PZT Actuated Seesaw SPDT RF MEMS Switch

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Abstract. A low actuation voltage and no contact stiction are important factors in applying micro-electro-mechanical-system (MEMS) RF switches to mobile communication devices. Conventional electrostatic RF MEMS switches require several tens of volts for actuation. In this paper we propose a piezoelectric actuated seesaw (PAS) RF MEMS switch which adopts Pb(Zr,Ti)O3 (PZT) actuators and seesaw cantilevers to meet the above requirements. The fundamental structures of PAS RF MEMS switches were designed, optimized, and fabricated. Through the developed process of PAS single pole double through (SPDT), RF MEMS switches were successfully fabricated on a 4” wafer and they showed good electrical properties. The driving voltage was less than 5 volts and the insertion loss was -0.5dB and the isolation was -35dB at 5GHz. The maximum switching speed was about 5kHz. Thus these RF MEMS switches can be applicable to mobile communication devices or wireless multi-media devices at a frequency lower than 6GHz.

1. Introduction

Field effect transistors (FET) and pin diodes are widely used as RF switches in communication and radar systems. But as the operating frequency rises, there are increasing problems of relatively high insertion loss and harmonic distortion. Therefore there have been many intensive studies to find a way of substituting them with micro-electro-mechanical-system (MEMS) RF switches.

RF MEMS switches have the advantages of low insertion loss, low power consumption, superior isolation in an OFF state, and relatively high handling power. Low actuation voltage is one of the most important factors for applying the RF MEMS switches to mobile communion devices. Many electrostatic actuation-type RF MEMS switches have been developed for their easy fabrication process and good dynamic characteristics. But their operation voltages were several tens volts. If the thickness of a cantilever is decreased to lower the spring constant and actuation voltage, the restoring force of the cantilever becomes low too. This hinders the switch from restoring and makes the cantilever stick to a substrate at a contact point. Therefore it is necessary to develop RF MEMS switches with no sticking problem and low operation voltages.[1][2]

In this paper we propose a piezoelectric actuated seesaw (PAS), single pole double through (SPDT) RF MEMS switches (figure 1) which adopt low voltage actuated Pb(Zr,Ti)O3 (PZT) actuators and seesaw cantilevers to achieve an active off operation. We designed the structure of the PZT actuators and seesaw cantilevers, and their electromagnetic, static, and dynamic properties were simulated and optimized.
Figure 1. Structure of PAS SPDT MEMS Switch, (a) wafer for PZT actuator, (b) wafer for RF electrodes and seesaw structure

The fabrication process of PZT actuators is not compatible with that of RF electrodes and seesaw structures, so we separately fabricated the PZT actuators on one wafer and RF electrodes and seesaw structures on another wafer and bonded them together by a solder eutectic bonding process [3]. In the bonding process it is very important to control the gap between the two wafers. We developed a method of precisely controlling the bonding gap by using stopper structures. To connect outer electrodes and inner electrodes, thousands of micro-through holes were fabricated by sand blast on a 4" glass wafer and filled with Cu by electroplating.

2. RF MEMS Switch Design
The structure of a designed PAS RF MEMS switch is depicted in figure 1. The switch is composed of a low voltage-operated cantilever type PZT actuator and a seesaw-type SPDT switch structure. The main benefit of the proposed PAS SPDT RF MEMS switch is that low voltage operation is possible, so the reliability can be improved by eliminating the sticking problem at contact points by use of an active OFF operation.

By separating the fabrication processes of PZT actuators and RF electrodes and seesaw structures in two different wafers, the RF MEMS switch’s performance and the structures can be optimized. And by adopting a solder eutectic bonding process, hermetic sealing and interconnection between electrodes can be achieved and an inexpensive wafer level packaging is possible.

The PZT actuator was designed to use high resistivity silicon (HRS) wafers as substrates, poly-silicon as a sacrificial layer, and SiN as a supporting layer of metal electrodes and thin PZT layer. The designed PZT actuator is composed of a lower Pt electrode, a thin PZT layer, an upper Pt electrode and the PZT actuator is driven by the applied voltage between the lower electrode and the upper electrode. An outer square ring is made of Au metal for solder eutectic bonding and a stopper structure is for precise bonding gap control.

RF electrodes and seesaw structures are designed to be fabricated on a 500 μm thick glass wafer in which thousands of through holes (diameter of 100 μm) have been made and filled with Cu electroplating and the surface of the wafer has been polished. In addition, there are outer square ring structures and stopper structures in the wafer for wafer bonding.

The operation principle of the proposed RF MEMS switch can be explained by figure 2. When the left PZT actuator is activated, as in figure 2(b), the left cantilever of the seesaw is pushed up and the left RF electrodes are connected and ON. At the same time, the right cantilever of the seesaw is moved down. On the contrary, as in figure 2(c), when the left PZT actuator is inactive and the right PZT actuator is activated, the right cantilever of the seesaw is pushed up and the right RF electrodes are ON. At that moment, the left RF electrode is in an active OFF state. By this active OFF operation, the sticking problem can be easily overcome, the OFF operation does not rely on the spring constant of the
seesaw cantilever, and the operation voltage can be lowered. Additionally, the separation between the seesaw cantilever and the RF electrodes, in an OFF state, is twice the initial value, so the isolation becomes better.

Figure 2. Operation principle of a proposed RF MEMS switch, (a) Normal state, (b) Left PZT actuator is activated, (c) Right PZT actuator is activated (the left RF electrode is in an active OFF state)

The design parameters of the RF MEMS switch are summarized in Table 1. The PZT actuator is designed to have an operating frequency of 5GHz, a driving voltage of 5V, and a displacement of 4.5 μm. The switch structure and the separation between PZT actuators and seesaw structures was optimized for RF characteristics. It was designed so that its insertion loss is less than 0.5dB and isolation is more than 30dB.

| Table 1. Design Parameters of an SPDT MEMS Switch |
|-----------------|---|-----------------|
| Parameters      | Value | Remark          |
| Insertion Loss  | 0.5dB | @ 5.0GHz        |
| Isolation       | 30±3dB| @ 5.0GHz        |
| Driving Voltage | 5V   | Level Control   |
| Contact Force   | 100μN |                |
| Spring Constant | 10N/m |                |
| Response Time   | < 1ms |                |
| Initial Gap     | 2 μm  | Off Gap = 4.5 μm|
| Actuator & Seesaw Gap | 2.5 μm |        |
| Actuator Layer  | Pt/PZT/Pt/SiN/Si |          |
| Seesaw Layer    | Au/Glass |               |
| Chip Size       | 2.5 X 2.5 X 1 mm³ |        |
3. Fabrication and Discussion

A PZT actuator fabricated by chemical solution deposition (CSD) of a PZT layer and the formation of Pt electrodes is shown in figure 3. In the figure, the lower Pt electrode is connected to the right and left pads, and the upper electrode is connected to the center pad with a bridge structure. To release the cantilever from the substrate the poly-silicon sacrificial layer beneath the cantilever was etched by XeF2 isotropic etching. The etched area can be seen in the figure.

The measurement result of the PZT actuator is shown in figure 3(b). The fabricated PZT actuators had an 1 μm thick SiN thin film and the measured displacement was about 5.5 μm at a 5V driving voltage, and the switching time was about 200μsec at atmospheric pressure. It is expected that the switching speed can be increased by vacuum packaging.

![Figure 3](image1.png)

**Figure 3.** Fabricated PZT actuator, (a) SEM image of the fabricated PZT actuator, (b) Displacement vs. applied voltage of the PZT actuator

In the fabrication process of RF electrodes and a seesaw structure, it is very difficult to fill the through holes with Cu without defects, as each hole’s diameter is 100 μm and the substrate's thickness is 500 μm. Figure 4 shows the Cu filled through holes, and the holes were made by sand blast. Dry film resist (DFR) is used as a blocking material, which is patterned by UV lithography on both sides of a glass wafer, and the sand blast process is done on both sides. As seen in the figure, the Cu-filled hole is an hourglass shape.

![Figure 4](image2.png)

**Figure 4.** Cu-filled through holes in a glass wafer (hourglass shape, diameter: 100 μm, height: 500 μm, space: 200 μm)
The top and bottom surfaces of the glass wafer were polished by a chemical mechanical polishing (CMP) process after Cu filling. RF CPW electrodes were formed by Au electroplating on both sides of the glass wafer. Photoresist (PR) was coated and patterned as a sacrificial layer for fabricating seesaw structures. A seed layer was deposited on the PR sacrificial layer and seesaw structures were formed by PR patternning and successive Au electroplating. The PR sacrificial layer was removed by O2 plasma. The thickness of the seesaw structures was 5 μm and the gap between the seesaw cantilever and the RF electrodes was 1.8~2.3 μm. Figure 6 shows a fabricated chip in which RF and DC electrodes, a seesaw structure, outer ring and stopper structures were formed. And as you can see in this figure, the seesaw structure is slightly separated from the RF electrodes

**Figure 5.** RF electrodes and a seesaw structure

By bonding two separately fabricated wafers -- one for the PZT actuator and the other for the RF electrodes and seesaw wafer -- the PAS SPDT RF MEMS switches were successfully fabricated as shown in figure 6. Bonding temperature was 250°C, bonding pressure was 1Kgf/wafer, and bonding time was 10 minutes.

The RF characteristics of the fabricated RF MEMS switch are shown in figure 7. The isolation value was less than -35dB, insertion loss was less than -0.5dB, and the return loss was -25dB.

**Figure 6.** A fabricated RF MEMS switch, (a) The PZT wafer and seesaw wafer were bonded by solder eutectic bonding. This picture was taken to show the inner RF electrodes and the seesaw structure through the transparent window, (b) wire bonding(ceramic package)
Figure 7. RF characteristics of the fabricated RF MEMS switch: (a) Isolation in the OFF state (10dB/Div, range = 0.04~10.0GHz), (b) Insertion loss (-0.5dB@5GHz) and return loss (-25dB@5GHz) in the ON state (10dB/Div, range = 0.04~10.0GHz)

4. Conclusion
The proposed PAS SPDT RF MEMS switch was successfully fabricated through several fabrication processes of PZT actuators, micro-through holes and metal filling, and RF electrodes and seesaw structures. The fabricated RF MEMS switch showed good results and meets the desired specification. The driving voltage was less than 5V, insertion loss was less than -0.5V, and the isolation value was less than -35dB. It is expected that the PAS SPDT RF MEMS switch can be applicable to mobile communication and multimedia devices at a frequency range lower than 6GHz.

Reference
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