A high sensitivity micromachined accelerometer with an enhanced inertial mass SOI MEMS process

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Abstract—This paper provides an enhanced inertial mass SOI MEMS process for the fabrication of a high sensitivity micromachined accelerometer. In the proposed process, the handle layer of the SOI wafer is used as an enhanced inertial mass, in this way, the inertial mass of the accelerometer can increase 5-15 times. Therefore, the sensitivity of the MEMS accelerometer can be significantly increased. In this paper, an in-plane single-axis accelerometer is designed firstly. And then, the accelerometer is fabricated in a low resistivity SOI wafer with 60μm thickness device layer and 400μm thickness handle layer through the developed enhanced inertial mass SOI MEMS process. The sensitivity of the fabricated MEMS accelerometer is 2.257V/g, the linearity of output is within 0.5%, and the power spectral density of the noises is as low as 6.79uV/√Hz.

Keywords- micromachined accelerometer; high sensitivity; enhanced inertial mass; SOI.

I. INTRODUCTION

Micromachined accelerometer constitute one of the largest segments in the micro-sensor market. The application fields range from consumer electronics to personal navigation systems due to their low fabrication cost, small size, and easy integration with CMOS. However, because of their low to medium sensitivity, high-precision accelerometer markets have not been dominated by micro-machined ones.

Thick silicon-on-insulator (SOI) wafer are used to fabricate high-precision accelerometer because various advantages, such as superior material properties of a single crystal material, easily achieved thick device, less residual stresses and simple fabrication processes. Thus, micro-machined accelerometer using an SOI wafer has been widely developed [1, 2].

To improve the performance of the accelerometer, several optimized structure schemes presented. In [1], a compact design of differential capacitive electrodes in the accelerometer is proposed, which is realized with refilled trench to electrically isolate silicon device layer. It suggests that more number of the sensing capacitors, higher is the capacitive sensitivity. In [3,4,5], the vertical comb electrodes is used to realize the three-axis accelerometer. In [6], a comb-shaped microelectrodes is designed to obtain a high sensitivity accelerometer. In [7, 8], the surface electrodes is designed, the lateral capacitance-based transducer enabling large capacitance change per acceleration and allowing a large dynamic range without electrode contact.

The above methods improve the performance by using some novel electrodes structures, however, a more direct way is to increase the inertial mass of sensors. One way to increase the mass is to increase the size of sensors. In [9], a full wafer dicing free dry release process is developed, and the proof mass of the fabricated accelerometer is $4\times7mm^2$ with a 60μm SOI wafer. Another way to increase the mass is to improve the thickness. In [10, 11], the handle layer of the SOI wafer is used to act as enhanced inertial mass. In this way, a Sub-micro-gravity accelerometers are fabricated and tested with measured sensitivity of 35 pF/g [10].

In this paper, we design and fabricated a micromachined accelerometer with enhanced inertial mass SOI process. In the proposed process, thinned handle layer is used as enhanced inertial mass, and a metal layer is used before DRIE to avoid notching.

II. SENSOR DESIGN

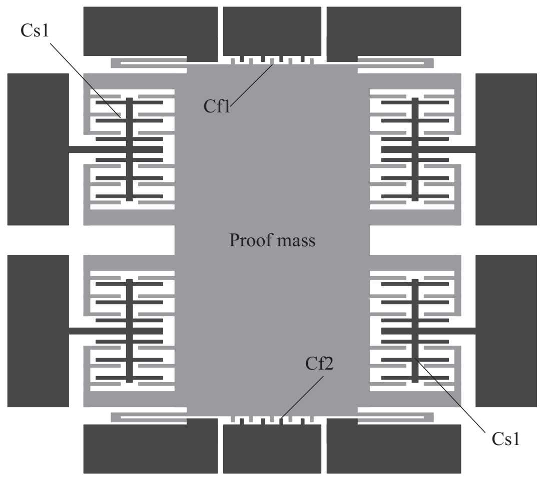

Fig. 1. Schematic diagram of the designed accelerometer with a fully differential structure.

The proposed in-plane single-axis accelerometer is designed with a fully diffential structure showed in Fig.1. External acceleration moves the proof mass of the sensor and leads a change in the area of capacitive combs. Capacitive changes of these combs vary in proportion to the external acceleration, and then are detected by follow-up electric circuit. This fully differential accelerometer has two sets of capacitive combs.

The Capacitors Cs1 and Cs2 serve as sensing capacitors, while Cf1 and Cf2 serve as feedback capacitors.

Extant capacitive accelerometers mostly use gap-changed capacitive combs to sense acceleration. To achieve the goal of high linearity, the movement of the proof mass is always designed to move in very little range, which leads the capacities to be small and in turn leads the sensitivity of the sensor to be limited. In our work, area-changed capacitive combs which could vary linearly in large range are adopted.

In order to get high linearity, good axial stiffness and low cross axis sensitivity between the deflection range, four folded beam structures (see Fig. 2) are chosen for the sensor, which has two beam structures on each side.

Fig. 2. Schematic of folded beam

The total spring constant of the micro accelerometer is

$$k_y \approx 2Et(\frac{w_b}{l_b})^3 \qquad (1)$$

Where E is the Young's models, t is the beam thickness, w_b is the beam width and l_b is the beam length.

The resonant frequency of the sensor is

$$f_y = \frac{1}{2\pi}\sqrt{\frac{k_y}{m}} = \frac{1}{2\pi}\sqrt{\frac{2Etw_b^3}{Nml_b^3}} \qquad (2)$$

Where m represents the mass of the sensor.

The calculated sensor specifications are listed in Table I.

TABLE I. MICROACCELEROMETER SPECIFICATIONS

Thickness of the device layer	60μm
Area of proof mass	4000μm×2200μm
Area of enhanced inertial mass	3800×2000μm
Thickness of enhanced inertial mass	350μm
Finger gap	2.5μm
Q factor	5
Resonant frequency	385Hz
Brownian noise equivalent acceleration	72.3ng/√Hz

III. FABRICATION PROCESS

The accelerometer is manufactured in a low resistivity (p=0.01Ω.cm) SOI wafer with device thickness of 60μm and handle layer thickness of 400μm. The process flow is a 3 mask SOI MEMS process, as shown in Fig. 3.

Oxide layers (2μm) are firstly grown on both sides of the wafer (Fig.2.a). Then the oxide layer on the back of handle layer is patterned to serve as a mask for later deep reactive iron etching (Fig.2.b). Then, the metal layer is patterned to form the mask of enhanced inertial mass (Fig.2.c). Using these two masks, the enhanced inertial mass is formed by two step of DRIE (Fig.2.d-f). The first DRIE define the size of the enhanced inertial mass, the handle wafer was etched through (Fig.2.d). Than the metal layer was removed away (Fig.2.e), followed by the second DRIE to define the thickness of the enhanced inertial mass (Fig.2.f).

Next, the second metal layer is formed to act as heat transfer layer during the next DRIE (Fig.2.g), in this way, the device layer will be able to protect from notching effect. Finally, the device layer is patterned (Fig.2.h) and etched to form the device after the DRIE and metal etch (Fig.2.i).

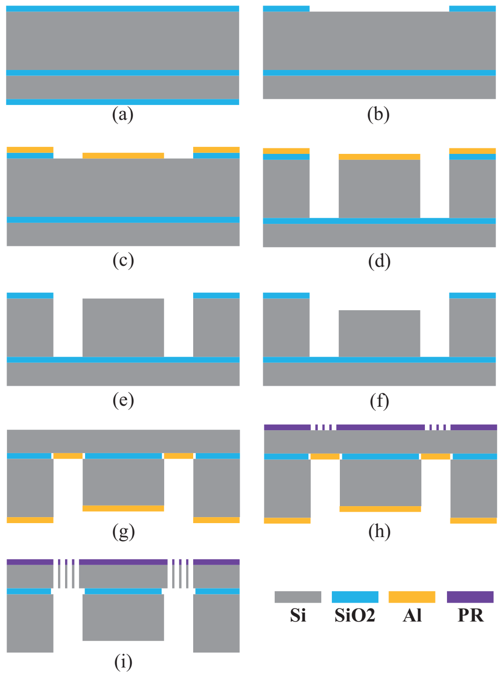

Fig. 3. Schematic diagram of the designed accelerometer with a fully differential structure.

Fig. 4 shows the top view of the fabricated micromachined accelerometer and the backside view is shows in Fig. 5. The proof mass is about 4000μm×2200μm×60μm, and the enhanced inertial mass is about 3800μm×2000μm×350μm. The inertial mass of the accelerometer increased 5 times. The close-up view of the sensing combs and suspension beams are shown in Fig.6, the gap of comb fingers is 2.5μm.

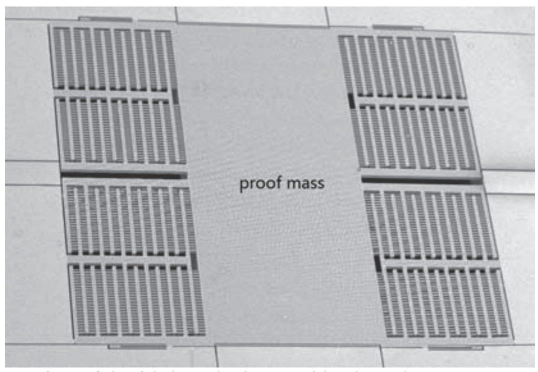

Fig. 4: Top view of the fabricated micromachined accelerometer.

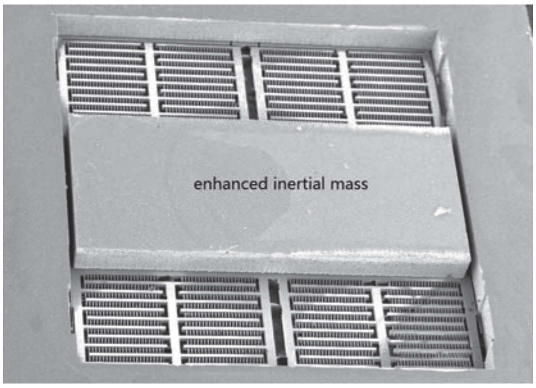

Fig. 5. Backside view of the fabricated micromachined accelerometer.

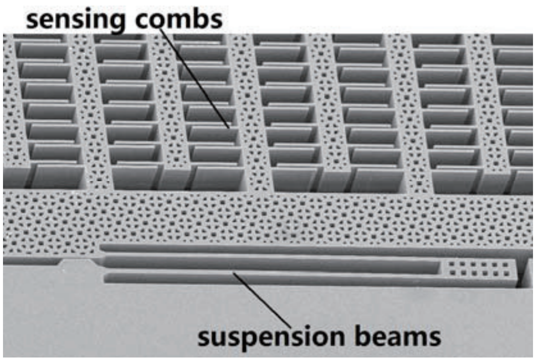

Fig. 6. Close-up view of the sensing combs and suspension beams

IV. MEASUREMENTS

To test the fabricated sensor, a testing circuit is designed (see Fig.7). The sinusoidal carrier wave produced by a crystal circuit is put on the proof mass of the sensor. Two charge amplifiers convert the change of capacitance on the sensing electrodes to voltages, which are then demodulated by diode envelop detection. In order to make the two detection channel symmetrical, two diodes for demodulation are Schottky diodes packed in dual units and resisters in the circuit are highly consistent. The two signals obtained at the demodulation are then filters in the RC second-order passive power filters which have the merits of small size, and simple structure. After the signals were processed in the instrumentation amplifier (INA), the output voltage of the whole circuit can be obtained.

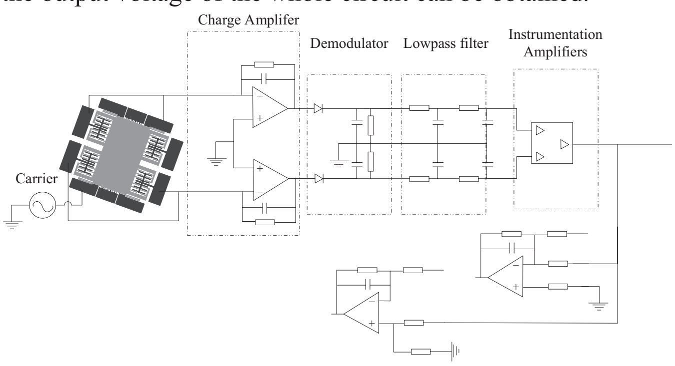

Fig.7. Schematic of testing circuit

The fabricated micromachined accelerometer was packaged at atmosphere pressure, and test at room temperaturte.

The sensitivity testing of a packaged sample is using a dividing head, as shown in Fig.8. The open-loop static response of the accelerometer is measured, as shown in Fig.9, and the measured sensitivity is 2.257V/g with a linearity of 0.5%.

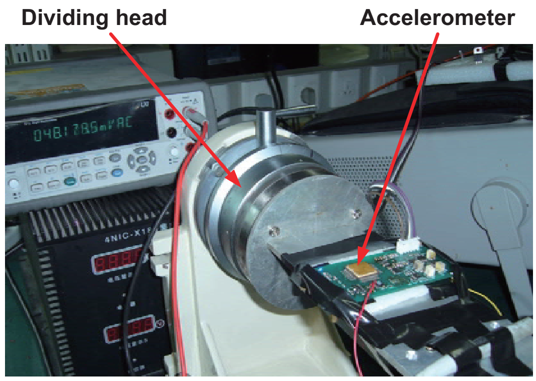

Fig. 8. Packaged micromachined accelerometer is test on a dividing head.

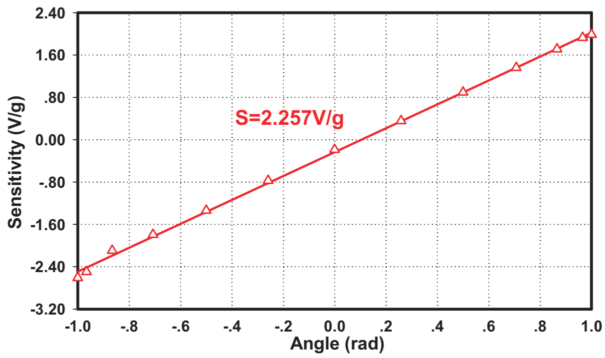

Fig. 9. The open-loop static response of the micromachined. The measured sensitivity is 2.257V/g with a linearity of 0.5%.

The noise floor of the fabricated accelerometer is shown in Fig.10. The power spectral density of the noises is as low as 6.79μV/√Hz.

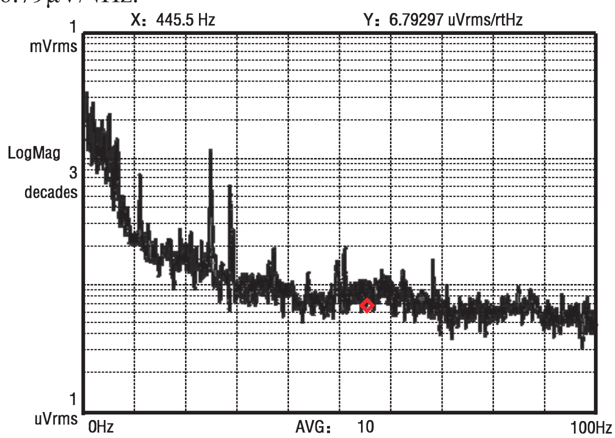

Fig. 10. Measured noise floor of the fabricated micromachined. The power spectral density of the noises is as low as 6.79μV/√Hz.

V. CONCLUSION

The paper present high sensitivity MEMS accelerometer fabricated by 60μm SOI wafer. We can draw some conclusions as follows. (1) Through the proposed enhanced inertial mass SOI MEMS process, the thickness of the sensor has been greatly improved and the mass of proof mass has increased 5 times. As a result, the mechanical noise and the sensitivity are improved greatly. (2) As the metal layer is used before the DRIE of device layer, there were no notching effect and stiction problem through fabrication. This great increase the yield of the processes. (3) The sensitivity of the sensor is 2.257V/g with a linearity of 0.5% and the power spectral density of the noises is as low as 6.79μV/√Hz. We can see that the sensor is quite qualified to be used in some high-precision area, such as oil exploration.

ACKNOWLEDGMENT

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