Single-Actuator Shunt-Series RF-MEMS Switch for Improved Hot-Switching Performance

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***Abstract*—This paper presents the design and experimental validation of a novel high isolation RF MEMS DC contact switch. The bending mechanics of a single cantilever beam is used to replace the typical series/shunt switch design that is employed for facilitating high isolation. In the OFF state the switch exhibits an isolation of -20 dB at 10 GHz and -14.7 dB at 20 GHz. When shunt contact is closed the isolation improves to -33 dB at 10 GHz and -22.3 dB at 20 GHz. In the ON state the insertion loss is -0.03 dB at 10 GHz and -0.10 dB at 20 GHz. In addition to the excellent loss/isolation performance, the switch holds great promise for high power operation under hot-switching conditions.**

***Index Terms*—RF MEMS, switch, relay, hot-switching.**

I. INTRODUCTION

High isolation DC contact switches are highly desirable RF devices for a plethora of applications. The most typical high isolation switch topology is to have a primary series switch and several shunt switches. The shunt switches can be turned on to significantly enhance the isolation. This has been demonstrated by several research groups [1] [2]. Recently, the shunt and series switches combination has also been proved to reduce the hot switching in series MEMS switch by placing solid state shunt switch at common port [3]. However, the biasing for this combination is complicated due to separately controlling the shunt and series switches.

In this work, we propose and demonstrate a single actuator shunt-series RF MEMS with with simple biasing to realize improved isolation and potentially improved hot-switching performance. Fig. 1 shows the proposed switch structure. A single cantilever beam with multiple contact points is used to realize the shunt-series switch configuration by utilizing the bending mechanism of the beam. The switch goes through a high-isolation state to an low-insertion loss ON-state without relying on multiple biasing electrodes.

II. DESIGN

Fig. 2 presents the simulated mechanical characteristics of the cantilever switch. The simulation is carried out in Coventorware. The layout of the switch is shown in Fig. 1(a). The cantilever beam is assigned as Au, with an area of $170\times100\ \mu\text{m}^2$ and a thickness of 4.5μm. The dimple thickness is $0.6\ \mu$m. The gap between dimple and bottom contact is $0.45\ \mu$m. The gap and the dimple thickness configuration is to reduce pull-in instability. An air bridge is constructed on top the biasing line passing through the ground plane. No dielectric material other than thermally grown oxide is deposited within the DC actuation field to reduce the charging problem. Additional mechanical supports are placed at the tip of the cantilever in case that the shunt contact dimples are destroyed during hot-switching to further improve the lifetime of the switch.

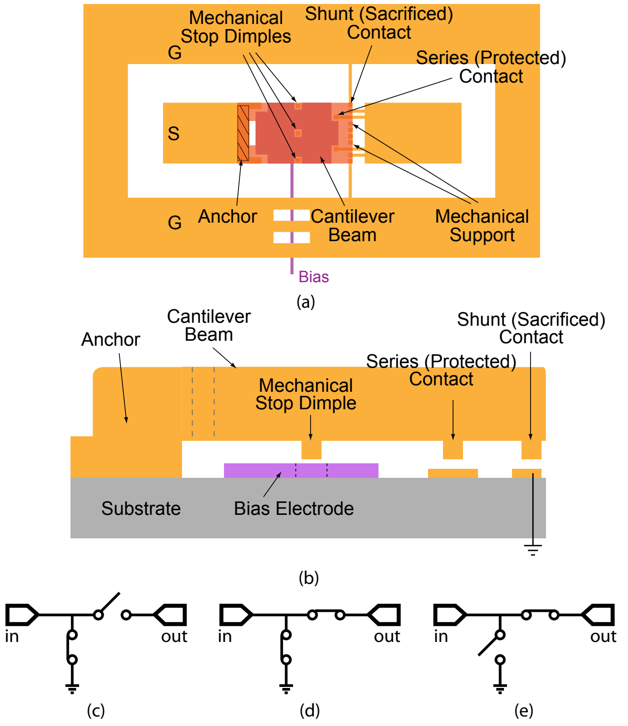

Fig. 1. Concept of single-actuator shunt-series RF MEMS switch: (a) Top view; (b) Profile view; Equivalent circuits of (c) isolation state; (d) Equivalent circuit of transition state when both series and shunt contacts are closed; (e) Equivalent circuit of closed state.

The movable part of the switch consists of a single cantilever beam with multiple contacts. Two shunt contacts (dimples), which are connected to the ground plane of the coplanar waveguide (CPW), are placed at the outer tips of the cantilever beam. Two series contacts (dimples), which are connected to the signal line at the other end of the CPW, are placed inward the cantilever beam. When the cantilever beam is actuated, it first makes contact at the shunt dimples (Fig. 2(b)). This results in an improved isolation in the OFF state for low-power applications. As the actuation voltage is increased, the cantilever beams is pulled further down, resembling a

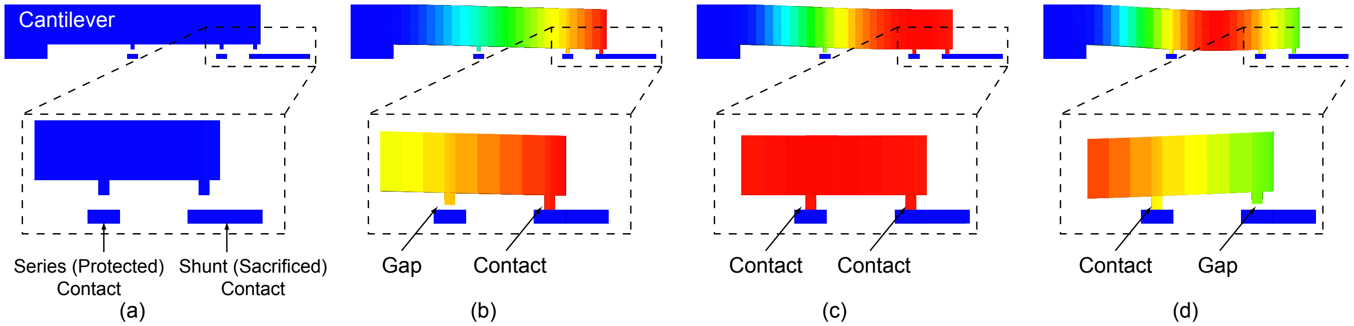

Fig. 2. Simulated electromechanical and RF performances of the proposed shunt-series RF MEMS switch: (a) Off state; (b) High isolation state; (c) Transition state; (d) ON state.

zipping motion [4] until it makes contacts at the series dimples (Fig. 2(c)). Upon further increasing the actuation voltage, the tip of the beam starts bending upwards (Fig. 2(d)), releasing the shunt contacts. In this state, the MEMS switch presents a low-loss ON-state.

Another major advantage of the proposed switch structure is the protection of the electrical contact in hot switching conditions, where gas discharge and breakdown causes significant contact degradation for direct-contact switches. In the proposed design, the shunt contacts creates a local voltage minima (current maxima at the short circuit), thus significantly reducing the voltage difference between the series contact and the signal line. In other words, a local cold-switching condition is created for the series contacts. This allows the series contacts to be made of high-conductivity metals, such as Au, to reduce the on-state resistance of the switch. In the release of the switch, the above process is reversed. The series contact is first lifted off while the shunt dimples are still in contact. A similar cold-switching condition is presented.

In this configuration, the shunt contacts are subject to the same hot-switching-induced degradation. In a sense, the series contacts are protected in hot-switching conditions at the sacrifice of the shunt contacts. However, the degradation of the shunt contacts has little effect either the OFF-state (except that the improvement in isolation when the shunt contacts are is slightly degraded) or the ON-state (in terms of insertion loss). In addition, the shunt contacts can be made of refractory metals, such as Ru, Pt, and Re, whose much higher mechanical hardness makes the contacts more resistant to degradation. While previous studies [3] have demonstrated similar concepts, the proposed structure in this paper presents a much simpler design without the need to use multiple actuation electrodes and complicated waveforms. The proposed structure also makes it inherently more resistant to contact degradation under hot-switching conditions.

Fig. 2 also shows simulated RF performances of the proposed switch in various states. Simulations are carried out in Ansys HFSS. The improvement in isolation can be clearly seen in Fig. 2(b).

III. EXPERIMENTAL VALIDATION

A. Fabrication

Fig. 3 shows a summary of the key processing steps for the switch fabrication. The fabrication begins on a high resistivity (∼10 kΩ-cm) oxidized silicon (0.5 μm) substrate. The first layer uses liftoff to pattern a 150 nm thick high resistance (∼ 1 kΩ/□) SiCr DC biasline (Fig. 3a). Next, a second liftoff is used to pattern the 150 nm thick bottom gold contacts (Fig. 3b). A 450 nm thick copper sacrificial layer is sputtered and patterned with liftoff processing (Fig. 3c). Positive photoresist is spincoated to 600 nm thick and is used to pattern the cantilever dimple (Fig. 3d). A 50 nm chromium and 150 nm gold seed layer is sputtered for subsequent electroplating. Positive photoresist is spincoated to 6 μm and patterned to form the electroplating mold for the cantilever (Fig. 3e). The cantilever is electroplated to 4.5 μm thick. The electroplating mold, seed layer metals, and sacrificial layers are etched in their respective dedicated etchants. Finally, the devices are released and dried (Fig. 3f). Fig. 4 shows an SEM image of the fabricated switch.

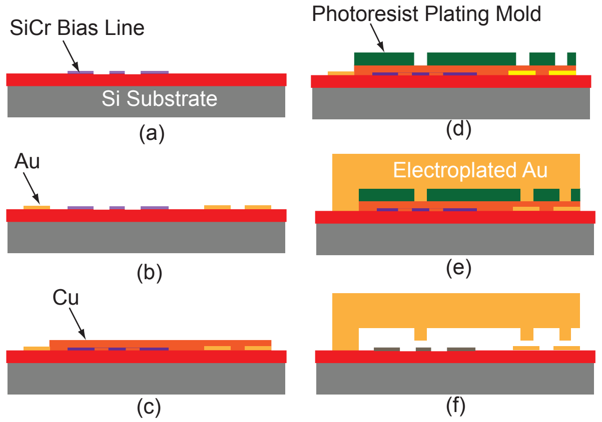

Fig. 3. Summary of key fabrication process steps of high isolation MEMS switch: (a) SiCr biasline pattering; (b) Bottom gold contact layer; (c) Cu sacrificial layer; (d) Photoresist dimple patterning; (e) Au electroplating for cantilever beam; (f) Released cantilever beam.

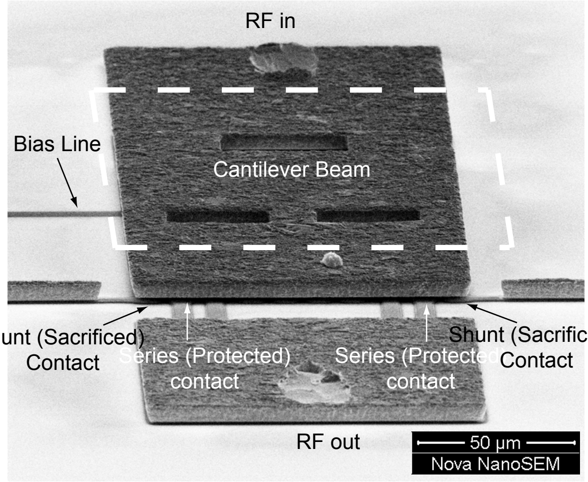

Fig. 4. SEM of the fabricated RF MEMS switch.

B. *Measurement and Discussion*

The RF measurements are performed with a E8364A network analyzer. Fig. 5 shows the measured operational states of the switch. When the switch is open (Fig. 5a) the isolation is -20 dB at 10 GHz and -14.7 dB at 20 GHz. A bias voltage of 33 V is applied to reach the high isolation state (Fig. 5a). In this state, the isolation improves to -33 dB at 10 GHz and -22.3 dB at 20 GHz. Fig. 5c shows the measurement at the transition state when both the shunt and series contacts are closed. This measurement is taken at a bias voltage of 100 V. Finally, Fig. 5d shows the on state of the switch. An insertion loss of -0.03 dB at 10 GHz and -0.1 dB at 20 GHz is achieved with a bias voltage of 168 V.

Compared to simulation, the measurement is in excellent agreement. The simulated OFF state isolation is -20.96 dB at 10 GHz and -14.86 dB at 20 GHz. The simulated insertion loss in the closed state is 0.1379 dB at 10 GHz and 0.1672 dB at 20 GHz for a 1 Ω contact resistance. Due to the high voltage used to obtain the closed state of the switch, the mechanical force is close to or exceeds 1 mN. This high force facilitates the low on resistance ($\sim$10s of mΩ) that is observed in the measurement.

IV. CONCLUSION

This paper presents the design and experimental validation of a novel shunt-series RF MEMS switch with improved off-state isolation. By exploiting the bending mechanics of the MEMS cantilever beam, a high isolation, low insertion loss switch design is accomplished. The MEMS switch has an isolation of -20 dB at 10 GHz and -14.7 dB at 20 GHz in the open state. When the shunt connection is closed, the isolation improves to -33 dB at 10 GHz and -22.3 dB at 20 GHz. When series contact is closed and the shunt contact is opened the insertion loss is -0.03 dB at 10 GHz and -0.10 dB at 20 GHz. Future work will include integration of refractory metals dimples, and high-power experimental characterization of the switch under hot-switching conditions.

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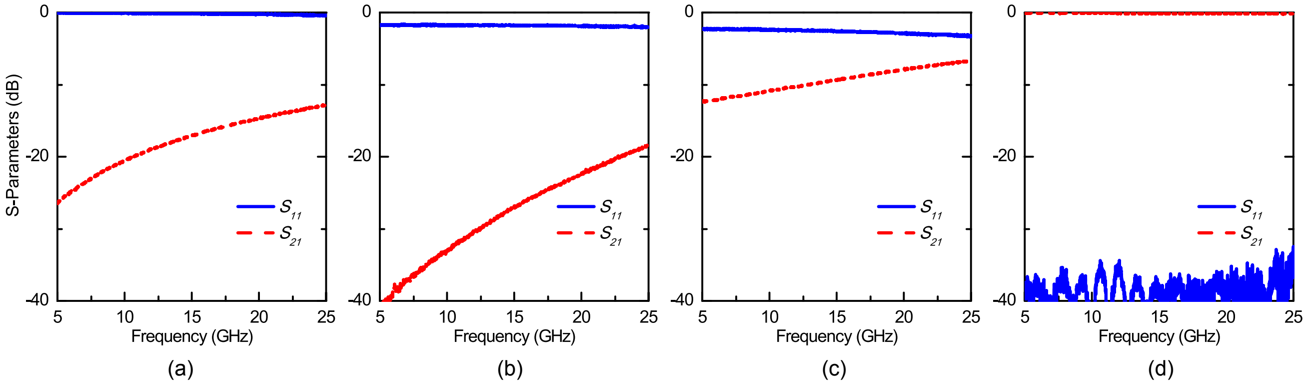

Fig. 5. Measured performance of the shunt-series switch: (a) Off-state; (b) High isolation state; (c) Transition from high-isolation- to on-state; (d) On state.