Simulation on Power Handling Enhancement for the Ohmic Contact RF MEMS Switch with Micro-spring Structure

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Abstract— This paper presents a RF MEMS (Radio Frequency Microelectromechanical System) switch which is capable of handling high power. By optimizing the design of its contact configuration and cantilever structure, the RF current distribution becomes more uniform through each contact of the multi-contact switch. The novel design of micro-spring cantilever structure also ensures a good contact between the contacts and top electrode when the switch is in the "on" state. The simulation results demonstrate the RF MEMS switch has excellent microwave performance: insertion loss < 0.15 dB, return loss > 31.6 dB and isolation > 14.5 dB from DC to 40 GHz as well as the ability of handling 3.1 W RF power which means a 300% improvement in power handling capability compared with traditional cantilever switch.

1. INTRODUCTION

The past 20 years has witnessed a booming development of the RF MEMS switch. Owing to their low insertion loss, low power consumption, wide frequency bandwidth, high isolation and high linearity, RF MEMS switches are believed to be the promising alternative to the conventional counterparts such as PIN diodes, field effect transistors (FETs) [1] and macro electromagnetic relays [2], which suffer from their disadvantages in high frequency performance, power consumption and linearity. However, the shortcomings of low power handling capability greatly prevent RF MEMS ohmic contact switches from being widely used in defense, industry and other fields of power applications.

The power handling capability of a switch can be defined as the maximum input power before the failure takes place. When the RF current gets through the ohmic contact switch increases, the temperature of the region near the contact will rise rapidly due to the small size of the whole structure and the larger contact resistance compared with the other parts. If the input power continues to grow, it will result in the micromelding and stiction at metal contact interface which causes failure of the switch, which is considered as the main factor of restricting the maximum power that a RF MEMS contact switch can handle.

The diverse range of approaches emerged in recent years to improve RF power handling capability of ohmic contact RF MEMS switch can be generally divided into two categories. One is to choose hard metals such as Platinum (Pt), Ruthenium (Ru) as the material of contact instead of Au-to-Au contact which would easily fail at high temperature [3]. A good example of this solution is the commercial contact RF MEMS switch from Radant MEMS Incorporation [4]. The other approach to improve power performance is by the application of novel switch structure design. The structure of multi-contact or multi-switch is proposed to realize the reduction of current through each contact [5–7], while additional hold electrode (pull-up electrode [8] and push-up electrode [9]) is proposed to avoid the self-actuation and adhesion of the RF MEMS switch under high power conditions. In addition, there are some unconventional structures like the 3D power switch based on springs and latches [10].

2. DEVICE OVERVIEW

The top view and cross section of the proposed ohmic contact switch are shown in Fig. 1. The structure is based on a cantilever with non-uniform thickness [11] which changes from 4 μm to 1 μm at its tip. This fixed-free cantilever topology is chosen because it has smaller size and lower pull-in voltage than fixed-fixed beam design. The thinner part at the tip of the cantilever, acting as a micro-spring which results in a larger deformation under the same actuation voltage, makes it easier to realize a stable contact without degrading the spring constant of the whole cantilever much. This advantage is especially important in multi-contact switch with thick top electrode for power application. Due to electromagnetic effect (skin effect and proximity effect) at high frequency, RF currents concentrate on the edges of transmission lines and tend to pass mostly by the outer contact dimples when the switch is in the "on" state. Thus, the contacts are configured in a 2×2 array to get more even current distribution instead of the traditional parallel contacts configuration. The 4 contacts on the signal line, with a size of 8 μm×8 μm and a height of 0.4 μm, form Au-to-Au contact with the cantilever together. The holes on the top electrode are applied to improve the speed of releasing sacrificial layer and reduce the influence of the squeeze film damping.

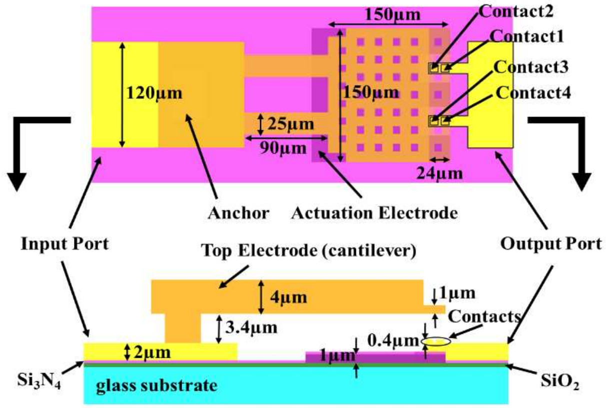


Figure 1: Top view and cross section of the ohmic contact switch.

3. DESIGN AND SIMULATION

3.1. Mechanical Design

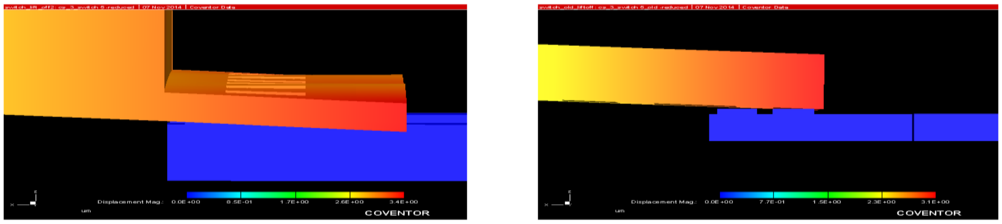
The switch for power applications is often proposed with thick top electrode of high spring constant which could offer large restoring force in order to lower down the possibility of failure caused by adhesion. But it's hard for thick cantilever and beam to make a stable contact especially when there are more than two contacts unless a large actuation voltage is supplied at the risk of breaking down. Furthermore, process variation and residual stress induces distortion of movable parts so that the contact area may not be reproducible from device to device. While thinner metal film, with its low spring constant, deforms more easily and is more likely to get a good contact with multiple contact dimples even when the voltage applied is low. A good solution to comprise contact with power performance is to come up with a geometry that its movable part can be constituted of parts with different rigidities. Consequently, a switch based on micro-spring structure cantilever of non-uniform thickness is proposed so that the switch could have large restoring force as well as a good contact in the "on" state.

Mechanical and Electromechanical simulations were performed using CoventorWare to compare the uniform cantilever (with the constant thickness of 4 μm) switch with the proposed micro-spring cantilever (with thickness sharply changed from 4 μm from to 1 μm) switch in 2×2 contact configuration. Their mechanical properties are summarized in Table 1.

According to the contact force data at 70 V actuation voltage in Table 1, two contacts in the uniform cantilever switch don't form contact with the cantilever while all of four contacts in the

Table 1: Summary of mechanical properties.

Mechanical properties		uniform cantilever switch	micro-spring cantilever switch
Resonant frequency (Hz)		1.08×10^4	1.23×10^4
Generalized mass (kg)		6.60×10^{-10}	5.03×10^{-10}
Pull-in voltage (V)		33.1	32.8
Release voltage (V)		30.3	30
Contact force of each contact at 70 V actuation voltage (μN)	Contact1	24.07	21.34
	Contact2	-	10.05
	Contact3	-	10.77
	Contact4	23.24	20.08



(a) (b)

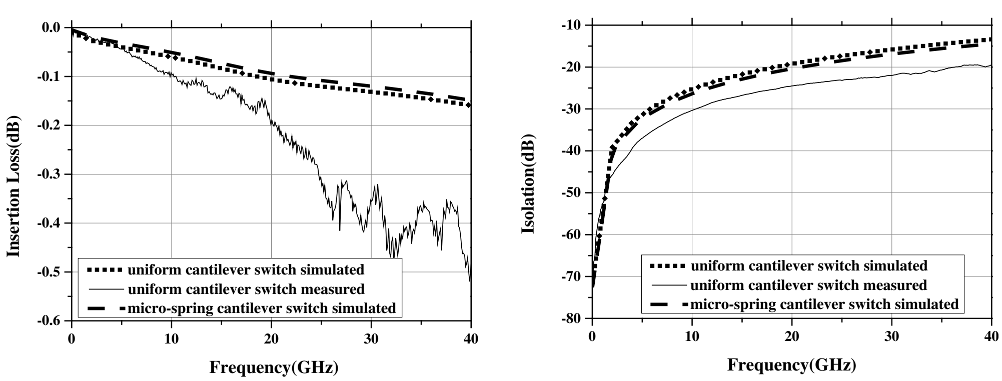
Figure 2: Simulation of the contacts condition by CoventorWare when the actuation voltage is 70 V, (a) uniform cantilever switch, (b) micro-spring cantilever switch.

micro-spring switch are in the contact state. Moreover, it can be seen from Fig. 2 that the thinner part of the micro-spring cantilever switch deflects a lot thus making a good contact with the four contacts, nevertheless, the tip of the uniform cantilever switch has little deformation so that the top electrode can only come into contact with front row of contacts. Therefore, the use of micro-spring cantilever structure has a significant effect in providing a good contact interface for high power multi-contact switches.

3.2. Microwave Performance Simulation

The size of CPW (Coplanar Waveguide) transmission line is optimized to guarantee a good impedance match at the Input and Output port. The finger structure used in signal line region under the cantilever reduces their overlap area as well as coupling capacitances, thereby resulting in an improvement in the isolation.

Figure 3 shows the simulated S-parameters of the uniform cantilever (with the constant thickness of 2 μm) switch and the proposed micro-spring cantilever switch through full-wave EM simulator-Ansoft HFSS as well as the measured S-parameters of this uniform cantilever switch [5] which implies a good consistence with the simulated results. The scanning electron micrograph of the uniform cantilever switch with two contacts in parallel is given in Fig. 4. The difference between the theoretical model and fabricated object, caused by process variation and bending upwards of the cantilever in the "off" state, leads to the difference between the simulated and measured results. From DC to 40 GHz, the simulation of the proposed RF MEMS switch exhibits outstanding microwave performance: insertion loss < 0.15 dB, return loss > 31.6 dB (not shown in the figure) and isolation > 14.5 dB.



(a) (b)

Figure 3: Simulated and measured S-parameters of the uniform cantilever switch and the proposed micro-spring cantilever switch, (a) insertion loss in the "on" state, (b) isolation in the "off" state.

3.3. Power Handling Enhancement Simulation

For ohmic contact RF MEMS switches, the RF power handling capability is typically limited by a localized temperature rise in the contact dimple owing to joule heating of the contact. The relationship among the temperature of the contact T_C, incident power P_{in} and contact resistance

R_C is as Equation (1).

$$T_C = \sqrt{\frac{R_C^2}{4L}\frac{P_{in}}{Z_0} + T_0^2} \tag{1}$$

where T_0 is the ambient temperature, L is the Lorenz number and Z_0 is the transmission line impedance ($50\,\Omega$). It can be seen from the equation that the contact temperature is in proportion to the contact resistance. In order to improve power handling capability of the RF MEMS switch, multiple contacts or multiple switches in parallel configuration are employed to reduce the total contact resistance and contact temperature. However, it is a big challenge to maintain even current distribution across multiple contacts (> 2) in high frequency.

To analyze the RF current distribution across each contact, simulations of the maximum RF current density through each contact in different contact configurations are done with the help of the EM simulator-Ansoft HFSS. The contact resistance in the HFSS switch model is set to be $0.2\,\Omega$ with a RLC module, which is extracted from the measured insertion loss. The simulation results indicate the current in the original switch (Fig. 5(a)) distributes equally between the two contacts with a maximum current density of 1.17×10^4 A/m at 10 GHz. As the original switch has been

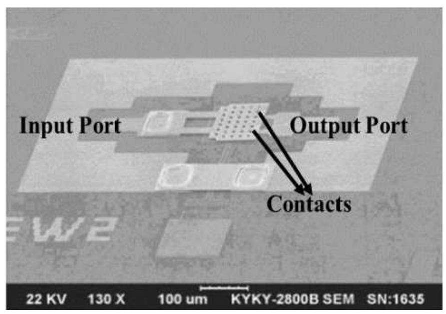
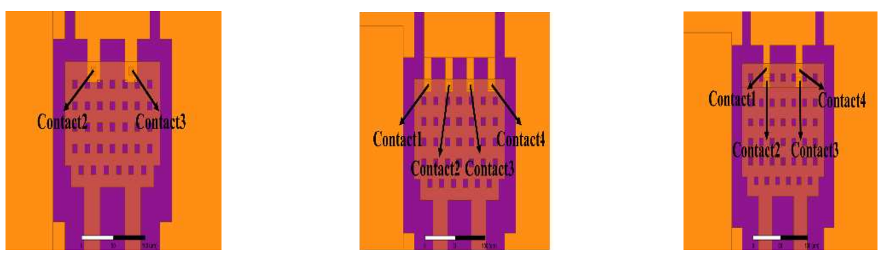
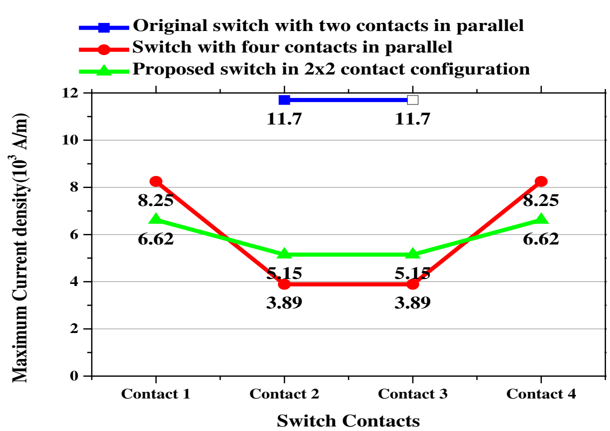


Figure 4: SEM micrograph of the uniform cantilever switch.



(a) (b) (c)



(d)

Figure 5: Current distribution in different contact configurations, (a) original switch with two contacts in parallel, (b) switch with four contacts in parallel, (c) proposed switch in 2×2 contact configuration, (d) HFSS simulations of current distribution for different switches with 1 W input signal at 10 GHz.

tested to possess the ability of handling 1 W RF power without failure at the same frequency [5], 1.17×10^4 A/m is set as a critical figure which limits the maximum current density that this kind of switch can operate properly at 10 GHz [12]. In other words, if the current density passes by one contact rises beyond the critical figure (1.17×10^4 A/m), the corresponding joule heat may cause the micromelding and stiction of the contact, eventually leading to the failure of the switch. In the optimized contact configuration, 4 contacts are arranged in 2×2 array (Fig. 5(c)) rather than parallel in a single row (Fig. 5(b)), which shows an improvement in the uniformity of current distribution across each contact as is shown in Fig. 5(d). The maximum current of the switch in 2×2 contact configuration doesn't reach the critical figure until the incident power increases to 3.1 W which implies that the proposed switch can at least deal with 3.1 W RF power at 10 GHz. Compared with the original switch, the power-handling capability of the designed switch improves over 300%.

4. CONCLUSION

A RF MEMS Switch with enhanced power handling capability based on the 2×2 contact array and micro-spring cantilever is proposed in this paper. Simulation results show that the adoption of optimized contact array ensures a more even current distribution between each contact in high frequency and therefore greatly improves its power-handling capability. While micro-spring cantilever structure exhibits a better performance than normal cantilever switch when dealing with the contact of multi-contact configuration for high power application. In addition, the microware performance of the switch is analyzed and simulated.

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REFERENCES

1. Rebeiz, G. M. and J. B. Muldavin "RF MEMS switches and switch circuits," *IEEE Microwave Magazine*, Vol. 2, No. 4, 59–71, 2001.
2. Patel, C. D., and G. M. Rebeiz "An RF-MEMS switch for high-power applications," *2012 IEEE MTT-S International Microwave Symposium Digest (MTT)*, 1–3, Montreal, Canada, June 2012.
3. Kwon, H., et al., "Contact materials and reliability for high power RF-MEMS switches," *IEEE 20th International Conference on Micro Electro Mechanical Systems, 2007. MEMS*, 231–234, Hyogo, Japan, January 2007.
4. Radant MEMS Inc., http://www.radantmems.com.
5. Liu, Z., Z. Hou, and Z. Li, "Study on RF MEMS switch with four parallel Ohm contacts for power handling enhancement," *Microwave and Optical Technology Letters*, Vol. 52, No. 3, 665–667, 2010.
6. Nishijima, N., J.-J. Hung, and G. M. Rebeiz, "Parallel-contact metal-contact RF-MEMS switches for high power applications," *17th IEEE International Conference on Micro Electro Mechanical Systems, 2004. MEMS*, 781–784, Maastricht, Netherlands, 2004.
7. Chow, L. L.-W., et al., "Lifetime extension of RF MEMS direct contact switches in hot switching operations by ball grid array dimple design," *IEEE Electron Device Letters*, Vol. 28, No. 6, 479–481, 2007.
8. Peroulis, D., S. P. Pacheco, and L. P. B. Katehi, "RF MEMS switches with enhanced power-handling capabilities," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 52, No. 1, 59–68, 2004.
9. Simon, W., et al, "Designing a novel RF MEMS switch for broadband power applications," *32nd European Microwave Conference, 2002*, 1–4, Milan, Italy, September 2002.
10. Choi, J.-Y., et al, "Three-dimensional RF MEMS switch for power applications," *IEEE Transactions on Industrial Electronics*, Vol. 56, No. 4, 1031–1039, 2009.
11. DiNardo, S., et al., "Broadband rf-mems based spdt," *The 1st European Microwave Integrated Circuits Conference, 2006*, 501–504, Manchester, UK, September 2006.
12. Zhao, C. X., et al, "Power handling capability improvement of metal-contact RF MEMS switches by optimized array configuration design of contact dimples," *Key Engineering Materials*, Vol. 609, 1417–1421, 2014.