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Performance optimization of the cantilever-based MEMS switch

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Abstract. Microelectromechanical system (MEMS) switches combine advantages of electromagnetic and semiconductor relays. However, a number of problems prevent the widespread use of these devices. One of them is high actuation voltage. In this work, voltage reduction is achieved by optimizing the shape of the electrodes. The switch is simulated by the finite element method. Dependences of the actuation voltage on the geometric parameters are obtained. The proposed shape of the electrodes reduces the voltage by almost two times compared to conventional design without deterioration of other working characteristics.

Keywords: MEMS switch, cantilever, actuation voltage, finite element method

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Оптимизация рабочих характеристик МЭМС-переключателя на основе кантилевера

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Аннотация. МЭМС-переключатели сочетают в себе достоинства электромагнитных реле и полупроводниковых ключей, однако до сих пор не нашли широкого применения. Одной из причин является высокое напряжение срабатывания. В этой работе снижение напряжения достигается путем оптимизации формы электродов. Выполнено моделирование переключателя методом конечных элементов. Получены зависимости напряжения срабатывания от геометрических параметров конструкции. Предложенная форма электродов уменьшает напряжение практически вдвое по сравнению с классическим исполнением без ухудшения других рабочих характеристик.

Ключевые слова: МЭМС-переключатель, кантилевер, напряжение срабатывания, метод конечных элементов

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Introduction

In recent decades, microelectromechanical systems (MEMS) have been actively developed in the world. MEMS switches for commutation of high-frequency signals receive a particular interest [1]. They combine advantages of electromagnetic relays and transistor-based devices: low insertion loss, good insulation and low power consumption combined with small size. In addition, MEMS switches are fabricated using microelectronic technology, which allows integration with other electronic components on a wide range of substrates, including Si [2], GaAs [3] and glass [4]. Such characteristics make MEMS switches attractive for use in 5G mobile network [5], reconfigurable antennas [6, 7], satellite communication systems [8], and other industries.

A typical MEMS switch is a metal beam with one fixed end (a cantilever), which is suspended above the driving and signal electrodes [9]. Applying voltage to the driving electrode makes the beam to bend under the electrostatic force and come in contact with the signal electrode. The classical design is simple and reliable, but it has high actuation voltage of about one hundred volts [10]. Such a voltage complicates the use of MEMS switches in modern electronic devices with an operating range of 3-5 V. This paper presents a technique for reducing the actuation voltage of a cantilever-based MEMS switch by optimizing the shape of the electrodes. Working characteristics are calculated using finite element method (FEM). The influence of the optimization on the resonant frequency of the cantilever, the switching time and the contact force are considered.

Materials and Methods

The switch is schematically shown in Fig. 1. The movable electrode is an aluminum cantilever located above the driving and signal electrodes made of platinum. The cantilever has a length $L = 50$ μm and a thickness $t = 2$ μm. Its end with the coordinate $x = 0$ is fixed. The width of the cantilever near the fixed end is W. The driving electrode has the length L_e and the width W_e. The air gap between the cantilever and the electrode is $g_0 = 1.5$ μm. The driving and signal electrodes have a thickness of 100 nm.

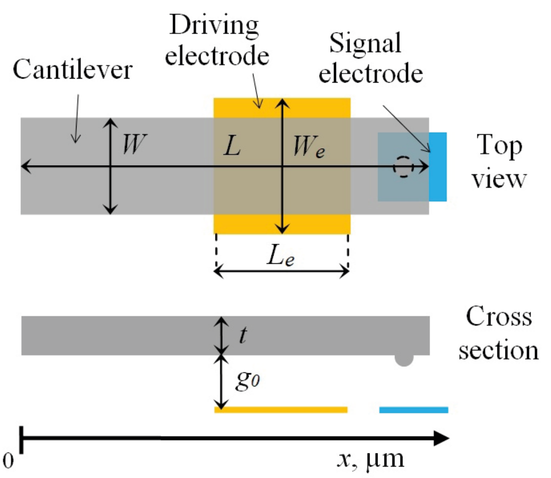

Fig. 1. Schematic illustration of the cantilever-based MEMS switch

The actuation voltage V_{PI} of the cantilever-based switch is given by the following expression [9]:

$$V_{PI} = \left(\frac{8k}{27\varepsilon\varepsilon_0 A} g_0^3 \right)^{\frac{1}{2}}, \tag{1}$$

where k is the spring constant of the beam, g_0 is the gap between the beam and the electrode, A is the overlap area of the electrode and the beam, and ε is the air permittivity. According to equation (1), the actuation voltage can be reduced by decreasing k and g and increasing A. However, the first method reduces the restoring force, thereby increasing the probability of stiction. The second way raises the capacitance between the cantilever and the signal electrode and degrades the radio frequency characteristics of the switch. In this work we consider the third method, which consists in optimizing the electrode shape.

Changing the design of the switch affects not only the actuation voltage, but also other characteristics such as switching time and contact force. The switching time t_{on} is determined by the following expression [9]:

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$$t_{on} \approx 3.67 \frac{V_{PI}}{V_D} \frac{1}{2\pi f_0}, \tag{2}$$

where V_D is the voltage applied to the driving electrode, and f_0 is the resonance frequency of the cantilever. The resonance frequency is calculated as follows [11]:

$$f_0 = \frac{1}{2\pi} \left(\frac{k}{m_{eff}} \right)^{\frac{1}{2}}, \tag{3}$$

where m_{eff} is the effective mass of the cantilever. The cantilever in the form of a rectangular parallelepiped has the mass of

$$m_{eff} = \frac{33}{140} m = \frac{33}{140} \rho WLt, \tag{4}$$

where ρ is the density of the cantilever material. The spring constant is expressed as

$$k = \frac{EW}{4} \left(\frac{t}{L} \right)^3, \tag{5}$$

where E is the Young's modulus of the cantilever material. The contact force F_C is determined by the difference between the electrostatic force F_{es} and the elastic force F_{el} acting on the cantilever in the closed state:

$$F_C = F_{es} - F_{el}. \tag{6}$$

Expressions (1)–(6) allow estimation of the performance, but numerical methods provide more precise data. The switch is simulated in a verified FEM software. The model contains about 10^6 tetrahedral elements. The switch operates in air under normal conditions. The cantilever material is aluminum with the following properties: E = 70 GPa, ρ = 2700 kg/m^3, Poisson's ratio 0.35. The cantilever is grounded, and an electric potential is applied to the driving electrode. The potential gradually increases until the electrostatic pull-in, when the position of the beam becomes unstable. The highest potential value for which the computer is able to calculate the cantilever position is considered as the actuation voltage.

Results and Discussion

According to the simulation, the switch with W = 10 μm, L_e = 18 μm and W_e = 12 μm has an actuation voltage of 146 V. This rather high value needs reduction. The decrease in V_{PI} is achieved by increasing the width of the electrode and the beam above it, as shown in the top inset of Fig. 2. This modification enlarges the overlap area of the electrode and the beam. The same figure shows the dependence of V_{PI} on the electrode width. The voltage goes down as the width increases, and for W_e = 22 μm it equals to 107 V. Further expansion may create a significant torque tending to rotate the cantilever around its axis. It may touch the driving electrode, and short circuit may occur. Therefore, W_e is limited to 22 μm.

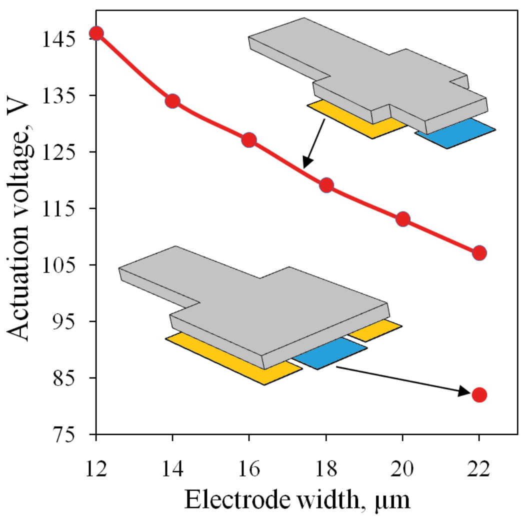

Fig. 2. Dependence of the actuation voltage on the width of the driving electrode

The actuation voltage of 107 V is still quite high and requires further reduction, which is achieved by extending the driving electrode towards the free end of the cantilever. The driving electrode goes around the signal one, as shown in the bottom inset of Fig. 2. The length of the electrode increases to L_e = 26 μm, and the actuation voltage decreases to 82 V. This value is acceptable, since it can be provided by a charge pump of the integrated driver [12].

Design optimization changes the switching time. According to expressions (3)–(5), the classical cantilever has a resonance frequency of 667 kHz. FEM simulation provides a close value of 664 kHz. The switch with widened electrode has the frequency of 567 kHz, while the design with widened and extended electrode exhibits f_0 = 481 kHz. The decrease in f_0 is explained by the growing effective mass of the cantilever and is accompanied by the increase of the switching time. At $V_D = V_{PI}$ the switch goes to the “on” state for 0.88, 1.03 and 1.21 µs, respectively. However, this change is not significant. The switching time remains in the microsecond range, which is typical for a MEMS switches.

The contact force is calculated using a specially created model in which the cantilever is initially brought in contact with the signal electrode. The contact bump is a platinum cylinder of 0.5 µm in height and 0.5 µm in radius. The base of the cylinder is set in contact with the electrode. Since the cantilever originally has a deformed shape, is does not develop the elastic force. This force is introduced in the model according to the analytical calculations.

The dependences of the contact force on the driving voltage for three types of switches are shown in Fig. 3. Each curve is built in the range from V_{PI} to the “second pull-in” voltage, at which the cantilever touches the driving electrode. For the classic switch, this voltage equals to 357 V, while the other designs demonstrate 291 and 284 V.

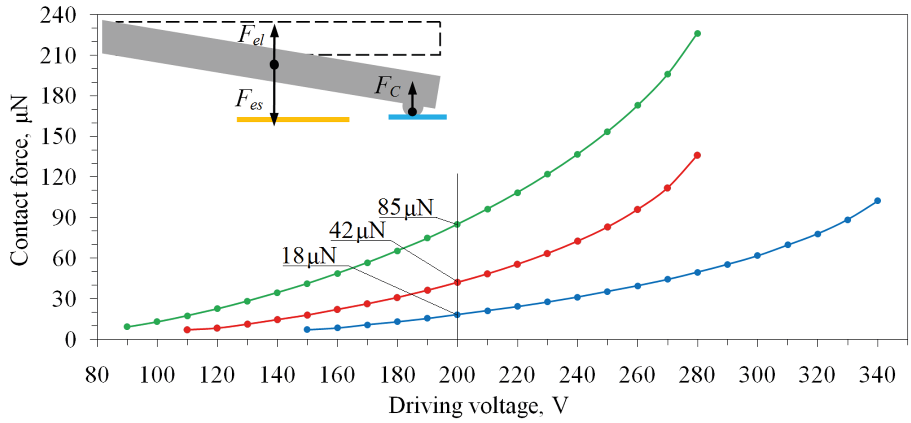

Fig. 3. Dependence of the contact force on the driving voltage. Blue color indicates the values for the classic version, while red color corresponds to the switch with the widened electrode, and the values for the switch with the widened and extended electrode are shown by green color

All the structures demonstrate the rise of the contact force with V_D due to the increase in the electrostatic force. However, the optimized switches exhibit significantly higher F_C compared to the classic design. At V_D = 200 V, the contact force equals to 18, 42 and 85 µN, respectively. This fact is explained by the increase in the overlap area between the electrode and the cantilever during optimization. The rise of F_C has a positive effect on the operation of the switch, since the contact resistance R decreases with the force according to the law $R \sim F_c^{-1/3}$. It is important to note that the elastic force remains unchanged (F_{el} = 16 µN), since the bending part of the cantilever is located close to the fixed end and does not change size. Therefore, optimization of the electrode shape does not increase the probability of stiction.

Conclusions

The paper considers an electrostatic MEMS switch based on the 50 µm long and 2 µm thick aluminum cantilever. Optimization of the electrode shape reduces its actuation voltage from 146 to 82 V. The switching time increases insignificantly and remains in the microsecond range. On the contrary, the contact force increases several times due to the increase in the working area of the electrostatic force. This change is considered positive because it should reduce the contact resistance. The optimization does not affect the restoring force and does not deteriorate the device performance.

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