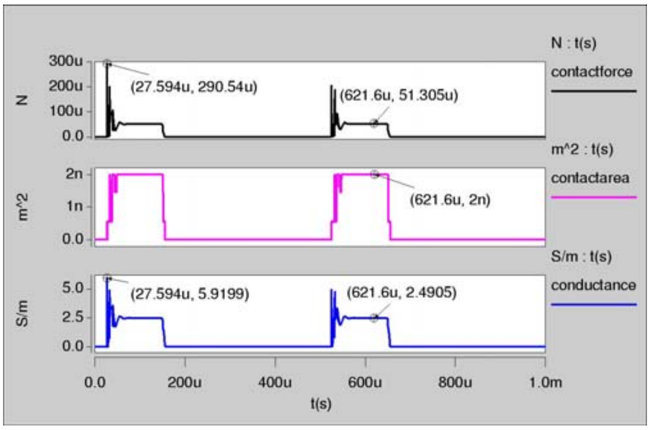

Fig. 8. Conductance, contact area and contact force when 1V RF input signal is applied

Figure 9 shows the expanded view of the Rf output during the transition time, when an RF signal with amplitude 1V, frequency 2GHz and tailored actuation pulse is applied. The produced graph is indicative of the influence of the capacitor which created between the cantilever and the contact area.

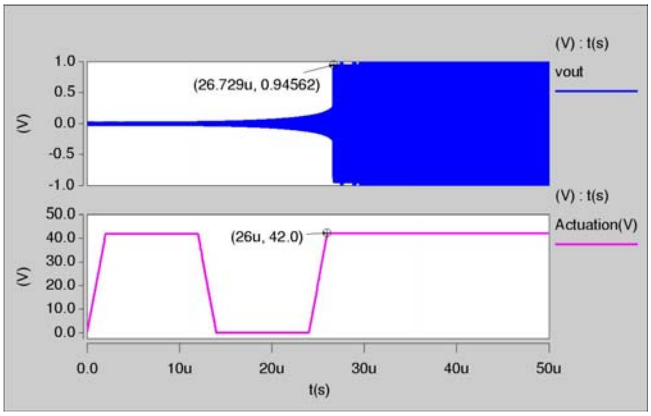

Fig. 9. Detailed switch behavior during transition time

Figure 10 presents the results of the FFT analysis of the output when an input signal with amplitude 1V and frequency 2GHz is applied, at three discrete periods of time.

For the time period 20 to 20.2μSec the switch is on the OFF state and the S/N ratio is 71.9dB. For the time period 26.5 to 26.7μSec, during the transition time of the switch, the S/N ratio deteriorates to 64.9dB. For the time period 40 to 40.2μSec the switch is on the stable ON state and the S/N ratio alters again to 78.9dB.

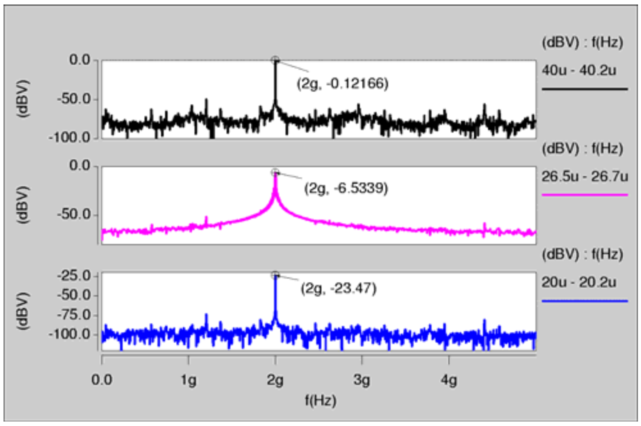

Fig. 10. FFT analysis of the output signal at three discrete periods of time

From the above analysis of the switch under hot mode operation can be concluded that it is working well enough with 1V of input RF signal and the S/N ratio is reserved in a very satisfactory level even during the transition time.

B. *Electromagnetic analysis*

A full electromagnetic wave analysis has been carried out to further investigate the S-parameters of the switch.

Figure 11 presents the return loss and the insertion loss graphs in the frequency range of 2 to 10 GHz, when the switch is in the ON state. The results of the simulation are very promising as the values of the Insertion and Return Loss are -0.022dB and -55.3dB, respectively, at 4 GHz.

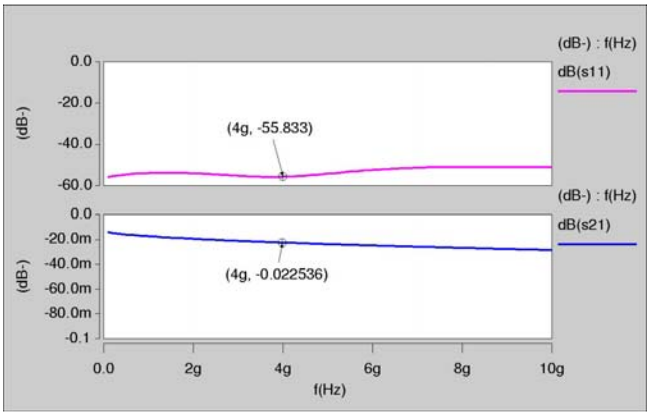

Fig. 11. Insertion and Return loss of the proposed switch in the ON state

The same parameters investigated in the OFF state of the switch, presenting significant results. The Return loss was -0.045dB and the Isolation -20.63dB at 4GHz. The results are illustrated in Fig.12.

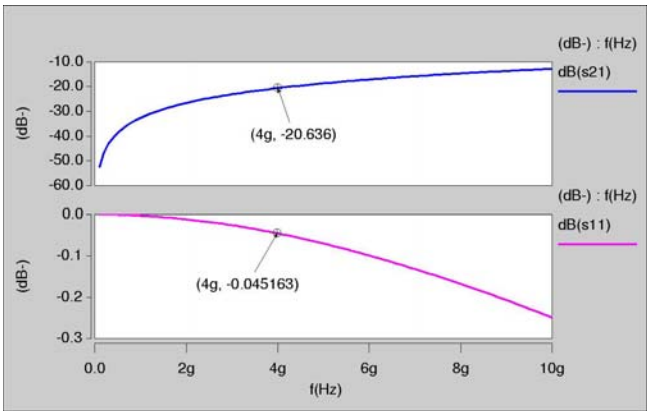

Fig. 12. Isolation and Return loss of the proposed switch in the OFF state

Finally the evolution of the S-parameters (S_{11}, S_{21}) has been investigated during the transition from the OFF to the ON state, under a DC voltage sweep analysis. The frequency of the RF input signal was 4GHz and the amplitude 1V. The results are shown in Fig.13.

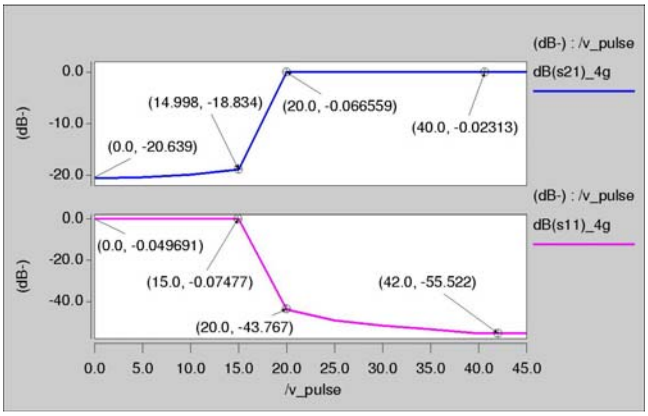

Fig. 13. Evolution of the S-parameters in 4GHz

A summary of the simulated electromechanical and electromagnetic results of the proposed all metal in line series ohmic RF MEMS Switch is presented in Table I.

TABLE I
SIMULATION RESULTS OF THE PROPOSED SWITCH

Parameter	Value	Parameter	Value
Length (cantilever)	350μm	Actuation(Vp) Full contact(Vs)	19V 42V
Width	150μm-220μm	Switching Time	26μS_ON 18μS_OFF
Height from electrode	3μm	Resonant frequency	8640.5Hz
Height from contacts	2μm	Gas damping (nitrogen 1atm)	2.03·μN
Cantilever Type	Gold	Impact velocity	5.4cm/Sec
Thickness of cantilever	5μm	Actuation current (max)	4.94uA
Holes to cantilever	Yes	Contact Area	2 contacts 40x50μm
Electrostatic Force	304μN (Vs)	Insertion Loss (4G)	-0.022dB
Contact Force	56μN	Return Loss (ON)	-55.83dB
Inductance of cantilever	14pH	Isolation (4G)	-20.63dB
Resistance of cantilever	0.011Ω	Return Loss (OFF)	-0.045dB
Capacitance (OFF)	2x8.15fF	SNR (Hot)_ON	78.9dB_ON
Switch Resistance (ON)	0.35Ω/per contact(Vs)	SNR (Hot)_OFF	71.9dB_OFF

V. CONCLUSION AND FUTURE WORK

The analysis, design and simulation of a novel all metal in line series ohmic RF MEMS switch has been presented. The new design is intended to be used in microwave applications.

The simplicity of the new switch due to the design technique and materials used (all metal Au design with no insulator layers) assures high fabrication yield keeping the manufacturing cost relatively low. Besides, high enough fabrication tolerances are allowed due to the wide range of actuation voltage that can be used to control the switch.

The s-shaped deformation of the cantilever adds enough restoring force to the switch in order to avoid stiction phenomena and wipes the contact area eliminating the contamination layer. In addition to that, the design's non-uniform shape and the distributed actuation force allow easy switching control and lower actuation voltage, comparing with a uniform shape cantilever [14], ensuring the effectiveness of the switch. The large contact surface in conjunction with the high restoring force assures good contact conditions, linearity and relatively high power operation increasing the reliability of the switch.

The electromechanical and electromagnetic simulation of the design presented significant results for the insertion loss in the ON state, the isolation in the OFF state, the required pull down voltage, the switching time, the conductance and capacitance in the ON and OFF states, respectively. The above characteristics make the presented RF MEMS switch suitable for many microwave applications.

This research work is still on-going as concerns the control of the ohmic switch, which is being further investigated via stochastic (PSO) and statistic (Taguchi) optimization routines [15] to achieve even lower impact velocity, elimination of the bouncing and settling time phenomena, while maintaining significant overall performance.

The proposed RF MEMS switch is being planned to get fabricated soon and it is anticipated that a full comparison in between theoretical and practical results will be presented in the near future.

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