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Poly-Silicon Micromachined Switch

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Abstract: By using LPCVD SiO_2 and poly-silicon as sacrificial layer and cantilever respectively, a poly-silicon micromachined RF MEMS (radio frequency microelectronic mechanical system) switch is fabricated. During the fabrication process, the stress of poly-silicon is released to prevent poly-silicon membrane from bending, and the issue of compatibility between RF switch and IC process technology is also resolved. The low residual tensile stress poly-silicon cantilever is obtained by the optimization. The switch is tested, and the preliminary test results show: the pull down voltage is 89V, and the switch speed is about 5μs. The switch provides the potential to build a new fully monolithic integrated RF MEMS for radar and communications applications.

Key words: poly-silicon micromachined switch; cantilever; sacrificial layer; restoring force
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1 Introduction

Compared with p-i-n switch, RF MEMS (radio frequency microelectronic mechanical system) switch has low insertion loss and high isolation for eliminating the use of semiconductor p-n and metal-semiconductor junctions that significantly reduced the resistive losses of device, so it will be the fundamental bases on which radar and communication systems are developed, and will replace the p-i-n switch[1,2]. The research on micromechanical switch dated back to 1979, the micromechanical switches were first demonstrated as electrostatic actuated cantilever switches used to switch low-frequency electrical signal[3]. And now the RF MEMS switch for radar and communications applications is being developed, the different materials (such as copper, gold, etc) are used for decreasing the on-state resistance of micromachined switch. For example, Zhu *et al.*[4] made a RF MEMS switch on the high resistance silicon substrate (3000Ω·cm) by using Ti-Au material in 2000. Since the silicon-IC is usually made on the low resistance silicon substrate and gold material is not used as metal interconnection for reliability, it is not easy for the process of these RF MEMS switches to be compatible with that of IC to achieve monolithic integrated RF MEMS and IC. RF MEMS switch is limited to the miniaturized communication application. This paper is focused on developing the poly-silicon switch and solving the key process of releasing the stress of poly-silicon membrane, etching the sacrificial layer, and compatibility with IC process. It provides the potential to build a new fully monolithic integrated

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RF MEMS for radar and communications applications.

2 Principle of operation

The poly-silicon switch utilizes the mechanical connection of two n^+ poly-silicon surfaces to actuate a low resistance connection and has low force of stiction and microwelding compared with the metal switch[5~8], however, the on-state resistance is higher than that of the metal switch for its high contact resistance. As a result, this switch may be of no use for high insertion loss. The poly-silicon switch described in this paper is designed to significantly reduce the on-state resistance of poly-silicon micromachined switch by replacing the poly-silicon with polysilcion ohmic contact by a capacitive connection.

Through electrostatic actuation, the poly-silicon micromachined switch realizes a switch function. Figure 1 shows the cross-sectional schematics of a typical single-pole, single-throw poly-silicon micromechanical switch. As shown in Fig. 1, the switch utilizes an air-bridge design, in which a bridge of conducting poly-silicon membrane is suspended 2μm over the output electrode. When an electrostatic potential is applied to the bottom poly-silicon, the attractive electrostatic force pulls the top poly-silicon beam down onto the bottom poly-silicon contact terminal, the dielectric film serves to prevent stiction between the two poly-silicon surfaces, yet provides a low impedance path of the signal between the two contacts. When the electrostatic potential is removed, the restoring force on the top poly-silicon membrane pulls it back to its original position. The electrostatic force applying to the top poly-silicon membrane is given by[5]

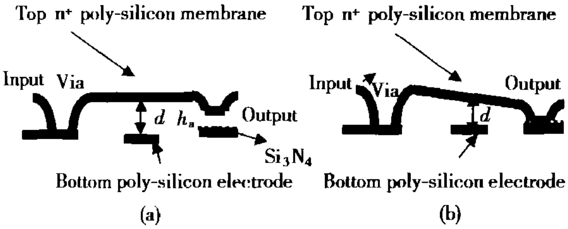

Fig. 1 Cross-sectional schematics of the poly-silicon switch (a) Switch up; (b) Switch down

$$f(x) = \frac{V^2}{2(d - v(x))^2} \qquad (1)$$

where $v(x)$ is the deflection at a position x along the beam, d is the distance between the top poly-silicon membrane and the bottom poly-silicon electrode. V is the potential applying on the bottom poly-silicon electrode.

When the poly-silicon membrane is not actuated, the air dielectric between the two contacts exhibits a very low capacitance, given by

$$C_{\mathrm{off}} = \frac{1}{\dfrac{h_D}{\varepsilon_D A} + \dfrac{h_a}{\varepsilon_0 A}} \qquad (2)$$

where C_{off} is the capacitance of the switch in the off state, ε_D and ε_0 are the dielectric constants of air and dielectric material used, h_D is the dielectric layer thickness, h_a is the air gap between the membrane and dielectric layer when the switch is at the up-position, and A is the contact area between the output electrode and the cantilever. When the switch is actuated, the polysilicon-dielectric-polysilicon sandwich possesses significant capacitance (C_{on}), described as follow:

$$C_{\mathrm{on}} = \frac{\varepsilon_D A}{h_D} \qquad (3)$$

Typical capacitance values in this position are 2～5pF. The ratio of available on-impedance to off-impedance of the switch is given by the ratio of the on-capacitance to off-capacitance. With proper design of switch geometry and material selection, this ratio can exceed 100, more than sufficient for switching signals at microwave frequencies.

The primary goals for the design of the poly-silicon micromachined RF switch are the low bottom potential voltage, the low insertion loss, and the high switch speed. The bottom potential may be reduced by increasing the area of the bottom electrode for increasing the electrostatic force acting on the top poly-silicon beam, and by reducing the distance between the beam and the bottom electrode. Reduction of on-resistance is made by increasing the width and thickness of the beam and by increasing doping of poly-silicon membrane for decreasing poly-silicon membrane resistance. The holes are achieved on the top poly-silicon membrane to increase switching speed. Reducing the insertion loss is made by increasing the contact area of the top poly-silicon membrane, and by replacing silicon substrate with dielectric poly-silicon substrate for eliminated the parasitical capacitance of silicon substrate. A thin Si_3N_4 is deposited on the bottom poly-silicon output contact terminal for reducing hysteresis. The geometry of the electrode and poly-silicon membrane is chosen to minimize the through-path resistance and achieve an on-capacitance that can be impedance matched to frequencies as high as 30GHz. The characteristics of the dielectric layer as well as the electrode, poly-silicon membrane, and gap geometry are set to achieve an on/off capacitance ratio of 100. Switch pull down voltages, dielectric breakdown, and switching speed also contribute to design tradeoffs that must be compromised with RF performance. The switch circuitry consists of coplanar waveguide (CPW) transmission lines which have an impedance of 50Ω that matches the impedance of the system. Following is the design of the poly-silicon MEMS switch: the cantilever is 250μm long and 80μm wide, the bottom poly-silicon electrode with width of 80μm is in the middle of the input and output electrodes.

3 Experiment of releasing stress of poly-silicon beams

The mechanical microstructures such as beams, bridges, suspended structures, motors, etc. are the basis of sensing/actuating elements for MEMS. These elements can easily be fabricated using poly-silicon as a structure material and silicon dioxide as the sacrificial/spacer layer. Low pressure chemical vapour deposition (LPCVD) of poly-silicon is a standard technique for micro-eletronic processes. It has also found wide acceptability and is being extensively used for surface micromachining applications, but residual stress and stress gradient are inherent in as-deposited poly-silicon films. As a result, the performance and control of the dimensions of these elements depend strongly on the residual stress and stress gradient in the structural layer, so the deposition and subsequent annealing parameters need to be tailored to obtain films with minimum residual stress and stress gradient, and the compatibility of the process with standard IC technology[7~10] should be kept in mind. Releasing the stress of poly-silicon beams is key process for making the poly-silicon switch. If the residual stress of the poly-silicon beams is a high compressive stress, the poly-silicon cantilever will fall down due to the low restoring force. If the residual stress is a high tensile stress, the poly-silicon switch will lose the switch function due to the poly-silicon cantilever wrapped. This paper presents a simple experiment for obtaining low tensile stress poly-silicon beams. The residual stress of poly-silicon film is dominated by the deposition, phosphorus concentration and annealing conditions. Releasing residual stress of poly-silicon has been done by varying the process conditions. The experimental method is as follows, a 2μm thick poly-silicon film is deposited on the silicon substrate with a 2μm thick PECVD SiO_2 as sacrificial layer, then the poly-silicon film is doped by phosphorus implantation, followed by phosphorus annealing, a 200μm long and 80μm wide strip is defined by RIE, and then the sacrificial layer is etched by 5∶1 diluted hydrofluoric acid, only part of the sacrificial layer under the poly-silicon strip is etched by pattern, subsequently a 100μm long poly-silicon strip is suspended, the poly-silicon suspended beam is formed, whose residual stress varied with conditions under which the poly-silicon beam is formed. The results are showed in Table 1.

From Table 1, we derived that the residual stress can be released by the optimal process. For high switch speed, the low residual tensile stress existed, so No. 5 is the optimal condition. The poly-silicon switch has been developed based on the optimal condition.

Table 1 Change of poly-silicon beam vs conditions under the poly-silicon beam being formed

Number	Deposition temperature/℃	Phosphorus doped concentration at 100keV/10^{14}cm^{-2}	Annealing time at 1050℃/s	Phenomena
1	575	1	10	Wrapped, and some fell away
2	575	10	10	Wrapped
3	575	10	20	Wrapped
4	590	40	20	No
5	590	100	40	Weakly wrapped
6	610	10	20	No
7	610	50	20	No
8	610	10	40	Fell down
9	610	100	20	Fell down
10	610	100	40	Fell down

4 Fabrication

Wafers with resistivity of 7～10Ω·cm are used as substrates. The thickness of 1μm insulating thermal oxide is first grown on the substrate, pattern used as MEMS switch substrate is defined, and the silicon is etched with KOH, the depth is 50～60μm, followed by 500μm dielectric poly-silicon is deposited. The silicon area for making IC and the dielectric poly-silicon area for making MEMS switch substrates are obtained by grinding/polishing process, so the substrate for fabricating the MEMS switch is prepared. The following is the process to make MEMS switch: insulating thermal oxide for 1μm is grown on the substrate, followed by 0.1μm thick Si_3N_4 is done. A 1μm thick layer of LPCVD poly-silicon is then deposited, followed by phosphorus diffusion is done. The poly-silicon film's deposition and phosphorus diffusion temperature are controlled to eliminate the local microwelding and reduce hysteresis caused by roughness poly-silicon film. The temperature conditions of the poly-silicon film's deposition and phosphorus diffusion are 610℃ and 950℃, respectively. The square resistance of the doped poly-silicon layer is 3～5Ω/□, which is necessary to reduce the poly-silicon film resistance. And pattern is defined for the bottom poly-silicon electrode and the input and output terminals. A 0.1μm thick Si_3N_4 is done before the first sacrificial layer, 1μm thick LPCVD SiO_2, is deposited, it prevents the bottom poly-silicon and SiO_2 to be etched. The hole on bottom contact poly-silicon terminal is made to form the contact tips for the beam to increase the switching speed and reduce hysteresis, followed by the second sacrificial layer for 2μm thick, the LPCVD PSG layer, is done. At the input terminal, the contact window is etched, and then the top poly-silicon layer is deposited, which is doped by phosphorus implantation in 1×10^{16}cm^{-2}, 100keV, followed by the top PSG layer 0.4μm thick is done. Anneal at 1050℃ in N_2 for 40s is done. In this step, the residual strain is released to prevent top poly-silicon beam from bending, and phosphorus is activated. The top PSG layer is then stripped, and the structural poly-silicon is then patterned by etching. The metal interconnection is done by sputtering and patterning. In the last step, the sacrificial layer is partially etched by a suitable wet etching process (5∶1 diluted hydrofluoric acid, the etching temperature is 40℃), and the poly-silicon micromachined RF switch is achieved, as showed in Fig. 2. This process is fully compatible with IC process, and the compatibility between RF switch and IC process technology has been achieved yet.

5 Preliminary results and discussions

On the basis of above fabrication process, the poly-silicon switch with 250μm long, 80μm wide suspended beam has been fabricated, as showed in Fig. 3. The switch is measured by TE2819 capacitance instrument, the off-state capacitance and on-state capacitance are 0.13pF and 2.5pF, respectively. And the pull down voltage is 89V, as showed in Fig. 4. The ratio of the off-state capacitance to on-state capacitance is about 20, less than the design ratio, since it may be affected by the encapsulation and measuring conditions.

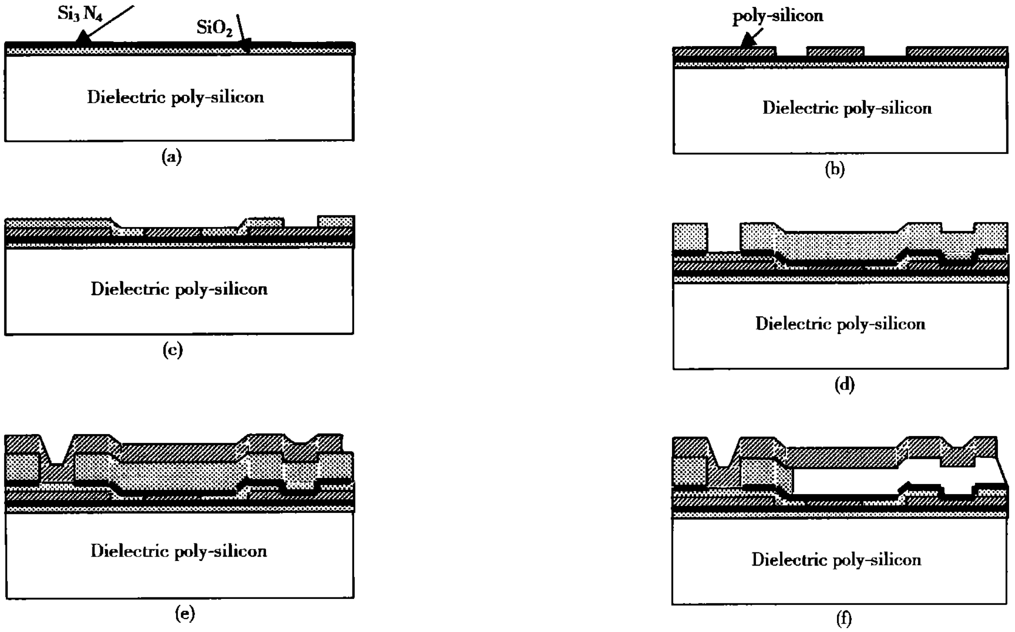

Fig.2 Process steps for fabricating poly-silicon micromachined switch (a) Silicon dioxide growth (1μm); (b) Poly-silicon deposition (0.5μm), phosphorus diffusion, and patterning; (c) SiO_2 deposition and contact tips patterns; (d) SiO_2 deposition and contact hole patterns; (e) Deposition poly-silicon, phosphorus implantation and annealing; (f) Etching sacrificial layer, forming switch

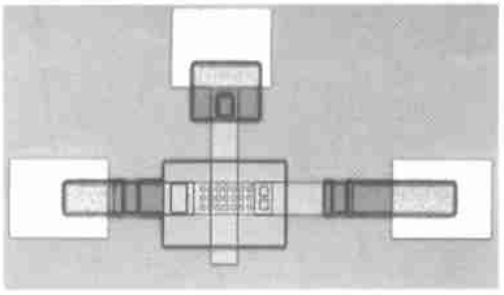

Fig.3 Micrograph of poly-silicon micromachined switch

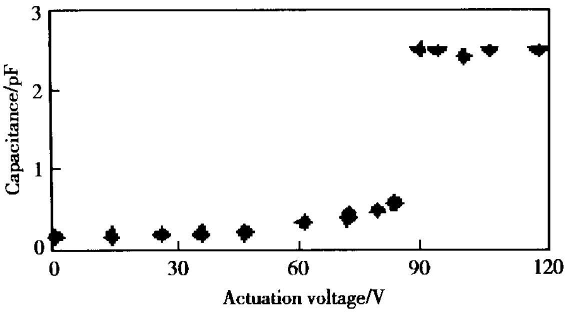

Fig.4 Curve of capacitance and actuation voltage of the poly-silicon micromachined switch

The measured switch speed is shown in Fig.5. The top trace of the oscilloscope shows the corresponding drive signal with 40kHz, 90V. The modulated 200MHz signal is shown at the bottom trace. The modulated signal shows a time delay of 5μs from the switching-off to the switching-on state. This time delay is defined as the switching speed of

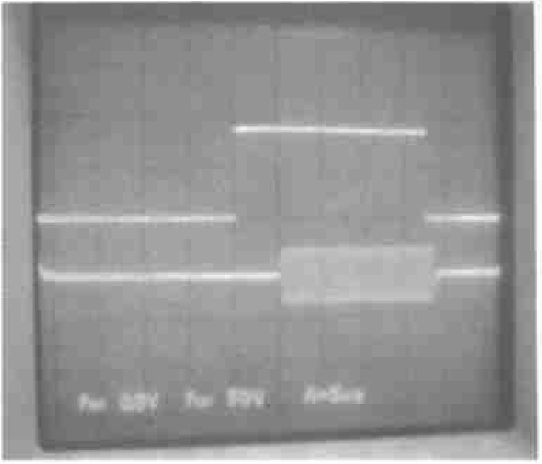

Fig.5 A switching speed measurement of a poly-silicon MEMS switch The control signal is shown at the top trace and the modulated signal is shown at the bottom trace.

a switch, so the switching speed is about 5μs. The insertion loss is not obtained for the lack of test condition. However, the insertion loss represents the ohmic resistance loss of the poly-silicon switch and substrate capacitance loss, so eliminating substrate capacitance and decreasing the resistance of poly-silicon are necessary for low insertion loss. And this method for making the poly-silicon switch is correct. This fabrication process is compatible with IC process. It will be a base for developing RF switch systems with IC.

6 Conclusion

The poly-silicon cantilever with low tensile stress is obtained by optimizing the poly-silicon deposition, and the poly-silicon MEMS switch is fabricated. The following is the result: the off-state capacitance and on-state capacitance are 0.1pF and 2.5pF, respectively, and the pull down voltage and switching speed are 89V and 5μs, respectively. This fabrication process is compatible with IC process. It will be a base for developing RF switch systems with IC.

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多晶硅微机械开关

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摘要：利用LPCVD SiO_2 和多晶硅作牺牲层和悬臂梁技术，解决了多晶硅应力释放问题以及微机械开关工艺与IC工艺兼容技术问题，获得了淀积弱张应力的多晶硅膜的最佳工艺条件，研制出多晶硅微机械开关. 初步测试出其开关的开启电压为89V，开关速度为5 μs，这为研制用于雷达和通讯的全单片集成的RF MEMS开关系统打下了基础.

关键词：多晶硅微机械开关；悬臂梁；牺牲层；恢复力
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