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A Novel Capacitive Biaxial Microaccelerometer Based on the Slide-Film Damping Effect*

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Abstract: A novel capacitive biaxial microaccelerometer with a highly symmetrical microstructure is developed. The sensor is composed of a single seismic mass, grid strip, supporting beam, joint beam, and damping adjusting combs. The sensing method of changing capacitance area is used in the design, which depresses the requirement of the DRIE process, and decreases electronic noise by increasing sensing voltage to improve the resolution. The parameters and characteristics of the biaxial microaccelerometer are discussed with the FEM tool ANSYS. The simulated results show that the transverse sensitivity of the sensor is equal to zero. The testing devices based on the slide-film damping effect are fabricated, and the testing quality factor is 514, which shows that the designed structure can improve the resolution and proves the feasibility of the designed process.

Key words: capacitive accelerometer; inertial sensor; high resolution; MEMS
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1　Introduction

Encapsulation in a vacuum or low vacuum environment can improve the performance of MEMS inertial sensors. For example, the noise resolutions of the Si-Flex series[1] from Colibrys SA corporation can reach 300 ~ 500 $ng_{rms}/\sqrt{Hz}$ and the dynamic range (100Hz bandwidth) can reach 120dB with a body-silicon fabrication process and encapsulation in a vacuum environment. The MEMS inertial sensors with super high precision and resolution are usually fabricated with a body-silicon process such as the DRIE process. When MEMS comb capacitive accelerometers are fabricated with the DRIE process, the combs are usually not parallel for complicated process factors, which affects the reliable working range and linearity of the sensors[2]. Furthermore, encapsulation in a vacuum increases the fabrication difficulty and cost. For capacitive sensing, a form of alternative electric testing signal is usually necessary for detecting the variation in capacitance; in this situation, the sensor is affected by the electrostatic force, inertial force, damping force, spring force, etc. In case of pull-in failure, the seismic mass of the inertial sensor is pulled into contact with the static electrode and remains there until the power supply of the sensor is reset.

Aiming at the disadvantage of the comb capacitive MEMS accelerometers, this paper presents a novel biaxial MEMS inertial sensor with slide film damping to reduce mechanical noise and increase resolution. The design includes combs controlling damping to adjust to response characteristic, and the capacitance is sensed by variations in area, which can increase the voltage of the electronic testing signal to reduce circuit noise and may reduce the precision demands of the DRIE process. The structure is completely symmetrical about the x-axis and y-axis, which realizes consistent performance of the sensor in both directions.

2　Theoretical analysis

2.1　Mechanical noise

The mechanical noise that is generated by the Brownian motion of the air around the sense element is one of the most important factors restricting the resolution of MEMS capacitive accelerometers. The air damping can be divided into squeezed-film air damping and slide-film damping according to the MEMS device structures. For the parallel plate capacitor structure, the squeezed-film air damping and slide-film damping in air pressure and temperature can by computed by[3,4]:

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$$c_{\mathrm{rec}} = \frac{\mu L B^3}{h^3}\left\{1 - \frac{192}{\pi^5}\left(\frac{B}{L}\right)\sum_{n=1,3,5}^{\infty}\frac{1}{n^5}\tanh\left(\frac{n\pi L}{2B}\right)\right\},$$

$$c_{\mathrm{sd}} = \frac{A\mu}{\delta} \times \frac{\sinh(2\tilde{d}) + \sin(2\tilde{d})}{\cosh(2\tilde{d}) - \cos(2\tilde{d})} \qquad (1)$$

where B is the width of capacitor plate, L is the length, μ is the viscosity coefficient of air, h is the distance between capacitor plates, $\delta=\sqrt{2\mu/\rho\omega}$ is the effective decay distance, A is the overlap area, and $\tilde{d}=d/\delta$, d is the distance between the electrodes. According to the definition of the quality factor: $Q = m\omega_r/c$, where m is the mass of the seismic, c is the coefficient of air damping, and ω_r is the resonant frequency, the quality factor can be improved by increasing the mass or decreasing the air damping of the sensor. According to Gabrieson's analysis[5], the effect of air damping on MEMS accelerometer can be expressed by:

$$\overline{a}_m = \sqrt{\frac{4k_B T\omega_n}{mQ}} \qquad (2)$$

where k_B, T, and ω_n are the Boltzmann constant, the absolute temperature, and the natural frequency, respectively. Because the squeezed-film damping is usually much larger than the slide-film damping, the accelerometer is based on slide-film damping to improve the resolution.

2.2 Electrical noise

The capacitive accelerometer has high precision, but its sensing circuit is complicated. In one solution, the high frequency carrier wave signal operates on MEMS sensing capacitors to modulate the acceleration signal, and then the signal is amplified and demodulated. In this situation, the electrical noise is determined mainly by the noise in the frond-end preamplifier. The electrical noise can be expressed by[6]:

$$\overline{a}_e = \sqrt{\frac{\alpha}{C + C_p} \times \frac{\omega_n^2}{V_s}\,\overline{v}_e} \qquad (3)$$

where α is the constant related to the sizes of the sensor, C is the sensing capacitance of the sensor, C_p is the parasitical capacitance, V_s is the voltage of the test signal, and $\overline{v}_e$ is the voltage of the input noise. The electronic noise of the sensing circuit can be reduced by increasing the sensing capacitance or amplitude voltage of the electronic testing signal when designing the capacitive inertial sensor.

In Ref. [7], finger and comb capacitances are used in the design of the high resolution accelerometer. The distance between the capacitor plates is symmetrically designed, by which the voltage amplitude of electronic testing signal can become large. But, non-linear electrostatic force induced by variable distance capacitance, which is relatively large in the design, restricts the further increase of the amplitude of electronic testing signal. Furthermore, the combs of the comb capacitive inertial sensors fabricated by a deep reactive ion etching are usually not parallel because of the imbalanced electric field caused by charge accumulation, which increases the non-linearity and reduces the reliable working range[2].

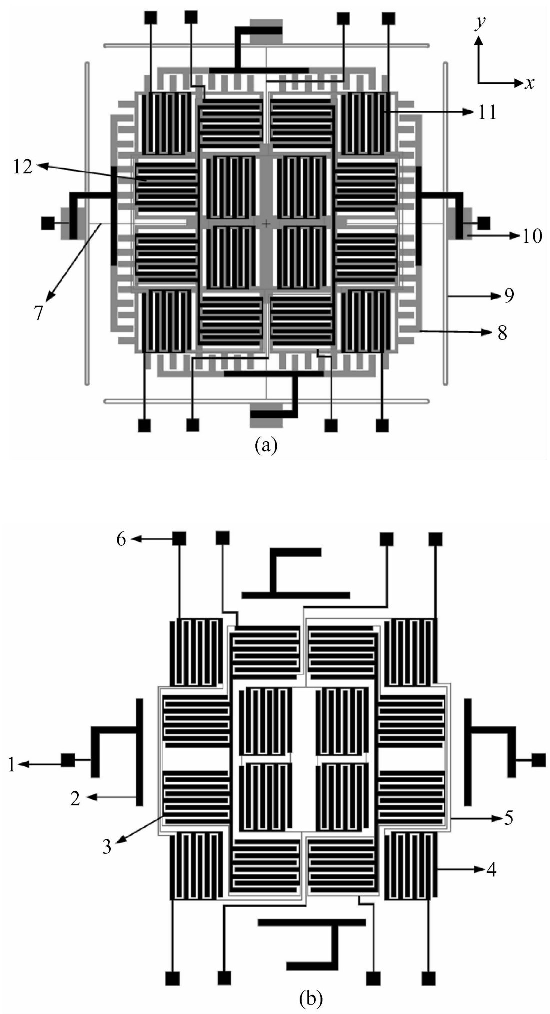

Fig.1 Schematic pictures of the biaxial MEMS inertial sensor (a) and comb electrodes (b) 1: Bonding point; 2: Connector between damping combs; 3, 12: Differential sensing capacitor in the y direction; 4, 11: Differential sensing capacitor in the x direction; 5: Connection line between electrodes; 6: Bonding in the x sensing direction; 7: Connection beam; 8: Damping combs; 9: Supporting beam; 10: Supporting anchor

3 Design and dynamics analysis of the sensor

According to the above analysis, the sensor is designed with the body silicon process to increase the mass of the seismic, and long bars are etched on the structure to increase the sensing capacitance. The resolution is also improved because a larger electronic testing voltage can be used on the capacitors with the

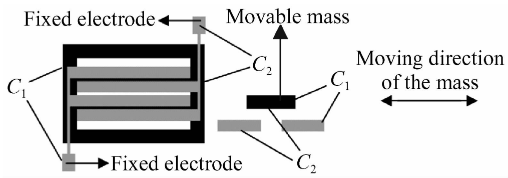

Fig. 2　Schematic picture of working principle of the sensor

designed sensing method. The mechanical noise is also reduced because the air damping in the x- and y-direction is mainly slide-film air damping. To show the consistent sensitivity of the MEMS sensor in the x- and y-direction and reduce the effect of cross axis, the structure of the sensor is completely symmetric about the x- and y-axis. To increase the linearity of the sensor, differential sensing capacitances are used in the design. Figure 1 shows the schematic pictures of a biaxial MEMS inertial sensor based on slid-film air damping whose structure is completely symmetrical and the electrodes are on the substrate.

In Fig. 1, 4 and 11 constitute differential capacitances sensed in the x direction, and the testing modules that are connected by aluminum sinuous line are disposed symmetrically in the x-y plane. 3 and 12 constitute differential capacitances sensed in the y direction that are also connected by the aluminum sinuous line.

Figure 2 shows the schematic picture of working principle of the sensor whose overlapping width is L. When inertial signal $\boldsymbol{a}_x$ in the x direction is applied on the sensor, movable mass has a small amount of displacement in x direction, inducing a change in the overlapping area of C_1 and C_2, and then a change in the sensing capacitance. The outside inertial signal $\boldsymbol{a}_x$ can be tested by detecting the output voltage of the sensor, which is converted from the change of differential sensing capacitance. The detecting principle in the y direction is uniform because the structure is completely symmetric.

The performance of the sensor is affected by the non-parallel comb induced by the DRIE process. Therefore, a long bar capacitance with a variable overlapping area is designed to eliminate the effect of the DRIE process on the performance of the sensor. This also reduces the precision requirement for the DRIE during the fabrication of the MEMS sensor.

Combs controlling damping are designed in the structure, as shown in Fig. 1. The damping of the combs is squeezed-film air damping. No capacitance exists between damping combs because the movable mass and the damping comb are connected by aluminum line due to the bonding of silicon and glass. The number of damping combs and distance between damping combs can be designed according to demands.

The damping between the movable mass and the fork electrode is slide-film air damping. If the air damping between the substrate and the movable mass is computed with the Couette flow model, and the air damping on the mass is computed with the Stokes flow model[4], the quality factor affected by slide-film air damping can be expressed by:

$$\frac{1}{Q} = \frac{1}{Q_{\mathrm{Cd}}} + \frac{1}{Q_{\mathrm{Sd}}} = \frac{\mu}{\rho_{\mathrm{m}} H\omega}\left(\frac{1}{d} + \frac{1}{\delta}\right) \tag{4}$$

where ρ_{m} is the density of the mass, ρ is the density of the air, H is the thickness of the movable mass, and ω is the resonant frequency of the sensor. In the design, the number of damping combs and the distance between damping combs can be chosen according to the bandwidth requirement and the response characteristic of the sensors. The damping of the damping combs can be computed by Eq. (1). The mechanical thermal noise of the designed sensor can be analyzed by Eqs. (2) and (4).

For example, for the device sizes shown in Table 1, the quality factor is 290 when the resonant frequency is 900Hz and the bi-direction sensor has no damping comb. When the number of the damping combs is 16, the quality factor decreases to 7.8. When the number increases to 32, the quality factor decreases to 3.75. These computations show that the minimum detectable accelerations that are decided by the mechanical thermal noise are 0.38, 2.33 and 3.34 ug/$\sqrt{\mathrm{Hz}}$, respectively, in these three instances, showing the effects of squeezed-film air damping on the resolution of the sensor. The number of damping combs in the presented structure can be designed according to specific demands.

4　Performance of the sensor

The performances of the designed sensor, such as, sensitivity and bandwidth, can be improved by adjusting the length and width of the supporting beams and connecting beam. We will analyze the performance of the bi-direction MEMS inertial sensor with the device sizes shown in Table 1.

Table 1　Geometric characteristic of the sensor

Geometric characteristics	Designed value
Length of the supporting beam	3800μm
Width of the supporting beam	22μm
Length of connecting beam	600μm
Width of connecting beam	14μm
Structure thickness	100μm
Sense capacitance	4.7pF
Overlapped length of damping combs	450μm
Gap between combs	4μm
Gap between structure and substrate	4μm

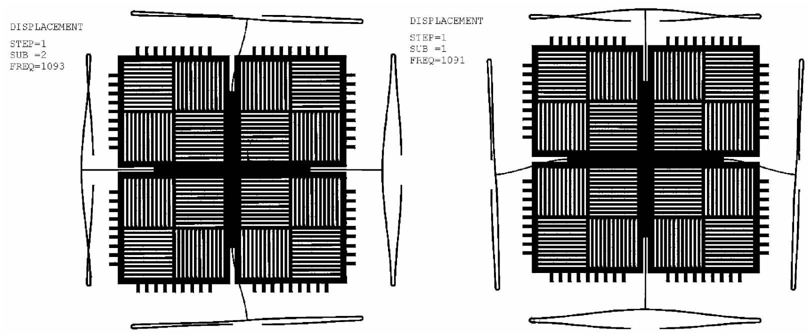

Fig.3 Modes of the sensor in x and y directions

4.1 Mode analysis

Figure 3 shows the vibration modes of the sensor in the x- and y-direction that is simulated by the FEM tool ANSYS. The resonant frequencies are 1093 and 1091Hz in the x- and y-direction, respectively. When 1g acceleration of gravity is applied on the sensor in the x- and y-direction, respectively, induced displacements are consistent in the two directions, namely 0.209μm.

4.2 Strength analysis

To affirm whether the MEMS sensor is destroyed or not when a large accidental shock is applied to the mass, we perform a FEM simulation. Overloading heaves can be designed in the sensitive direction for protecting the frame when the sensor is shocked by a large inertial signal. For the non-sensitive direction along the z axis, the maximum stress which distributes in the root fringe of the connector between movable mass and connecting beam is 299MPa when the mass is shocked by a 1000g acceleration. The result shows that the designed sensor can sustain a 1000g acceleration shock when the breaking stress of silicon is 1.3GPa[8].

4.3 Transverse sensitivity

The output signal in the x direction that is affected by the signals from the y and z directions for the effect of cross-axis can be expressed by:

$$V_{\mathrm{out\_x}} = s_x a_x + s_{yx} a_y + s_{zx} a_z \qquad (5)$$

where s_x is the sensitivity in the x direction, and s_{yx} and s_{zx} are the transverse sensitivity in y-x and z-x directions, respectively.

To simulate the transverse sensitivity of the biaxial sensor in the x sensitive direction, we use the following method. 1g acceleration is applied both in the x- and y-direction, and the maximum displacements of the movable mass in the x- and y- and z-direction are analyzed with ANSYS. 2g acceleration is applied in the y-direction while maintaining 1g acceleration in the x-direction. The maximum displacements in the x- and y- and z-direction are analyzed with ANSYS, the transverse sensitivity is computed by $a = k\Delta x/m$, and the effect on the output voltage is computed by Eq.(5). Table 2 shows the simulated results, which indicate the transverse sensitivity of the x-axis in the y- and z-direction is almost equal to 0, i.e. $s_{yx} = s_{zx} \doteq 0$. The transverse sensitivity of the y-axis can be confirmed to be almost equal to 0 with the same method. The simulated errors in Table 2 mainly come from the partition of FEM gridding.

Table 2 FEM results of cross effect of the sensor

Displacements simulated by FEM		Δx	Δy
$a_x = 1$g	$a_y = 1$g	0.209	0.209
$a_x = 1$g	$a_y = 2$g	0.208	0.419
$a_x = 1$g	$a_z = 1$g	0.209	0.00019
$a_x = 1$g	$a_z = 2$g	0.210	0.00018

4.4 Primary experiment

In this paper, a biaxial MEMS inertial sensor based on slide-film air damping whose sensing capacitance is composed of the silicon bars and fork aluminum electrodes is designed. To validate the sensing acceleration by capacitance with variable overlapping area, and the extent of reduction in noise by slide-film air damping, a device is fabricated. Figure 4 shows the SEM picture and fabrication process of the device. The tested quality factor can reach 514. The biaxial MEMS inertial sensor based on slide-film air damping can be fabricated with the silicon-glass bonding process and the designed structure can reduce mechanical thermal noise and increase the resolution of the MEMS sensor.

5 Conclusion

A novel capacitive biaxial microaccelerometer with a highly symmetrical microstructure has been developed in this paper. The sensor is composed of a single seismic mass, grid strip, supporting beam, joint beam, and damping adjusting combs. The sensing method of changing capacitance area is used in the

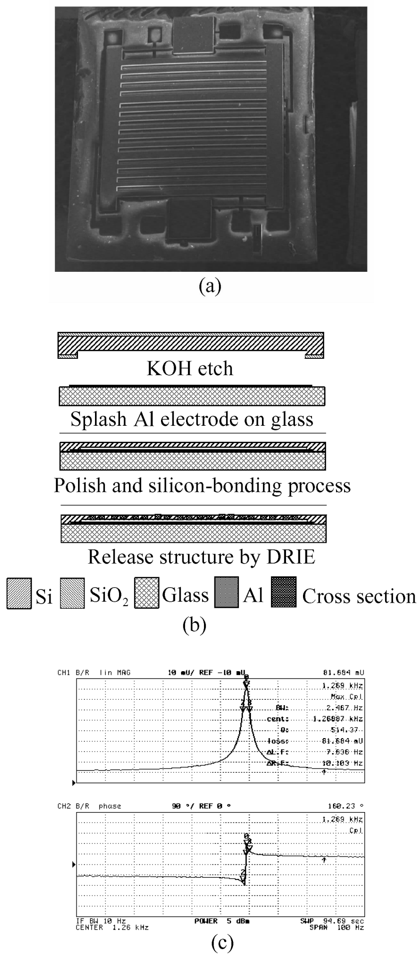

Fig. 4　Device testing slide-film damping (a), fabrication process (b) and tested Q curves (c)

design, which depresses the requirement of the DRIE process, and decreases electronic noise by increasing sensing voltage to improve the resolution. The damping combs in the structure can adjust the air damping of the sensor by changing the number of combs. For the instance described in the paper, the minimum detectable acceleration decided by the mechanical thermal noise is reduced from 380 to 3.34 $\mathrm{ug}/\sqrt{\mathrm{Hz}}$ when the number of combs changes from 0 to 32.

The parameters and characteristics of the biaxial microaccelerometer are discussed with the FEM tool ANSYS. The simulation results show that the transverse sensitivity of the sensor is equal to zero. The analysis of strength shows that for the non-sensitive direction z axis, the maximum stress that distributes in the root fringe of the connector between movable mass and connecting beam is 299MPa when the mass is shocked by a 1000g acceleration, and the designed sensor can sustain a 1000g acceleration shock. Devices based on slide-film damping effect were fabricated, and the testing quality factor is 514, which shows that the designed structure can improve the resolution and proves the feasibility of the designed process.

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一种新型的基于滑膜阻尼的电容式双向 MEMS 惯性传感器*

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摘要：设计了一个新型的结构完全对称的双向 MEMS 电容式惯性传感器.该传感器主要由可动质量块、栅形条、支撑梁、连接梁、阻尼调整梳齿组成.设计的结构采用变电容面积的检测方式，在降低空气阻尼的同时也降低了对 DRIE 工艺的要求，并通过加大测试信号电压来降低电路噪声，从而提高传感器的分辨率.用有限元工具 ANSYS 详细讨论了传感器的参数和性能，并模拟验证了设计的双向传感器的交叉效应近似为零.制作了滑膜阻尼测试器件，在大气压下，测得的品质因子可达 514，验证了该结构设计可以提高传感器的分辨率和该工艺设计的可行性.

关键词：电容式传感器；惯性传感器；高分辨率；MEMS
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