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

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Abstract. MEMS switches are of particular interest for advanced radio electronic systems, but their application is limited by the lack of reliability. The switch develops low contact force, which leads to high and unstable contact resistance. The force is typically increased by using complex shaped and large area electrodes, while a simple and compact design is more preferable. This work presents a switch based on a miniature cantilever. The contact force is enhanced by selecting the vertical dimensions of the structure. The trial samples are fabricated and tested. Their performance is compared with theoretical predictions.

Keywords: MEMS switch, cantilever, contact force, contact resistance, pull-in voltage

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МЭМС-переключатель на основе кантилевера с увеличенным контактным усилием: первые результаты

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Аннотация. МЭМС-переключатели представляют значительный интерес для перспективных радиоэлектронных систем, но невысокая надежность ограничивает их применение. Переключатель развивает малое контактное усилие, что приводит к высокому и нестабильному контактному сопротивлению. Усилие обычно увеличивается за счет использования электродов сложной формы и большой площади, однако простая и компактная конструкция более предпочтительна. В этой работе представлен ключ на основе миниатюрного кантилевера. Описана методика увеличения силы прижима путем подбора вертикальных размеров изделия. Тестовые устройства изготовлены и испытаны, выполнено сравнение рабочих характеристик с результатами расчетов.

Ключевые слова: МЭМС-переключатель, кантилевер, контактное усилие, контактное сопротивление, напряжение срабатывания

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Introduction

Microelectromechanical systems (MEMS) switches are promising electronic components for RF and microwave devices [1]. Small size, low insertion loss, high isolation, and low power consumption make them attractive for use in 5G communication networks [2], adaptive antennas [3], aviation and space technology [4]. A conventional MEMS switch is a cantilever suspended above driving and signal electrodes. Applying voltage to the driving electrode bends it under the electrostatic force and brings in contact with the signal electrode. The cantilever-based design is simple and reliable. Small size ensures resistivity to mechanical stress and fast switching. However, such devices usually develop a low contact force, which increases the contact resistance and makes it unstable. This paper presents a MEMS switch based on a compact cantilever with an increased contact force due to the optimization of the vertical dimensions. The restoring force is also enhanced to overcome contact stiction. In order to debug technological processes, test samples are fabricated. Switches are tested in cold mode, and the first results are described.

Design of the switch

The switch is shown schematically in Fig. 1, *a*. The movable electrode is an aluminum cantilever located above the driving and signal electrodes made of ruthenium. The cantilever has a length $l = 50$ μm and a thickness $t = 2$ μm, a width $w = 10$ μm at the fixed end and $w_e = 20$ μm above the driving electrode. The driving electrode surrounds the signal one in order to increase the electric field area. The shape of the electrodes was selected previously in order to provide the largest contact force at a given length [5]. The driving and signal electrodes have a thickness of 100 nm. The air gap between the cantilever and the electrode is $g_0 = 1.5$ μm, the contact dimple height is $h = 0.5$ μm. Along with a single cantilever, a dual design shown in Fig. 1, *b* is considered. The dual cantilever has two fixed regions and two contact dimples, which make it more stable in the bottom position.

In this work, the contact force F_C is increased by optimizing the vertical dimensions of the switch, namely, the height of the contact dimple h, the gap between the cantilever and electrodes g_0, and the thickness of the cantilever t. The contact force was calculated analytically using a simplified model, in which the cantilever profile in the closed state is approximated by a straight line. The electrostatic force acting on the cantilever is given by:

$$F_{ES} = \frac{\varepsilon_0 A V^2}{2g^2}, \tag{1}$$

where ε_0 is the vacuum permittivity, A is the overlap area of the cantilever and driving electrode, V is the applied voltage, g is the average gap between the cantilever and the driving electrode in the closed state.

The restoring force is an elastic force determined by the expression:

$$F_R = k\left(g_0 - h\right), \tag{2}$$

where k is the stiffness of the cantilever. Taking into account the position of the driving electrode with respect to the fixed end, the stiffness is determined as follows [6]:

$$k = 2Ew\left(\frac{t}{l}\right)^3 \frac{1 - x_1/x_2}{3 - 4\left(x_1/x_2\right)^3 - \left(x_1/x_2\right)^4}, \tag{3}$$

where $E = 70$ GPa is the Young's modulus of aluminum, $x_1 = 25$ μm and $x_2 = 50$ μm are the coordinates of the left and right edges of the electrode, respectively. The contact force F_C is determined by the difference between the electrostatic and elastic forces:

$$F_C = F_{ES} - F_R. \tag{4}$$

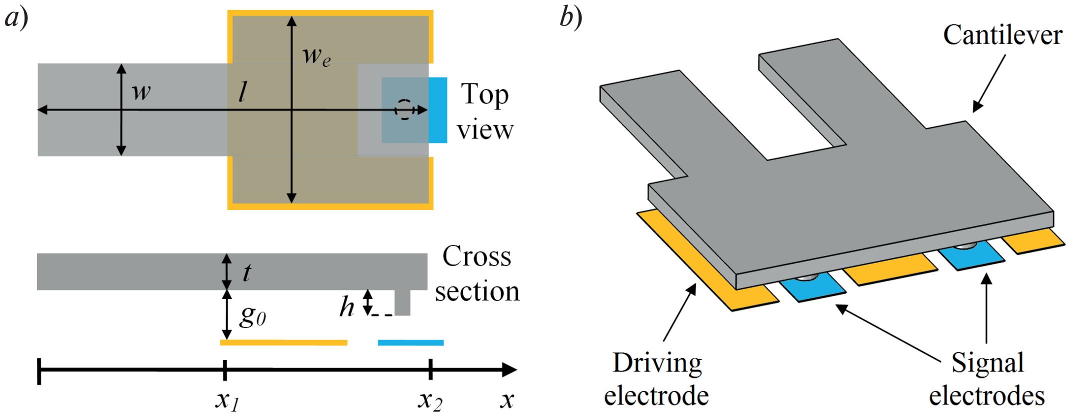

Fig. 1. Cantilever-based MEMS switch: top view and cross section (*a*); 3D view of the double structure (*b*)

Changing vertical dimensions affects the pull-in voltage $V_{pull\text{-}in}$ and the collapse voltage $V_{collapse}$. The pull-in voltage, at which the dimple touches the signal electrode, is given by the expression [6]:

$$V_{pull-in} = \sqrt{\frac{8k}{27\varepsilon_0 A} g_0^3}. \tag{5}$$

The collapse voltage, at which the cantilever buckles and touches the driving electrode, is calculated by finite element method.

The first step is to select the height of the contact dimple. The calculations are performed for a driving voltage of 90 V. Reducing h increases F_C, as shown in Fig. 2, *a*. The growth takes place due to an increase in the electrostatic force caused by a decrease in the gap in the closed state (equation (1)). According to analytical calculations, a drop of h from 0.5 to 0.1 μm raises the contact force from 10 to 50 μN. The simulation predicts a stronger growth from 10 to 89 μN, since the cantilever buckling is taken into account. At $h = 0.1$ μm, the collapse voltage is about 120 V and comes close to the operating range. Increasing the dimple height raises $V_{collapse}$. At $h = 0.2$ μm, the collapse voltage equals to 220 V, which ensures safe operation of the switch. Thus, the height of 0.2 μm is an optimal value. It corresponds to the contact force of 32 μN and restoring force of 25 μN.

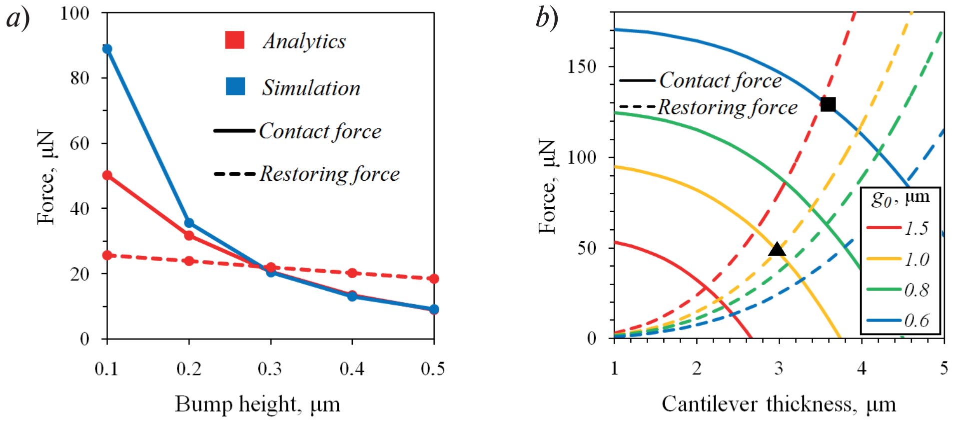

Fig. 2. The contact and restoring force as a function of the dimple height (*a*) and the cantilever thickness at various gap values (*b*)

The next step is to plot the dependence of the contact and restoring forces on the cantilever thickness for various gap values, as shown in Fig. 2, *b*. For reliable operation of the switch, the ratios $F_C > 100$ μN and $F_C / F_R < 3$ must be fulfilled. They are realized at $t = 3.6$ μm and $g_0 = 0.6$ μm (square marker on the graph). These dimensions differ significantly from those used earlier [7], so the switch fabrication requires debugging of technological processes. As trial values, $t = 3$ μm and $g_0 = 1$ μm are chosen (triangular marker). With these dimensions, both the contact and restoring force are of 50 μN, and the pull-in and collapse voltage are of 64 and 220 V.

Fabrication and testing

The switch is fabricated on a thermally oxidized silicon wafer of 100 mm in diameter. The main stages are presented in Fig. 3. At the first stage, ruthenium driving and signal electrodes are formed by magnetron sputtering and lift-off. The next step is the deposition of 1 μm thick sacrificial layer of amorphous silicon (*a*-Si). Holes for anchors and signal lines are etched isotropically in SF_6 plasma through a photoresistive mask (stage 2). After that, 0.2 μm deep dimples are formed in the sacrificial layer by plasma etching and filled with a 0.1 μm thick Ru layer (stage 3). Next, a 1.5 μm thick aluminum layer is deposited, from which the first cantilever layer is formed by wet etching (stage 4). Further, the deposition of Al is repeated, and the second layer is made (stage 5). A two-stage fabrication of the cantilever with a total thickness of 3 μm is used to reduce the lateral undercut of Al. The final stage was the removal of a-Si from under the cantilever using isotropic etching in SF_6 plasma. A detailed description of the fabrication technology can be found in [8].

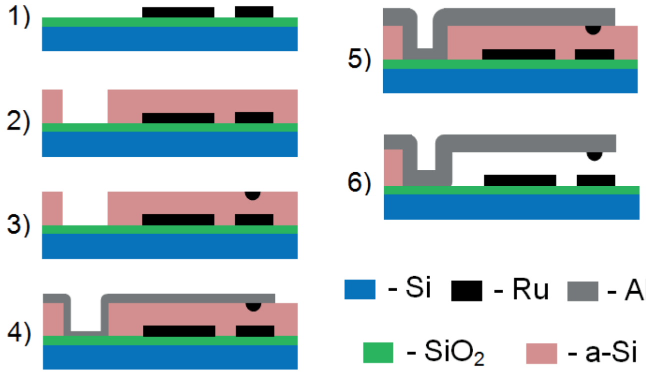

Fig. 3. Fabrication procedure

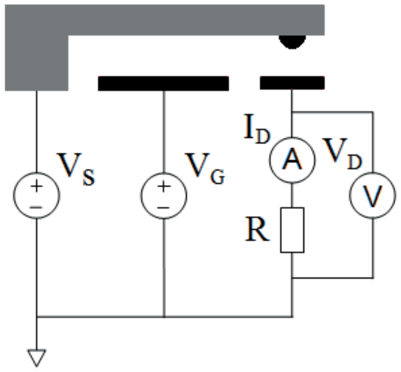

Fig. 4. Wiring diagram

The switches are tested under standard laboratory conditions without packaging. A measuring setup is assembled, including a Mitutoyo FS70 microscope with an extended working distance and measuring equipment controlled by a personal computer. The devices are connected to the sample according to Fig. 4. The driving voltage V_G is supplied by a National Instruments (NI) PXI-6221 multifunctional input/output module and amplified 20 times with a class AB homemade power amplifier. The input voltage V_S is fed from an Agilent E3647A DC power supply. The output voltage V_D is measured by the NI PCI-6221. The driving and output signals were recorded by a Keysight DSOX2024A oscilloscope. The current I_D of about 1 mA is determined by a load resistor R = 4.7 kOhm.

Results and discussion

The fabricated switches are shown in Fig. 5. The lateral undercut of aluminum is of 2.5 μm per side, which exceeds an expected value for isotropic etching by 1 μm. The photomasks are designed to take possible overetching into account, so the required lateral size of the cantilever is obtained with acceptable accuracy. The pull-in voltage is of 29 V, which is more than two times lower than the calculated value. The discrepancy is caused by a decrease in g_0 due to the tilt of the cantilever under the residual mechanical stress. At the fixed end the gap is of 1.0 μm, while at the free end it is of 0.5—0.7 μm. The pull-in voltage decreases with the number of switching cycles, as shown in Fig. 5, *a*. After 40 thousand cycles, $V_{pull\text{-}in}$ is of 19 and 25 V for single and double cantilevers, respectively. Probable reasons for voltage drop are the creep of aluminum [9] or the charging of the SiO_2 layer [10].

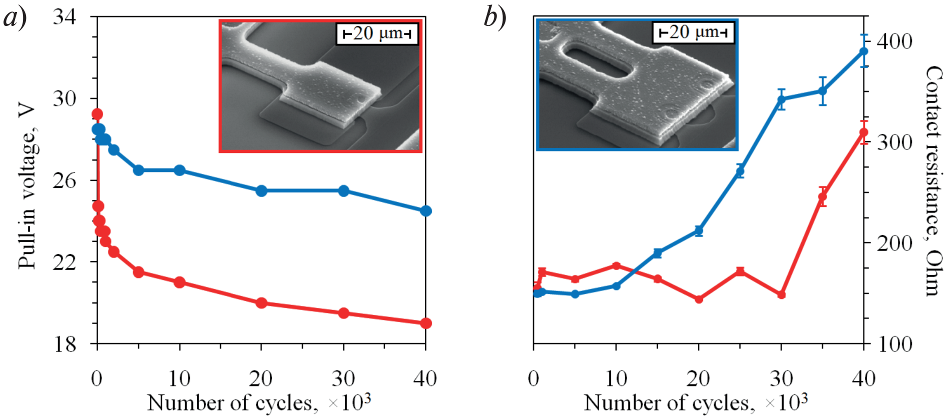

Fig. 5. Dependence of the pull-in voltage (*a*) and contact resistance (*b*) on the number of switching cycles for switches with a single and double cantilever

The dependence of the contact resistance on the number of switching cycles is shown in Fig. 5, *b*. At the beginning of the test, it is about 150 Ohms. During 40 thousand cycles the resistance rises to 300 and 380 Ohms for a single and double switches, respectively. The relatively large initial value is due to the contamination of ruthenium contacts. The growth of the resistance is explained by the formation of friction polymers [11].

Conclusion

This paper presents an electrostatic MEMS switch based on a 50 μm long aluminum cantilever. An approach for optimizing the vertical dimensions is proposed, which increases the contact force from 10 to 112 μN. The growth of the contact force is accompanied by an increase in the restoring force from 18 to 59 μN. Optimization requires a reduction in the dimple height to 0.2 μm and the air gap to 0.6 μm, as well as an increase in the cantilever thickness to 3.6 μm. In order to debug technological processes, trial samples are fabricated. Bending the cantilever under the residual stress reduces the pull-in voltage by half compared to the calculated value. In addition, the voltage is reduced during long-term operation. For 40 thousand cycles, it drops from 29 V to 19 and 25 V for single and double cantilevers, respectively. The probable reasons for this effect are the creep of Al and charging of SiO_2.

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