MEMS switch with the active contact breaking mechanism

I V Uvarov, V V Naumov, O M Koroleva and I I Amirov
Yaroslavl Branch of the Institute of Physics and Technology, Institution of Russian Academy of Sciences, 150007, Universitetskaya Street 21, Yaroslavl, Russia

E-mail: ilnik88@mail.ru

Abstract. Electrostatically actuated MEMS switch with resistive contact is presented. Movable electrode of the switch is a beam suspended by torsion springs. Low stiffness of springs allows to achieve the low values of the actuation voltage. Main feature of the switch is a mechanism of the active contact breaking, allowing to solve the problem of adhesive sticking of the beam to the signal electrode. The active opening of the switch is realized by the presence of two driving electrodes. The theoretical analysis, finite element simulation and experimental investigation of the switch characteristics are performed.

1. Introduction

Electrostatically actuated MEMS switches are widely used in various radio frequency and microwave systems [1]. They have advantages of low power consumption, small insertion losses in the closed state, high isolation in the opened state, low harmonic distortion, high radiation resistance, wide operating temperature range and the possibility of integration with CMOS circuits [2]. The one of main disadvantages of MEMS switches is the high actuation voltage, which is a few tens of volts [3]. The most effective way to make the actuation voltage lower is to reduce the stiffness of the movable electrode. However, in the vast majority of conventional switches the breaking of a contact between the movable electrode and the signal electrode is carried out by the force of elasticity (passive opening). Reducing the stiffness of the movable electrode increases the probability of its stiction to the signal electrode by forces of adhesion, and hence reduces the reliability of the switch. The design of the switch must contain mechanisms, which allow, if necessary, to overcome the adhesion forces and open the electrodes (active opening).

2. MEMS switch design and principle of operation

Design of the switch is schematically shown on figure 1. Movable electrode is a metallic beam, attached in the middle of its length to the torsion suspension. Driving and signal electrodes (also metallic) are situated under each arm of the beam symmetrically with respect to the clamping point. Each driving electrode occupies the space from the clamping point of the beam almost to its free end, thereby providing a large area of an electric field. Beam has the contact bumps on its bottom side. Bumps localize the area of contact of the beam with the signal electrode and prevent the contact of the beam with the gate electrode when triggered.

Initially the beam is in a horizontal position (figure 1). When the voltage is applied to one of driving electrodes, beam bends towards the electrode under the electrostatic force and comes in contact with the signal electrode (figure 2, state 1). Elastic force is generated in the torsion hinges, which tries to return the beam to its initial position. The stiffness of hinges is selected to be small in order to provide...
low values of actuation voltage. Elastic force is insufficient to overcome the adhesion forces and to detach the beam from the signal electrode. Therefore, when the driving voltage is removed, switch retains its state. To break the contact, driving electrode located under the raised arm of the beam is used. Voltage is applied to it, the beam is tilted to the opposite direction and comes in contact with another signal electrode (figure 2, state 2). Thus, two states of the switch, shown on figure 2, are realized during operation. The horizontal state of the beam is not reached. This design provides a mechanism of active contact breaking, which is realized by the presence of the driving electrode 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 signal electrode.

![Figure 1. MEMS switch design.](image1)

![Figure 2. Possible states of the switch.](image2)

3. Calculation of the pull-in voltage

Switch design with the designation of dimensions is shown on figure 3. The beam has a length $L_{\text{beam}}$ and a thickness $t_{\text{beam}}$. Torsion hinges have a length $L_{\text{hinge}}$, width and thickness $w_{\text{hinge}}$ and $t_{\text{hinge}}$. The gap between the beam and the electrodes is $g$. The beam and the electrodes have the same width $w$. The driving electrode is located at a distance $a_1$ from the center of the switch, and has a length of $a_2-a_1$.

![Figure 3. Design of the switch with the designation of dimensions: (a) side view, (b) top view.](image3)

Let the beam of the switch in a horizontal position. DC voltage $V$ is applied between the beam and one of the driving electrodes. Electrostatic force bends the beam at an angle $\alpha$ towards the electrode (figure 3a). Assuming small angle $\alpha$, an element of the beam length $dx$ and a part of driving electrode,
located under it, can be considered as two parallel plates. Neglecting fringing fields, we write the electrostatic force acting on a small element of the beam \[4\]:

$$dF = \frac{\varepsilon_0 w V^2}{2(g - x\alpha)} dx,$$

(1)

where \(\varepsilon_0\) is the vacuum permittivity. Full torque generated by the electrostatic force is given by the expression:

$$M_e = \int_{a_1}^{a_2} xdF = \int_{a_1}^{a_2} \frac{\varepsilon_0 w V^2 x}{2(g - x\alpha)^2} dx.$$

(2)

Doing the integration in the equation (2), we obtain \[5\]:

$$M_e = \frac{\varepsilon_0 w V^2}{2\alpha^2} \left[ \frac{g}{g - a_2\alpha} - \frac{g}{g - a_1\alpha} + \ln \left( \frac{g - a_2\alpha}{g - a_1\alpha} \right) \right].$$

(3)

The torque generated by the elastic force is given by the expression \(M_{\text{mech}} = K\alpha\), where \(K\) is the stiffness of torsion hinges \[6\]:

$$K = \frac{Gw_{\text{hinge}} t_{\text{hinge}}^3}{8L_{\text{hinge}}} \left[ \frac{16}{3} - 3.36 \frac{t_{\text{hinge}}}{w_{\text{hinge}}} \left( 1 - \frac{t_{\text{hinge}}^2}{12w_{\text{hinge}}^2} \right) \right],$$

(4)

where \(G\) is the shear modulus of the material of hinges.

For a given driving voltage, the position of beam is determined by the condition of balance between the electrostatic and mechanical torques: \(M_e = M_{\text{mech}}\). In expanded form:

$$\frac{\varepsilon_0 w V^2}{2\alpha^2} \left[ \frac{g}{g - a_2\alpha} - \frac{g}{g - a_1\alpha} + \ln \left( \frac{g - a_2\alpha}{g - a_1\alpha} \right) \right] = K\alpha.$$

(5)

Equation (5) represents a dependence of the tilt angle \(\alpha\) on a driving voltage \(V\). With the gradual increase of \(V\), the increasing electrostatic force is no longer balanced by the elastic force, and the beam sharply tilts and touches the signal electrode (electrostatic pull-in). The voltage at which this occurs is called the pull-in voltage, \(V_{\text{PI}}\). The expression for \(V_{\text{PI}}\) is derived from the equation (5) using numerical methods \[7\]:

$$V_{\text{PI}} = \sqrt{\frac{0.8275 Kg^2}{\varepsilon_0 wd_2} \left[ 1 - \left( \frac{a_1}{a_2} \right)^2 \right]^{-0.5} \left[ 1 + 0.6735 \left( \frac{a_1}{a_2} \right)^{1.931} \right]^{0.3244}}.$$

(6)

Pull-in voltage values, calculated using equation (6), and the nominal values of switch dimensions are shown in the table 1. Four types of switch design were considered, having different width of the beam and the electrodes \(w\). The material of torsion hinges was chromium (\(G = 115\) GPa), the material of beam was aluminum. According to the equation (4), stiffness of hinges is equal to \(3.9 \times 10^8\) N·m. Pull-in voltage of the switch should be between 4.1 V in the case of \(w = 32\) µm and 8.2 V for \(w = 8\) µm.

4. FEM modeling of the switch

The proposed design of the switch should be modified to facilitate its production and improve the performance. Firstly, the beam should have etching holes (perforation). They allow to speed up the removal of the sacrificial layer from under the beam, and partially take off the residual stresses in the beam material. Secondly, only twist of the torsion hinges should occur during operation of the switch, the beam should not bend. To this end, the beam must have sufficient stiffness. Effective method of increasing the stiffness of the beam is the formation of ribs on its surface. Ribs can increase the stiffness without increasing the thickness of the beam material, and hence avoid the increasing of the beam mass and reduce the bending of the beam under influence of residual stress \[8\].
Table 1. Dimensions of the switch and results of analytical calculation and FEM modeling of $V_{PI}$.

| Switch type | $L_{beam}$ (µm) | $t_{beam}$ (µm) | $L_{hinge}$ (µm) | $w_{hinge}$ (µm) | $a_1$ (µm) | $a_2$ (µm) | $G$ (µm) | $w$ (µm) | $V_{PI}$ (V) analytic | $V_{PI}$ (V) FEM |
|-------------|-----------------|-----------------|------------------|------------------|-----------|-----------|--------|--------|----------------------|-----------------|
| 1           | 102             | 1               | 1.5              | 3                | 0.3       | 4         | 44     | 0.5    | 8                    | 8.2             |
| 2           | 16              | 5.8             | 9.5              | 4                | 44        | 7.9       | 7.0    | 24     | 8.2                  | 9.5             |
| 3           | 32              | 4.1             | 7.0              | 4                | 44        | 12.8      | 16     | 8.2    | 16                   | 12.8            |

The influence of perforation and ribs on the properties of the switch can be considered using finite element method (FEM) simulation. The simulation was performed using validated FEM software. Ribs having 98 µm length, 4 µm width and 1 µm height were located on the upper surface of the beam. Etching holes having area of 2×2 µm² were located between the ribs.

FEM model of each type of the switch included a beam, the one driving and one signal electrode. Dimensions of the switch, used in simulations, are indicated in table 1. The ends of the torsion hinges were fixed. The beam was grounded. Electric potential was applied to the driving electrode. Potential was gradually increased until the pull-in occurrence. The dependence of the distance between the end of the beam and the signal electrode on the applied potential, calculated for the four switch types, is shown on figure 4. Pull-in voltage was determined from this dependence.

Figure 4. Dependence of the distance between the end of the beam and the signal electrode on the driving voltage.

Values of $V_{PI}$, obtained by FEM simulation, are presented in table 1. Simulated values exceeded ones calculated analytically at 1.5-1.7 times. The reason of such an excess could be etching holes, which reduced the overlap area of the beam and the driving electrode and therefore increased the actuation voltage. According to the simulation results, the lowest value of the pull-in voltage should be 7 V.

5. Experimental results

Switches were fabricated by surface micromachining. The main steps of the manufacturing process are shown on figure 5. At the first step the dielectric layer was formed on the silicon wafer. The wafer was thermally oxidized in wet oxygen to a SiO$_2$ layer thickness of 1 µm. Next, driving and signal electrodes of the switch were performed on SiO$_2$ layer (figure 5a). For this purpose, chromium layer with 50 nm thickness was deposited on the wafer by magnetron sputtering, followed by contact photolithography and wet etching of chromium.

At the next step the wafer was coated by a sacrificial layer of amorphous silicon (a-Si, figure 5b). In order to obtain the contact bumps of the beam, the dimples with nearly 200 nm depth were formed on the surface of the sacrificial layer (figure 5c). 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.
Further, torsion hinges and a beam of the switch were formed on the sacrificial layer. Cr layer with 0.3 µm thickness was deposited, anchors and hinges were made from it using contact lithography and wet etching (figure 5d). Next, ribs of the beam were formed (figure 5e). For this purpose, Al layer with 1 µm thickness was deposited, followed by lithography and wet etching. Another Al layer with 1 µm thickness was deposited over the ribs, and the beam was formed from it (figure 5f). The final stage of fabrication was the removal of the a-Si sacrificial layer from under the beam by etching in SF$_6$ plasma (figure 5g). Fabricated switch of type 3 is shown on figure 6.

![Figure 6. SEM image of the fabricated switch (type 3).](image)

The switch had five contact pads with dimensions of 1.4×1.4 mm$^2$, which were connected to the beam and electrodes by means of metallic lines with 200 µm width. Probes were placed to the contact pads. Measurement equipment was connected to the probes, wiring diagram is shown on figure 7. All the measurements were performed in air under normal conditions [9]. Experimentally obtained values of the pull-in voltage are shown in table 2. The switches with the widest beam had lowest pull-in voltage. The minimum value of $V_{PI}$ was 6.0 V. On one hand, the experimental values should exceed simulated ones, because the etching of aluminum when forming the beam caused a significant change of its lateral dimensions (about 1.5 µm per side). It can be clearly seen at the perforation holes with a diameter of 5 µm (see figure 6), while the nominal dimensions of the holes is 2×2 µm$^2$. Reduction of the lateral dimensions of the beam and enlargement of perforation led to decrease in the overlap area of the beam and the driving electrode, and hence, reduced the electrostatic force. On the other hand, the reduction of lateral dimensions was also observed at the step of forming the chromium hinges (about 300 nm per side). This effect led to a narrowing of hinges and caused the decrease of its stiffness, which should lower $V_{PI}$. Additionally, suspensions bent under the weight of the beam, resulting in a decrease of the distance between the beam and electrodes. It also had to reduce the pull-in voltage. Apparently, the factors listed above compensated one another so that there was good agreement between the experimental data and the results of FEM simulation (table 1).

![Figure 7. Scheme of connection of the measurement equipment to the switch.](image)

| Switch type | $V_{PI}$ (V) | $V_{REC}$ (V) | $R$ (Ω) |
|-------------|--------------|--------------|--------|
| 1           | 13.0 ± 0.7   | 27.7 ± 5.1   | 344 ± 41 |
| 2           | 10.6 ± 1.1   | 32.0 ± 8.3   | 318 ± 33 |
| 3           | 9.0 ± 1.5    | 26.7 ± 3.9   | 336 ± 95 |
| 4           | 6.5 ± 0.5    | 24.6 ± 5.2   | 317 ± 20 |
Experimentally obtained values of recovery voltage are shown in table 2. The lowest value of $V_{REC}$ was 19.4 V. Recovery voltage exceeded the pull-in voltage at 3-4 times. There are two main reasons for the excess. Firstly, the air gap between the raised arm of the beam and the driving electrode exceeded the initial value $g$. Secondly, to open the contact, the adhesion forces between the beam and the signal electrode had to be overcome. Since the magnitude of these forces is difficult to calculate, the calculation of $V_{REC}$ is also difficult. At the same time, it is possible to reverse the path: knowing the recovery voltage (from the experiment) and the switch geometry, it is possible to determine the value of adhesion forces. However, this is a separate research task. It is worth noting that during the switch operation $V_{REC}$ is the actuation voltage, since the horizontal position of the beam will not be achieved. At the initial stage of the work, recovery voltage was relatively high (20-40 V). In the future we plan to reach lower values by reducing the gap between the beam and the electrodes and, possibly, by modifying the beam design.

The resistance of the switch in a closed state was 250-400 Ω (table 2). The decrease of resistance with the increase of the beam width was not observed. Although the wider the beam, the less its own resistance, and it contained the more contact bumps. The absence of dependence of the resistance on the width of the beam can be explained by the fact that much of the resistance was caused by metal lines, connecting the contact pads with the beam and electrodes. The contact resistance of the switch was difficult to determine from the total resistance. Presented switches had Al-to-Cr contact. It is planned to use the MEMS contact materials such as gold or platinum, in order to achieve low contact resistance and reliable contact of the beam with the signal electrodes.

6. Conclusion
Electrostatically actuated MEMS switch with resistive contact was designed and fabricated. The main feature of the switch was the mechanism of active opening, solving the problem of adhesive stiction of the beam with the signal electrodes. Active opening was realized by the presence of two driving electrodes. The fabrication procedure of the switch was developed using standard processes of microelectronics. The experimental values of the pull-in voltage were in agreement with the results of finite element modeling. Recovery voltage of the switch was 20-40 V. In the future we plan to get lower values, since the switch design allows to achieve it.

The reported study was supported by RFBR research project No. 14-07-31156 mol_a, by Facilities Sharing Centre “Diagnostics of Micro- and Nanostructures” and by the Ministry of education and science of Russian Federation.

References
[1] Rebeiz G M 2003 RF MEMS: Theory, Design, and Technology (Hoboken, New Jersey: John Wiley & Sons, Inc.)
[2] Dai C-L and Chen J-H 2006 Microsyst. Technol. 12 1143
[3] Sharma A K, Gautam A K, Farinelli P, Dutta A and Singh S G 2015 J. Micromech. Microeng. 25 035014
[4] Younis M I 2011 MEMS linear and nonlinear statics and dynamics (New York: Springer Science + Business Media, LLC)
[5] Degani O, Socher E, Lipson A, Leitner T, Setter D J, Kaldor S and Nemirovsky Y 1998 J. Microelectromech. Syst. 7 373
[6] Timoshenko S P and Goodier J N 1970 Theory of Elasticity (New York: McGraw-Hill)
[7] Degani O and Nemirovsky Y 2002 J. Microelectromech. Syst. 11 20
[8] Gupta A, Barron L, Brainin M and Lee J-B 2014 J. Micromech. Microeng. 24 065023
[9] Uvarov I V, Naumov V V and Selyukov R V 2014 Proc. SPIE 9440 94400W