

A Compact Single-Cantilever Multi-Contact RF-MEMS Switch with Enhanced Reliability

Yuhao Liu, *Member, IEEE* Jiansong Liu, Bo Yu, *Student Member, IEEE* and Xiaoguang “Leo” Liu, *Member, IEEE*

This paper presents a novel cantilever and electrode biasing design of a metal-contact radio frequency micro-electromechanical systems (RF-MEMS) switch to integrate multiple contact points in a single cantilever to improve the reliability of the switch. In the design presented in this paper multiple contact points are integrated in a single cantilever. The contact points are used to conduct RF current one by one until one point fails. To switch between the contact points, two actuator electrodes are placed under the cantilever and biased with different voltages and the touching point between the cantilever and bottom RF electrode are changed. The parasitic capacitance of the switch are kept to be the same with that of a single contact point RF-MEMS switch. The off-state isolation will not be worsen, while accumulation of the lifetime of each contact point can improve the overall lifetime of the switch. Without the need of shrinking the actuator to maintain small parasitics capacitance, the contact force is also not sacrificed when comparing to the case of putting several miniature switches together. The performance and reliability improvement of the switch are experimentally demonstrated. The insertion losses of the switch of different contact points are <1 dB, and the isolation is better than 10 dB up to 20 GHz.

Index Terms—MEMS, RF-MEMS, Reliability, MEMS switch, Tunable filter, Hot-switching

I. INTRODUCTION

Radio-Frequency Micro-ElectroMechanical (RF-MEMS) switches have superior RF performance in terms of insertion loss, isolation, power handling, and linearity over other RF switching devices [1]. However, the limited reliability of RF-MEMS switches, especially under high-power and hot-switching conditions, has hindered their application in practical RF systems. Contact degradation is one of the most important failure mechanisms for DC-contact RF-MEMS switches [2]. To improve the reliability of the metal-contact RF-MEMS switch, the contact reliability of the switch must be improved. For most of the switches designed in the past [1], only limited contact points can make contact during the entire life time of the switch, which means that when the contact points fail the entire switching circuit fails. Recently, switches with multiple contact points were demonstrated to achieve much better reliability than single switch with limited contact points [5], [6], the improvements in reliability come from the use of refractory metal and extra contact points to withstand damage. In these works, the switch life-time is ultimately still limited by the life-time of each individual switch.

Manuscript received Nov 22, 2017; accepted Jan 22, 2018. The authors are with the Department of Electrical and Computer Engineering, University of California, Davis, Davis, CA 95616 USA. (email: yuhliu@ucdavis.edu).

In this paper, we present a novel design that can prolong the lifetime of single RF-MEMS switches. The proposal scheme is illustrated in Fig. 1. Compared to traditional RF-MEMS contact switches, where one or more contact dimples are used, the proposed switch structure uses a continuous bar-shaped region to make contact and two actuation voltages to adjust the actual contact point. As such, the switch life-time is prolonged as new contact points could be used when an existing contact point is damaged.

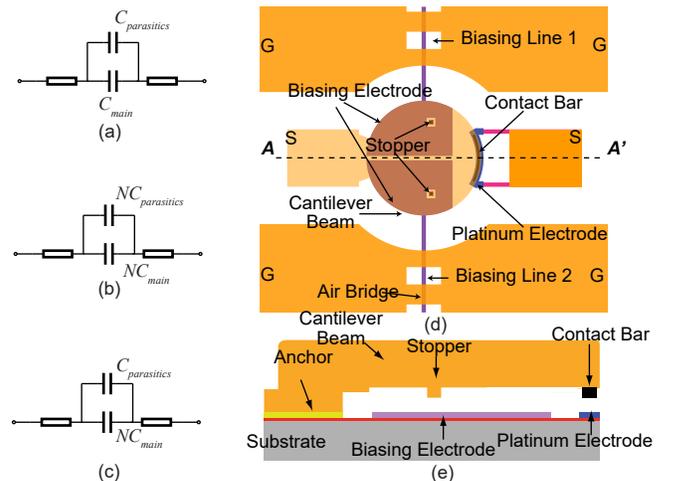


Fig. 1. (a) Off-state capacitance of a single RF-MEMS switch; (b) off-state capacitance of RF-MEMS switches placed in parallel; (c) off-state capacitance of the proposed design; (d) top view of the proposed design; (e) side-view of the proposed cantilever design.

II. SWITCH DESIGN

When using a single RF-MEMS switch as switching circuit, the contact points failure on the single RF-MEMS switch means the failure of the overall switching circuit. If multiple switches are placed in parallel, one switch failure will not lead to overall switching circuit failure. Furthermore, the biasing of the switches can be separate. For example, one switch can be biased to ON and OFF, while the other switches will not be biased, leaving them in the OFF state. The next switch will be biased until the current switch fails. The lifetime of the switching circuit will be the sum of the lifetime of each RF-MEMS switch in the switching circuit. Alternatively [3], the RF-MEMS switches in the switching circuit can also be biased together. The power will be distributed on each RF-MEMS switch elements. Each RF-MEMS switch will meet less RF power, and the reliability will be improved. To keep the overall size of

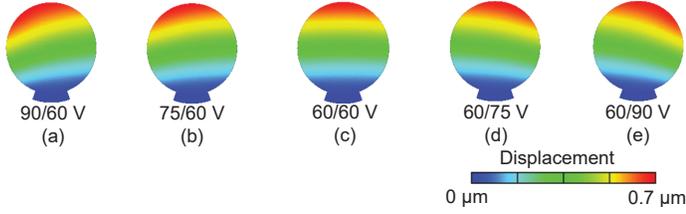


Fig. 2. Cantilever displacement under different voltage combinations.

the switching network small and reduce unwanted parasitics, each switch has to be miniature. However, the chance of adhesion problem will increase due to smaller restoring force of a narrower cantilever. If one of the switches has adhesion problem, the entire switching circuit will fail. With smaller actuator, the contact force is also small. The overall on-state resistance R_{on} will not decrease much if there is no significant increase in the total electrode area.

Putting several regular-size switches without reducing contact force in parallel will inevitably degrade the off-state isolation due to increase of overall device size. The off-state isolation is mainly determined by off-state capacitance. Lowering the off-state capacitance will increase switch isolation. The off-state capacitance (C_{off}) includes two parts: contact overlap capacitance (C_{main}) and parasitic capacitance ($C_{parasitics}$) as shown in Fig. 1(a). The parasitic capacitance is due to the coupling between cantilever and substrate and bottom electrodes. Having several RF-MEMS (assume the number is N) switch in parallel will change the overall off-state capacitance to NC_{off} , as shown in Fig. 1(b). However, If the multiple contacts are integrated in a single cantilever, only one parasitic capacitance will be considered. The contact points can share the same cantilever without sacrificing the contact force. The off-state capacitance is reduced to $NC_{main} + C_{parasitics}$, as shown in Fig. 1(c). The off-state capacitance is reduced by $(N - 1)C_{parasitics}$, comparing to the previous case. Thus, the isolation can be improved. The overall figure of merit ($FOM = R_{on}C_{off}$) remains the on the same level of a single contact RF MEMS switch with the similar device size, but the reliability can be improved by times of N because of the extra contact points. To integrate the contact points in a single cantilever, a circular type of cantilever is designed [4], as shown in Fig. 1(d) and (e). The cantilever is controlled by two separate electrodes. The two electrode will provide pull-down force to the cantilever. Moreover, when the biasing voltages on both electrode are different, a torque is created along axis AA'. The rotation and pulling-down of the cantilever will create different contact points in the contact bar placed at the tip of the cantilever. Comparing to other traditional RF MEMS switches [1], the structure not only creates z-direction movement to switch on an off, but also x- and y- direction movement to switch contact spots. Fig. 2 shows finite element method (FEM) the cantilever under different biasing voltage combinations to show the operation concept of the proposed idea. The maximum displacement is $0.7 \mu\text{m}$, which is the gap between the contact bar and the bottom electrode. The contact bar will touch different contact points under different voltage combinations. The switch, thus, can switch between different

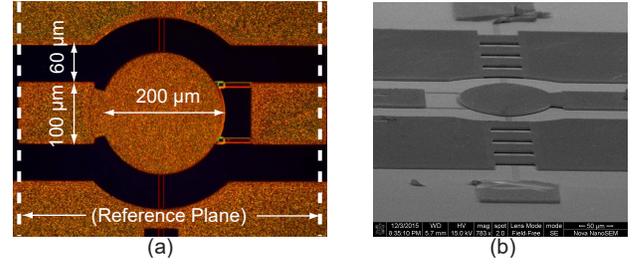


Fig. 3. (a) Optical image of the fabricated switch; (b) SEM image of the fabricated switch

contact spots. When operating this switch, if one contact point fail the switch can change to different fresh contact point to avoid an overall device failure. The lifetime of the switch can be extended.

The transmission line configuration is coplanar waveguide. The width of the center metal line is $100 \mu\text{m}$, and the width of the gap is $65 \mu\text{m}$. The radius of the circular cantilever is $100 \mu\text{m}$. The cantilever is made of gold, and the bottom electrode is made of platinum. High resistive biasing line is used to reduce DC and RF coupling. Air bridge is formed on top of the biasing line to let biasing line pass through ground plane. Mechanical stopper is placed underneath the cantilever to prevent accidental short-circuit between cantilever and biasing electrode. The switch was fabricated using all-metal process [5]. Fig. 3(b) shows the scanning electron microscopy (SEM) image of the cantilever. The beam thickness is $3.5 \mu\text{m}$. The thickness of contact bar and mechanical stopper is $0.3 \mu\text{m}$.

III. EXPERIMENTAL VALIDATION

The small-signal RF performance was measured using an Keysight 8722D network analyzer with Ground-Signal-Ground (GSG) microwave probes. Short-Open-Load-Through (SOLT) technique was used to calibrate the probes to the reference plane shown in Fig. 3(a). The S-parameter measurement results are shown in Fig. 4. The isolation of the switch is shown in Fig. 4(a). The isolation is 34.44 dB at 1 GHz , and 18.96 dB at 10 GHz . The measurement results have good agreement with FEM simulation result. The insertion loss of the switch under different voltage combination is shown in Fig. 4(b). For $90/85 \text{ V}$ actuation voltage, the insertion loss is 0.67 dB at 1 GHz . For $85/90 \text{ V}$ actuation voltage, the insertion loss is 0.74 dB at 1 GHz . For $90/60 \text{ V}$ actuation voltage, the insertion loss is 0.90 dB at 1 GHz . For $60/90 \text{ V}$ actuation voltage, the insertion loss is 0.97 dB at 1 GHz . The differences of contact force and contact point cause the differences in insertion loss between different voltage combinations. The switching time of the switch is measured in open air lab environment at room temperature in order to determine the time period of the square biasing wave in the reliability test. The switch has a switch-on time of $103 \mu\text{s}$ and a switch-off time of $155 \mu\text{s}$, shown in Fig. 5. The relatively long switching time is due to large resistance of the biasing line. The RC constant is larger than designed value, because the chromium etching step accidentally increases the resistance of the biasing line.

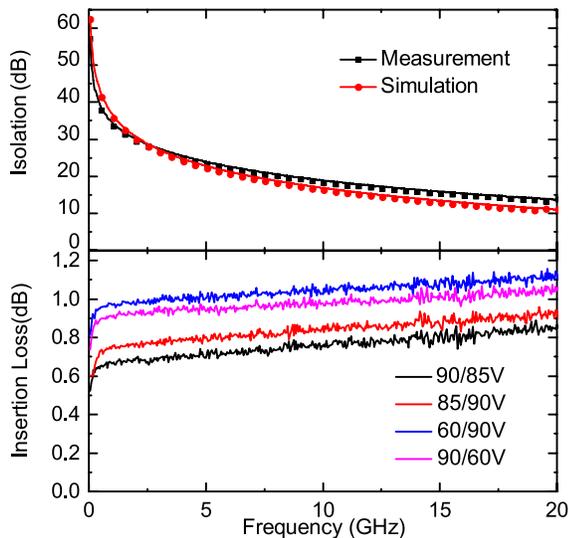


Fig. 4. Simulated and measured isolation of the switch and measured insertion loss under different voltage combinations.

The lifetime characterization of two devices were measured and shown in Fig. 6. The top and bottom figures shows the contact resistance changes of two devices under different voltage combinations up to 1 million cycles. To accelerate the change of the contact resistance, the device is cycled under 100-mW hot-switching condition. The RF frequency is 2.4 GHz. For each device, the device were actuated on and off using 90/60 V actuation voltage first up to 1 million cycles. Then, the device were actuated on and off using 60/90 V actuation voltage to change contact spot up to 1 million cycles. Lastly, the device were actuated on and off using 90/90 V actuation voltage to change the contact spot up to 1 million cycles. From Fig. 6, it can be seen from both of the devices that at 1 million cycles the contact resistance of the 90/60 V contact spot is larger than that at the beginning, which means that the contact spot is damaged during hot-switching cycles. When the contact spot changes to the 60/90 V one, the contact resistance decreases, meaning that a fresh contact spot is used. After another 1 million cycles, the contact resistance increases and the spot is damaged again. After changing the biasing voltage to 90/90V, the contact spot of the switch changes again, by observing that the contact resistance decreases again. After 1 million cycles, the contact resistance increases again. The lifetime characterization of the device shows that the contact resistance of the switch can be refreshed and lowered by changing contact spots. If the switch only had one contact spot, the switch would fail after that contact spot wears out. Thus, the lifetime of the switch can be increased by the number of times of changing voltage combination. More voltage combinations can be used to further increase the cycling times of this switch. The two devices that we tested show consistent findings.

IV. CONCLUSION

In this paper, a novel single cantilever with multiple contact points RF-MEMS switch is designed, simulated, and experimentally verified. The effectiveness of the design has been

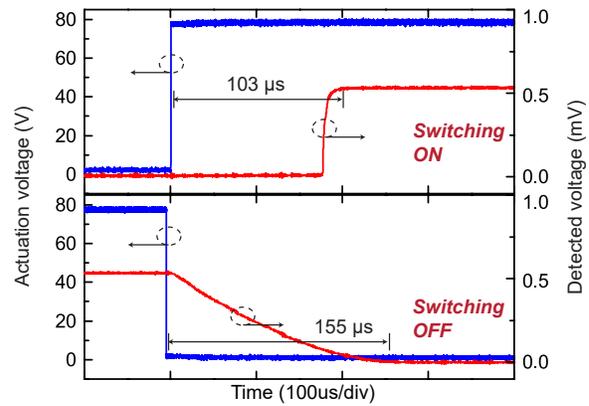


Fig. 5. Switching-on time and switching-off time.

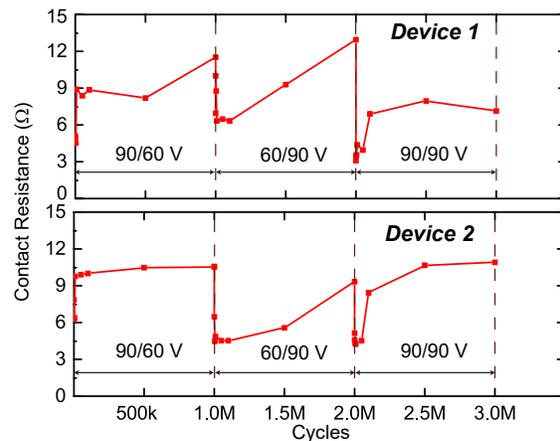


Fig. 6. Lifetime characterization of two devices under different voltage combinations.

demonstrated by the lifetime characterization of the switch in different switching voltage combination.

REFERENCES

- [1] G. M. Rebeiz, RF-MEMS: Theory, Design, and Technology. Wiley, 2003.
- [2] A. Basu, G. G. Adams, and N. E. McGruer, "A review of micro-contact physics, materials, and failure mechanisms in direct-contact rf mems switches," in *Journal of Micromechanics and Microengineering*, Sep 2016.
- [3] R. Stefanini, M. Chatras, P. Blondy and G. M. Rebeiz, "Miniature MEMS Switches for RF Applications," in *Journal of Microelectromechanical Systems*, vol. 20, no. 6, pp. 1324-1335, Dec. 2011.
- [4] H. Sedaghat-Pisheh, J. Kim, and G. M. Rebeiz, "A Novel Stress-Gradient-Robust Metal-Contact Switch," in *IEEE 22nd International Conference on Micro Electro Mechanical Systems (MEMS)*, Jan. 2009
- [5] Y. Liu, Y. Bey, and X. Liu, "Extension of the hot-switching reliability of RF-MEMS switches using a series contact protection technique," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 10, pp. 3151-3162, 2016.
- [6] Y. Liu, Y. Bey, and X. Liu, "High-Power High-Isolation RF-MEMS Switches With Enhanced Hot-Switching Reliability Using a Shunt Protection Technique," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 9, pp.3188-3199, Sept. 2017.