

# Ultra High Performance In-line Contact MEMS RF Switch

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## ABSTRACT

This paper reports an in-line contact RF MEMS switch using electrostatically actuated membrane. The proposed switch was designed and the surface micro machining was used to fabricate it. Finally, RF performances and switching time were measured. The previous in-line MEMS switch showed good RF performances but the actuation voltage was very high. The proposed switch is a series type and additionally has a supportive membrane to lower the actuation voltage. A membrane acts as an electrostatic actuator, and the floating signal line is attached to the center of the membrane. In this design, there is single contact point at the end of the floating signal line and this single contact makes the proposed switch have lower contact resistance than two contact switch when the same contact force is applied. This makes the switch have ultra high RF performance. The device fabrication is based on surface micromachining and the gold was used as a contact material. Thermal and multiphysics analysis with ANSYS was used to design the switch and to verify the results. The measured actuation voltage was 13V. The insertion loss of -0.06 dB, the isolation of -35.4 dB at 2 GHz was measured. The switching time was calculated and the measured ON/OFF time was each 25 $\mu$ s and 20 $\mu$ s.

**Keywords:** microactuators, in-line contact, RF MEMS switch

## 1 INTRODUCTION

Wireless mobile communication systems have to involve multi-band services as new generation system shows up and, in addition, customers expect to have multi-functional services such as video recording, MP3 playing, and global positioning system (GPS). Consequently, these requirements force RF components to be smaller and have ultra high performance [1] and RF MEMS switches have been widely studied during last 15 years since L. E. Larson presented a MEMS switch transmitting RF signals up to a few tens of GHz [2]. RF MEMS Switches are still the promising candidate to replace conventional semiconductor switches due to its outstanding performances such as high electrical isolation, low insertion loss, and negligible power consumption.

RF MEMS switches are mostly divided into series switches and shunt switches if it is classified by circuit type. Series switches are normally off and the RF signals can be transmitted when the switches connect the input line to the

output line. On the contrary, shunt switches are normally on and the RF signals go out of the switches to the ground when the switches are down. The former is suitable for DC to RF applications, especially for mobile handset, and the latter is used for microwave frequencies. [3]

Most studies on MEMS RF switches of wireless mobile communication systems have been focused on series switches with metal contact. Series switches with metal contacts have no choice but to have two contact points, however this factor makes switch unreliable and its driving force is also divided into contact points. Moreover, the MEMS structure based on the surface micromachining is usually bent or twisted due to the residual stress and this unbalanced MEMS structure might result in making only one contact of two or a reliable contact and, then, it fails to transmit RF signals from an input port to an output port. This failure mode can also occur when switches are in use. In addition, in-line direct contact switch with single contact can lower the contact resistance physically if the same contact force is applied. Two concepts are illustrated in Fig. 1.

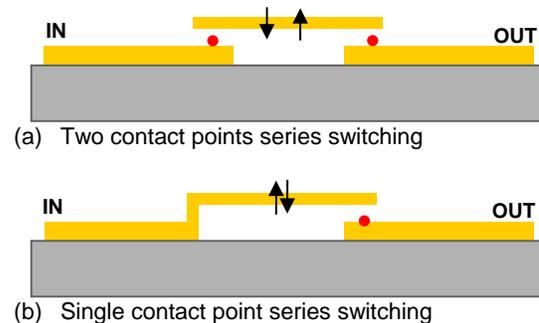


Fig. 1. Comparison of two contact point switching and in-line direct contact switching.

This in-line MEMS switch showed very low insertion loss because the driving force is concentrated on its single point and also demonstrated low actuation voltage using an electrostatically actuated membrane.

## 2 DESIGN AND FABRICATION

There have been a few switches using in-line direct contact from the beginning of RF MEMS switch. However, these switches used very high actuation voltage because the previous switch used the small electrode area under the signal line [4]. A high contact force switch and a high power switch were developed but applied voltage was not good [5] [6].

Another in-line switch was studied. It was first curled up due to the built-in stress and was actuated by electrostatic force between the curled cantilever and bottom electrode [7].

The proposed MEMS RF switch has single contact point, which means that part of the RF input line is floating and it moves up and down to connect the signal. To lower the actuation voltage of MEMS switch, a supportive membrane was used and single contact point is located in the middle of the floating signal line. A schematic view of the proposed MEMS RF switch is illustrated in Fig. 2 where parameters are also explained.

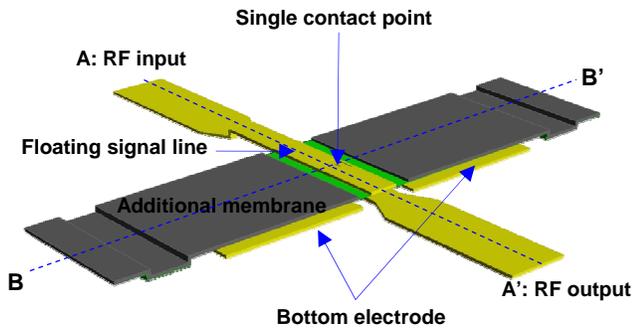


Fig. 2. Schematic view of the in-line MEMS RF Switch

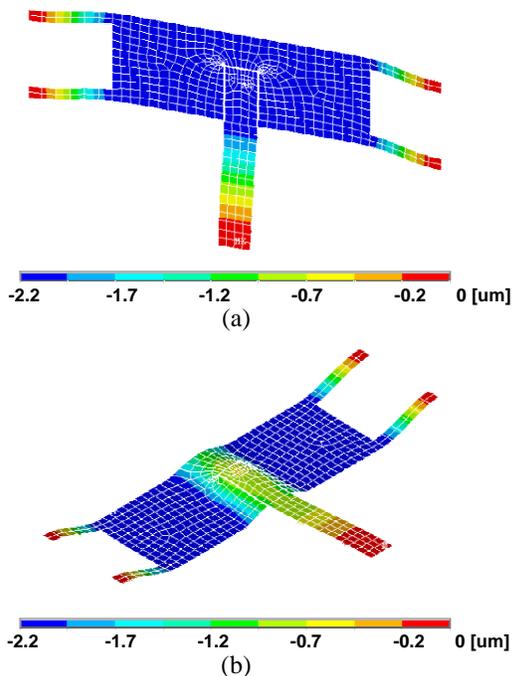


Fig. 3. (a) the approximate pull-in analysis and (b) the pull-in analysis including contact pairs (Displacement)

To design the switch, finite element analysis was used. First, a pull-in analysis using ANSYS TRANS126 element was performed and approximate pull-in voltage was decided. Next, the pull-in analysis including contact pairs was analyzed. The simulated pull-in voltage is around 8V and it is reported that the actuation voltage is generally a little higher than pull-in voltage. The spring constant is 12 N/m. In this structure, contact force was concentrated on the single contact point when the membrane was pulled down as you see in Fig.3 (b).

The active electrode area is  $200 \mu\text{m} * 155 \mu\text{m} * 2$  and the floating signal line is  $200 \mu\text{m}$  long and  $50 \mu\text{m}$  wide. The contact area is  $20 \mu\text{m}$  wide and  $15 \mu\text{m}$  long. The gap between electrodes is  $2.2 \mu\text{m}$ . Surface micromachining was used to fabricate it and fabrication processes of the proposed switch are divided into 5 steps. Fig. 4 illustrates whole processes. First, the substrate was etched and a  $1.5 \mu\text{m}$ -thick Cr/Au layer is sputtered for CPW. 1<sup>st</sup> sacrificial layer is patterned for planarization. Secondly, 2<sup>nd</sup> and 3<sup>rd</sup> sacrificial layers are patterned for the anchor of the floating signal line and the contact part. Third, a  $1 \mu\text{m}$ -thick Au/Cr was sputtered for a floating signal line and the single contact point was shaped in this process together. The thickness of a floating signal line is different from coplanar waveguide (CPW) because thick floating metal line requires higher actuation voltage. Figure 5 showed scanning electron microscopy image of the fabricated in-line RF MEMS switch after releasing process.

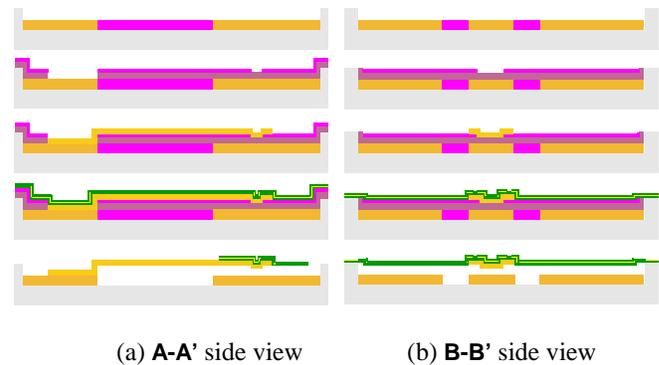


Fig. 4. Processes of the proposed RF MEMS switch fabrication

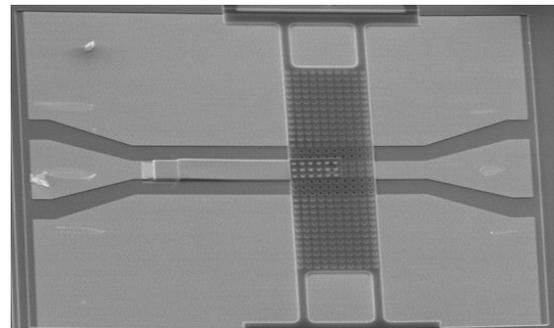


Fig. 5. Scanning electron microscopy (SEM) image the fabricated in-line direct contact RF MEMS switch

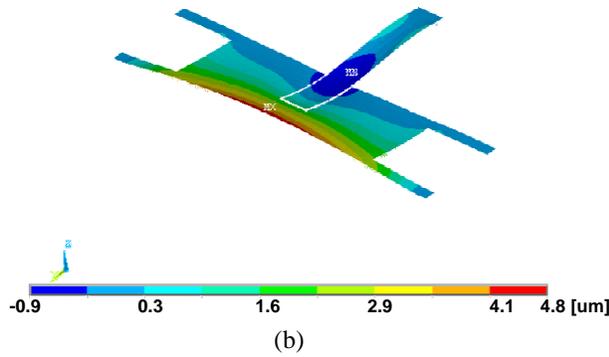
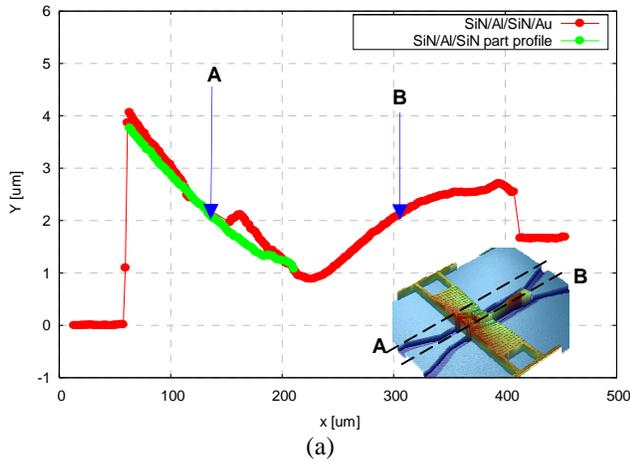


Fig. 6. (a) 2-D profile data of the fabricated switch (b) thermal analysis including process temperature (Displacement)

Next, membrane layers are deposited and patterned. All membranes including springs consist of SiN/Al/SiN due to the thermal stress compensation. Lastly, all sacrificial layers are removed.

The stress of a supportive membrane was well compensated as you see in Fig. 6 (a). However, the membrane was inclined due to the expansion of the gold-made floating signal line. Thermal analysis considering the highest process temperature, 570K, verified it. Fig 6 compared measured surface profile to the simulated thermal analysis and two images coincided.

### 3 TEST AND EVALUATION

The pull-in voltage depends on the spring constant  $K$ , the gap between a top electrode and a bottom electrode  $d$ , and the electrode area  $A$  as given by (1).

$$V_p = \sqrt{\frac{8Kd^3}{27\epsilon A}} \quad (1)$$

Parameters	Value	Unit	Comments
Au	19300	kg/m <sup>3</sup>	density
SiN	2700	kg/m <sup>3</sup>	density
Al	2300	kg/m <sup>3</sup>	density
m	5.5x10 <sup>-10</sup>	kg	calculated mass
K	12	N/m	simulated spring constant
f	23.3	KHz	calculated (small damping)
V <sub>p</sub>	8	V	simulated pull-in voltage
V <sub>s</sub>	15	V	source voltage
T <sub>off</sub>	25	μs	measured switch OFF time
T <sub>on</sub>	20	μs	measured switch ON time
T <sub>cal</sub>	14	μs	calculated switch time

Table 1 Data for the switching time calculation

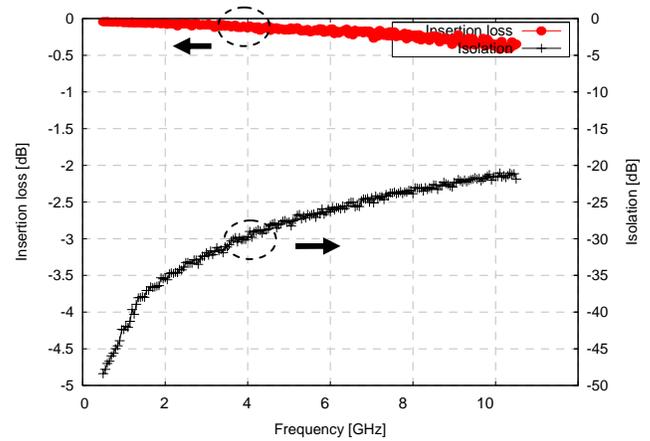


Fig. 7. RF characteristics of the fabricated in-line RF MEMS Switch

This expression comes from a simple approximation that the electrostatic force of the mechanical switch is the same as those in a parallel plate capacitor [8]. The measured actuation voltage of the fabricated in-line switch was higher than the simulated pull-in voltage. According to equation (1), it is mainly because the initial gap is different due to the thermal stress of the floating signal line and the spring constant was strengthened by the stiffening effect of membrane structure.

Switching time was also measured and calculated. To measure switching time, a sinusoidal wave with a frequency of 200 kHz and a peak-to-peak voltage of 4 V was applied to an input port as an input signal and an output port was connected to an oscilloscope to measure the output signal. The source voltage was 15V and a square wave with 200Hz was used to operate the switch. Measured switching ON and OFF time were 25μs and 20μs and the calculated switching time with a small damping is about 14μs. All data for the switching time calculation were shown in Table 1.

RF characteristics of the proposed RF MEMS switch are shown in Fig. 7. All measurements were performed on the

wafer without any de-embedding the probing pads, and HP 8510 network analyzer was used to measure RF performances. The insertion loss is -0.06 dB at 2 GHz when the actuation voltage is 13V. The off-state isolation is -35.4dB at 2GHz.

#### 4 CONCLUSIONS

The in-line contact RF MEMS switch was proposed, fabricated, and tested. The proposed switch has only single contact point at the end of the floating signal line and it is attached to the center of the membrane. The switch has a supportive membrane and is actuated by electrostatic force. The actuation voltage is 13V, and the measured insertion loss and isolation are -0.06 dB and -35.4 dB at 2 GHz, respectively. It is believed that performance can be improved with optimization of design and fabrication: thickness of CPW, dimension of spring, and configuration of electrodes.

In resistive series switch, two contact points connecting signal lines exists inevitably, therefore, there is physical limitation on decreasing the contact resistance unless a overwhelming contact force is applied. There is tradeoff between actuation voltage and contact force: The low voltage operation switch is very desirable for wireless mobile communication system and, at the same time, the big contact force is needed. Switches having single contact point can not only reduce the contact resistance but also prevent an unreliable contact and in-use failures due to the stress.

Consequently, an in-line direct contact switch or a single contact-like switch can be a proper approach to design a high performance RF MEMS switch.

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