An improved design of a seesaw-type MEMS switch for increased contact force

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Abstract. Microelectromechanical systems (MEMS) switches have a wide range of possible applications due to their promising working characteristics, but commercial success of these devices is limited by low reliability. In contrast with macroscopic electromechanical relays, MEMS switches typically develop a small contact force, which results in unstable and high contact resistance. In this paper we propose the design that ensures several times higher contact force in comparison with previously used structure. Enhancement of the force is achieved without increasing the footprint and operating voltage of the switch. The analytical calculation and finite element simulation of the working characteristics are performed. At the driving voltage of 100 V the modified switch provides the contact force as high as 130 µN, which is an order of magnitude higher than the force developed by the basic device.

1. Introduction
MEMS switches with resistive contact combine advantages of electromechanical and solid state relays. They provide superior radio frequency characteristics, small size, low power consumption in combination with high integration capability [1] and are used in switchable routing networks for RF front-ends, connection to capacitor banks, phase shifters, tunable filters, reconfigurable antennas, high-resolution pulsed radar sensors, and space applications [2]. An important parameter of the switch is the contact resistance that is directly related to the contact force [3]. In contrast with macroscopic counterparts, MEMS switches develop a rather weak force ~10 µN. This results in a high and unstable contact resistance due to a small contact spot and inability to break contamination films [4]. For reliable operation, the contact force has to be increased. Here we describe the optimized design, which provides several times higher force in comparison with the previously demonstrated switch. The force is increased without enlargement the size and actuation voltage of the device. The results of analytical calculation and finite element modelling are reported.

2. Design of the switch
The basic seesaw-type switch is shown in figure 1a. The movable electrode is an aluminium beam attached to the anchors by torsion hinges. The beam is perforated in order to speed up the removal of the sacrificial layer and to reduce the switching time. Platinum gate and drain electrodes are placed under the each arm of the beam. Platinum contact bumps are located on the bottom side of the beam in order to localize a contact area and prevent the beam from contacting the gate electrodes. The switch demonstrates an average contact resistance $R_c = 380 \Omega$ with the scatter from 30 to 2000 Ω. Such a high and unstable value is due to low contact force $F_c$ of about 10 µN at the driving voltage $V_g \approx 30$ V [5].

A straightforward way to increase $F_c$ is to enhance the electrostatic force between the beam and the driving electrode. It can be done by enlarging the lateral size of the switch and the actuation voltage,
or reducing the gap between the beam and the electrode. However, these approaches make the switch bulky and deteriorate its performance. Another way is to optimize the design in order to enlarge the overlap area of the beam and the driving electrodes without increasing an overall footprint of the switch. The optimized design is shown in figure 1b. Firstly, the area of the signal electrode is reduced in comparison with the basic design. It allows lengthening the driving electrode. Secondly, the width of the beam and the driving electrodes is increased. Thirdly, the part of the driving electrode located close to the hinges is removed since it negligibly contributes to the contact force.

![Figure 1(a, b). A seesaw-type MEMS switch: (a) SEM image of the basic device; (b) An illustration of the modified switch. The insets schematically show driving and signal electrodes.](image)

3. Analytical calculation

The switch is schematically shown in figure 2. The beam has a width $w$ and a thickness $t$. The gap between the beam and the electrodes is $g$. The gate electrode is located at a distance $r_1$ from the center of the switch and has a length $r_2 - r_1$. The contact bump with the height $t_b$ is placed at a distance $L_b$ from the center.

Initially the beam is in the horizontal position. When a voltage $V$ is applied to one of the gate electrodes, an electrostatic force arises, under the influence of which the beam tilts at an angle $\alpha$. If the value of the applied voltage is greater than the pull-in voltage, the beam comes into contact with the drain electrode. Assuming that the angle $\alpha$ is small, it is possible to determine its value from the expression:

$$\alpha = \frac{g - t_b}{L_b}. \quad (1)$$

![Figure 2. Schematic illustration of the switch.](image)
Let us consider the segments of the beam and the gate electrode with the length $dx$ and width $w$ as two plates located at the distance $x$ from the center. Assuming the beam deflection insignificant, the distance between the plates is $g - \alpha x$. Neglecting edge effects, we can describe the electrostatic force acting on one of the plates using the following expression [6]:

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

where $\varepsilon_0$ is the vacuum permittivity. The torque generated by the electrostatic force is given by the expression:

$$M_e = \int x dF = \int_{x_1}^{x_2} \frac{\varepsilon_0 w V^2 x}{2(g - x\alpha)^2} dx.$$  

After the integration in the equation (3) we obtain:

$$M_e = \frac{\varepsilon_0 w V^2}{2\alpha^2} \left( \frac{g}{g - r_2\alpha} - \frac{g}{g - r_1\alpha} - \ln \left[ \frac{g - r_2\alpha}{g - r_1\alpha} \right] \right).$$

When the beam is tilted, an elastic force arises in the torsion hinges. The torque created by this force is described by the expression:

$$M_t = K_t \alpha,$$

where $K_t$ is the elastic constant of the hinges, which have the shape shown in figure 3a. The simulation shows that this shape provides the same $K_t$ as the rectangular design illustrated in figure 3b.

![Image](https://via.placeholder.com/150)

Figure 3(a, b). The size and shape of the torsion hinges, top view: (a) the real hinge; (b) the design used in calculations.

The elastic constant for rectangular-shaped hinges with the length $L_h$, width $w_h$ and thickness $t_h$ is given by the expression [7]:

$$K_t = \frac{2Gw_h^2}{3L_h} \left[ 1 - \frac{192t_h}{\pi w_h} \tanh \left( \frac{\pi w_h}{2t_h} \right) \right].$$

where $G$ is the shear modulus of the material. The contact force can be calculated from the equation of torque balance:

$$\bar{L}_c \times \vec{F}_c + \bar{M}_i = \bar{M}_e,$$

$$F_c = \frac{M_e - M_i}{L_b}. $$
Figure 4a shows the arm of the beam for the basic design. It contains six pairs of perforation holes with the radius $R_h$. The holes are located at a distance $r_{hi}$ from the center of the switch, where $i$ is the pair number.

The torque of the electrostatic force (3) can be calculated as follows:

$$M_e = \frac{1}{n} \left[ \int_{r_1}^{r_n} \frac{\varepsilon_0 w V^2 x}{2(g - x \alpha)^2} \, dx - \int_{r_1}^{r_n} \frac{\varepsilon_0 \sqrt{R_h^2 - (x - r_{hi})^2} V^2 x}{2(g - x \alpha)^2} \, dx \right] - \sum_{i=2}^{5} \frac{\varepsilon_0 \sqrt{R_h^2 - (r_{hi} - r_{h-1})^2} V^2 x}{2(g - x \alpha)^2} \, dx. \tag{9}$$

After integration, the dependence of $M_e$ on the gate voltage for the basic design with the dimensions shown in table 1 has the form $M_e = 0.20V^2$, where the torque is expressed in $\mu\text{N} \cdot \mu\text{m}$.

**Table 1. Geometrical dimensions of the basic switch.**

| $w$ (µm) | $w_2$ (µm) | $w_3$ (µm) | $g$ (µm) | $r_1$ (µm) | $r_2$ (µm) | $r_3$ (µm) | $r_4$ (µm) | $R_h$ (µm) | $r_{h-1}$ (µm) | $r_{h-2}$ (µm) | $r_m$ (µm) | $r_m$ (µm) | $\alpha$ (rad) |
|---------|------------|------------|---------|------------|------------|------------|------------|------------|-------------|-------------|------------|------------|----------------|
| 24      | 46         | 18         | 1       | 4          | 44         | 18         | 53         | 1          | 8           | 4           | 18         | 36         | 0.0103        |

The modified arm has three perforations with the radius $R_h$, see figure 4b. One hole is located at the distance $r_{m1}$ from the center, while two others are placed at the distance $r_{m2}$. The electrostatic torque can be calculated as:

$$M_e = \int_{r_1}^{r_n} \frac{\varepsilon_0 w_2 V^2 x}{2(g - x \alpha)^2} \, dx + \int_{r_1}^{r_n} \frac{\varepsilon_0 w_3 V^2 x}{2(g - x \alpha)^2} \, dx - \int_{r_1}^{r_n} \frac{\varepsilon_0 \sqrt{R_h^2 - (x - r_{m1})^2} V^2 x}{2(g - x \alpha)^2} \, dx - \int_{r_1}^{r_n} \frac{\varepsilon_0 \sqrt{R_h^2 - (x - r_{m2})^2} V^2 x}{2(g - x \alpha)^2} \, dx. \tag{10}$$

Thus, for the modified design $M_e$ depends on the gate voltage as $M_e = 0.67V^2$. The basic and modified structures have the same hinges. According to the expression (5), the torque of elasticity is $M_t = 170 \mu\text{N} \cdot \mu\text{m}$. Therefore, the contact force is described by the equation $F_c = 0.0041V^2 - 3.5 \mu\text{N}$ for the basic design and $F_c = 0.0138V^2 - 3.5 \mu\text{N}$ for the modified structure. The corresponding graphs are presented in figure 5.
4. FEM simulation
To verify the calculations, the contact force is modelled by the finite element method (FEM). The model of the switch is shown in figure 6. It consists of \( \sim 10^5 \) tetrahedral elements. Figure 7 illustrates the comparison of the modelling with the analytical results. Below 60 V the discrepancy is less than 5%, which indicates that both approaches are applicable. At the higher voltage the simulation provides a higher contact force than the analytical method. The discrepancy increases up to 30%, when the gate voltage reaches 100 V. The reason is the bending of the beam towards the driving electrode, which is not taken into account in the analytical calculation.

![Figure 6. FEM model of the switch.](image)
5. Conclusion
The modified switch has been designed in order to achieve higher contact force compared to previously used structure. The analytical calculation provides $F_c = 13 \, \mu N$ at $V_g = 60 \, V$ for the basic design. The modified switch develops $F_c = 46 \, \mu N$, which is 3.5 times higher than the force of the basic structure. Since the contact resistance is proportional to $F_c^{-1/3}$, the increment in the force should reduce $R_c$ by 1.5 times. The contact force is also simulated by the finite element method. The simulation provides higher $F_c$ than the analytical approach. The analytical calculation is applicable below 60 V. It is worth noting that at $V_g = 100 \, V$ the modified switch provides the contact force as high as $130 \, \mu N$, which is an order of magnitude higher than the force developed by the basic device. It is expected that the optimized switch will have significantly lower and more stable contact resistance.

Acknowledgments
This work is supported by Program No. 0066-2019-0002 of the Ministry of Science and Higher Education of Russia for Valiev Institute of Physics and Technology of RAS and performed using the equipment of Facilities Sharing Centre “Diagnostics of Micro- and Nanostructures”.

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