Robust Fulcrum-Type Wafer-Level Packaged MEMS Switches Utilizing Al-Ru/AlCu Contacts Fabricated in a Commercial MEMS Foundry

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***Abstract*— This paper reports robust wafer level packaged radio-frequency (RF) microelectromechanical systems (MEMS) switches fabricated in a commercial high volume MEMS foundry. A novel wafer level packaging method is developed to improve the mechanical robustness of the movable shuttle. Two SPST switches are packaged in a single die utilizing a shared seesaw-type membrane that pivots on a fulcrum. Single metal contact (S1) and triple metal contact (S2) switch tips provides low-loss and high isolation respectively. The proposed seesaw-type switch offers a unique solution to improve MEMS reliability with the use of non-metallic thick membrane that minimizes stiction, cantilever sagging/curling, contact degradation and micro-welding problems commonly found in MEMS switches. The packaging method does not degrade the RF performance and operates at 30 V. Packaged S1 MEMS switch shows less than 0.6 dB of insertion loss and better than 20 dB of isolation while S2 switch demonstrates lower than 1 dB of insertion loss and higher than 45 dB of isolation from dc to 20 GHz.**

***Keywords*— MEMS switch, RF switch, Seesaw-type, SPST switches, Wafer level packaging.**

I. Introduction

From past two decades, advancements in radio frequency microelectromechanical systems (RF MEMS) switches have provided unique solutions to realize a variety of reconfigurable circuits like phase shifters, phased-array antennas, filter/capacitor banks, variable attenuators, multi port switch matrices, and matching networks. RF-MEMS switches are used as a fundamental unit cell in many of the circuits and sub-systems [1]. A typical RF-MEMS switch consists of a suspended metal membrane in the form of a fixed-fixed bridge or a cantilever, that work on the principle of thermal or electrostatic actuation [1]–[3]. In comparison to widely available semiconductor technology, RF-MEMS demonstrate exceptional RF performance [4], [5], high power handling, linearity and near zero static power consumption [6] On a contrary side, RF-MEMS suffer from reliability concerns including stiction issues, contact degradation, contact-welding, beam warping/sagging, thin film buckling are few of the primary cause of device failure in MEMS technology.

Most of the electrostatically actuated MEMS switches are developed using a thin metal beam with gold (Au) to Au contact for signal transmission, but due to residual stress gradient [7] during micro-fabrication, thin beams often susceptible to warp resulting in increased actuation voltage. Thin metal films also sag over time which results in signal leakage issues. Au contacts also degrade over time and hot switching such membranes leads to micro-welding. Due to the soft nature of metal, high stresses can also lead to catastrophic device failure.

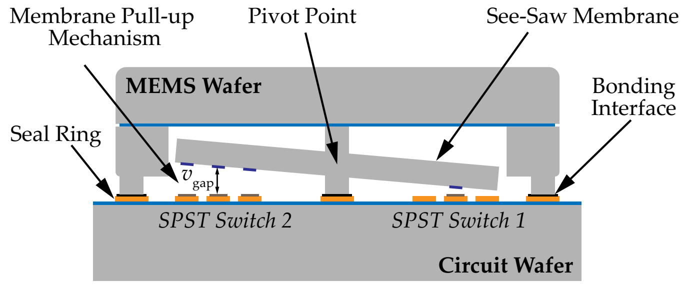


Fig. 1. Operation principle of the packaged seesaw-type RF MEMS switch.

RF-MEMS need to be hermetically packaged to be used in real-world applications which increases the device size. Various wafer level packaging techniques are available including fusion bonding, eutectic bonding, anodic bonding, eutectic bonding, and glass frit bonding [8]–[10]. While a cost effective method of encapsulating the fabricated devices using benzo-cyclo-butene (BCB) polymers which requires spin coating on fragile and released MEMS devices or by using through-silicon via (TSV) or through-glass via (TGV) technology which complicates the fabrication process [11], [12].

This paper presents a reliable solution to develop robust RF-MEMS switches to supplant thin metal beams by utilizing thick silicon membrane as a movable actuator. Silicon can tolerate high stress gradient and offers high stiffness over commonly used metals [13]. The proposed switch is a seesaw-type membrane that pivots on a fulcrum. A shared membrane offers two unique and independent single-pole single-throw (SPST) switches. Au-Ru/AlCU contacts are incorporated to drastically minimize contact degradation and micro-welding problems. Switches are hermetically sealed by using wafer level packaging eutectic bonding approach.

II. Device Description and Operation Principle

Two unique and independent RF SPST switches are designed in a single package by incorporating seesaw-type membrane. The operation principle of the proposed RF-MEMS switch is shown in Fig. 1. A central pivot point of the seesaw-type membrane is anchored to top cavity and bottom wafer providing structural support. Either side tip of the seesaw-type membrane makes or breaks the RF switching contact. One side of the membrane has a single contact point

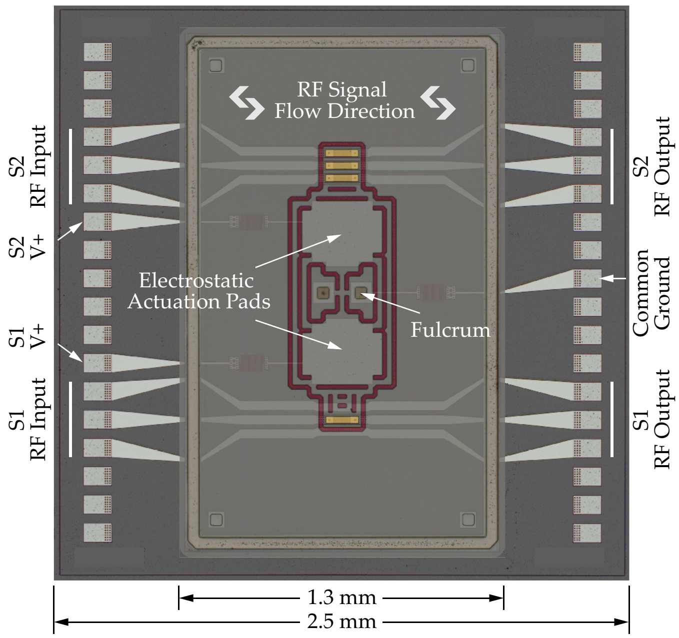
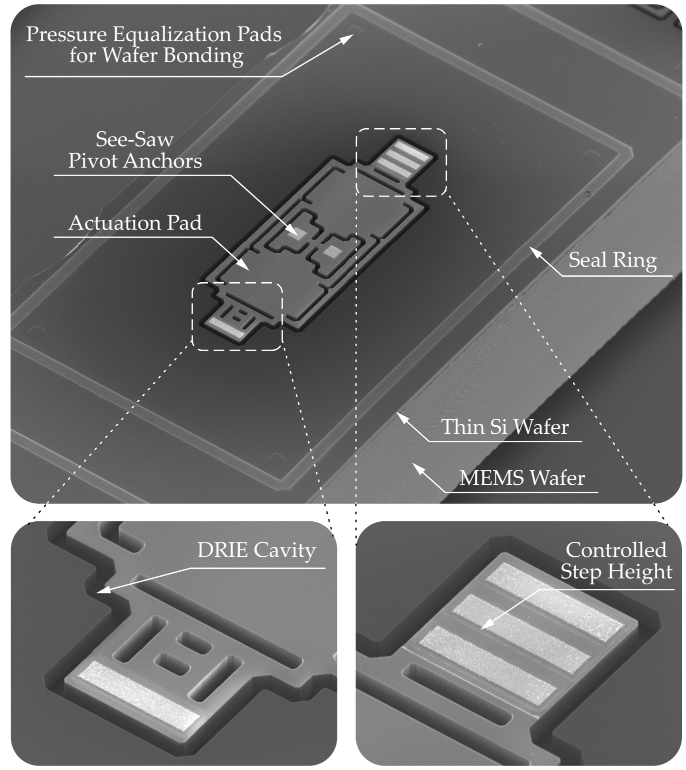


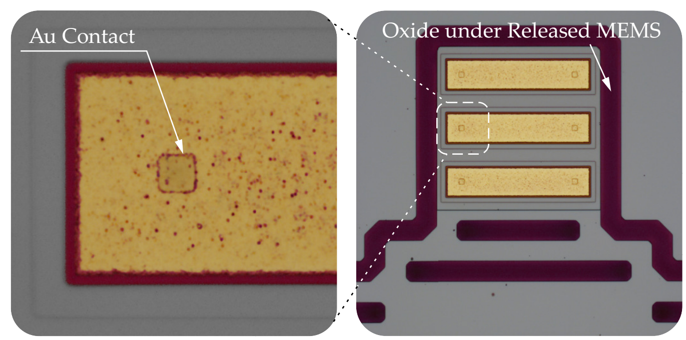
Fig. 2. Optical micrograph of the packaged MEMS switch without MEMS handle wafer. Images of circuit wafer shows electrostatic pads, DC/RF ports and fulcrum. Optical micrograph of the membrane is taken by delidding the MEMS wafer and aligning with circuit wafer. Membrane wafer's opacity is reduced to highlight seesaw-type switch.

(switch S1) that connects or disconnects the RF signal line, and the other side of the membrane has three contacts (switch S2), which disconnect not only the RF signal line but also both the ground planes of the CPW lines. Seesaw-type membrane when in actuated state (for S1 or S2 switch) provides high isolation at the non-actuated side by increasing the vertical gap (v_{gap}) as shown in Fig. 1. Switch S2 due to the use of triple contacts, completely disconnects the signal line. Pull-out motion is achieved through a fixed fulcrum that avoids any stiction concerns in the switch due to the unique membrane design as shown in Fig. 2. Flexure lengths of the membrane are optimized such that when either S1 or S2 switch is actuated, the flexures pull the beam upwards to increase the v_{gap} on the other size of the membrane. Without the side flexures, the membrane will only act as two cantilevers attached back to back, which defeats the purpose of reliability.

Switch S2 or S2 is actuated by applying dc voltage to the desired side of the membrane and common ground terminal is shared with the membrane as shown in the optical micrograph of the fabricated device in Fig. 2. The switches are fabricated in a commercial MEMS foundry on 200 mm high resistivity silicon wafers. The MEMS devices are fabricated using three wafers, including circuit wafer, membrane wafer and a handle wafer. membrane and handle wafer are bonded together to form MEMS wafer. Circuit and MEMS wafers are hermetically packaged using eutectic bonded. This unique solution isolates the free standing membrane which further provides precise tuning of the micro-fabrication processes. The proposed fabrication methodology offers high yield and endurance of the MEMS structures by not involving any



(a)



(b)

Fig. 3. SEM micrograph of delidded MEMS wafer highlighting seesaw-type RF MEMS switch membrane and central fulcrum, electrostatic actuation pads, pressure equalization pads and seal ring, (a): SEM micrograph of zoomed-in view of single and triple contact switch tips; (b). Optical Micrograph of triple contact MEMS switch tip showing released MEMS membrane and zoomed-in view of single Au contact.

post-processing technique which can potentially damage the free-standing structures. The support structures are attached to the circuit and MEMS wafer to offer better reliability of the anchors. The RF devices incorporate Au-Ru/AlCu contacts to avoid contact degradation and micro-welding problems. Thick silicon core offers less stresses in meander beams and also offers near zero beam warping or sagging to keep the actuation voltage consistent.

SEM micrograph of the delidded MEMS wafer is shown in Fig. 3 highlighting RF MEMS seesaw-type membrane and pivot anchors. A seal ring and pressure equalization support pads are used for eutectic bonding. Individual switches are

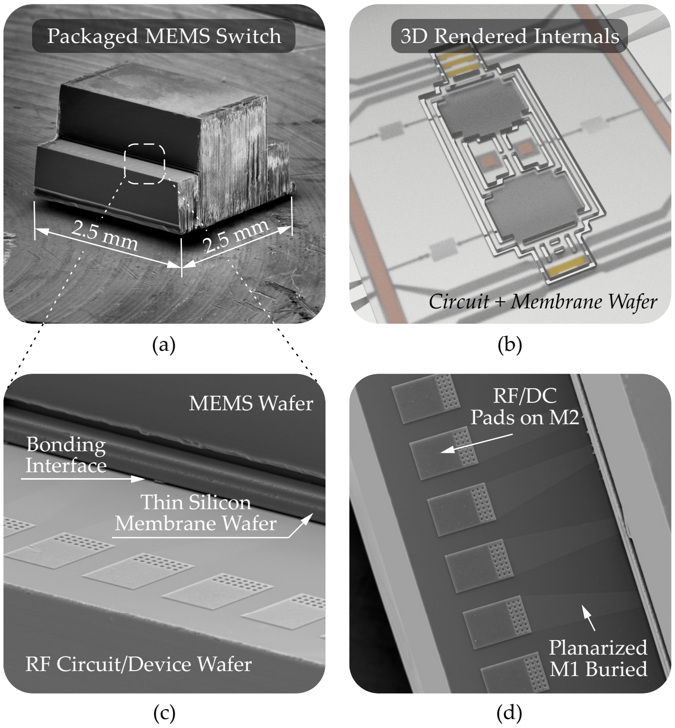


Fig. 4. (a): SEM micrograph of diced wafer level packaged MEMS switch, streaks on the sidewall is due to laser dicing, (b): 3D rendered internals of MEMS switch without top MEMS handle wafer, (c): SEM micrograph of zoomed-in view of packaged MEMS switch highlighting thin silicon membrane wafer and bonding interface, and (d): SEM micrograph of MEMS switch showing IO pads and signal lines on M1 and M2 layers.

diced via laser dicing system. Fig. 3(a) shows the zoomed-in view of seesaw-type membrane tips and deep-reactive ion etching (DRIE) cavity. Top view of the upside down triple contact membrane tip is shown in Fig. 3(b). SEM micrograph of the diced RF switch is shown in Fig. 4(a). The overall device periphery of 2.5 mm^2. 3D rendered view of the internal membrane and circuit wafer is shown in Fig. 4(b), while the SEM micrograph of the bonding interface is shown in Fig. 4(c) and the RF/DC pads on planarized and polished M1 and M2 layer are shown in Fig. 4(d).

III. Results and Discussions

The proposed MEMS switch is EM simulated using Ansys HFSS to evaluate and optimize the RF performance, while the mechanical membrane is designed and optimized using FEM COMSOL Multiphysics. Rocking motion of the simulated beam is shown in Fig. 5(a). The actuated side of the switch makes contact with downward 1.25 μm displacement, while at the same time, the other end of the membrane moves 0.5 μm upwards. The actuated membrane shows almost negligible stress of less than 35 MPa as shown in Fig. 5(b). Side view of the actuated membrane is shown in Fig. 5(c).

The RF performance is simulated and measured from dc to 20 GHz. The proposed RF MEMS single contact switch S1 exhibits less than 0.6 dB insertion loss and better than 20 dB return loss in the ON-state, while offers higher than

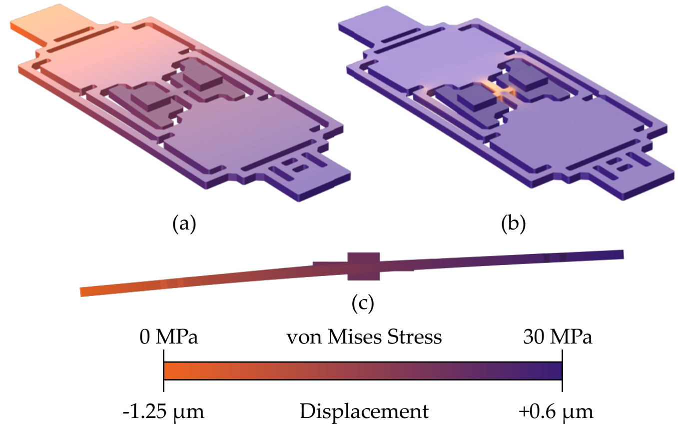


Fig. 5. FEM simulations of (a). Displacement, (b). von Mises stress, and (c). Membrane displacement side view.

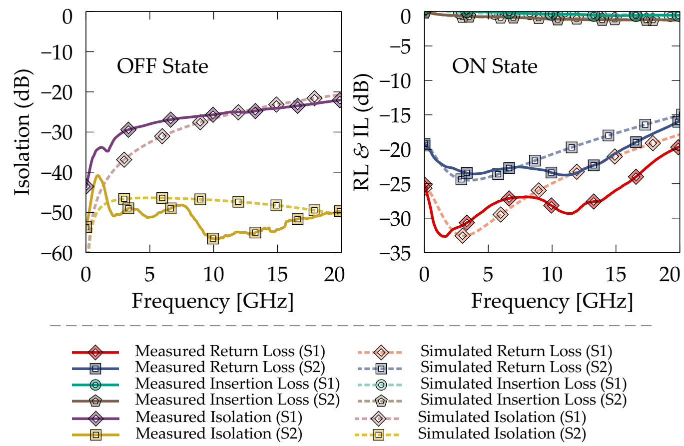


Fig. 6. Measured and simulated S-parameters of single contact (S1) and triple contact (S2) RF MEMS switch from DC–20 GHz. Results are measured after dicing individual MEMS switch.

20 dB isolation in the OFF-state. Triple contact switch S2 demonstrates less than 1 dB insertion loss, better than 16 dB return loss in the ON-state and more than 40 dB isolation in the OFF-state as shown in Fig. 6. If only S1 switch is used, the isolation can be vastly improved by actuating S2 (non-connected) to move the S1 tip in upward direction that reduces any signal leakage path. The switch has been successfully cycled for more than 100 times without any mechanical failure.

IV. Conclusion

A high-reliability robust wafer level packaged RF-MEMS switch is developed. The switch utilizes seesaw-type mechanism that provides two unique and independent RF switches in a single hermetically sealed package. The switch incorporates non-metallic thick silicon membrane to improve mechanical robustness, while gold-ruthenium metal contacts minimizes any micro-welding and contact degradation problems. Eutectic packaging approach is used so minimize any post release packaging issues. The proposed switch exhibits excellent RF performance while providing two switches in a single package.

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