A seesaw-type MEMS switch with enhanced contact force: the first results

I V Uvarov$^1$ and N V Marukhin$^2$

$^1$Valiev Institute of Physics and Technology of Russian Academy of Sciences, Yaroslavl Branch, Universitetskaya 21, 150007 Yaroslavl, Russia
$^2$P.G. Demidov Yaroslavl State University, Sovetskaya 14, 150003 Yaroslavl, Russia

Abstract. Outstanding working characteristics make microelectromechanical systems (MEMS) switches attractive for many applications. However, the lack of reliability prevents their commercial success. Due to the small size, MEMS switches develop low contact force compared to their macroscopic counterparts, which leads to instability and fast increase of the contact resistance. This work describes the switch providing significantly larger force than the previously reported device. The enlargement is achieved by the modified shape of the beam and electrodes with the same footprint and lower actuation voltage. Design, simulation, fabrication and first experimental results for the switch are presented.

1. Introduction
In recent time, an intensive growth of radar and wireless communication systems takes place. The growth is achieved due to advanced electronic components, including switches for processing and routing of RF signals. But the enhancement of conventional relays has exhausted, so the new approaches have to be found. The devices provided by MEMS industry are good candidates to substitute conventionally used products. They demonstrate high integration capability in combination with great radio frequency performance, small size and low energy consumption [1]. A significant characteristic of the MEMS switch is the contact resistance that strongly depends on the contact force $F_c$ [2]. The device provides rather low $F_c \sim 10$ μN due to the tiny size. This makes the contact spot small and leads to instability and fast increase of the contact resistance. In addition, the switch becomes unable to overcome contamination. Obviously, the force has to be increased in order to ensure reliable operation. Here we present the switch that develops much higher $F_c$ compared to the previous device [3]. High force is achieved at the same footprint and lower pull-in voltage. Performance of the switch is calculated using finite element method (FEM). Samples ready for the test are fabricated and analyzed.

2. Design of the device
The switch is schematically shown in figure 1. A movable electrode (source) is a 100 μm long beam suspended by torsion hinges. The device has two pairs of gate and drain electrodes placed under each arm of the beam. The beam is separated from the electrodes by 1.5 μm gap. It contains 0.5 μm high contact bumps at the bottom side. The material of bumps and electrodes is platinum, while the beam is made of aluminum. Driving voltage fed to the gate attracts the beam to the corresponding drain, turning the device on. The contact breaks under the elastic force of torsion hinges when the voltage is removed.
The previously reported switch, which is further called basic switch, provides quite low contact force $F_c = 12 \mu N$ at the gate voltage $V_g = 60 \text{ V}$ [4]. In order to increase $F_c$, one has to make the electrostatic force higher. This may be achieved by raising the driving voltage, enlarging the overlap of the electrodes, or reducing the air gap. But these methods increase the switch size and worsen its performance. In this work, we modify the design in such a way that the overall footprint of the working part does not change. The modified shape of the beam and electrodes compared to the basic design is shown in figure 2. The gate is widened to 45 $\mu$m and surrounds the contact point. The beam is expanded according to the gate. The length of the electrode, in turn, is reduced. Such configuration increases the area for electrostatic force and transfers large portion of this force to the contact [5]. In addition, the switch withstands higher driving voltage. Thorough information on the modified design is given in our theoretical work [4].

![Figure 1. Schematic illustration of the switch.](image)

![Figure 2. The basic design (a) and modified structure (b), top view.](image)

### 3. Calculation of working characteristics

Pull-in voltage and resonant frequencies of the modified switch are calculated using validated FEM software according to the previously described procedure [6]. The displacement of the contact bump as a function of the gate voltage is shown in figure 3. The bump sharply falls to the drain at $V_g = 27 \text{ V}$, while for the basic design the pull-in takes place at $V_g = 45 \text{ V}$. Thus, the modified switch is actuated by lower voltage that reduces power consumption.

Vibration modes of the beam are shown in figure 4. Notice that we add perforation holes in order to remove the sacrificial layer faster. The first mode has a torsional shape and a frequency $f_1 = 144.4 \text{ kHz}$. This mode determines the switching time [1]:

---

---
$$t_{on} = \frac{3.67 \ V_g}{2 \pi f_1 \ V_{pi}},$$  \hspace{1cm} (1)$$

where \( V_{pi} \) is the voltage of electrostatic pull-in. Assuming \( V_g = V_{pi} \), the switch should go to the on-state in 4 \( \mu \)s. This value is about 1 \( \mu \)s longer than \( t_{on} \) of the basic device, which has higher eigenfrequency [3]. The second mode corresponds to bending oscillations and has a frequency of 415.0 kHz. Further we will compare these values with experimental data.

**Figure 3.** The gap between the contact bump and drain as a function of the gate voltage.

**Figure 4.** Eigenmodes of the beam: the first (a) and second (b) mode.

A significant characteristic is the dependence of the contact force on the gate voltage. A contact of two bodies is a non-trivial task for FEM simulation, so we use the analytical approach described previously [4]. The result is shown in figure 5. For the same \( V_g \), the modified switch develops 3.5 times higher force than the classical device. At the voltage of 85-100 V the force exceeds 100 \( \mu \)N. The contact resistance is in proportion to \( F_c^{-1/3} \) [2]. Thus, increasing the force is expected to lower the resistance by about 30%. Besides, one can expect an improved ability to break contamination films and, therefore, more stable resistance.
Figure 5. Contact force as a function of the gate voltage.

4. Fabrication

The fabrication sequence is illustrated in figure 6 and thoroughly described in our recent paper [7]. In short, it is carried out on thermally oxidized silicon wafers. The gates and drains are fabricated from Cr/Pt 10/100 nm film by lift-off technique. The beam is reinforced by 1 µm thick frame (figure 6e) and has a total thickness of 2 µm, while the hinges have a thickness of 1 µm. Amorphous silicon (a-Si) is used as a sacrificial material. It is removed from under the beam by plasma etching. Dry release ensures the absence of the fabrication-induced stiction under the capillary forces. In addition, the use of a-Si as a sacrificial material reduces contamination of contacts with organic residues, which is typically observed for the sacrificial photoresist layers. Thus, the proposed route is rather simple and ensures high yield. The fabricated switch is demonstrated in figure 7. One can see main parts of the device, including the contact area.

Figure 6. Fabrication sequence: (a) the bottom electrodes are patterned; (b) the sacrificial layer is deposited and etched to form the openings for anchors; (c) the dimples are etched; (d) the dimples are filled with platinum; (e) the first layer of aluminum is patterned to form the reinforcing frame; (f) the second layer of aluminum is patterned to form the anchors, hinges and beam; (g) the beam is released.
5. Testing

After fabrication, one has to verify that the resonant frequencies and pull-in voltage of samples correspond to theoretical predictions. This will mean that the switch develops the contact force according to the curve depicted in figure 5. The resonant frequencies are measured with a homemade laser vibrometer [8] under the air pressure of $10^{-1}$ mbar. In order to excite oscillations of the beam, a sinusoidal voltage with the amplitude of 1 V is fed to the gate. The oscillations are detected by an optical lever unit. Laser light is focused at the beam and reflected to the photo-detector. The resonant curve contains two peaks corresponding to the first and second vibration modes, as shown in figure 8. The resonant frequencies are 15-20% lower than those predicted by FEM. A probable reason is the mismatch between the actual and nominal lateral size of the beam due to excessive undercut of aluminum layers, as well as the difference in elastic properties between thin-film and bulk aluminum. Further, we plan to measure the pull-in voltage and contact resistance in order to estimate the advantages of the modified design.

![Figure 8. Output voltage of the photo-detector as a function of the excitation frequency.](image-url)
6. Conclusion
The paper describes electrostatically actuated MEMS switch with protection against stiction. In comparison with the previously demonstrated switch, it provides 3.5 times higher contact force due to the modified design of the beam and electrodes. The modification increases the area for electrostatic force and transfers a large portion of this force to the contact point. The overall footprint of the device is not enlarged, while the pull-in voltage becomes lower. According to FEM simulation, the switch can be actuated by the voltage as low as 27 V. The device is successfully fabricated by surface micromachining using the well established route. Fabricated samples demonstrate 15-20% lower resonant frequencies compared to FEM predictions. The probable reasons are the excessive undercut of aluminum layers during the wet etching and the difference in elastic properties between thin-film and bulk material. Further, it is planned to determine the pull-in voltage and perform long-term measurements of the contact resistance in order to confirm the advantages of the modified design.

Acknowledgments
This work was supported by the grant of President of the Russian Federation № MK-945.2021.4 and the program No. 0066-2019-0002 of the Ministry of Science and Higher Education of Russia for Valiev Institute of Physics and Technology of RAS. The authors thank the Facilities Sharing Centre “Diagnostics of Micro- and Nanostructures” for technical assistance.

References
[1] Rebeiz G M 2003 RF MEMS: Theory, Design, and Technology (Hoboken, New Jersey: John Wiley & Sons)
[2] Toler B F, Coutu R A and McBride J W 2013 J. Micromech. Microeng. 23 103001
[3] Uvarov I V and Kupriyanov A N 2019 Microsyst. Technol. 25 3243
[4] Marukhin N V and Uvarov I V 2020 J. Phys.: Conf. Ser. 1695 012157
[5] Stefanini R, Chatras M, Blondy P and Rebeiz G.M. 2011 J. Microelectromech. Syst. 20 1324
[6] Uvarov I V, Naumov V V, Koroleva O M, Vaganova E I and Amirov I I 2016 Proc. SPIE 10224 102241A
[7] Uvarov I V 2021 Microelectron. Reliab. 125 114372
[8] Uvarov I V, Naumov V V, Amirov I I 2012 Proc. SPIE 8700 87000S-1