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A seesaw-type MEMS switch with Pt and Ru contacts

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Abstract. Microelectromechanical systems (MEMS) switches have outstanding working characteristics and a wide range of possible applications, but suffer from the lack of reliability. The main reason of failure is the degradation of metal contacts, which increases the on-resistance or leads to stiction. A proper choice of the contact material may solve the problem. In this work, the performance of Pt-Pt and Ru-Ru contacts is investigated. The study is performed using a recently proposed stiction-protected MEMS switch. The contact resistance and lifecycle in the cold switching regime are measured and compared.

Keywords: MEMS switch, electrostatic actuation, contact resistance, lifecycle

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Материалы конференции
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МЭМС-переключатель с контактами из платины и рутения

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Аннотация. Переключатели, изготовленные по технологии микроэлектромеханических систем (МЭМС), обладают выдающимися рабочими характеристиками и представляют интерес для множества применений. Недостатком этих устройств является невысокая надежность, обусловленная деградацией металлических контактов. Подбор материала контактов может решить проблему. В этой работе исследуются рабочие характеристики контактов из платины и рутения. Выполнены измерения сопротивления и ресурса контактов в холодном режиме.

Ключевые слова: МЭМС-переключатель, электростатическое управление, контактное сопротивление, ресурс

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Introduction

Wireless communication and radar systems demonstrate significant progress in recent years. The evolution is achieved due to advanced electronic components, including switches for routing of radio frequency and microwave signals. However, the development of electromagnetic and semiconductor relays has almost exhausted, and new approaches are required to support the trend. MEMS switches are considered as a promising alternative to conventional devices. They provide superior radio frequency characteristics in combination with small size, low power consumption and capability of integration with CMOS circuits [1]. An important characteristic of the switch is the lifecycle, which is mainly determined by the durability of contacts. Metallic surfaces degrade during operation due to friction, contamination and other phenomena [2]. The degradation is considered as the main reason for the switch failure, because it increases the contact resistance or leads to stiction. Several methods to overcome the problem are known, including elimination of the contact bounce [3], two-stage switching [4] and refreshing the contact point [5]. But more straight way is the selection of contact materials. Typically, the contacts are made of noble metals due to their chemical inertness and low resistivity. In this paper we compare working characteristics of Pt-Pt and Ru-Ru contacts. The study is performed at the recently developed seesaw-type MEMS switch [6]. The modified design provides enhanced contact force at a reasonable driving voltage. The on-resistance and lifecycle for both materials are analyzed and compared.

Materials and Methods

The switch is shown in Fig 1, *a*. A source electrode is a 100 μm long and 45 μm wide beam made of aluminium. It is suspended by torsion springs above two pairs of gate and drain electrodes. The gap between the beam and electrodes is of 1.5 μm. The beam has contact bumps on the bottom side. When the driving voltage is applied to the gate, the electrostatic force tilts the beam, and the bump touches the drain turning the switch on. When the voltage is removed, the switch returns to the off state under the elastic force of the springs. In case of stiction, the voltage is applied to the opposite gate, which creates the recovery force that breaks the contact. The beam and electrodes have an optimized shape that ensures several times higher contact force in comparison with the previous design [6].

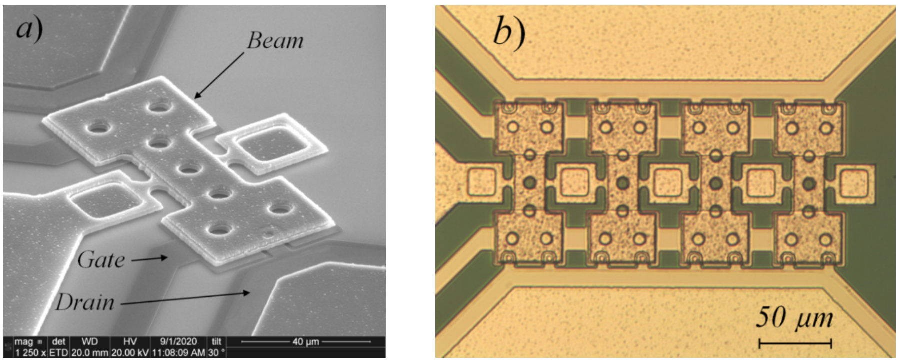

Fig. 1. MEMS switch under investigation: scanning electron microscope image of the basic single-beam device (*a*); optical image of the four-beam switch, each beam contains four contact bumps (*b*)

The switch is fabricated by surface micromachining on an oxidized silicon wafer using the five-mask process described previously [7]. The bumps and electrodes are made of platinum or ruthenium, so the switch provides Pt-Pt and Ru-Ru contact. Each arm of the beam contains one or two contact bumps. In addition, we fabricate the switch with four beams, which are connected to each other and actuated simultaneously by the common gate, see Fig. 1, *b*. Both one- and four-beam switches are fabricated in one- and two-bump versions.

The switches are tested in standard laboratory conditions without packaging. Measuring equipment is connected to the sample according to Fig. 2. Rectangular pulses of the gate voltage V_{G1} and V_{G2} are applied to both sides of the switch alternately with the frequency of about 1 Hz. The device has a pull-in voltage of 27 V, so the gate voltage of 30 V should be enough for actuation. However, both Pt-Pt and Ru-Ru contacts are prone to stiction. To recover the switch, an increased voltage is applied. Two values of 55 and 80 V are chosen to test the device at various contact force. The DC signal V_S = 5 V is fed to the beam. In order to prevent the damage of contacts by electric arcing, the switch operates in a cold regime. The source voltage is applied to the beam after the contacts are closed and is removed before they are opened. Load resistors $R_1 = R_2$ = 5 kOhm limit the drain current I_D by 1 mA, which is controlled at the left channel by a multimeter. Thus, the transmitted power does not exceed 5 mW. Contact resistance R_C is calculated at each actuation cycle using the resistive divider circuit, which contains R_C and the corresponding load resistor.

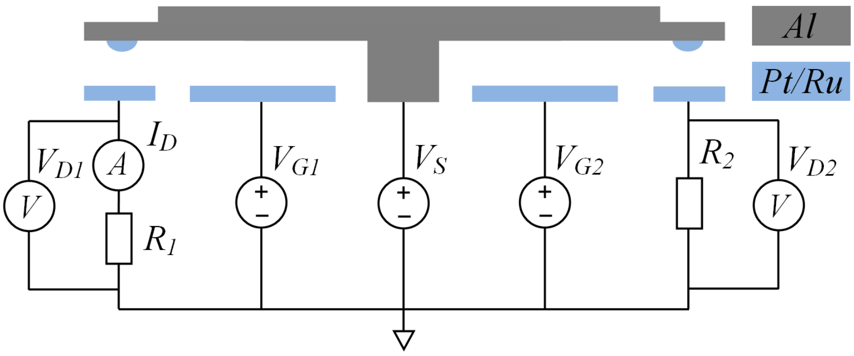

Fig. 2. Schematic illustration of the experimental setup

Results and Discussion

First of all, we test the basic switch with one beam and one bump per arm. A typical graph of the contact resistance throughout the first thousand cycles is shown in Fig. 3, *a*. The switch with Pt-Pt contacts demonstrates rather unstable R_C. It varies from 66 to 619 Ohm and has the average value of 281 Ohm. Ruthenium provides more stable resistance of 76-199 V with the average value of 157 Ohm, which is 44% lower compared to platinum. To all appearance, the instability is caused by accumulation of carbon-containing contaminants on the contact surfaces, as was observed for the Pt-based switch of the previous design [8]. Such contamination called "frictional polymerization" is a feature of platinum group metals due to their electron structure [9]. It was demonstrated that Pt adsorbs carbon from the ambient air and forms nonvolatile carbon contamination [10]. However, the surface of ruthenium may undergo a slight oxidation during fabrication. The layer of RuO_2 prevents the accumulation of carbon [11]. This is a probable reason for the more stable behavior of the Ru-based device.

The contact resistance during the long-term test is shown in Fig. 3, *b*. The switches fail due to the sharp increase of R_C to the megaohm level. Platinum-contact devices have a lifetime below $4 \cdot 10^4$ working cycles, while ruthenium-based switches withstand more than $3 \cdot 10^5$ actuations. High durability of Ru contacts is explained by low contamination rate and high hardness, although the jumps of the resistance are also observed. The sharp decrease of R_C to 20–60 Ohm takes place when the contamination film is damaged by a mechanical impact or electrical breakdown.

Further, we test several samples of each type in order to collect statistical data. Only the ruthenium-based devices are considered. The basic switch provides the average contact resistance of 209 Ohm at V_G = 55 V. Increasing the voltage up to 80 V rises the contact force F_C from 38 to 84 μN, according to a finite element simulation [6]. When the force equals to several tens of micronewtons, asperities of the contact surfaces experience elastic deformation. The resistance depends on the force as $R_C \sim F_C^{-1/3}$ [2]. Therefore, at V_G = 80 V one can expect $R_C \approx 160$ Ohm. However, the switch demonstrates somewhat higher value of 195 Ohm. To all appearance, tribopolymers make a contribution.

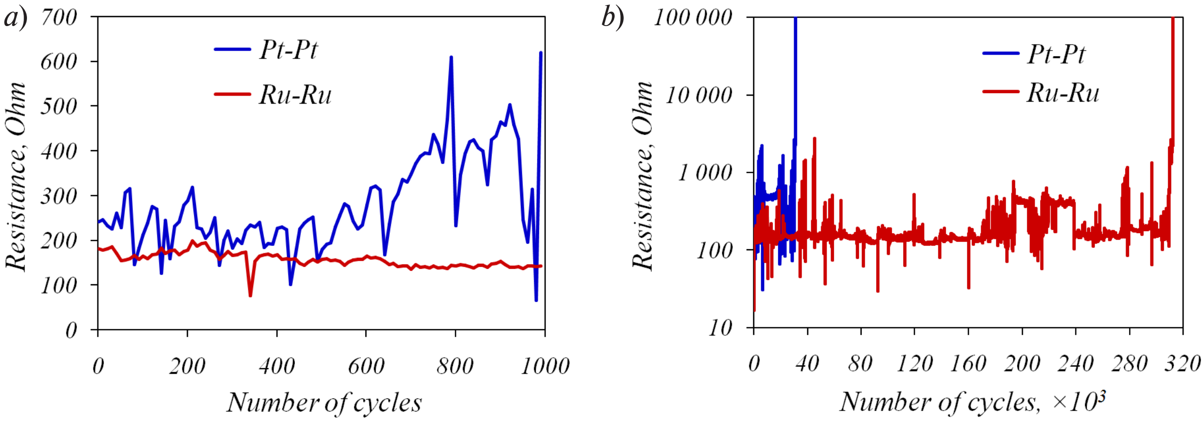

Fig. 3. Contact resistance of switches with Pt-Pt and Ru-Ru contacts during the first thousand of working cycles (*a*) and throughout the whole lifecycle (*b*)

The use of two bumps per arm increases the tendency to stiction. For the one-bump switch the gate voltage of 50–55 V is enough to overcome stiction, while the two-bump device requires 70–75 V. This is explained by the growth of adhesion force with the larger contact are. In addition, the average resistance is increased to 223 Ohm at V_G = 80 V. Apparently, the contact force is divided between two bumps, thereby reducing the contact pressure. It is worth noting that the use of four beams connected in parallel also does not improve the performance. This result disagrees with expectations, because the four-beam switch provides larger contact area at the same F_C per bump. Additional measurements are required to verify this result.

Conclusion

The paper reports the first measurements of the performance for a recently proposed seesaw-type MEMS switch. The device is fabricated by surface micromachining using the five-mask process. In order to select the optimal contact material, the switch is equipped by Pt-Pt and Ru-Ru contacts. The tests are performed in the cold regime without packaging. The input voltage equals to 5 V, while the current does not exceed 1 mA. The platinum-based switch demonstrates a rather high and unstable contact resistance, which is determined by the formation of tribopolymers. Ruthenium provides more stable and low resistance, probably, due to oxidation of the contacts during fabrication. Increasing the contact force reduces the resistance, although a stronger effect is expected. Using two contact bumps per arm instead of one bump does not improve the performance, but increases the probability of stiction. Increasing the number of beams connected in parallel also does not improve working characteristics, but this result needs further analysis. Ruthenium contacts provide almost ten times longer lifecycle compared to platinum contacts. Thus, Ru is more preferable material for the demonstrated switch.

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