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An SOI bulk-micromachined dual SPDT RF-MEMS switch by layer-wise separation design of waveguide and switching mechanism

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Abstract: A compact monolithic RF-MEMS switch (2 mm × 4 mm in area) with the dual single-pole-double-throw (SPDT) configuration was developed by using the SOI bulk micromachining technique. The electrostatic comb-drive actuators and the mechanically movable coplanar waveguides were implemented on the low-resistive active SOI layer and the high-resistive handle layer, respectively, to effectively allocate the device footprint. Electrical crosstalk between the waveguide and the electrostatic actuator was suppressed by using the buried silicon dioxide layer. At a driving voltage of 35 V, the switch exhibits an insertion loss of 3 dB and isolation of 30 dB at 12 GHz.

Keywords: RF-MEMS switch, SOI wafer, layer-wise layout, electroplating, electrostatic actuator, laterally actuated

Classification: Micro- or nano-electromechanical systems

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1 Introduction

Micro-electro-mechanical systems (MEMS) technology is a promising approach to realize future multi-band wireless communication devices in terms of its large tunable range, high quality factor and extremely low-loss RF-transmission characteristic [1, 2]. Amongst microwave (3–30 GHz) and millimeter-wave (30–300 GHz) applications for satellite communication or defense systems, RF-MEMS switch is expected to replace the solid-state switches such as field-effect transistor (FET) or p-intrinsic-n (PIN) diode particularly because of its low insertion loss and high isolation performance in the broad spectrum range (DC to 100 GHz) [3]. Low-loss RF-MEMS switch can help to eliminate one or two steps of the front-end amplifier stages in both the transmitter and receiver circuitry, and thus result in small-size, low-power comsumption, low noise, and low cost systems for commercially applicable products.

Most conventional RF-MEMS switches were developed by surface-micromachining technology [4, 5] due to fabrication compatibility with the solid-state device processes. Recent bulk micromachined MEMS switches also have waveguides and actuators integrated on the same surface of a device chip [6, 7]. As a result, the potentials of the bulk micromachined RF-MEMS switches are yet to be discovered alongside the fast development of the silicon deep reactive ion etching (DRIE) and related processes. In this letter, we propose a novel RF-MEMS switch structure on SOI wafer by using layer-wise patterning based on silicon bulk-micromachining. This new method overcomes the trade-off of the conventional RF-MEMS switch in terms of actuator size and performance as well as microwave characteristics.

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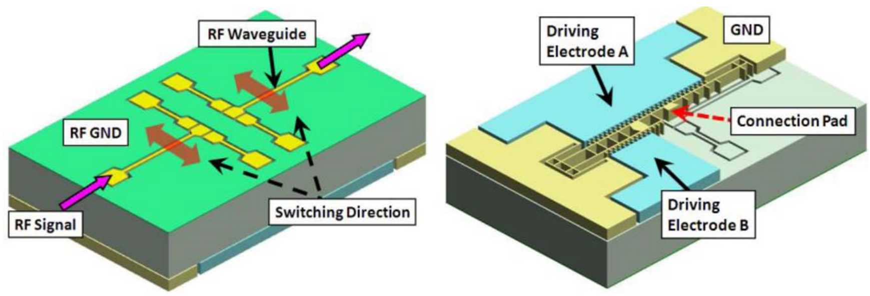
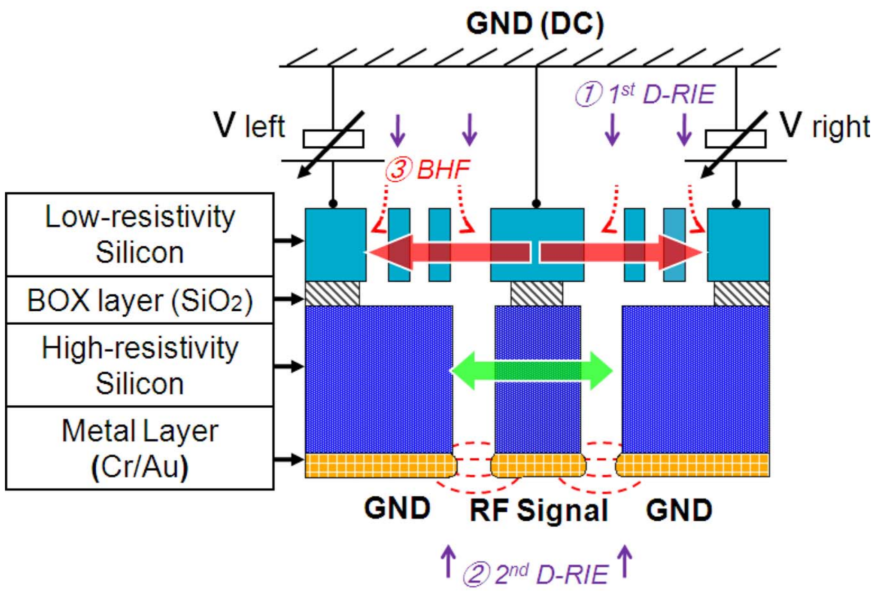
2 Layer-wise design

Fig. 1 (a) shows the RF-waveguide side of the proposed dual single-pole double-throw switch (D-SPDT). This D-SPDT switch accommodates two identical sets of an SPDT MEMS switches in one chip for a specific use of transmission-line selecting device. In our design, one D-SPDT switch occupies smaller footprint than two SPDT switches thanks to the laterally actuated mechanisms implemented on the SOI side. Fig. 1 (b) illustrates the actuator side of the D-SPDT switch, where the electrostatic comb-drive actuators and the suspensions are located. Thanks to the layer-wise separation



(a) (b)



(c)

Fig. 1. Schematics of Layer-wise designed RF-MEMS switch.
(a) RF waveguide on handle layer.
(b) Electrostatic actuator on device layer.
(c) Cross-section view of layer-wise designed RF-MEMS switch with showing main process steps.
① 1^{st} D-RIE on device layer for electrostatic actuator.
② 2^{nd} D-RIE on handle layer for MEMS CPW.
③ silicon dioxide (BOX layer) etching by BHF.

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design, the actuators can occupy nearly the entire area of the SOI surface, resulting in relatively large force generation capability. It is also beneficial for the RF-waveguide design that are separately made and arranged in a CPW style on the backside of the chip. Driving voltages are applied to the anchor parts of the comb-drive actuators, and the movable structures are always set to be electrically grounded. The actuator mechanisms are shared for both input and output ports to save the device area.

3 Fabrication

The cross sectional view of the layer-wise design of the MEMS switch is shown in Fig. 1 (c). The active device layer of low-resistive silicon ($1 \sim 10\,\Omega$cm) was used for electrostatic actuator, and the handle layer of high-resistive silicon ($10{,}000 \sim 50{,}000\,\Omega$cm) for the low-loss RF-waveguides. Fig. 1 (c) also depicts three key processes in the MEMS fabrication. The design of waveguide was MEMS-based coplanar waveguide (CPW) that is separated from the ground planes by the lateral air gap to lower the dielectric loss. Thanks to the geometrical and electrical separation between the RF-waveguide area and the electrostatic actuators, the transmission lines were electrically decoupled from the drive electrodes of the actuator. Fabrication processes are as follows: 1) The handle layer was grinded and polished chemically and mechanically (CMP) to 100 μm in the thickness for the ease of the subsequent DRIE process. 2) The SOI device layer was patterned and etched by the 1^{st} D-RIE down to the buried silicon dioxide (BOX) layer with the aluminum etching mask on. 3) The etched device layer was passivated under a negative photoresist (OMR-83) to protect the structures from the subsequent photolithography and plasma-etching process. 4) The handle layer was etched by the 2^{nd} D-RIE process using aluminum mask. 5) After the double side D-RIE processes, the BOX layer was wet-etched in a buffered hydrofluoric (BHF) acid to release the movable parts. Etching time was monitored to maintain the mechanical connection between the actuator and the waveguide. The anchor regions were intentionally designed to be larger than the movable regions for easier estimation on how much etching should be sufficient.

4 Prototype

The RF-MEMS switch was successfully fabricated as shown in Fig. 2. Fig. 2 (a) is a scanning electron microscope (SEM) picture of the RF-waveguide side. The movable transmission line was 1 mm long and 7 μm wide. The contact edge of the movable-waveguide tip was 100 μm long, and the initial contact gap was 6 μm. The top of the CPW was furnished with sputtered metals of 20 nm chromium and 800 nm gold for better electrical conductivity. Fig. 2 (b) shows the actuator side of the MEMS switch. The chip size was 2 mm by 4 mm in area, and the comb-drive electrodes with a 2 μm gap were suspended by four beams of 1.5 μm wide and 530 μm long. Fig. 2 (c) presents the video of the switching operation under sinusoidal wave voltage of 35 V at 2 Hz.

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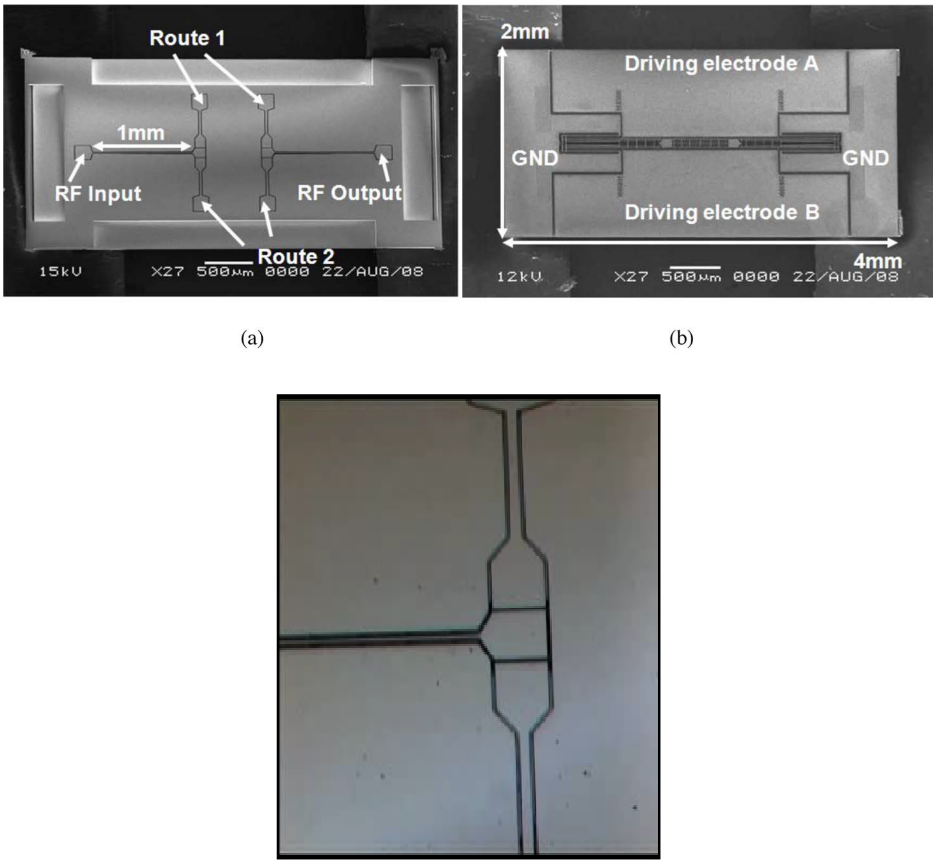

Fig. 2. SEM pictures of a fabricated RF-MEMS switch.
(a) RF waveguide on handle layer.
(b) Electrostatic actuator on device layer.
(c) Video of switching (2 Hz operation, 35 V driving voltage).

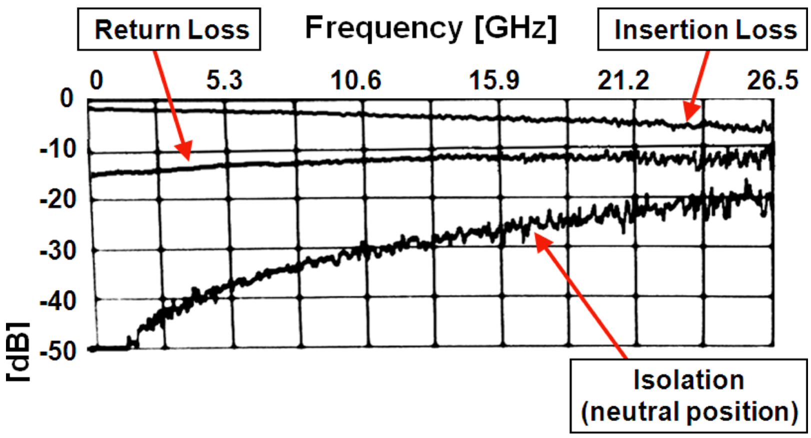

Fig. 3. Measurement results of RF characteristics.

At the pull-in voltage of 3.61 V, switching speed of 5 kHz was measured by timing between the adjacent positive square pulses. Switch response ("ON" and "OFF") with respect to the voltage was found to be 12 microseconds.

Fig. 3 shows Microwave performance of the MEMS switch measured with

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the Agilent 8510 network analyzer under the condition of 10 mW RF signal power. The target frequency band was X-Ku (8–18 GHz) for satellite communication systems. At 12 GHz and a driving voltage of 35 V, insertion loss and return loss of the MEMS switch were measured to be 3 dB and 12 dB, respectively. Isolation was found to be 30 dB between the movable signal lines at the neutral rest position.

5 Conclusion

Layer-wise design for RF-MEMS switch was successfully demonstrated as a D-SPDT MEMS switch by using an SOI wafer of low-resistive active layer (for electrostatic switching mechanism) and high-resistive handle layer (for low loss coplanar waveguide). The layer-wise fabrication method offered a higher degree of freedom in designing novel monolithic silicon RF-MEMS device, thanks to the effective use of the limited chip area.

A prototype switch was fabricated, and the switch contact was observed at the pull-in voltage of 3.7 V with a mechanical response of 12 microseconds. At a carrier frequency of 12 GHz, the insertion loss, the return loss, and the isolation of the MEMS switch were measured to be 3 dB, 12 dB, and 30 dB, respectively. Based on the observations from separate experiments, we believe that the RF characteristics could be further improved if the waveguides are electroplated [8] by gold.

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