Resistive contact MEMS switch in a “hot” operation mode

I V Uvarov, V V Naumov, A N Kupriyanov, O M Koroleva, E I Vaganova and I I Amirov
Yaroslavl Branch of the Institute of Physics and Technology RAS, 150007, Universitetskaya Street 21, Yaroslavl, Russia

Abstract. Electrostatically actuated MEMS switch with the active contact breaking mechanism is tested in a “hot” regime. In this mode the lifetime of the switch is sufficiently restricted by the electrical failure mechanisms occurring at the contacts. Input DC voltage is applied to the source electrode during the actuation, output voltage at the drain electrode is registered. Measurements of the working characteristics of the switch including actuation voltage, contact resistance and lifecycle are performed. Experimental data is compared with the results of finite element simulation.

1. Introduction
Electrostatically actuated MEMS switches are widely used in radio frequency and microwave systems [1]. In comparison with switches based on pin-diodes and field-effect transistors, MEMS switches have advantages of low power consumption, small insertion loss in the closed state, high isolation in the opened state, low harmonic distortion and high radiation resistance. One of the main disadvantages of electrostatically actuated MEMS switches is the high actuation voltage, which is typically around a few tens of volts [2]. The most effective way to make the actuation voltage lower is to reduce the stiffness of the movable electrode. However, this approach increases the probability of stiction of the electrodes. Therefore, design of the switch must contain mechanisms allowing, if necessary, to overcome stiction and to detach the electrodes (active contact breaking).

MEMS switch with the active contact breaking mechanism was designed and fabricated by our group. Preliminary testing in the “cold” mode confirmed the significant mechanical reliability of the structure [3]. An important parameter of the switch is the ability to work in the “hot” mode, i.e. to be actuated repeatedly with applying input power during actuations. In this regime the additional failure mechanisms like temperature, current density and material transfer take place at the contact area [4]. They cause rapid degradation of contacts and increase the probability of stiction. Here we present the first results of testing the switch with the active contact breaking mechanism in the “hot” mode.

2. Design and operation principle of the switch
Design of the MEMS switch is schematically shown on figure 1. The movable electrode (source) is a metallic beam, suspended on torsion hinges. Gate and drain electrodes are fixed and located under each arm of the beam symmetrically with respect to the clamping point. Thus, the switch has two output channels. Each gate occupies the area from the clamping point of the beam almost to its free end, thereby providing a large area of an electric field. The beam has the contact bumps on its bottom side. These bumps localize the area of contact of the beam with the drain and prevent the short circuit with the gate when triggered. The beam also has the longitudinal ribs on the upper side. They allow to
increase the stiffness of the beam without sufficient growth of its mass and to reduce the bending of the beam under the influence of residual stress [5]. To speed up the removal of the sacrificial layer from under the beam and to partially take off the residual stress in the material the perforation holes are included in the design. They also reduce the air damping [6] and the mass of the beam, thereby increasing the switching speed. The beam has the length of 102 µm, the width from 8 to 32 µm depending on the design, and the thickness of 2 µm in the rib region. The gap between the beam and the gate is 1.5 µm. Detailed dimensions of the structure are given in the earlier work [3]. SEM image of the switch with the beam width of 32 µm is presented on the figure 2.

The switch operates as follows. Initially the beam has the horizontal position, as shown on figure 1. When the certain voltage is applied to one of the gates, the beam tilts towards the electrode under the electrostatic force and comes in contact with the drain. This voltage is usually called pull-in voltage \( V_{\text{PI}} \). Elastic force is generated in the torsion hinges, which tries to return the beam to its initial position. If the elastic force is insufficient to overcome the adhesion forces and to detach the beam from the drain, the switch retains its state when the gate voltage is removed. To break the contact the gate located under the raised arm of the beam is used. Applying the voltage to it, the beam tilts to the opposite direction and comes in contact with another drain. This voltage is called recovery voltage \( V_{\text{REC}} \). Thus, two states of the switch are realized during operation, and the horizontal state of the beam is not reached anymore. This design provides a mechanism of active contact breaking, which is realized by the presence of the gate under the each arm of the beam. It is important that the beam should be sufficiently stiff and should not bend when trying to detach it from the drain.

Figure 1. Design of the switch.

Figure 2. SEM image of the switch.

3. Fabrication procedure

The switch was fabricated by surface micromachining. The main steps of the process are shown on figure 3. At first the dielectric layer was formed on the silicon wafer. The wafer was thermally oxidized in wet oxygen to a SiO\(_2\) layer thickness of 0.9 µm. Next, driving and signal electrodes of the switch were performed on the SiO\(_2\) layer (figure 3a). For this purpose, adhesive Ti layer and Pt layer with the thicknesses of 10 and 100 nm, respectively, were deposited on the wafer by magnetron sputtering followed by lift-off.

In the next step the wafer was coated by a sacrificial layer of amorphous silicon (a-Si, figure 3b). In order to obtain the contact bumps of the beam, the dimples with the depth of nearly 500 nm were formed on the surface of the sacrificial layer (figure 3c). To do this, the round windows of 2 µm in diameter were formed in the photoresist layer. Through these windows the a-Si layer was etched in SF\(_6\) plasma. Then 100 nm thick Pt layer was deposited and the lift-off was performed (figure 3d).

Further, anchors, torsion hinges and the beam were formed on the sacrificial layer. For this purpose the first aluminum layer with 1 µm thickness was deposited, followed by lithography and wet etching. Ribs of the beam were formed from this layer (figure 3e). Next, the second Al layer with 1 µm
thickness was deposited over the ribs. The anchors, torsion hinges and the beam were made from it (figure 3f). The final fabrication stage was the removal of the a-Si sacrificial layer from under the beam by SF$_6$ plasma etching (figure 3g).

In the previous work [3] the mechanical reliability of the switch design was investigated, and the contact materials (Cr and Al) were used for reasons of the fabrication simplicity. In the present work the contact region played a significant role, and Pt-to-Pt contact was realized in the switch. Platinum has been selected as the contact material due to its chemical inertness and relatively high values of hardness (5.1 GPa) and melting point (2045 K) [7].

![Figure 3. Procedure of the MEMS switch fabrication.](image)

4. Experimental setup
Testing of the switches was performed in ambient air under normal conditions. Wiring diagram is shown on figure 4. Driving DC voltage (gate voltage, $V_G$) was applied from the power supply Agilent E3647A in order to actuate the switch. Input DC signal (source voltage, $V_S$) was applied from the power supply Mastech HY3005D. Output signal (drain voltage, $V_D$) was observed using the oscilloscope PicoScope 5000 and measured by the multimeter Keysight 34461A. The equipment was controlled by LabView software via GPIB interface using National Instruments PCI-GPIB controller. All the measurements were done in the low-current mode, the source-drain current was no higher than 0.1 mA. In this regime no stiction was observed, and breaking of the contact was carried out in a passive way.

![Figure 4. Connection of the measurement equipment to the switch.](image)
5. Results and discussion

To determine the pull-in and pull-out voltage ($V_{PI}$ and $V_{PO}$), the gate voltage was gradually increased from 0 to 60 V and then decreased as shown on figure 5. The moments of closing and opening the switch are clearly visible by the sharp change of the drain voltage. Experimental results are given in table 1. Pull-in voltage was in the range of 29÷46 V and depended on the beam width. Finite element method (FEM) simulation was performed using the validated software, details can be found in the previous work [3]. Simulation results are also given in table 1. Experimental values of $V_{PI}$ were 25% lower than it was predicted by the modeling. Probable reason of discrepancy was the reduction of the air gap between the beam and the fixed electrodes caused by the initial deformation of the beam under the residual stress. Pull-out voltage was in the range of 21÷33 V which is about 30% lower than the pull-in voltage.

![Gate and drain voltages during the pull-in and pull-out measurements. $V_S=1$ V.](image)

**Figure 5.** Gate and drain voltages during the pull-in and pull-out measurements. $V_S=1$ V.

**Table 1.** Simulated and experimentally obtained values of the pull-in and pull-out voltage.

| Switch type | FEM | Experiment |
|-------------|-----|------------|
|             | $V_{PI}$ (V) | $V_{PI}$ (V) | $V_{PO}$ (V) |
| 1           | 68  | 45.7 ± 6.1 | 32.8 ± 8.7 |
| 2           | 53  | 42.7 ± 3.7 | 30.6 ± 5.0 |
| 3           | 45  | 31.6 ± 4.5 | 22.6 ± 3.3 |
| 4           | 40  | 29.3 ± 2.2 | 20.7 ± 2.5 |

$^a$The types of the switch differ from each other by the width of the beam [3].

$^b$Details of the FEM simulation are given in [3].

To measure the lifecycle of the switch, rectangular voltage pulses were alternately applied to the each gate and the output voltage at both drains was recorded. The frequency of the driving pulses was 1 Hz. $V_G$ and $V_D$ at the same channel of the switch are shown on figure 6. It is worth noting that the drain signal was not rectangular. This indicates that the contact was not completely stable. Typical dependence of the drain voltage on the number of actuation cycles is shown on figure 7. During the first few dozen cycles the output voltage was $V_D = 0.99 \times V_S$, and after approximately 1500 cycles it decreased to $V_D = 0.5 \times V_S$. Contact region degraded completely after 9000 cycles, which corresponded to $V_D < 0.1 \times V_S$. 
Contact resistance $R_C$ of the switch was calculated using the following equation:

$$R_C = R_0 \left( \frac{V_S}{V_D} - 1 \right) - R_S - R_D,$$

where $R_0 = 100 \, \text{k}\Omega$ is the resistance limiting the source-drain current (figure 4), $R_S \approx 1 \, \Omega$ and $R_D \approx 50 \, \Omega$ are the resistances of the lines connecting the source and the drain with the corresponding contact pads of the sample. The initial value of $R_C$ was about 1 kΩ, which is high for the ohmic MEMS switches. Contact resistance exceeding 5 Ω is considered as a resistive failure [1]. After several hundred cycles $R_C$ increased to 100 kΩ. It is clear that the lifecycle of the switch in the “hot” mode has to be improved. We plan to investigate the degradation of the contact in detail and to choose the materials allowing to reduce the contact resistance and to increase the reliability.

6. Conclusions
MEMS switch with the active contact breaking mechanism was tested in a “hot” regime for the first time. All the measurements were performed in the low-current mode, so that no stiction was observed and the contact breaking was carried out passively. Pull-in voltage was 25% lower than it was predicted by FEM simulation probably because of the initial deformation of the beam. Lifecycle of the switch was about several hundred cycles, and it was restricted mainly by degradation of the contact area. Further we plan to investigate the resistive failure mechanisms in order to increase the lifecycle.

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