

行政院國家科學委員會專題研究計畫 成果報告

子計畫三：智慧型微感測元件之研究

計畫類別：整合型計畫

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行政院國家科學委員會專題研究計畫年度報告

題目：應用於無線感測網路之超低耗能無線感測模組的設計與製作-
子計畫三：智慧型微感測原件之研究

“The Study of Smart Micro-Sensor Devices”

計畫編號：NSC94-2215-E-009-055

執行期限：94 年 8 月 1 日至 95 年 7 月 31 日

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一、 中文摘要

本計畫提出一個以 0.35 μ m 2P4M 標準 CMOS 製程製作之微震盪器，其使用靜電的方式進行驅動，並利用壓阻作為感測元件，可應用於感測多種物理參數。結構中利用了 CMOS 製程常見的殘餘應力的結構翹曲效應，使得結構可以往出平面的方向產生翹曲，進而增加微震盪器的震盪空間，並提升壓阻感測元件於共振狀態的輸出準位。經由量測得到此微震盪器的共振頻率為 14.5 kHz，品質因數為 36。

關鍵詞：震盪器、靜電、梳狀致動器、壓阻、CMOS 製程。

Abstract

In this project, a prestress vertical comb drive resonator with piezoresisted sensor is developed. The proposed resonator consists of a set of comb fingers fabricated along the composite beam. One end of the composite beam is clamped to the anchor, whereas the other end is elevated vertically by the residual stress. The actuation occurs when the electrostatic force, induced by the fringe effect, pulls the composite beam downward to the substrate. The piezoresistor is designed to sense the vertical vibration frequency of the resonator. The device is fabricated through a standard 0.35 μ m 2P4M

CMOS-MEMS process. The measurement results indicated that the resonant frequency of the device is 14.5 kHz, and the quality factor is about 36.

Keywords : resonator; electrostatic; comb-drive; piezoresistor; CMOS-MEMS process.

二、 計畫緣由與目的

Micromachined resonators have been widely investigated, and currently they are employed in various applications such as temperature, humidity, gas detection, and biological technology, etc [1-3]. In most resonators a change of the resonance frequency is detected, but also vibration amplitude, phase and quality factor are used as output signals. Frequency is the most often used form of resonator signal output since its quasi-digital form allows an unproblematic signal transfer and precise readout [4].

Several kind excitation methods of resonator had been proposed such as thermal, piezoelectric and electrostatic [4]. The thermal excitation is based on the difference in thermal expansion of different materials in a composite cantilever beam. This excitation principle is easy to implement, but needs higher power consumption. Piezoelectricity is the most often utilized principle for excitation of a resonator.

However, piezoelectric material could result in hysteresis and not compatible with CMOS process. Electrostatic excitation is also widely used in micromachined devices. The main benefit of the electrostatic excitation is its characteristic small power consumption. However, a vertical resonator with parallel plate electrostatic actuator exhibit a nonlinear phenomenon, called pull-in, which seriously constrains the stable region at one-third the length of the gap [5].

For this consideration, a vertical resonator with comb structure is proposed. The vertical comb drive is used for obtaining a large displacement. The design concept, simulation, fabrication process, and experimental results are given in the following sections.

三、 研究方法及成果

3.1 Design concept

Fig. 1 schematically depicts a resonator with different driven states [6]. The resonator consists of an anchor, a composite beam and a set of comb fingers. These comb fingers, design along the composite beam, acted as the movable and fixed comb fingers. Fig. 1(a) shows one end of the composite beam, which is clamped to the anchor, and the other end is elevated due to the residual stress between the two deposited materials. When a voltage, V , is applied between the movable and fixed comb, the movable composite beam can be pulled downward to the substrate by the electrostatic force induced by the fringe effect, as shown in Fig. 1(b). The taper-like distances between each movable and fixed comb are obtained from the free end to the fixed end based on the curved-up shape of the composite beam. In the actuating mechanisms, the movable comb fingers that are closed to the anchor provide the main actuation force. As the actuation progresses, the retral movable comb fingers will be pulled down accordingly. As the driving voltage is increased, the vertical displacement of the free end of the resonator is increased. Compare to the parallel plate electrostatic actuator, the vertical comb drive exhibits no pull-in and hysteresis phenomenon.

Notably, the electrostatic force is constrained when the movable comb finger is closed to the fixed comb finger, independently of the input driving voltage, as shown in Fig. 1(c).

3.2 Simulation

To fully understand the resonant characteristics of the resonator, a FEM simulator, IntelliSuite, is used to calculate the resonant frequencies and the corresponding mode shapes. The resonator consist of a $500 \times 44 \mu\text{m}^2$ composite beam that is fixed to an anchor structure with 34 movable comb fingers orthogonally mounted on the composite beam, and 35 fixed comb fingers are mounted on the silicon substrate. The dimension of the comb finger is $68 \times 3.6 \mu\text{m}^2$, and the overlap length is $60 \mu\text{m}$. Note that in the present FEM simulations, we solely require movable comb and composite beam to calculate the resonant frequencies. Table I shows the mode shape simulation results of the proposed resonator. In the 1st mode, there is an anti-node in the free end and a node in fixed end. Thus, the entire cross section elements are actuated in the same direction. In the 2nd yaw and roll mode, attention must be paid to avoid shorting due to the contact between movables and fixed comb. In the 3rd mode, the resonator is vibrating in yaw motion. These simulation results can be used as the reference data in determining the resonant modes during the actual experimental measurements.

3.3 Fabrication

The resonator device was fabricated through standard $0.35 \mu\text{m}$ 2P4M (double polysilicon quadruple metal) CMOS process and post-CMOS process [7]. Fig. 2(a) illustrates the cross-section of the chip with the MEMS components and the circuits, fabricated by the standard 2P4M CMOS process. The microstructures of the MEMS components consist of polysilicon, metal and dielectrics. The contact and via holes are filled with tungsten plugs. The four metal layers are made of aluminum. The multilevel interconnect process involves chemical and mechanical polishing to

yield plane surfaces. The dielectric layers/sacrificial layers are silicon dioxide and the passivation layer includes silicon nitride and silicon dioxide. The etched holes are filled with silicon dioxide. The FOX (field oxide) layer is silicon dioxide. A thick PR layer is coated onto the chip and patterned by an additional photo mask to generate a PR mask on the chip, as shown in Fig. 2(b). The name of the additional photo mask is defined as RLS (release). The PR mask is applied to protect the bonding pads, the unneeded etched regions of the MEMS components and the electronic circuits during RIE dry etching. Fig. 2(b) depicts how the RLS is used to define micromachining regions. The maximum line width of the RLS depends on the design of the microstructures. The ratio of the line width of the suspended structures to that of the RLS does not exceed 2.5. Finally, CF₄/O₂ RIE is used to etch the silicon dioxide in the etching holes respectively, and then SF₆/O₂ RIE is applied to etch the silicon substrate and thus release the suspended structures of the MEMS components. The PR mask on the chip is removed to complete the post-CMOS process, as shown in Fig. 2(c).

Fig. 3 illustrates the cross-section of the comb fingers. The comb finger consists of Poly2, CO, M1, via1, M2, via2, M3, via3 and M4. The composite beam consists of M3, M4 and all dielectric layers. After the post-CMOS process, the composite beam is bended due to the residual stress. The piezoresistor made of polysilicon is at the fixed end of the composite beam and the resistance value is 51 k Ω . Fig. 4 shows the fabricated resonator device through CMOS process.

3.4 Static characteristic measurement

In order to exam the static characteristics of the resonator device, WYKO interferometer is used for preliminary measurement. The initial tip height at the free end due to residual stress is about 60 μ m. The 3D image of the initial state is shown in Fig. 5(a). When a dc voltage is applied, the resonator is pulled down by the electrostatic force, as shown in Fig. 5(b). The tip height at the free end of resonator versus the applied dc bias

driving voltage between movable and fixed combs is shown in Fig. 6. The resistance value of piezoresistor is changed with the deflection of the resonator. The variation of piezoresistor is also shown in Fig. 6. The result indicates that the piezoresistor possesses linear characteristic between 40~80 volt.

3.5 Frequency response measurement

Fig. 7 shows the frequency response of the resonator that is measured by using MEMS Motion Analyzer (MMA) and pizeoresistor. The piezoresistor output is connected to a Wheastone bridge and instrumentation amplifier with gain of 25, and therefore the variation of piezoresistor could be transformed to voltage output. Note that the resonator is biased by a sinusoidal wave with voltages peak to peak, 0 ~ 60 V, and the frequency is ranged between 5 kHz and 20 kHz. The first resonant frequency mode is measured at 14.5 kHz, and it is closely matched with the simulation result. The error is due to fabrication process such as thickness of each layer and undercut of silicon. Thus, the actual mass of resonator may be different with simulation. The quality factor is calculated at 36. Notably, a “half mode” peak before first mode peak resonance in 7.25 kHz is also observed in this measurement. It is also observed in different experiments without an exclusive discussion [8]. Jin et al. has pointed out that the half mode characteristic is due to the double frequency and nonlinear effect in electrostatic resonator [9].

四、 結論與討論

A vertical comb drive resonator with piezoresistor sensing component is proposed in this project. The static characteristic and frequency response of the resonator is measured. The proposed resonator device is implemented using standard 0.35 μ m 2P4M CMOS process and post-CMOS process. The design, simulation and measurement are also presented. Preliminary measurement indicates the initial lift height by residual stress is about 60 μ m and the first resonant frequency is 14.5 kHz.

In the future, the resonator will be used for

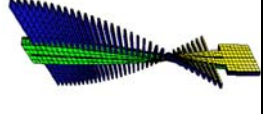
humidity and gas sensing. The ALD (Atomic Layer Deposition) system will be utilized to coat special material on the surface of resonator as reaction layer. For example, Al₂O₃ film possesses a hydrophile characteristic which can be used for humidity detection, and ZnO film can be used for carbon monoxide detection due to its chemical reaction. Therefore, the resonator could be used to measure different physical parameters depend on different applications.

Besides the proposed resonator, an infrared temperature sensor is also designed in this project. Infrared temperature sensors using non-contact radiation detect the temperature variance. According to Black theory, temperature variance occurs in any body which in higher than absolute zero degree. Infrared temperature sensor fabricated by CMOS MEMS process and the sensor called thermopile. It can detect the differential temperature between the human body skin and room temperature.

五、 參考文獻

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TABLE I. The mode shape of the resonator.

Mode	Frequency(Hz)	Motion	Solid Mode shape
1 st	16790.7	Pitch	
2 nd	103433	Yaw & Roll	
3 rd	105726	Roll	

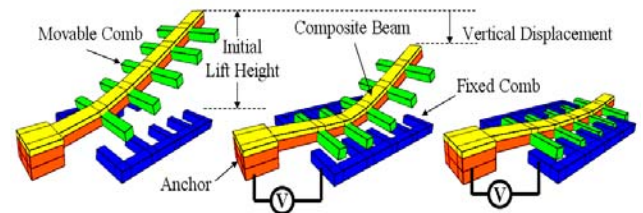


Figure 1. The resonator at different driving states. (a) Initial state. (b) Bias voltage state. (c) Critical bias voltage state.

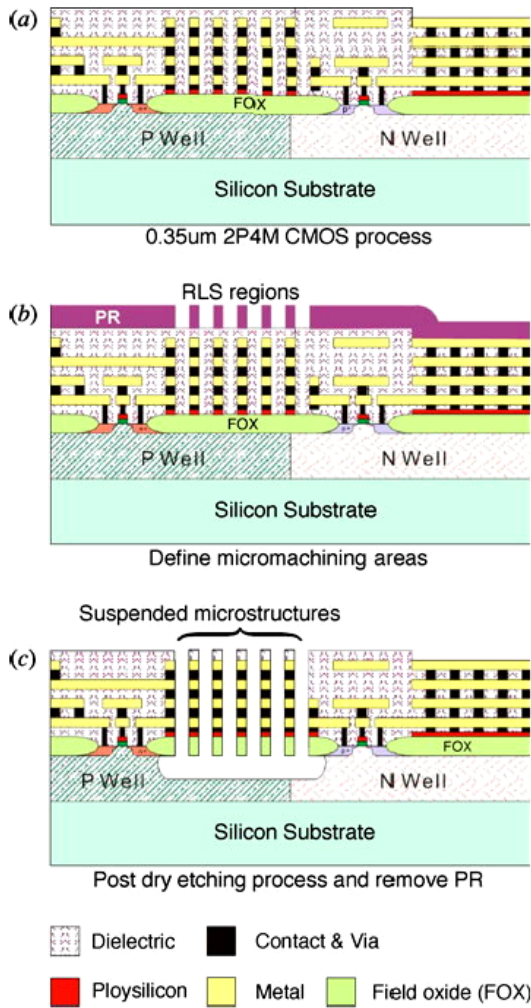


Figure 2. Process flow [7]. (a) Completion of CMOS process. (b) Patterning a PR mask to protect unneeded etched regions. (c) Etching sacrificial layers and substrate to release suspended microstructure and remove the PR.

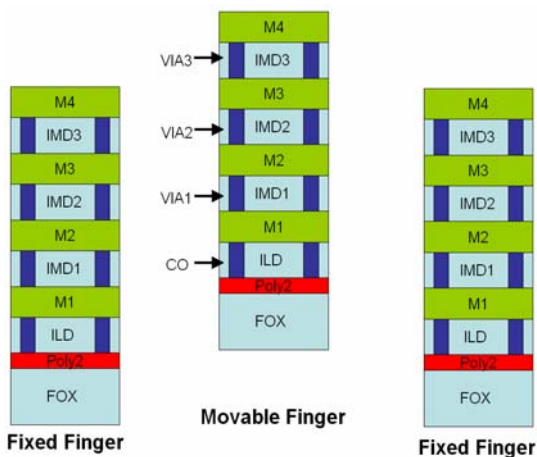


Figure 3. Cross-section of the movable and fixed comb.

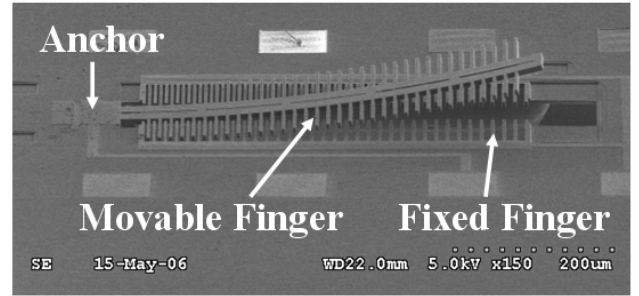
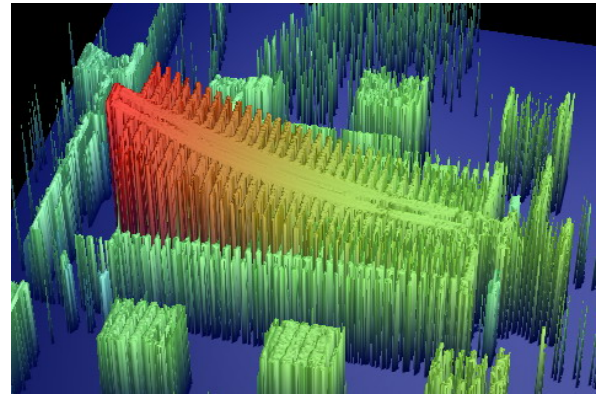
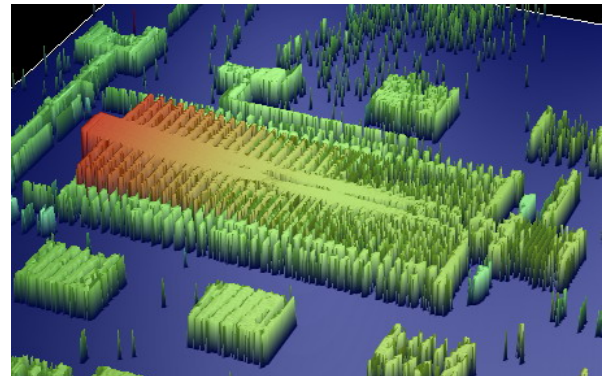


Figure 4. Fabricated resonator device.



(a)



(b)

Figure 5. 3D image of (a)the initial state (b)when a dc voltage(160V) is applied.

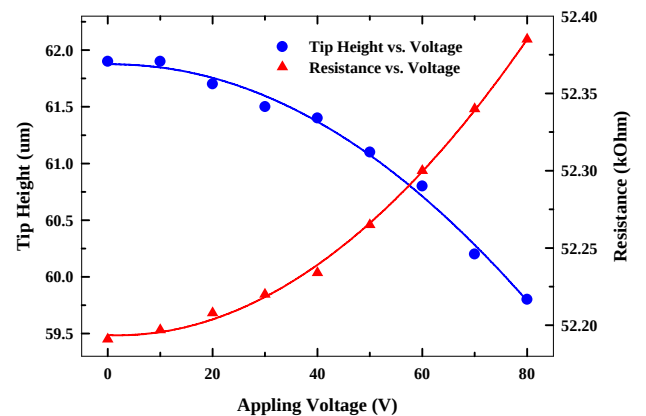


Figure 6. The static characteristic of the resonator.

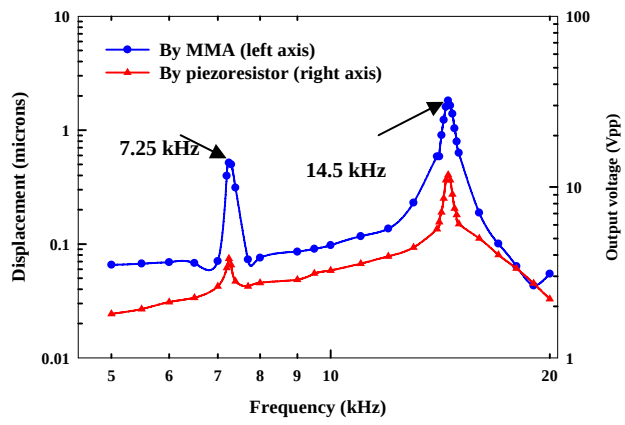


Figure 7. The frequency response of the resonator.