Reliability of platinum contacts in a cold operated MEMS switch

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Abstract. Lifetime testing results of an electrostatically actuated microelectromechanical systems (MEMS) switch with Pt-Pt contact are presented. Moveable electrode of the switch is an aluminium beam with platinum contact bumps, which comes in contact with platinum thin-film electrodes. The switch operates in a cold DC mode. Testing is performed at several levels of the input current. Dependence of the switch resistance in the “on” state on the number of actuation cycles is measured. Lifetime of the device is limited by the sharp increase of the on-resistance up to 100 MΩ and depends on the switch design and the input current. Morphology and chemical composition of the contacting surfaces are investigated and mechanisms of the contact degradation are determined.

1. Introduction
Resistive contact MEMS switches have advantages of superior RF performance, low power consumption and high radiation resistance over switching devices based on pin-diodes and field-effect transistors. Compared to conventional electromechanical relays, MEMS switches are significantly smaller and have shorter switching time. They are used in radio frequency and microwave systems for signal routing and control [1] and in integrated circuits as an alternative to semiconductor switches [2].

However, relatively low reliability limits the incorporation of MEMS switches into commercial products [3]. Degradation of contacts during cyclic operation is one of the most important failure mechanisms [4]. At present, a lot of research is carried out to improve the reliability of contacts. Proper selection of the contact material plays an important role. The widely used material is gold [5-7]. 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 [8, 9]. Platinum group metals such as Ru, Rh, Ir and Pt are considered as an alternative to Au [10, 11]. They provide acceptable contact resistance and high reliability simultaneously due to higher hardness and chemical inertness. In this work the reliability of the MEMS switch with Pt-Pt contact is investigated.

2. Design of the switch and experimental setup
SEM image of the switch is shown in figure 1. The device is based on a 2-µm-thick aluminum beam attached to the anchors by the torsion springs. It has a length of 100 µm and a width of 8, 16, 24 or 32 µm depending on the design. The beam plays the role of a source electrode. 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 SPDT configuration with 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 is obtained. The switch is fabricated by surface micromachining on the oxidized silicon substrate. Details of the design and the fabrication process can be found in our previous works [12, 13].

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.

Testing of the switches is performed in room air without packaging. Measurement equipment is connected to the sample as shown in figure 3. Driving voltage \(V_{G1}, V_{G2}\) is periodically applied to the gates from the DC power supply Agilent E3647A in such a way that the channels are 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 [13]. The amplitude of pulses is chosen to be 60 V in order to ensure the actuation. The switch operate in a cold DC mode. Input voltage \(V_S\) is applied to the source from the analog output module National Instruments PXI-6711. It is 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 are tested at \(V_S = 5\) V. Output voltage \(V_{D1}, V_{D2}\) is registered at the drain electrodes by the oscilloscope PicoScope 5442B and the multifunction input/output module NI PXI-6143. The current \(I_D\) flowing through the switch is adjusted by the load resistors \(R_1\) and \(R_2\). It is measured at the one of the channels \((I_{D1})\) by the multimeter Keysight 34461A. The equipment is controlled by the LabView software. On-resistance \(R_{ON}\) of the both channels is calculated at each actuation cycle from the resistive divider circuit containing \(R_{ON}\) and the load resistor. The experiments are performed at three current levels: 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 4. $R_{ON}$ is changing between 100 and 2000 $\Omega$ during the test. Such instability is observed for all the samples. After several thousands of cycles $R_{ON}$ sharply increases up to 100 M$\Omega$ that is considered as a failure. The on-resistance of the “fresh” devices is in the range of 150÷350 $\Omega$. $R_{ON}$ measured at $I_D = 5$ mA is approximately two times lower and more stable than at 0.05 and 0.5 mA (figure 5a). This fact is probably connected with the calculation method, whose accuracy depends on the relation between the load resistance and the resistance of the switch. Another probable reason is that at the higher current level the asperities of the contacting surfaces are melted easier, thus increasing the effective contact area which results in the lowered contact resistance.

It is worth noting that $R_{ON}$ is rather high for ohmic MEMS switch, typical value should be less than 5 $\Omega$ [1]. On-resistance consists of two parts:

$$R_{ON} = R_S + R_C,$$  \hspace{1cm} (1)

where $R_S$ 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 $R_{ON}$ is partly caused by the small thickness of the drain electrodes and their connecting lines, which have the resistance of about 100 $\Omega$. $R_C$ 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. Probably, this component is responsible for the instability of $R_{ON}$. Further we plan to minimize $R_S$ by increasing the thickness and reducing the length of the signal lines. This will reduce $R_{ON}$ and allow precise investigation of $R_C$.

Contact resistance of the switch is usually estimated using the following equation [14]:

$$R_C = \frac{\rho}{2a},$$  \hspace{1cm} (2)

where $\rho$ is the resistivity of the contact material (15.5 $\mu\Omega$ cm for Pt [8]), $a$ is the radius of the contact spot. For plastic deformation of contacting surfaces $a$ is given by [14]

$$a = \sqrt{\frac{F_C}{\pi H}},$$  \hspace{1cm} (3)

where $F_C$ is the contact force and $H$ is the Meyer indentation hardness of the contact material (5.1 GPa for Pt [8, 9]). Combining equations (2) and (3) it can be seen that $R_C$ is inverse proportional to $F_C^{1/2}$. 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 is no clear dependence of the $R_{ON}$ on the beam width (figure 5a). Careful estimation of the contact force and precise measurement of the contact resistance is needed to explain this result.

Lifetime of the switch is limited by the sharp increase of the on-resistance and varies from $2 \times 10^3$ to $5 \times 10^4$ cycles. The samples with the narrowest beam ($w = 8$ $\mu$m) fail with the least number of cycles at all current levels (figure 5b). Probably, it is due to the lowest contact force that is insufficient to break the continuously growing contamination film. Switches with $w = 24$ $\mu$m typically show the longest lifecycle. At $I_D = 5$ mA the lifecycle is slightly lower than at 0.05 and 0.5 mA. It is connected with the higher temperature of the contact spot that caused intensified wear of the contacting surfaces. In general, the obtained data correspond to the endurance of the switches with the Pt-Pt contact available in the literature [9, 11]. Although the switches are able to withstand a relatively small number of actuation cycles, the stiction is not observed even at the current of 5 mA, which corresponds to the transmitted power of 25 mW. In the future we plan to increase the current and evaluate the capabilities of switching the high-power signals.
Figure 4. Dependence of the on-resistance on the number of actuation cycles obtained for three samples having different width of the beam $w$. Measurements are performed at $I_D = 0.5$ mA.

Figure 5. Dependence of the initial on-resistance (a) and the lifecycle (b) on the beam width.

In order to identify the reason of the on-resistance instability and sudden resistive failure of the switch the contacting surfaces are inspected using SEM Zeiss Supra 40. To make them observable, a piece of adhesive tape is glued to the switch and then peeled off. Thus, the beam is flipped over. Figure 6 shows the contact bump and the drain electrode of the switch that failed after $5 \times 10^4$ cycles at $I_D = 0.5$ mA. Both parts have damaged areas with the lateral size of about 500 nm. Clusters of material are formed on the contact bump possibly due the transfer of platinum from the drain. These clusters are up to 50 nm in height. As a result of their formation, the contact area can decrease, which increase the contact resistance.

Dark regions are observed on the contact bump around the clusters (figure 6a, b) and on the drain electrode inside the damaged area (figure 6c, f). In order to determine the chemical composition of these regions, energy dispersive X-ray (EDX) analysis is performed using Oxford Instruments INCA x-ACT. Two areas of the drain electrode with the size of $500 \times 500$ nm$^2$ are investigated. The position of the areas is shown in figure 7. Area 1 is located at the unaffected surface of the electrode, while area 2 contains the damaged surface. Data on the chemical composition are presented in table 1. The damaged area contains approximately 35% more carbon than the clean area. This indicates that carbon accumulates on the contacting surfaces during cycling. This phenomenon is known as contamination or frictional polymerization. It is widely observed at the contacts made of platinum group metals [4, 9-11]. Buildup of the frictional polymer causes the instability and rapid increase of the contact resistance during the operation of the switch. It is also known that alloying with Au lowers the contamination rate [11]. However, it increases the susceptibility of the contacts to wear and stiction. Further we plan to select the optimal contact material in terms of low contamination rate and resistance to wear.
The results of the EDX analysis also show that the area 2 contains slightly less platinum than the area 1. This confirms the transfer of platinum from the drain electrode to the contact bump. Material transfer increases the amount of oxygen and silicon in the X-ray spectrum of the sample, because the thinner Pt layer becomes more transparent for X-ray radiation generated in the SiO$_2$ layer.

![Figure 6](image1.png)

**Figure 6.** SEM images of the contact bump (a, b, c) and the drain electrode (d, e, f) of the switch that failed after $5 \times 10^4$ actuation cycles. Black circles indicate the damaged areas. Images (a, d) are made with the magnification of 30000x at the angle of 90° with respect to the surface of the sample; (b, e) – 100000x, 90°; (c, f) – 100000x, 20°.

![Figure 7](image2.png)

**Figure 7.** SEM image of the drain and gate electrodes of the switch. Black squares indicate the location of the EDX analysis areas.

| Element | Area 1 Wt % | Area 1 At % | Area 2 Wt % | Area 2 At % |
|---------|-------------|-------------|-------------|-------------|
| C       | 0.82        | 10.66       | 1.20        | 14.41       |

**Table 1.** Results of the EDX analysis.
4. Conclusions
Electrostatically actuated MEMS switch with Pt-Pt contact was tested for reliability 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 beam width. The resistance was unstable during the test, varying from 100 to 2000 Ω. After several thousands of cycles it sharply increased up to 100 MΩ that was considered as a failure of the device. The lifetime of the switches was from $2\times10^3$ to $5\times10^4$ cycles. The samples with the narrowest beam had the shortest lifecycle, no longer than $1\times10^4$ cycles, probably because of the lowest contact force. A damage of the contacts was clearly observed. EDX analysis showed the accumulation of carbon at the contacting surfaces, which probably caused the instability of the resistance and failure of the device. The lifecycle did not decrease significantly with increasing the input current. No stiction was observed even at the highest transmitted power of 25 mW. Further we plan to test the switch for transmission of higher power signals.

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