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Fabrication and Numerical Simulation of a Micromachined Contact Cantilever RF-MEMS Switch

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Abstract: This paper reports a contact cantilever MEMS switch. The designed switch has a metal cantilever that acts as an electrostatically activated switch with processing options to achieve dielectric isolation of the control-voltage path from the signal path. To obtain good material properties, an ANSYS FEA tool is used to optimize the structure. The RF MEMS switch is fabricated via a surface micromachining process. The switch has an actuation voltage of 12V, which is close to the simulated value of 11V. The measured and the HFSS simulated isolations are both higher than -20dB from 0.05 to 10GHz. The measured insertion loss is less than -0.9dB, relatively larger than the simulated loss of less than -0.2dB from 0.05 to 10GHz. This is because a contact resistance introduced due to poor physical contact between the bottom lines and the metal cantilever.

Key words: cantilever RF-MEMS switch; insertion loss; isolation
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1 Introduction

The emerging MEMS technology has been attracting a lot of interest in the microwave community due to its excellent RF performance. Most of the RF MEMS switches show superior RF characteristics, such as low insertion loss, high isolation, and even high frequency mechanical switching, compared to their semiconductor-based counterparts[1~3].

The cantilever beam is the most commonly used structure for MEMS components. Cantilever RF switches have been reported by some groups[4,5]. Most of the cantilevers are fabricated by utilizing a thick silicon nitride integrated with a thin metal layer and require a very high actuation voltage. In this work, a metal cantilever topology will be discussed. We emphasize the material properties and the mechanical reliability of the design. The designed switch has a relatively low actuation voltage.

Material properties and design are important in the switch operation. Stresses in a suspended cantilever affect the device operation. Compressive stress is undesirable since it will cause the cantilever to buckle. High tensile stress is also undesirable since it will lead to the curl of the cantilever, dramatically increasing the actuation voltage. On the other hand, the dimensions of the cantilever beam, including the length, the width, and the thickness, also affect the switch operation. If the length and the width exceed certain values, the cantilever beam cannot return to its initial position and suffers from a stiction problem when the beam is bent. If the beam is too short or too thick, a large voltage will be needed to move the beam down to contact the signal line.

To obtain good material performance and mechanical reliability of the designed switch, an ANSYS FEA tool is used to optimize the material and the dimension of the switch.

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2 Structure design and FEA simulation

The basic concept is sketched in Fig. 1. There is a coplanar signal line with a gap which blocks the signal. A conducting cantilever can be moved down to close the gap. A voltage applied to the actuator supplies the force that closes the switch. This design scheme offers some advantages. First, the cantilever beam is electrically connected to the ground plane, separating the actuation signal from the RF signal. The intermodulation between the actuation voltage and RF signal can be alleviated. This also leads to an extremely broadband RF characteristic.

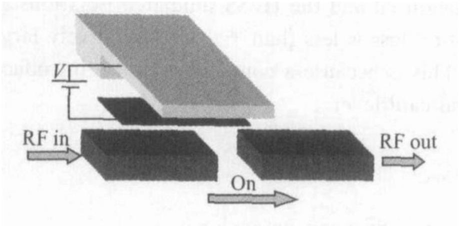

Fig. 1 Schematic of the DC contact series switch

To obtain good mechanical performance and a relatively low actuation voltage, an ANSYS FEA tool is used. First, two different Al and Au materials are compared. Figure 2 shows that the actuation voltage of the Al cantilever, 11.0V, is lower than that of the Au cantilever, 14.0V, with the same cantilever dimensions of 200μm in length and 120μm in width. This is mainly because there is less tensile stress in the Al film than in the Au film. Then the Al cantilevers with different dimensions are analyzed. Figure 3 shows that the actuation voltage depends on the dimensions of the cantilever —the shorter the cantilever, the higher the actuation voltage. As shown in Fig. 3, the actuation voltage rapidly rises to 17V when the cantilever is shortened to 150μm. If the cantilever is shortened to 120μm, the cantilever cannot be pulled down unless a voltage of more than 50V is applied. Such high voltage operation will make RF MEMS devices impractical in many wireless communication applications. The voltage can be decreased by lengthening the cantilever. However, a long cantilever cannot return to its primary position after it is moved down. According to the ANSYS analysis, a cantilever with a dimension of 120μm ×120μm is optimal, and Al combined with photoresist gives the lowest tensile stress. Moreover, the curl can be further alleviated by thinning the metal cantilever and using holes in the metal layer to release the residual stress of the cantilever.

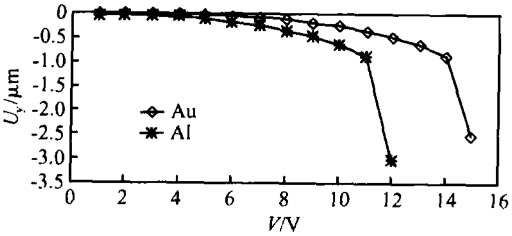

Fig. 2 Simulated actuation voltages of Al and Au cantilevers with the same dimensions using ANSYS analysis

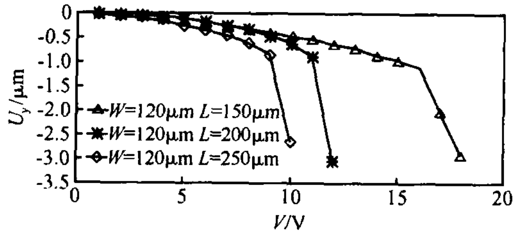

Fig. 3 Simulated actuation voltages of Al cantilevers with different dimensions

3 Fabrication process

A high-resistivity silicon wafer is chosen as a substrate to reduce the signal loss, and the RF MEMS switch is fabricated by using surface micromachining techniques. The 5-mask fabrication process includes the steps of sputtered metal deposition, PECVD and LP-CVD dielectric deposition, electron-beam metal deposition, sacrificial layer patterning, selective wet etching, and reactive-ion etching (RIE). A brief description of the process is as follows: A 1μm-thick layer of silicon dioxide is used as a buffer layer. A 0.6μm sputtered Cr/Au seed layer is first deposited and patterned to define the signal lines and bottom electrode, and the bottom electrode is covered with a 200nm-thick PECVD Ta_2O_5 layer for DC isolation. A 300nm layer of sputtered gold is deposited on the overlap region between the cantilever beam and the signal line as the contact metal. A 3μm-thick electron beam Al alloy layer is deposited and wet etched to define the posts for the membranes. A 3μm-thick sacrificial layer of photoresist is spin-coated and patterned to create the air-gap. A 1μm sputtered Al alloy layer is deposited and wet etched to define the membranes. Holes of 6μm in diameter are formed in the membrane to facilitate the release of the membrane and to reduce damping to improve the dynamic performance. The sacrificial material is removed by oxygen plasma etching to release the membrane.

4 Results and discussion

The fabricated switch is shown in Fig. 4. The cantilever is 200μm long and 120μm wide, and the bottom electrode is 100μm ×140μm. The contact resistance is 1～1.5Ω. The contact area is around 20μm ×40μm on each side of the switch, and the gap in the t-line is 40μm. The measured actuation voltage is 12V, which is close to the simulated value of 11V. If kept in good condition, the designed switch can work for a long time. However, the switch reliability is limited by the oxidation of the aluminum bridge. If the switch is properly packaged, the oxidization of the aluminum bridge can be avoided and the reliability can be improved.

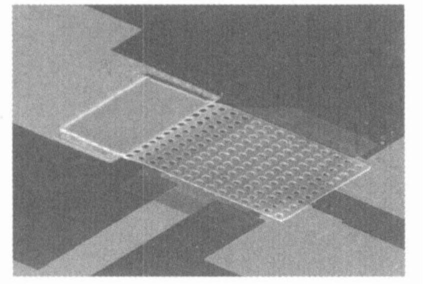

Fig. 4　SEM image of the fabricated switch

RF performance is measured using an HP network analyzer. External electrical control signals are applied on the fabricated switch for actuation, and S-parameters of the input and output ports are extracted using a network analyzer as shown in Fig. 5. At the same time, the full wave electromagnetic simulation of the switch is carried out by a finite element method using an Ansoft high frequency structure simulator (HFSS). In the simulation, a size of 800μm ×800μm ×1000μm is used and boundary radiation conditions are imposed on the six sides of the box. Then the full wave analysis is performed. S-parameters extracted in the frequency range from 0.05 to 10GHz are also shown in Fig. 5. The insertion loss measured during the ‘ON’ state denotes the parasitic signal loss from coupling to the ground and increases as frequency goes up. The insertion loss of the switch is characterized by measuring S_{21} parameters through the input and output terminals in the ‘ON’ state with the cantilever actuated downward. The measured and simulated insertion losses are less -0.9 and -0.2dB from 0.05 to 10GHz, respectively. The measured insertion loss is relatively large compared to the simulated loss. This is because a contact resistance introduced during the measurement, and a good physical contact has not been made between the bottom metal lines and the cantilever due to some residues stress after removing the photoresist sacrificial layer. To reduce the insertion loss, the introduced resistance should be alleviated.

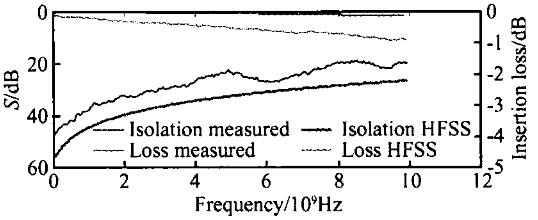

Fig. 5　Measured and HFSS simulated RF characteristics of the fabricated switch

The isolation represents the performance of the ‘OFF’ state and was measured with the S_{21} parameters along the signal lines with no electrical control signal. The measured isolation is higher than -20dB from 0.05 to 10GHz. The simulated and measured isolations have the same behavior, but the measured value is appreciably smaller than the simulated one. The reason for this is that the cantilever is not perfectly flat after the removal of the photoresist sacrificial layer.

5 Conclusion

Measurements and numerical analysis demonstrate that the direct contact cantilever switch has good mechanical and RF performance. The measured values, such as the actuation voltage and isolation, are close to the simulated values. The measured insertion loss is relatively large compared to the simulated value. The insertion loss is mainly caused by the contact resistance introduced during the measurement. In future work, more attention should be paid to this resistance. This switch offers a potential application in telecommunications and phase antenna array systems.

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接触式悬臂梁RF-MEMS开关的研制与数值模拟分析

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摘要: 研究了一种直接接触悬臂梁式RF-MEMS开关,悬臂梁采用Al金属材料. 开关通过静电控制,且与信号通道分离. 为了优化材料结构和获得好的性能,进行了有限元ANSYS模拟. 采用表面微加工工艺来制作开关,获得满意结果. 器件的驱动电压为12V,与ANSYS模拟结果11V基本相符;器件的隔离度,在0.05～10GHz的范围内,实验测试与HFSS模拟的结果基本一致,都优于-20dB;器件的插入损耗,HFSS模拟小于-0.2dB,而实验测试小于-0.9dB,偏高是由于悬臂梁表面不平,导致接触电阻增大,在测试中引入接触阻抗所致.

关键词: 悬臂梁RF-MEMS开关; 插入损耗; 隔离度
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