Lifetime testing of a MEMS switch with Pt-Pt contact

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Abstract. This paper presents the lifetime testing results of an electrostatically actuated microelectromechanical systems (MEMS) switch with the resistive contact and the active contact breaking mechanism. Moveable electrode of the switch is an aluminium beam with platinum contact bumps located on its bottom surface, which comes in contact with platinum thin-film electrodes. The switch operates in a cold DC mode in a standard laboratory environment. Testing is performed at three levels of the input current: 0.05, 0.5 and 5 mA. The dependence of the resistance in the “on” state on the number of actuation cycles is measured. Resistance of the “fresh” samples is in the range from 150 to 350 Ω. Instability of the resistance is observed during cycling, that is probably related to contamination of the contacts. Lifetime of the switch is limited by the sharp increase of the on-resistance up to 100 MΩ and varies from $2 \times 10^3$ to $5 \times 10^4$ cycles depending on the switch design and the input current.

1. Introduction
Resistive contact MEMS switches are used in radio frequency and microwave systems for signal routing and control [1]. Attenuators [2], phase shifters [3], filters [4] and other devices based on the MEMS switches are presented. Among various actuation mechanisms, electrostatic actuation is the most popular. In comparison with switches based on pin-diodes and field-effect transistors, electrostatically actuated MEMS switches have low power consumption, good RF performance and high radiation resistance. Compared to conventional electromechanical relays, they are significantly smaller and have shorter switching time. MEMS switches are also used in integrated circuits and are considered as an alternative to semiconductor switches [5]. The simplest logic elements [6] and memory cells [7] are demonstrated. Furthermore, MEMS switches can be fabricated using conventional microtechnology, which allows them to be integrated into CMOS circuits [8].

However, incorporation of MEMS switches into commercial products is limited by their relatively low reliability [9]. The most common reason of failure is an increase of the contact resistance during cyclic operation, which occurs due to contamination, oxidation, and mechanical damage of contacting surfaces [10]. At present, a lot of research is carried out to increase the reliability of contacts. Proper selection of the contact material plays an important role. One of the most widely used materials is gold [11-13]. Its chemical inertness and high conductivity provides insensitivity to contamination and low contact resistance. However, low hardness and low melting point of Au makes a switch susceptible to stiction and unable to transfer high-power signals [14, 15]. Harder platinum group metals such as Ru, Rh, Ir and Pt are considered as an alternative to Au [16, 17]. They allow to overcome the shortcomings of the gold contacts and to provide acceptable contact resistance and high reliability simultaneously. In this work the lifetime of an electrostatically actuated MEMS switch with Pt-Pt contact is investigated.
2. Design of the switch and experimental setup

SEM image of the switch is shown on figure 1. The device is based on a 2-µm-thick aluminum beam (source) attached to the torsion springs. The beam has a length of 100 µm and a width of 8, 16, 24 or 32 µm depending on the design. Gate and drain electrodes are made of 100 nm thick Pt film and placed under the each arm of the beam, so the switch has two symmetric output channels. The gap between the beam and the gate electrodes is 1.5 µm. Platinum contact bumps of 0.5 µm in height are located on the bottom side of the beam (one bump per arm, figure 2). Thus, Pt-Pt contact was obtained. The switches were fabricated by surface micromachining on the oxidized silicon substrates. Details of the design and the fabrication process can be found in our previous works [18, 19].

![Figure 1. SEM image of the switch.](image1)

The switch operates as follows. Initially the beam has the horizontal position. When the driving voltage is applied to one of the gates, the beam tilts towards the electrode under the electrostatic force and comes in contact with the corresponding drain. Thus, the switch goes to the “on” state. When the voltage is removed, the beam returns to the initial state under the elastic force of the springs. In case of stiction, i.e. when the elastic force is insufficient to overcome the forces acting between the bump and the drain, the switch retains the “on” state. In order to detach the beam from the drain, the voltage is applied to the opposite gate. The beam tilts to the opposite direction and comes in contact with another drain. Therefore, the design of the switch provides the active contact breaking mechanism, which protects the device against stiction.

Testing of the switches was performed in a standard laboratory environment, the samples were unpackaged. Measurement equipment was connected to the switch as shown on figure 3. Driving voltage \(V_{G1}, V_{G2}\) was periodically applied to the gates from the DC power supply Agilent E3647A in such a way that the channels were actuated alternately with the frequency of 2.5 Hz. The minimal gate-to-source voltage needed to close the switch was measured previously and the range of 29-46 V was obtained [19]. The amplitude of pulses was chosen to be 60 V in order to ensure the actuation. The switches operated in a cold DC mode. Input voltage \(V_S\) was applied to the source from the analog output module National Instruments PXI-6711. It was turned on 40 ms after closing and turned off 60 ms before opening the switch in order to avoid hot operation and excessive wear of the contacts. All the samples were tested at \(V_S = 5\) V. Output voltage \(V_{D1}, V_{D2}\) was registered at the drain electrodes by the oscilloscope PicoScope 5442B and the multifunction input/output module NI PXI-6143. Typical gate and drain signals observed during the test are shown on figure 4. The current \(I_D\) flowing through the switch was adjusted by the load resistors \(R_1\) and \(R_2\). It was measured at the one of the channels \((I_{D1})\) by the multimeter Keysight 34461A. The equipment was controlled by LabView software. On-resistance \(R_{ON}\) of the both channels was calculated at each actuation cycle from the resistive divider circuit. The experiments were performed at three levels of the current: 0.05, 0.5 and 5 mA.
3. Results and discussion

Typical dependence of the switch resistance in the “on” state on the number of actuation cycles is shown in figure 5. $R_{ON}$ was changing between 100 and 2000 $\Omega$ during the test. Such instability was observed for all the samples. After several thousands of cycles $R_{ON}$ sharply increased up to 100 $M\Omega$ that was considered as a failure of the switch. The on-resistance of the “fresh” devices was in the range of 150÷350 $\Omega$. $R_{ON}$ was approximately two times lower and more stable at $I_{D} = 5$ mA than at 0.05 and 0.5 mA (figure 6a). This fact was probably connected with the calculation method, whose accuracy depends on the relation between the load resistance and resistance of the switch. Another probable reason is that at high current level the asperities of the contacting surfaces are melted easier, thus increasing the effective contact area which results in lowered contact resistance.

It is worth noting that $R_{ON}$ was rather high for ohmic MEMS switch, typical value should be less than 5 $\Omega$ [1]. Measured resistance consisted of two main parts. One part is the sheet resistance of the thin metal film of the drain electrode, the beam and the signal lines. This resistance cannot be eliminated from the measurement because of practical limitations on the geometry and placement of the contact pads. High resistance of the switch was partly caused by the small thickness of the drain electrodes and their connecting lines, which have the resistance of about 100 $\Omega$. The other part is the contact resistance caused by the current flowing through a small contact area (it is also called constriction resistance). It includes a resistance coming from the contamination thin film between the metal contacts. It is known that Pt-group metals are susceptible to contamination and frictional polymerization [10, 15-17] that can lead to unstable and increased contact resistance during the switching cycles. Probably, this component was responsible for the instability of $R_{ON}$. As a result, both parts contributed sufficiently to the total on-resistance. Further we plan to minimize the sheet resistance by increasing the thickness of the signal lines. This will reduce the total resistance of the switch and allow to investigate the contact resistance more precisely. It is also necessary to inspect the contacting surfaces for wear and contamination in order to identify the reason of the on-resistance instability.

Contact resistance of the switch is usually estimated using the following equation [20]:

$$R_{C} = \frac{\rho}{2a},$$

(1)

where $\rho$ is the resistivity of the contact material (15.5 $\mu\Omega$ cm for Pt [14]), $a$ is the radius of the contact spot. For plastic deformation of contacting surfaces $a$ is given by [20]

$$a = \sqrt{\frac{F_{C}}{\pi H}},$$

(2)

where $F_{C}$ is the contact force and $H$ is the Meyer indentation hardness of the contact material (5.1 GPa for Pt [14, 15]). Combining equations (1) and (2) it can be seen that $R_{C}$ is inverse proportional to $F_{C}^{1/2}$. 

Figure 3. Connection of the measurement equipment to the switch.

Figure 4. Gate and drain signals of the switch during the test.
Contact force is determined by the electrostatic force acting between the beam and the drain electrode in the “on” state and is proportional to the beam width. Therefore, switches with the widest beam should have the lowest on-resistance. Nevertheless, there was no clear dependence of the $R_{\text{ON}}$ on the beam width (figure 6a). Careful estimation of the contact force and precise measurement of the contact resistance is needed to explain this result.

Lifetime of the switches was limited by the sharp increase of the on-resistance and varied from $2 \times 10^3$ to $5 \times 10^4$ cycles. The samples with the narrowest beam ($w = 8 \ \mu m$) failed with the least number of cycles at all current levels (figure 6b). Probably, it was due to the lowest contact force that was insufficient to break the continuously growing contamination film. Switches with $w = 24 \ \mu m$ typically showed the longest lifecycle. At $I_D = 5 \ mA$ the lifecycle was slightly lower than at 0.05 and 0.5 mA, that was connected with the intensified wear of the contacting surfaces. In general, the obtained data corresponded to the endurance of the switches with the Pt-Pt contact available in the literature [15, 17]. Although the switches were able to withstand a relatively small number of actuation cycles, the stiction was not observed even at the current of 5 mA, which corresponded to the switching power of 25 mW. In the future we plan to increase the current and evaluate the capabilities of switching high-power signals.

![Figure 5](image)

**Figure 5.** Dependence of the on-resistance on the number of actuation cycles for three samples having different width of the beam $w$. Measurements are performed at $I_D = 0.5 \ mA$.

![Figure 6](image)

**Figure 6.** Dependence of the initial on-resistance (a) and the lifecycle (b) on the beam width.
4. Conclusions
Electrostatically actuated MEMS switch with Pt-Pt contact was tested for reliability. The samples operated in a standard laboratory environment under cold switching conditions. Testing was performed at the input current from 0.05 to 5 mA. The dependence of the on-resistance on the number of switching cycles was measured. The initial contact resistance was from 150 to 350 Ω and did not depend on the switch design. The resistance was unstable during the test, varying from 100 to 2000 Ω. The possible reason of instability was the contamination of contacting surfaces that is typical for platinum group metals. After several thousands of cycles the resistance increased sharply up to 100 MΩ that was considered as a failure of the device. The lifetime of the switches was from $2 \times 10^3$ to $5 \times 10^4$ cycles. Switches with the narrowest beam had the shortest lifecycle, no longer than $1 \times 10^4$, probably because of the lowest contact force. The main reason of failure was the increase of the resistance during cycling. The stiction was not observed even at the highest current. Further, we plan to increase the input current and test the switch for transmission of high-power signals.

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