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Study on High Precision MEMS Inertial Sensor with Increased Detection Capacitance Driven by Electromagnetism

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Since the reactive ion etching technique of depth particle is complex, the sensor with large mass and large initial capacitance can hardly be achieved. This paper improves this defect by greatly increasing the capacitance of the sensor during the static test driven by electromagnetism. The results show that the mechanical noise reaches 0161Lg per square root of Hertz, and its simulated resonance frequency is 598Hz, indicating that the design of this paper has good performance on production technology and parameters setting, and the test driven by electromagnetism is feasible.

1. Introduction

High-performance capacitive MEMS inertial sensor is mainly used in inertial navigation, earthquake prediction and some other fields. The basic principle of the sensor is: by causing displacement of its vibrator through external inertial signal, the detection capacitance can be changed and the size of the external inertial signal can be inferred by the change at this time. On this premise, the performance of various parts of the sensor needs to be guaranteed, and in order to improve the performance of the sensor, theoretically the noise of the system such as thermal mechanical and electronic noise should be reduced, and appropriate MEMS processing technologies such as bulk silicon micromachining technology and surface micromachining technology should be adopted at the same time.
Based on different theories, this paper studies the common deficiencies of MEMS sensor, i.e. sensor noise and the limitations of the traditional process (including the limitations of deep reactive ion etching, hereinafter referred to as Deep RIE), and then correspondently designs the improved the MEMS sensor. In order to verify the validity and reliability of the design, this paper first analyses every parameter of the designed sensor, then demonstrates actual operation of the designed sensor through simulation analysis. In this way the parameters of designed sensor can be tested to show whether they meet the improving requirements. The results show that the sensor designed in this paper has good performance on production technology and parameters setting, which satisfies the improving requirements.

2. Review

The research of MEMS sensor first appeared in twentieth Century, and the silicon strain device came out in 1954. In the past 1960-1970 years, people began to study silicon micro sensors. In 1962, the silicon micro pressure sensor appeared. The scholar Chaudhary and Savari proposed two kinds of sensors, acceleration and piezoresistive silicon pressure, and the manufacturing process was more advanced. The silicon glass bonding technology appeared (Chaudhary and Savari, 2017). The capacitance sensor appeared in 70s of this first Century. In 1977, a capacitive pressure sensor developed by Stanford University was developed, and then a capacitive accelerometer was developed. 80s is the period of rapid development of MEMS. All over the world have joined the field of MEMS research, its manufacturing technology is more perfect, processing technology is more advanced, and the application field is more extensive. The concrete manifestation is that Evanschitzky and Erdmann realized the integration of silicon and IC in 1985, and made the polysilicon resonant beam, laying the foundation for the combination of silicon micro sensor and IC integrated circuit (Evanschitzky and Erdmann, 2017). Silicon glass bonding technology and etching technology are more perfect.

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LIGA micro processing technology has emerged, and the capacitance plate structure with high aspect ratio can be manufactured. The technology of bonding silicon with silicon has been developed. For these micro sensors, micro actuators and other micro devices, MEMS as the name of this research field was officially put forward in 1989.

In the late 90s, NEMS appeared, with its characteristic size ranging from several nanometers to several hundred nanometers. People pay more and more attention to MEMS. The state has invested a lot of funds in this direction, which makes MEMS more in-depth research on basic theory, structure design, function simulation, performance simulation, processing technology. They finished product testing and so on. The application of MEMS products in various fields is also more extensive. It also encourages developers to invest a lot of money in building R & D departments, production lines and sales. The research of micro inertial sensors is becoming more and more mature. Because the size of MEMS device is small and the accuracy is high, the manufacturing cost is high. To solve this problem and reduce the cost, the American MCNC uses UCB processing technology to produce three layers of silicon, which promotes the expansion of the MEMS research field and promotes MEMS into the university research area. Jia and others put forward soft photolithography and used this technology to produce microdevices for polymeric polymeric materials (Jia et al., 2016). Jindal and so on greatly reduced the cost and production cycle of the devices and promoted the development of microfluidics. (Jindal et al., 2017).

From the history of the development of MEMS, the micro sensor based on MEMS has been studied in the early stage of the development of MEMS technology. With the improvement of micromachining technology and the development of MEMS technology, the scholar Liu and Muro think that the micro sensor has become an important direction in the research field of MEMS, and the miniaturization, intelligence, high precision and high sensitivity have already been made (Liu and Muro, 2017). Scholars Liu and Dickensheets consider that the size of the micro sensor is unmatched by the ordinary sensor. Because its size is usually in the micron level or even the nanoscale, it has the sensitive mechanism that the sensor does not have in the traditional macro size, and thus the characteristics of its high performance are realized (Liu and Dickensheets, 2017). These advantages make the micro sensor not only become the main object of sensor research, but also the important development direction of MEMS research and production.

Scholars Nemoto and Yamaguchi believe that silicon micro sensors occupy the dominant position in micro sensors. The reason is that silicon materials have excellent physical properties and can make use of silicon materials to realize the high-performance requirements of micro sensors. And the use of silicon materials can make various kinds of sensors, such as piezoresistive, capacitive, resonant, piezoelectric, tunnel effect mechanism of the micro sensor (Nemoto and Yamaguchi, 2016).

The common micro sensors are: capacitance micro sensor, piezoresistive micro sensor, tunnel current micro sensor, piezoelectric micro sensor and resonant micro sensor. Among them, capacitive micro sensors use physical or chemical changes to cause capacitance changes to achieve detection of the target. A capacitive sensor consists of two parallel capacitor plates, which can change the size of the capacitor by changing the space or area of the capacitor plate and can change the capacitance by changing the dielectric constant. However, it is not the main research direction. Scholars Su and Yu think that capacitive sensors consist of two electrodes, which are composed of a fixed substrate and a sensitive mass, which form a pair of parallel capacitance plates (Su and Yu, 2017). When the test signal is on the micro sensor, the mass in the micro sensor begins to vibrate in the direction of the sensor, which leads to the change of the displacement, which then leads to the change of the induction spacing or the size of the effective induction area, and eventually causes the change of the capacitance.

Because of its own characteristics, MEMS sensor has been widely used in automotive electronics, biomedicine, consumer electronics, military, aerospace and other fields. At present, the advent of the Internet of things will further promote the development of MEMS sensors. One of the essential factors in the realization of Internet of things is embedding sensors, sensing and processing them through sensors. The realization of this process can be accomplished by MEMS sensor. From the previous introduction, the MEMS sensor is a multidisciplinary field, and the future development of MEMS will cover the fields of light, electricity, chemistry, physics and biology, and combine them together. The trend of development meets the needs of the realization of the Internet of things.

To sum up, the above research work shows that the development prospect and application field of MEMS will be broader. The future consumer and automotive electronics market will be the main driving force for the development of MEMS technology. From the view of the application of MEMS sensors in China, the application of consumer electronics is very large, and the domestic suppliers will pay more attention to the marketing and application of MEMS in this field. Therefore, based on the above research status, this paper designs a magnetic actuator based on the principle of the absorption effect of the capacitor pole, thereby reducing the spacing of the electrode and improving the depth and width ratio of the capacitor plate, and analysing the factors that affect the noise of the system to optimize the distance between the electrodes and the factors of air damping. The method of reducing the air damping after reducing the distance between the capacitor plates is studied. Finally, the edge effect of the device is analysed.

3. Research method

3.1 Analysis on sensor deficiency

Common deficiencies of MEMS sensor mainly include sensor noise and the limitations of Deep RIE. The following part analyzes the two deficiencies respectively:
1. Sensor noise. MEMS sensor noise can be divided into mechanical and electronic noise; mechanical noise is mainly caused by Brownian movement of air molecules around vibrator, which is one of the most important factors affecting the resolution of the micro sensor, and its effect on the performance of MEMS inertial sensors can be expressed as: $\partial m = \sqrt{\frac{4kbt\omega}{m \cdot Q}}$ where k, b and t are Boltzmann's constant, absolute temperature and the natural frequencies of the sensor respectively, m is vibrator mass, Q is the quality factor of the device. From this formula, either increasing the vibrator mass or decreasing the damping can reduce the mechanical noise and improve the resolution. Capacitive MEMS inertial sensor has high precision, but its detection circuit is very complex. One of the detection methods is to use high frequency carrier to act on the capacitor in detection, and then it is modulated by acceleration signal before amplifying the signal and demodulation. At this point, the electronic noise is mainly determined by the noise of the front amplifier, which can be expressed in the following formula: $\partial m = \sqrt{\frac{a\omega_n^2}{c+c_p V_s}}$, where a is the constant related to the sensor size, c is the detection capacitance of the sensor, cp is the parasitic capacitance, vs is the test signal voltage, ve is the input noise voltage. It can be seen from the above formula that by increasing the initial detection capacitance of the sensor, the electronic noise of the modulation and demodulation scheme can be reduced.

3.2 Limitations of deep RIE

Bulk silicon micromachinery can produce MEMS with large mass, and Deep RIE is one of the most important bulk silicon micromachining technologies. However, due to the loading effect and under-cutting effect of Deep RIE, the depth to width ratio of the processing device is usually less than 30B1, which limits the possibility of increasing the mass and detection capacitance of the vibrator by increasing its thickness so as to reduce mechanical and electronic noise. When the capacitor spacing between designed comb teeth is small, Deep RIE will cause non-parallel effect between capacitor plates, which affects the sensitivity, resolution and reliable working range of the capacitive sensor. In order to increase the detection capacitance, a kind of accelerometer with adjustable capacitance detecting spacing has been put forward based on SOI-Deep RIE technology, and its lithographic accuracy can reach 1 Lm. Another kind of MEMS accelerometer with grid capacitance and comb tooth detection capacitance based on silicon-glass bonding technology has also been put forward by a research and the comb tooth tilt effect of the sensor was analyzed. In these two designs, the electromagnetism is driven by static electricity to reduce the initial detection capacitance spacing, and thus the detection capacitance can be increased. Because static electric drive requires large test signal voltage, this paper proposes a new type of high precision MEMS capacitive inertial sensor driven by electromagnetism, and analyzes its relevant performance.

3.3 Working principles of the designed MEMS inertial sensor

Firstly, when the electrified conductor stands in a magnetic field, the drift of its internal carrier under electric fields will be influenced by lorentz force, and be passed on to the wires in a thermal collision mode, generating ampere force at this time. If the current strength of a wire of length L is I, when it is in a uniform magnetic field B, the ampere force that it suffers can be calculated by the formula: $F = B \cdot I \cdot L \cdot sin\theta$, where H is the direction of the ampere force of the angle between the wire and the direction of magnetic field, and the direction of the current and the magnetic field intensity are in accordance with the right hand rule. This sensor adopts permanent magnet to obtain uniform magnetic field and make the current direction perpendicular to the magnetic field direction. At this time, the driving force acting on the wire is $F = B \cdot I \cdot L$. Figure 1shows the working principles of the drive.
When current I flows in metal wires of the drive, by setting appropriate uniform magnetic field and through the right-hand rule, the direction of the current can be determined and the ampere force produced can be downward, as shown in Figure 1. The initial detection capacitance spacing of the damping slot on the drive is d1, and the regulated spacing between the drive and the isolation block is d2. When the ampere force of the wires is large enough, the drive should be driven to move downwards and attached to the isolation piece. At that time, the comb teeth detection capacitance spacing decreases from d1 to d1-d2, and the initial comb teeth detection capacitance of the sensor will increase.

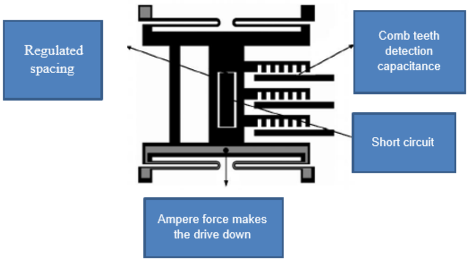

Figure 1: Working principles of the drive

3.4 Structure of the designed MEMS inertial sensor

Working principles of the designed sensor is shown in Figure 2: The sensor consists of a vibrator, a driver, an aluminum electrode on a glass substrate, a supporting beam, a soldering point, and a drive wire on the drive. There are two drives on each side of the vibrator, and the ampere force generated on the two wires is equal in size, opposite in direction and make the comb teeth detection capacitance spacing smaller. The damping slot is etched on the drive's comb teeth to reduce the mechanical noise, and the grid capacitance is etched on the vibrator to further increase the initial detection capacitance, as shown in Figure 3. When the displacement $y of the vibrator is generated in sensitive direction y under the influence of inertia signal a, the grid differential capacitances Cg1 and Cg2 will be changed.

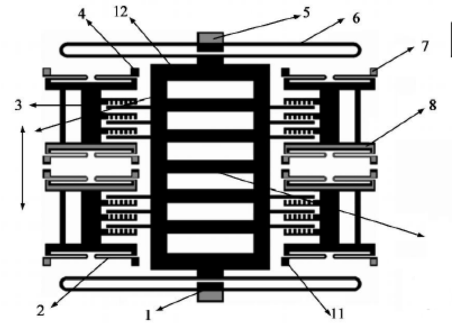

Figure 2: Working principles of the designed sensor

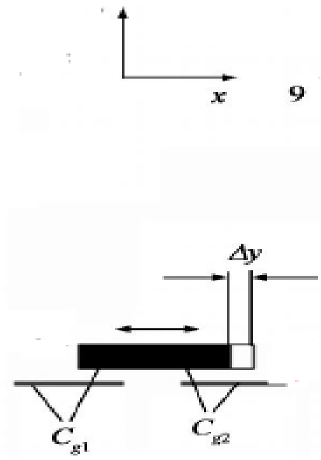

Figure 3: Grid differential capacitances

4. Results and discussion

4.1 parameter design of the sensor

The parameter design of the sensor is shown in Table 1. The sensitivity and bandwidth of the designed sensor can be adjusted by changing the size of beam and other characteristics. By taking the sensor size characteristics shown in Table 1 as an example, this paper analyses the performance of sensor with increased detection capacitance driven by electromagnetism.

Table 1: The parameter design of the sensor

Sensor size characteristics	Design value
Plane size of vibrator	3800Lm×5124Lm
The distance between the vibrator and the substrate electrode	4
Vibrator thickness	300
Initial spacing of comb capacitor	20
Working distance of comb capacitor	4
Superposition length of comb capacitor	790
Oscillator mass	4.715

If there is no etching damping slot on the drive's comb tooth, it is a traditional parallel plate structure, and the air damping between the two comb tooth capacitor plates can be expressed by the formula: $c_{rce} = \frac{\mu L B^3}{h^3}\left\{1 - \frac{192}{\pi^5}\right\}$, where L is the length of the comb tooth, B is the thickness, h is the capacitance spacing of the comb tooth electrode plate, and L is the vis cosity coefficient of air. Put the correspondent dimension in Table 1 into the formula, and the coefficient of the damping force between the comb tooth capacitance plates can be calculated as 0100452, while by using the 4 nodes elements FLUID136 in the FEM tool ANSYS to cover on the vibration microstructure, the air damping force between comb tooth capacitor plates can be simulated and the correspondent damping force coefficient is 0100425, and its stress distribution is shown in Figure 4.

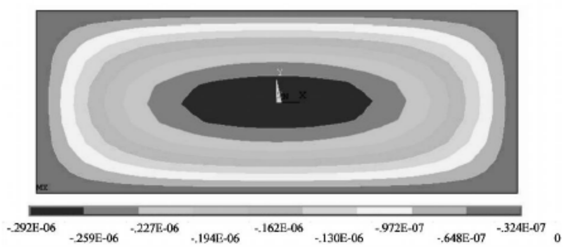

Figure 4: Stress distribution diagram

4.2 Comb tooth capacitance of damping

If the comb tooth of the drive has the damping slot etched on it for reducing mechanical noise, when the comb tooth capacitance spacing is 4 Lm, the Reynolds number is far less than the critical one of the micro-channel because the sensor's resonance frequency (598 Hz) is relatively small. Therefore, the air flow in capacitance spacing is still laminar. Since the motion speed of the high-precision sensor vibrator is small (0-1500Lm /s) and the damping slot width of the designed sensor is large (20Lm), it is assumed that no eddy current is generated when the air molecules between the comb teeth move.

4.3 Static detection capacitance comparison

If the comb tooth capacitance belongs to traditional parallel plate structure, according to the sensor size characteristics in Table 1, the static capacitance of the sensor is 6116 p before the drive works. When the driving current increased to a certain extent, the static detection capacitance can be increased to 16124 pf. In order to reduce the mechanical noise, the damping slot should be etched on the comb-tooth capacitance plates.

4.4 Finite element analysis of the designed sensor

According to Table 1, the simulation analysis was carried out on the performance of the sensor by using the finite element tool ANSYS, the first three vibration modes of the designed sensor are shown in Figure 5, which shows that the first, second and third resonance frequency of the sensor is 598, 5767, 5976 Hz respectively, and the sensor's main mode is in the sensitive direction of Y axis while the stiffness of the beam in non-sensitive direction is larger, which significantly inhibits the axial cross effect of sensors. According to the simulation results in Figure 5, the static sensitivity of sensor is 017 Lm/g.

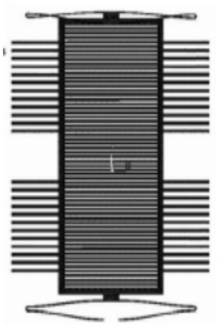

Figure 5: The first three vibration modes of the designed sensor

5. Conclusion

This paper based on the traditional MEMS sensors, analyzes the limitations of Deep RIE technology, and then puts forward a new design concept of high-precision MEMS inertial sensor with increased detection capacitance driven by electromagnetism. From the theoretical aspect, the comb tooth capacitance of the designed sensor can breakthrough traditional parallel plate structure; and from the practical aspect, when it works as a drive, the initial static capacitance of the designed sensor can increase from 6116 pf (the value of traditional sensor) to 6124 pf. In the aspect of reducing mechanical noise, the damping slot is etched on the comb-tooth capacitance plates in this article so that the static capacitance increases from 5118 pf (the value of traditional sensor) to 1113 pf when the drive works.

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