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Combined resistive-capacitive MEMS switch for advanced communication systems

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Abstract. The main characteristic of a capacitive microelectromechanical system (MEMS) switch is the ratio of capacitances in the open and closed states. In conventional switches, this ratio typically does not exceed ten and can be increased several times by using a floating potential electrode. The dependence of the capacitive characteristics, isolation and insertion loss of a switch with the “floating” electrode on the substrate material is investigated.

Keywords: MEMS switch, capacitance ratio, isolation, insertion loss, floating potential, finite element method

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Комбинированный резистивно-емкостной МЭМС-переключатель для передовых систем связи

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Аннотация. Основной характеристикой емкостного микроэлектромеханического (МЭМС) переключателя является отношение емкостей в замкнутом и разомкнутом состоянии. В стандартных изделиях это отношение обычно не превышает 10 и может быть увеличено в несколько раз за счет использования электрода с плавающим потенциалом. В работе исследуется зависимость емкостных характеристик, изоляции и вносимых потерь ключа с “плавающим” электродом от материала подложки.

Ключевые слова: МЭМС-переключатель, отношение емкостей, изоляция, вносимые потери, плавающий потенциал, метод конечных элементов

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Introduction

MEMS switch is a micron-sized electromechanical relay fabricated by microelectronic techniques [1, 2]. It provides low insertion loss and high isolation, combined with small dimensions and virtually zero power consumption [3]. These features make MEMS switches attractive for advanced communication systems, radar equipment and other areas of radio electronics [4]. Recent growth of wireless communications and increased demands driven by 5G and 6G standards offer an ideal opportunity for MEMS switches.

The main characteristic of a capacitive switch is the ratio of capacitance in the down and up states of the movable beam C_{down}/C_{up}. In a conventional design, this ratio typically does not exceed 10 and does not ensure the required switching effect [5–7]. To increase this ratio, various methods have been suggested, such as using dielectrics with high dielectric constant, reducing the thickness of the dielectric layer or increasing the air gap [8, 9]. However, these methods have several drawbacks. For example, using non-standard dielectrics requires significant adjustments to the fabrication process, and enlarging the air gap increases the actuation voltage.

One of the most effective methods for increasing C_{down}/C_{up} is to use a floating potential electrode. This technique eliminates disadvantages mentioned above and allows one to vary the capacitance over a wide range without altering the design of the moving part. A metal electrode of the desired size is placed on the dielectric coating of the transmission line, creating a metal-to-metal connection between the beam and electrode. As a result, the switch becomes a resistive-capacitive device. This paper explores the performance of this type of switch, which is intended for use in advanced communication systems.

Materials and Methods

The proposed MEMS switch is schematically shown in Fig. 1, *a*. A movable electrode is an aluminum beam with a length of 100 μm, which is fixed on torsion suspensions. A transmission line is a coplanar waveguide running under the beam at a gap of 1 μm (Fig. 1, *b*). A thin metal electrode is formed on top of the dielectric layer. In the up state, the potential of the electrode is floating. The capacity of the beam-line system is small, so the signal passes from the input to the output with minimal loss. In the down state, the beam touches the electrode, and their potentials are equalized. The capacity between the beam and the transmission line increases significantly, so the switch shunts the line. The signal does not pass from the input to the output, and high isolation is achieved. Driving electrodes are located under both arms of the beam, so an additional restoring force may be applied in case of stiction. This design significantly improves the reliability of the switch compared to the classical cantilever structure.

The switch is simulated by the finite element method (FEM). The model includes a substrate with dimensions of 9.6×4.3 mm and a thickness of 460 μm, coated with a layer of SiO_2 with a thickness of 1 μm, as shown in Fig. 1, *c*. A transmission line with a length of 7.2 mm is formed on the insulating layer, with 1×1 mm contact pads for the central conductor and 1.4×1.4 mm pads for grounded conductors. The relatively large size of the pads is needed for welding electrical terminals. To speed the calculations up, the closure and opening of the switch was simulated by increasing the height of the contact bump, which has a cylindrical shape. The opposite signal electrode and driving electrodes were excluded from the model. At the same time, the model is located in a volume of air with the size 9.6×4.3×1 mm.

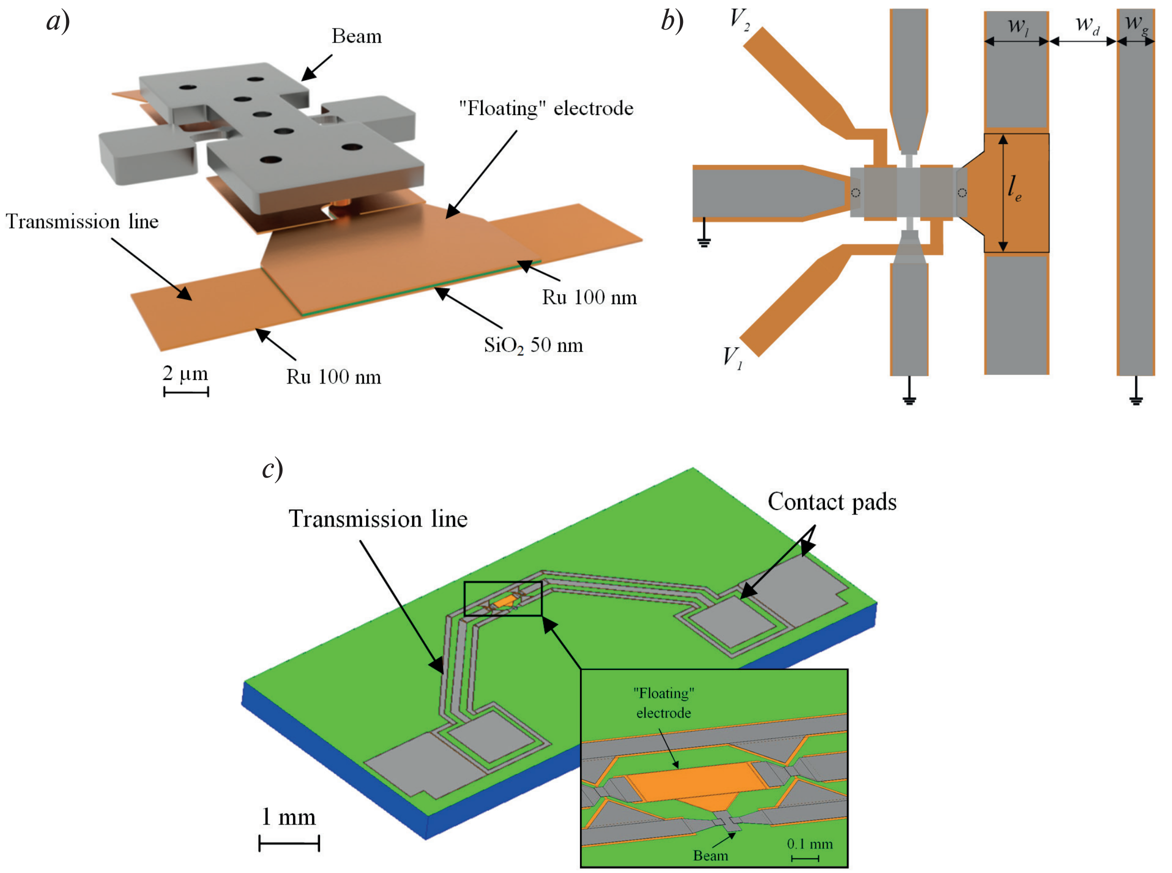

Fig. 1. A switch with a "floating" electrode: 3D view (*a*); top view of the switch built into the transmission line (*b*); a model of a chip (*c*)

Results and Discussion

The analytical calculation of the capacitance ratio is carried out using the formula (1), which was derived in our previous work [10]:

$$\frac{C_{down}}{C_{up}} = \varepsilon_r \frac{l_e w_l}{S} \frac{g - t_d - t_e}{t_d} = 1.5 \cdot 10^5, \tag{1}$$

where g is the air gap between the beam and the "floating" electrode, ε_r is the dielectric constant of the insulating material, w_l is the width of the transmission line, l_e is the length of the electrode that has a "floating" potential, S is the area of overlap between the beam and electrode, t_d is the thickness of the insulating material under the electrode, and t_e is the thickness of the "floating" electrode.

Expression (1) does not take into account the parasitic capacitance. Finite element simulation considers the real configuration of the transmission line and substrate properties. The dependence of the capacitance on the resistivity ρ of the silicon wafer is shown in Fig. 2. Increasing ρ reduces both C_{down} and C_{up} due to a decrease in the parasitic component. In turn, the drop of C_{up} increases the capacitance ratio. The maximum value is 7.4 at $\rho = 50$ kΩ·cm, which is significantly lower than the analytical prediction. The reason for the discrepancy is the relatively large $C_{up} = 7$ pF. Dielectric substrates significantly increase the capacitance ratio compared to silicon, see Table for details. The highest value of $C_{down}/C_{up} = 46.1$ is provided by borosilicate glass Borofloat 33. Sapphire substrate gives a capacitance ratio of 27.7. Thus, the proposed switch has a several times higher C_{down}/C_{up} in comparison to conventional capacitive switches.

Table

Material properties and simulation results for various substrates

Material	ε_r	ρ, Ω·cm	C_{down}, pF	C_{up}, pF	C_{down}/C_{up}
Low-resistivity silicon	11.7	12	120.89	74.25	1.6
High-resistivity silicon	11.7	$5\cdot10^3$	89.44	43.18	2.1
		$50\cdot10^3$	53.94	7.33	7.4
Sapphire	9.3	10^{16}	48.45	1.75	27.7
Borofloat 33	4.6	10^8	47.74	1.03	46.1

The next step is the estimation of insertion loss and isolation. These values are described by a single parameter S_{21} in the open and closed states of the switch:

$$|S_{21}|^2 = \frac{4}{\omega^2 C_{down}^2 Z_0^2}, \tag{2}$$

where Z_0 is the transmission line impedance, ω is the frequency of the switched signal. Measurements of these parameters were conducted in the frequency range of the switched signal ω from 1 to 20 GHz. Substrates made of glass, sapphire, and high-resistivity silicon (ρ = 5 kΩ·cm) were used in the calculations. Low-resistivity silicon was not considered, because it provides small capacitance ratio, while high-resistivity silicon (ρ = 50 kΩ·cm) was excluded due to its high cost and low availability.

For all the substrates, there is a trend towards decreasing isolation with the frequency, as shown in Fig. 3. Silicon and sapphire have similar isolation across the entire frequency range, while glass provides significantly better isolation in the 3–16 GHz range. As for insertion loss, silicon and sapphire provide similar results that do not exceed 0.8 dB across the entire range. However, the glass substrate has strong fluctuations in loss and large peak values of up to 1.6 dB. The acceptable S-parameter values are higher than 15 dB for isolation and less than 1 dB for insertion loss. The switch fabricated on the glass wafer ensures these characteristics over a frequency range from 1 to 12 GHz. The switches made from sapphire and silicon, on the other hand, have operating ranges of 1–10 GHz and 1–9 GHz, respectively.

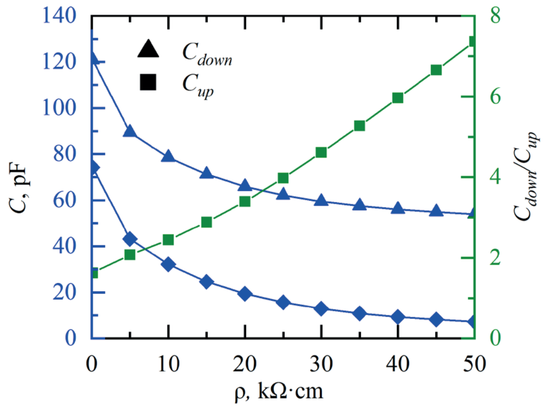

Fig. 2. The dependence of capacitive characteristics on the substrate resistivity

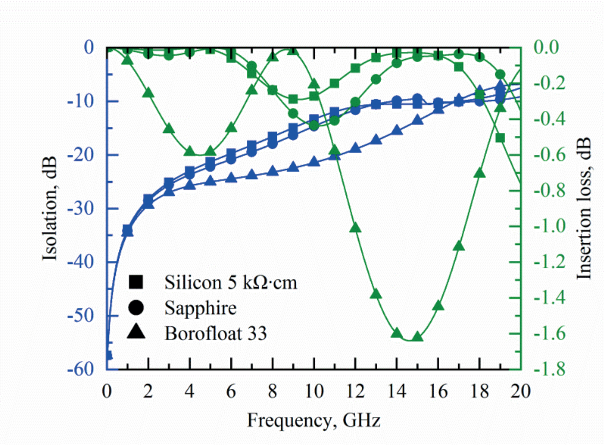

Fig. 3. The dependence of isolation and insertion loss on the signal frequency

Conclusion

The paper describes a combined resistive-capacitive MEMS switch equipped with a “floating” electrode that provides an enhanced capacitance ratio. The finite element method was used to calculate the capacitive characteristics, as well as the isolation and insertion loss in the 1–20 GHz frequency range. The use of low-resistivity silicon as the substrate material gives low capacitance ratio of 1.6. However, increasing the resistivity to 50 kΩ·cm increases C_{down}/C_{up} to 7.4. Even higher values can be achieved with dielectric substrates made of sapphire or borosilicate glass, which give ratios of 27.7 and 46.1, respectively. A switch on a sapphire substrate offers acceptable isolation of more than 15 dB and insertion loss lower than 1 dB in the 1–10 GHz range. The borosilicate glass substrate can extend the operating range up to 12 GHz.

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