A novel capacitive micro-accelerometer with grid strip capacitances and sensing gap alterable capacitances*

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Abstract: The comb capacitances fabricated by deep reactive ion etching (RIE) process have high aspect ratio which is usually smaller than 30 : 1 for the complicated process factors, and the combs are usually not parallel due to the well-known micro-loading effect and other process factors, which restricts the increase of the seismic mass by increasing the thickness of comb to reduce the thermal mechanical noise and the decrease of the gap of the comb capacitances for increasing the sensitive capacitance to reduce the electrical noise. Aiming at the disadvantage of the deep RIE, a novel capacitive micro-accelerometer with grid strip capacitances and sensing gap alterable capacitances is developed. One part of sensing of inertial signal of the micro-accelerometer is by the grid strip capacitances whose overlapping area is variable and which do not have the non-parallel plate's effect caused by the deep RIE process. Another part is by the sensing gap alterable capacitances whose gap between combs can be reduced by the actuators. The designed initial gap of the alterable comb capacitances is relatively large to depress the effect of the maximum aspect ratio (30 : 1) of deep RIE process. The initial gap of the capacitance of the actuator is smaller than the one of the comb capacitances. The difference between the two gaps is the initial gap of the sensitive capacitor. The designed structure depresses greatly the requirement of deep RIE process. The effects of non-parallel combs on the accelerometer are also analyzed. The characteristics of the micro-accelerometer are discussed by field emission microscopy (FEM) tool ANSYS. The tested devices based on slide-film damping effect are fabricated, and the tested quality factor is 514, which shows that grid strip capacitance design can partly improve the resolution and also prove the feasibility of the designed silicon-glass anodically bonding process.

Key words: capacitive accelerometer; inertial sensor; high precision; deep RIE

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1. Introduction

Encapsulation in vacuum or low vacuum environment can improve the performance of the MEMS inertial sensors, for example, the noise resolutions of Si-Flex series[1] of Colibrys SA Corporation can reach to 300–500 $\mathrm{ng_{rms}}/\sqrt{\mathrm{Hz}}$ and dynamic range (100 Hz bandwidth) can reach to 120 dB by bulk silicon fabricating process and encapsulation in vacuum environment. For the MEMS inertial sensors having super high precision and resolution, the fabricating method usually uses the bulk silicon process, for example, deep reactive ion etching (RIE) process. If the comb capacitances of MEMS comb capacitive accelerometers are fabricated by deep RIE (DRIE) process, the combs are usually not parallel for complicated process factors, which affects the reliable working range and linearity of the sensors[2]. Since MEMS accelerometers are used in many systems, the noise characteristics of MEMS accelerometers are very important. The noise characteristics will influence the performance of the accelerometers, such as resolution and sensitivity. The noise of the micro-accelerometer is divided into the mechanical and electrical noise components.

The mechanical noise which is generated by the Brownian motion of the air around the sense elements is one of the most important factors restricting the improving of the resolution of micro capacitive accelerometers. According to the definition of 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 effect of air damping on MEMS accelerometer can be expressed by the following equation according to the analysis of Gabrieson[3]:

$$\overline{a_m} = \sqrt{\frac{4k_B T\omega_n}{mQ}}, \tag{1}$$

where k_B, T, ω_n are the Boltzmann constant, absolute temperature and natural frequency, respectively. This equation shows that the mechanical noise can be reduced by increasing the mass or decreasing air damping of the sensor.

The capacitive accelerometer has high precision, but its

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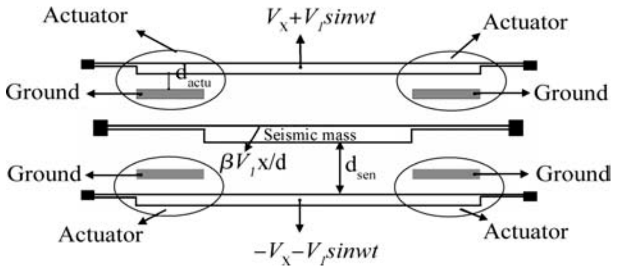


Fig. 1. The simplified schematic structure of the accelerometer.

sensing circuit is very complicated. It is one of the solutions that high frequency carrier wave signal operates on MEMS sensing capacitors to modulate the acceleration signal, and then the signal is amplified and demodulated. In the situation the electrical noise is determined mainly by the noise in the frond-end preamplifier. The electrical noise can be expressed by[4]

$$\overline{a_e} = \sqrt{\frac{\alpha}{C + C_p} \frac{\omega_n^2}{V_s} \overline{v_e}}, \tag{2}$$

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 testing signal, and $\overline{v_e}$ is the voltage of input noise. It can be seen from the above equation that the electronic noise of the sensing circuit can be reduced by increasing the sensing capacitance in designing the capacitive inertial sensor.

The thickness of the seismic of the micro-accelerometers fabricated by DRIE process is restricted by the aspect ratio which is usually smaller than 30 : 1 and DRIE error such as loading-effect and under-cutting effect, which also restricts the increases of the mass and sensitive capacitance to reduce the mechanical noise and electrical noise. To increase the sensitive capacitance, Je *et al.*[5] presented a sensing gap reconfigurable capacitive type MEMS accelerometer to make patterns which is smaller than 1 μm. But the accelerometer is fabricated by using SOI process-DRIE, and the effects of the DRIE which are greater in higher aspect ratio structure on the performances of the capacitive accelerometer are also not analyzed. In this paper, a novel capacitive type MEMS accelerometer whose fabricated process is based on the silicon-glass bonding and the aspect ratio of the mass is larger than 50 : 1 is presented. The effects of non-parallel plates on the accelerometer are also analyzed. The sensitive capacitances of the accelerometer are increased by two kinds of method, namely, decreasing the gaps of combs capacitors by the designed actuators and appending grid strip capacitances whose damping is slide-film air damping, which reduces greatly mechanical noise. The performance of the micro-accelerometer is improved obviously for the increase of the mass of the seismic and the sensitive capacitance.

2. Working principle of the micro-accelerometer

The picture of working principle of the micro-accelerometer is shown in Fig. 1. When the movable plate of the actuator is supplied with an electronic testing signal $V_x + V_1 \sin wt$ or $-V_x - V_1 \sin wt$, and the fixed plates are connected to ground, an electrostatic force is applied to the movable plates of the actuator, pulling it towards the fixed electrode as shown in Fig. 1. After the movable plates of the actuators fall into contact with the fixed plates of the actuators, the movable reference plates can be considered to be anchored as the fixed electrodes of the micro-accelerometer. The sensitive capacitance of the micro-accelerometer is increased to

$$C_{sen} = \frac{\varepsilon\varepsilon_0 A}{d_{sen} - d_{actu}}, \quad d_{actu} < d_{sen}, \tag{3}$$

where A is the overlapping area of the capacitor, and d_{sen} and d_{actu} are shown in Fig. 1.

2.1. Pull-in voltage of the actuator

According to Fig. 1, the electrostatic force of the actuator can be computed by

$$F_e = \frac{\varepsilon\varepsilon_0 A}{2d^2} (V_x + V_1 \sin wt)^2 . \tag{4}$$

As the electronic testing signal frequency, ω, is much higher than the natural vibration frequency of the micro mechanical actuator, the average electrostatic force applied on the seismic mass is

$$\overline{F_e} = \frac{\varepsilon\varepsilon_0 A}{2d^2} \left(V_x^2 + \frac{V_1^2}{2} \right). \tag{5}$$

According to the pull-in effect[6], when the balanced positions of the movable plates of the actuators are larger than one third of its original distance from the fixed plate, namely, $y > d_{actu}/3$, the movable plates of the actuators will fall into contact with the fixed plates of the actuators. The pull-in voltage can be found by

$$V_x^2 + \frac{V_1^2}{2} \geqslant \frac{8kd_{actu}^3}{27A\varepsilon\varepsilon_0}. \tag{6}$$

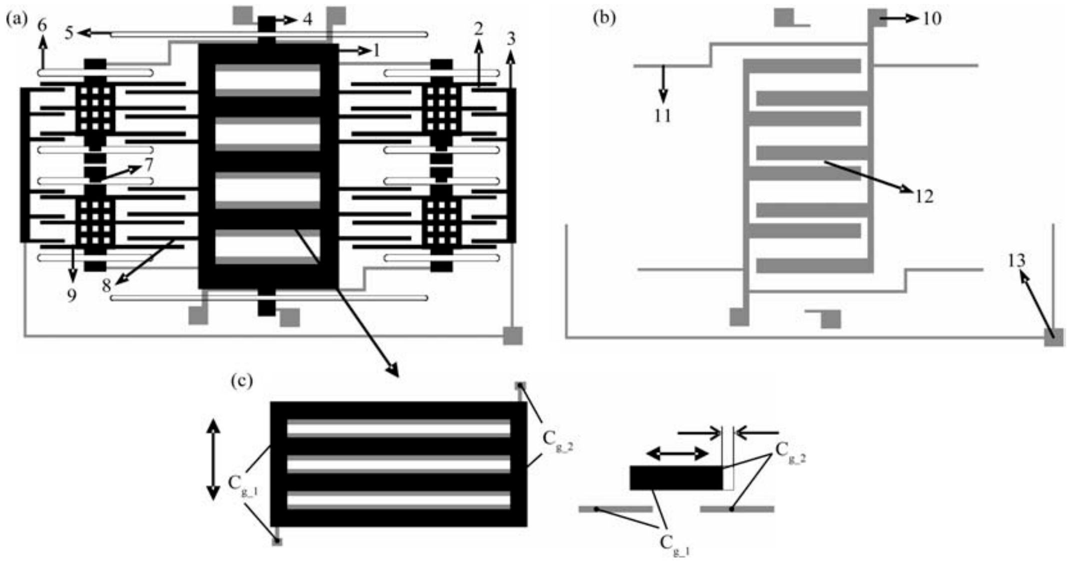
We define $\lambda = V_1/V_x$, the pull-in voltage is thus found to be

$$V_x \geqslant \sqrt{\frac{8kd_{actu}^3}{27A\varepsilon\varepsilon_0} \frac{2}{2 + \lambda^2}}. \tag{7}$$

When V_x is larger than the pull-in voltage, the sensitive capacitance will reach to the maximum value.

2.2. Design of the micro-accelerometer

Schematic figures of the novel capacitive micro-accelerometer are shown in Fig. 2. The micro-accelerometer is mainly composed of a single seismic mass, supporting beam, grid strips, combs, and actuators. The sensing capacitances include grid strip capacitances and comb capacitances. The sensing capacitances are increased by the novel structure design, which depresses electrical noise. The damping of the grid strip capacitances is slide-film air damping, which depresses the mechanical noise. Figure 2(c) shows the working principle of grid strip capacitances. When inertial signal $\boldsymbol{a}$ is applied on the sensor, movable mass changes a little displacement, which induces the change of overlapping area of C_{g_1} and C_{g_2}, and then the change of sensing capacitance. The outside inertial



1. seismic mass 2. driving capacitor of the actuator 3. supporting anchor of the actuator 4. supporting anchor of the accelerometer 5. U-shape sensitive beam 6. beam of the actuator 7. pull-in heave 8. sensing capacitor 9. actuator 10. bonding of the sensitive mass 11. connecting line between capacitors 12. grid strip aluminum electrodes 13. bonding of the actuators.

Fig. 2. Schematic pictures of the designed MEMS capacitive micro-accelerometer: (a) Simplified schematic model of the sensor; (b) Simplified aluminum electrodes on the glass substrate; (c) Schematic model of grid strip sensing capacitors.

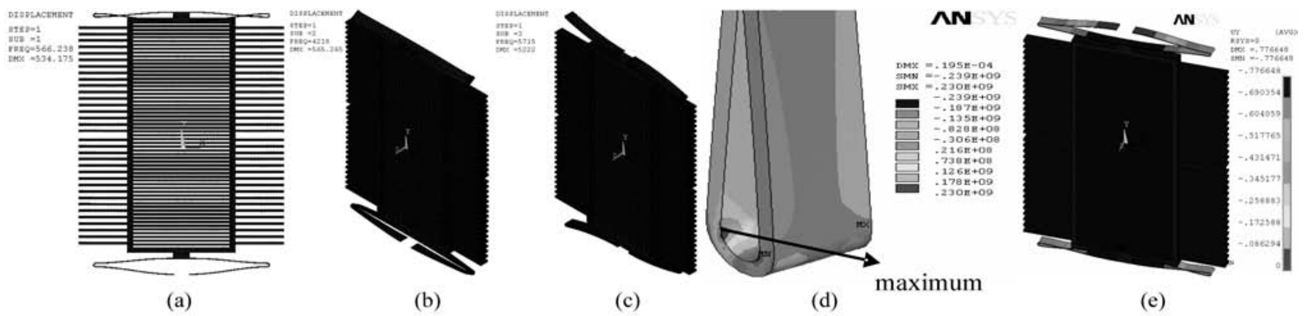


Fig. 3. Modes and stress of micro-accelerometer obtained by FEM tool ANSYS.

Table 1. Geometric characteristic of the sensor.

Geometric characteristics	Designed value
Resonant frequency	566 Hz
Size of the seismic	$4000 \times 4689 \times 200$ μm^3
Gap between structure and substrate	4 μm
Initial sensing gap of combs	8 μm
Working sensing gap of combs	4 μm
Sensing capacitance	15.8 pF
Simulated sensitivity	0.777 μm/g

signal $\boldsymbol{a}$ can be tested by detecting the output voltage of the sensor which is converted from the change of differential sensing capacitance.

3. Analysis of the novel micro-accelerometer

3.1. Mode and sensitivity analysis

The geometric characteristic of the designed sensor is shown in Table 1. According to the designed parameters, the performances of the sensor are analyzed by field emission microscopy (FEM) tool. Figure 3 shows the first three vibration modes of the micro-accelerometer which are simulated by the FEM tool ANSYS. The resonant frequencies of the first, second and third modes are 566, 4218, 5715 Hz, respectively. It can be seen from Figs. 3(a) to 3(c) that the primary mode is in the sensitive direction. Different resonant frequencies of accelerometer can be obtained by changing the sizes of the sensitive beams. The simulated sensitivity is 0.777 μm/g as shown in Fig. 3(e). The sensing capacitance can reach to 15.8 pF for the size of the seismic $4000 \times 4689 \times 200$ μm^3, which will greatly reduce the electrical noise of the sensor.

3.2. Strength analysis

To affirm whether the MEMS sensor is destroyed or not when large accidental shock is applied on the mass, FEM simulation is performed. Overloading heaves can be designed in the sensitive direction for protecting the frame when the sensor is shocked by large inertial signal. For non-sensitive direction z axis, the maximum stress induced by the accidental shock 1000 g, as shown in Fig. 3(d), distributes in the root fringe of the U shape sensitive beam when the mass is shocked by the large accidental inertial signal. The stress is usually smaller

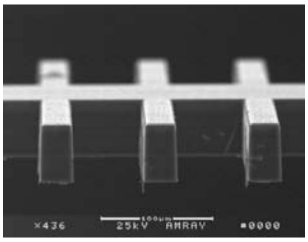


Fig. 4. SEM picture of the cross section of non-parallel combs.

than the breaking stress of silicon which is 1.3 GPa[7].

3.3. Effects of non-parallel combs induced by DRIE process

If the combs of the comb capacitive accelerometers are fabricated by DRIE, its width will increase linearly with the depth similar to the single crystal ion etching and metallization micromachining process. This non-ideal feature is greater in high aspect ratio structure. The non-parallel combs effect is shown in Fig. 4.

For a force-balanced accelerometer with a feedback voltage V_r as shown in Fig. 1, for a small displacement, the feedback voltage is proportional to the displacement of the mass: $\beta V_1 x/d$ where β is the feedback coefficient of the circuit. Obviously, both V_x and V_r are restricted by the supply voltage[8]. With the feedback voltage, the electrostatic force on the mass is

$$F_e = \frac{A\varepsilon\varepsilon_0}{2(d_{sen}-d_{actu})^2}\left[\frac{(V_x + V_1\sin wt - \beta V_1 x/d_0)^2}{(1-\tilde{x})^2} - \frac{(V_x + V_1\sin wt + \beta V_1 x/d_0)^2}{(1+\tilde{x})^2}\right], \tag{8}$$

where $d_0 = d_{sen} - d_{actu}$, $\tilde{x} = x/d_0$.

Comb capacitive accelerometers fabricated by bulk silicon process are usually etched by DRIE process to have high silicon etching rates, high aspect ratios and high selectivity to mask materials. But the combs are usually not parallel for well-known micro-loading effect and other complicated process factors. When the seismic mass has a small displacement y due to outside acceleration of a, the electrostatic force applied on the seismic mass for the situation that the angle of the decline of the oblique comb electrodes is very small is[2]

$$F_e = \frac{\varepsilon\varepsilon_0 A V_x^2}{2(d_{sen}-d_{actu})^2}\left[\frac{(1+\lambda\sin wt - \beta\lambda\tilde{x})^2}{(1-\tilde{x})(1-\tilde{D}_0)} - \frac{(1+\lambda\sin wt + \beta\lambda\tilde{x})^2}{(1+\tilde{x})(1+\tilde{D}_0)}\right], \tag{9}$$

where $\lambda = V_1/V_x$, h is the thickness of the seismic, α is the oblique angle between nonparallel capacitor plates, and $\tilde{D}_0 = 1 - 2h\alpha/d_0$.

The capacitance, C_{comb}, between a pair of combs with a little oblique angle α caused by DEIR process can be computed by[9]

$$C_{comb} = \frac{\varepsilon\varepsilon_0 w_c}{2\alpha}\ln\left(\frac{d}{d-2h\tan\alpha}\right), \tag{10}$$

where d, ε, ε_0, h, and w_c are the gap between combs, the permittivity of a vacuum, the relative permittivity of the air, the thickness of comb, overlapping length between the combs, respectively. The capacitance, C_g, between grid strips and the aluminum electrodes on the glass substrate is

$$C_g = \frac{N_g\varepsilon\varepsilon_0 L_g w_g}{d_g},$$

where N_g is the number of the gird strips, L_g is the length of the grid strip, and w_g and d_g are the overlapping width and gap between grid strip and electrode on the substrate, respectively. Therefore, the sensing capacitance of the micro-accelerometer can be expressed as

$$C_0 = \varepsilon\varepsilon_0\left[N_c\frac{w_c}{2\alpha}\ln\left(\frac{d}{d-2h\tan\alpha}\right) + \frac{N_g L_g w_g}{d_0}\right]. \tag{11}$$

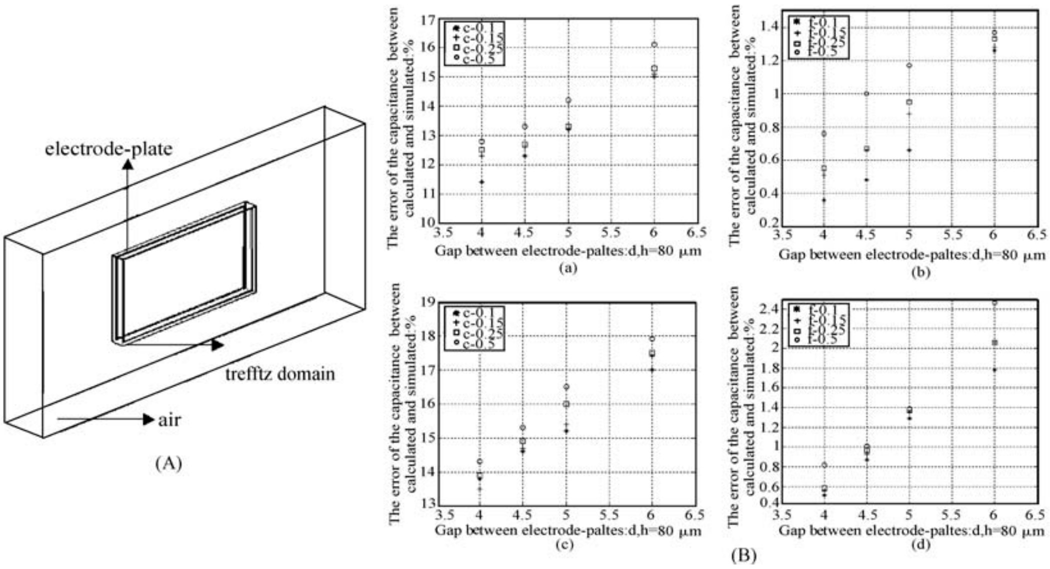
For MEMS accelerometers with differential sensing capacitance, the change of the capacitance caused by outside inertial signal can be computed by

$$\Delta C \doteq \varepsilon\varepsilon_0\left[N_c\frac{w_c}{2\alpha}\ln\left(\frac{d+y}{d-y}\frac{d-y-2h\tan\alpha}{d+y-2h\tan\alpha}\right) + 2\frac{N_g L_g}{d_0}y\right], \tag{12}$$

where y is the displacement generated by the external inertial signal. The above expression shows that the inclination of the combs induced by DRIE process will cause nonlinearity change of the sensing capacitance, but do not affect grid strip capacitance. Therefore, the design appending grid strip capacitance reduces the nonlinearity of the micro-accelerometer induced by DRIE process.

The edge effects of electric field are not considered when above capacitance and electrostatic force are calculated. To analyze the edge effect of electric field and the non-parallel effect between combs, a hybrid finite element-Trefftz method of FEM tool ANSYS 5.7 is used to simulate oblique comb capacitance and electrostatic force between oblique combs. Trefftz domain model is shown in Fig. 5(A). The simulated values of the capacitance and electrostatic force of oblique combs obtained by ANSYS 5.7 are shown in Fig. 5(B) where the length of the comb is 100 μm, the thickness of the comb capacitance is 60 and 80 μm, respectively, and the angle of decline is 0.1°, 0.15°, 0.25°, and 0.5°, respectively.

It can be seen from Fig. 5 that the error of the oblique comb capacitances between computed and simulated values decreases as the gap between oblique combs decreases, and smaller the oblique angle between combs is, smaller the error is, this is because the edge effect of the electric field decreases as the gap decreases. Therefore, the oblique comb capacitance can be computed more exactly by above models when the gap of comb capacitor is reduced by the actuator for increasing the sensitive capacitance. The error of electrostatic forces between computed and simulated values is small for a very small oblique angle (0.1°) whose minimum value reaches to 0.36%, and the error changes a little as the gap between combs or thickness of combs changes. Furthermore, it decreases as the thickness of the combs increases from 60 to 80 μm for the



1. Trefftz domain of the oblique combs 2. Error of simulated and computed results of capacitance and electrostatic force

Fig. 5. Modeling of capacitance and electrostatic force of oblique combs by ANSYS.

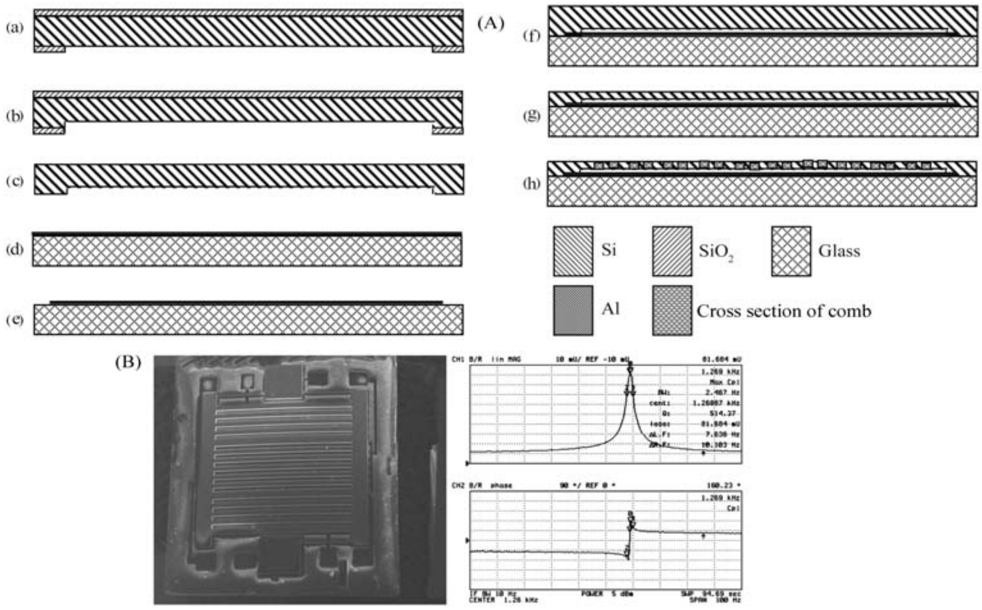


Fig. 6. (A) Fabrication process flow of the device; (B) Device testing grid strip capacitance and tested *Q* curves.

decrease of edge effect of electric field, which shows that the electrostatic force can be obtained more exactly as the thickness of the comb increases.

4. Micro-fabrication process and preliminary testing

A double side polished N-type (100) low resistivity silicon and Pyrex glass wafers are used to fabricate the micro-accelerometer by using bulk micromachining process. The process flow is shown in Fig. 6(A). (a) SiO_2 on the silicon wafer is first removed by HF to etch suspending area; (b) Silicon wafer with thermal SiO_2 is etched to form a suspending cavity; (c) SiO_2 on the silicon is entirely removed; (d) Aluminum is splashed on Pyrex 7740 glass substrate; (e) Aluminum interdigitated electrodes are patterned on Pyrex 7740 glass wafer; (f) Silicon and glass wafer are then anodically bonded; (g) Thin and polish the silicon on the glass to appropriate thickness; (h) Photo resist is patterned as mask and DRIE process is used to etch through the silicon wafer and release the micro-accelerometer structure. SEM picture of the device testing grid strip capacitance and the tested *Q* curves are shown in Fig. 6(B). The tested quality factor can reach to 514. The experimented device show that the designed micro-accelerometer with grid strip capacitances and sensing gap alterable capacitances can be fabricated by silicon-glass bonding process and the appending grid strip capacitance structure can obviously reduce mechanical thermal noise and increase the resolution of the MEMS sensor. The above designed micro-accelerometer depresses greatly the requirement of deep RIE process. For example, even if the thickness of the comb is 200 μm, the initial gap of the sensitive capacitance fabricated by deep RIE may be 3–4 μm by the novel design, which increases greatly the sensitive mass and capacitance and consequently, improves greatly the precision of the micro-accelerometer.

5. Summary

The comb capacitances fabricated by DRIE process have high aspect ratio which is usually smaller than 30 : 1 for the complicated process factors, and the combs are usually not parallel for the well-known micro-loading effect and other process factors, which restricts the increase of the seismic mass by the way of increasing the thickness of comb to reduce the thermal mechanical noise and the decrease of the gap of the comb capacitances for increasing the sensitive capacitance to reduce the electrical noise.

Aiming at the disadvantage of the DRIE, a novel capacitive micro-accelerometer with grid strip capacitances and sensing gap alterable capacitances is developed in this paper. One part sensing inertial signal of the micro-accelerometer is by the grid strip capacitances whose overlapping area is variable and which have not the non-parallel plate's effect caused by the DRIE process. Another part is by the sensing gap alterable capacitances whose gap between combs can be reduced by the actuators. The designed initial gap of the alterable comb capacitances is relatively large to depress the effect of the maximum aspect ratio (30 : 1) of DRIE process. The initial gap of the capacitance of the actuator is smaller than the one of the comb capacitance. The difference between the two gaps is the initial gap of the sensitive capacitance. The designed structure depresses greatly the requirement of DRIE process. For example, even if the thickness of the comb is 200 μm, the initial gap of the sensitive capacitance fabricated by DRIE may be 3–4 μm by the novel design, which increases greatly the sensitive mass and capacitance and consequently, improves greatly the precision of the micro-accelerometer.

The effects of non-parallel combs on the accelerometer are also analyzed. The characteristics of the micro-accelerometer are discussed by FEM tool ANSYS. The analysis of strength shows that for non-sensitive direction z axis, the maximum stress distributes in the root fringe of the connector between movable mass and connecting beam. That the primary mode of the designed structure is in the sensitive direction is validated by ANSYS. The tested devices based on slide-film damping effect are fabricated, and the tested quality factor is 514 in air, which shows that grid strip capacitance design can improve partly the resolution and also prove the feasibility of the designed process.

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