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A Comparative studies of MEMS Inertial Sensors on its Design and Fabrication

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ABSTRACT

Background: This paper reviewed the method used to design and fabricate MEMS Inertial Sensors. The device description used in reviewed papers for each device are compared and summarized. The fabrication techniques of the devices approach are discussed. When compared the method, the pros and cons of the approaches are shown. Finally, the best methods of designing and fabricating the sensor for overall performances factors are discussed.

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INTRODUCTION

Currently, MEMS (Micro Electromechanical System) has become an emerging technology that covers from house appliance to automotive and even in medical. The remarkable development in MEMS which initiated from integrated circuit technologies, and evolved to highly functional system in miniaturized version. MEMS sensor comes from an input of mechanical signal which are converted using an interface circuit to a corresponding electrical signal that used to produce the required control function (Gogoi, 2008). This incorporation between MEMS sensor with the help of the interface circuit can be done using silicon or package it completely. Most MEMS devices are prepared from silicon wafer which same like an IC where MEMS fabrication also shares the same standard process like etching, photolithography oxidation, diffusion and deposition. This review will focus on three MEMS inertial sensors devices (capacitive accelerometer) as an example.

Literature review:

As mention above, the inertial sensor on this paper review will be using a capacitive accelerometer. Interfaces in capacitance sensor have some great features where it can function equally as actuators and sensors. It is highly sensitive but naturally unaffected to temperature (Andrejašiˇc, 2008).

$$C = \frac{\varepsilon o \varepsilon A}{d} \tag{1}$$

From above formula, Capacitance, C is equal to permittivity, εoεA and the area, A are divided by the distance, d. The fundamental parts for a capacitive accelerometer are the housing that is attached to the object of the acceleration that needed to be measured. The seismic mass or proof mass that tied to the housing are moving a “comb-like” part back and forth. By measuring the motion of this central section, the orientation (X, Y, Z plane) of the object can be determined. The fingers on the accelerometer structure can make up differential capacitor which will result the center section moves and allowing current to flow (Lee, 2008; Boser, 1997; Leondes, 1997).

$$(V_x + V_0)C_1 + (V_x - V_0)C_2 = 0 \tag{2}$$

$$Vx = V0\frac{C_2 - C_1}{C_2 + C_1} = \frac{x}{d}V0 \tag{3}$$

$$a = \frac{ks}{m}x = \frac{ksd}{mVo}Vx \tag{4}$$

where the voltage of the proof mass is voltage output, Vx and x is the displacement.

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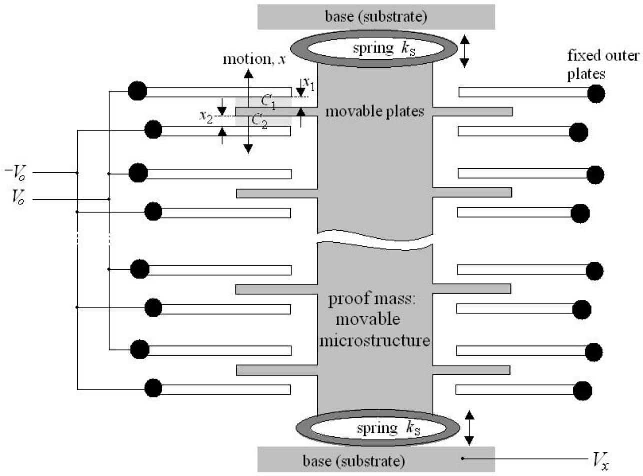

Fig. 1: Accelerometer structure. The springs (kS: spring constant)) is attached to proof mass at substrate where it moved up and down. From the movable and fixed plates, the capacitors is determined (Lyshevski, 2002)

Device description:

Typically, MEMS inertial sensors consist of accelerometers and gyroscope that widely used either in industrial, variety of consumer and especially in automotive application. (Ronald Kok, 2005) Parameters such proof mass, fill factor, folded springs or even capacitive comb need to be taken into consideration when designing MEMS inertial sensors due to its high natural frequencies.

First example (Xu, 2009), device is using method of bulk micromachining to fabricate on Silicon-on-Insulator (SOI) wafers. In addition, the dry release process is used for DRIE (Deep Reactive Ion Etching) technology instead of wet etching. With this combination, performance of MEMS inertial sensor can be improve with high proof mass and capacitance sensing capabilities.

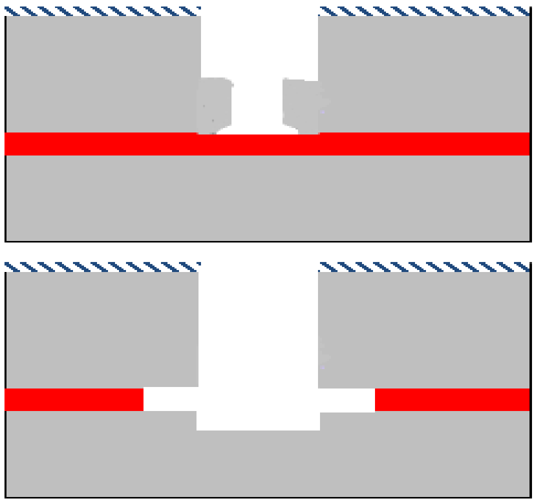

Fig. 2: Layout schematic before (top) a) and after (bottom) b) anti-footing method (Xu, 2009).

By using 4 inch SOI wafers that consist of 400 µm handle layer, 40 µm structure layer and 2 µm buried oxide, two mask releasing process will be needed. DRIE will help to solve footing problem and avoid stiction effects that effect

In second example (Haogang, 2009), the seismic mass is used as the movable electrode and a compliant stationary electrode is placed above it. The device structure method is redesigned as a centro-symmetric construction with the fixed electrode transformed from two bridge-type beams to one cross beam (see figure below). With this redesign structure; switch on time can be pro-long with fewer amounts of bouncing affect and to reduce the off-axis sensitivity.

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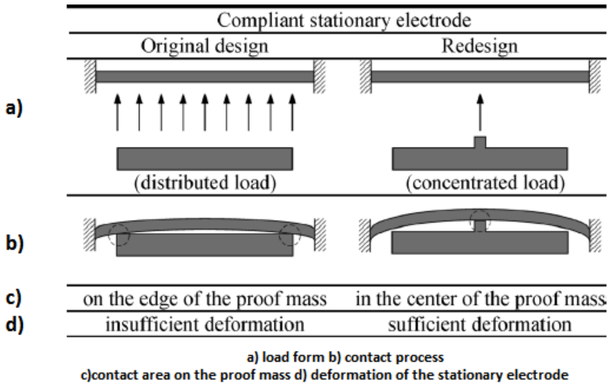

Fig. 3: Before and after redesign device structure (Haogang, 2009)

In the third design example (Dong Linxi, 2009), the MEMS capacitive accelerometer is designed and fabricated based on a silicon-glass bonding process where the designed capacitance sensing technique is alter the capacitance area, which can decrease the air damping in the middle of the sensing capacitor plates and lessen the condition for the DRIE process precision. It also decreases the electronic noise by increasing the sensing voltage of the design capacitive accelerometer sensor.

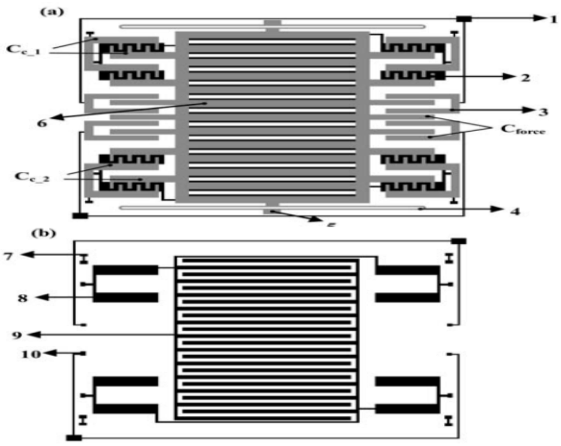

Fig. 4: Schematic of design MEMS capacitive sensor (Dong Linxi, 2009)

The entire device uses capacitive types of sensor. So based on all the three MEMS inertial sensor device description, the devices are design based on what type of criteria and parameter that they wanted to improve in. Furthermore, the sensitivity of sensor is the most important characteristic that need to be discussed.

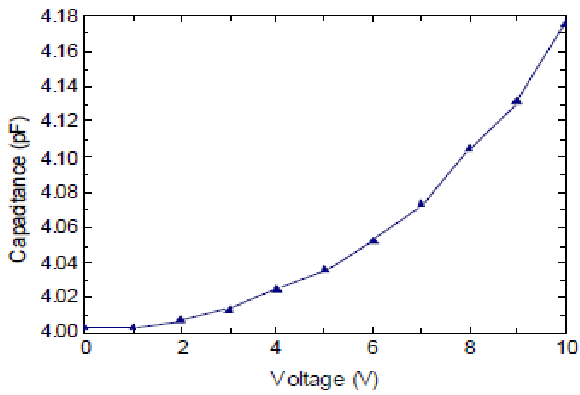

Fig. 4: Sensing capacitance vs driving voltage of the accelerometer (XU, 2009)

Sensitivity of the inertial sensor:

In sensor, device which obtains and then reacts to a signal when affected. When the measured parameters changes, the sensitivity specifies how much the sensor's output deviated. The first device, (XU, 2009) for creating a high performance MEMS inertial sensors, a large proof mass and sensing capacitances are preferred. Furthermore, to produce high quality single crystal silicon constructions with even viscosity and low build-in stress, a method of combining a SOI wafers with DRIE technology is used. From the measurement result in figure 4 shown below, the capacitance varied according to the voltage applied between the movable and fixed electrodes.

But the suggested process is the variation of capacitive of the inertial sensors lessens the sensitivity of the inertial sensor due to the condition of the unsmooth substrate influenced by the etching during the final releasing of DRIE. To minimize the effect of parasitic capacitors, sputtered another Al layer behind the SOI wafer as electrodes and attached with the movable constructions.

As for second device, (HAOGANG, 2009) device is design to decrease the off-axis sensitivity by re-designed the structure as a Centro-symmetric construction with the stationary electrode altered from two bridge-type beams to one cross beam. Also by decreasing the electrode gap, the perpendicular sensitivity of the inertial switch could be adjusted. In standard design, 40g of minimum of acceleration is required to turn on the switch.The result after re-designed; the switch-on time took 30μs much longer than 12μs of the original design at 85 g shock acceleration, which shows that the sensitivity contact effect of the compliant stationary electrode was effectively enhanced.

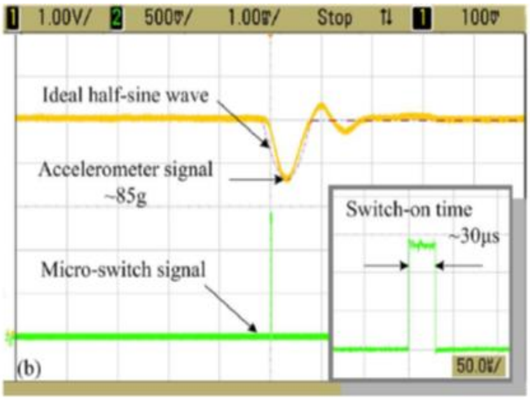

Fig. 5: Test result under 85g acceleration (HAOGANG, 2009)

Therefore, the sensitivity of the contact effect was improved which would enable the signal processing and enhanced the reliability.

But in third device, (DONG LINXI, 2009) the sensitivity of the capacitance can be increased by altering the capacitance area. This method lessens the air damping between the sensing capacitor plates. Also by increasing the sensing voltage, the electronic noises are reduced. Furthermore, the process design technique via bulk micromachining and DRIE process, it delivers greater proof mass and capacitive area, which gives a better sensitivity.

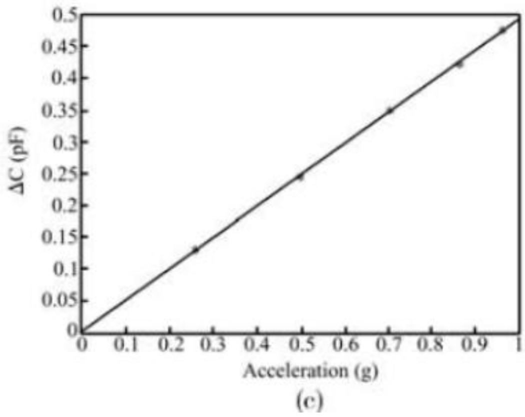

Fig. 6: The tested inertial sensor and the test principle [10]

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When an acceleration of 1g given to the sensitive axis, result above shown that the sensing capacitance changes linearly with the gravitational acceleration inertial. When rotating the circuit turntable from 0◦ to 180◦ in 15◦ phases, the acceleration sensor's sensitivity path differs from 0 g to 1 g. So, the sensitivity of the inertial sensor is resolute as high as 0.492 pf/g.

After knowing the kind of device, parameter needed and the sensitivity of the sensor, the process design can be personalized according to the specification that the design required.

Process design:

In MEMS fabrication process design, the fundamental technologies such micromachining is to incorporate microelectronic with micromachined electromechanicals construction to create the high performance MEMS. Bulk and surface micromachining are the most established fabrication technique in the microelectronic industry.

Bulk micromachining consist of procedure that deeply etching into substrate. Silicon has been used as a substrate mostly because it stronger than steel, lighter than aluminum, single crystal or polycrystalline. Plus, it has been used in micromachining for a long time. Other than Silicon, materials such glass, ceramic or plastic can also be the substitution. For bulk micromachined, by carefully etch the deep of the substrate, it can define the structure entirely. There are numerous methods to etch the wafer. First the Anisotropic wet etch that uses etchants that etch the silicon crystal structure by rearranged the atoms periodically in lines and planes. There is also Reactive Ion Etching (RIE) types of etching that uses chemically reactive plasma to get rid of substantial deposited on the substrate. In RIE, electromagnetic field will caused a low pressure vacuum and the water surface will be attack with high energy ions from plasma and react with it. (SANDBORN, P.P., 2006)

Next, the Surface micromachining type of process is in contrast to the bulk micromachining. The differences is surface micromachining comprises of constructing the layers by depositing thin films of new material on top of the exterior of the substrate. Typically, to create self-supporting constructions like air-bridges it uses sacrificial layers. Before the final construction is placed, the structure is pattern by using micro-lithographic. Next, the sacrificial layer is detached by a proper etchant to get the desired device structure.

Fabrication technique for the first device (XU, 2009), it uses bulk micromachining type of (100) plane oriented with 4 inch SOI wafers used as substrate. There are two mask used for these designs which are aluminum (Al) and photoresist (PR) (two mask releasing process).In this design, Deep RIE process are used three times which can be seen in Fig c),d) and f) below. The stiction problems will not occurred since this is a dry release process

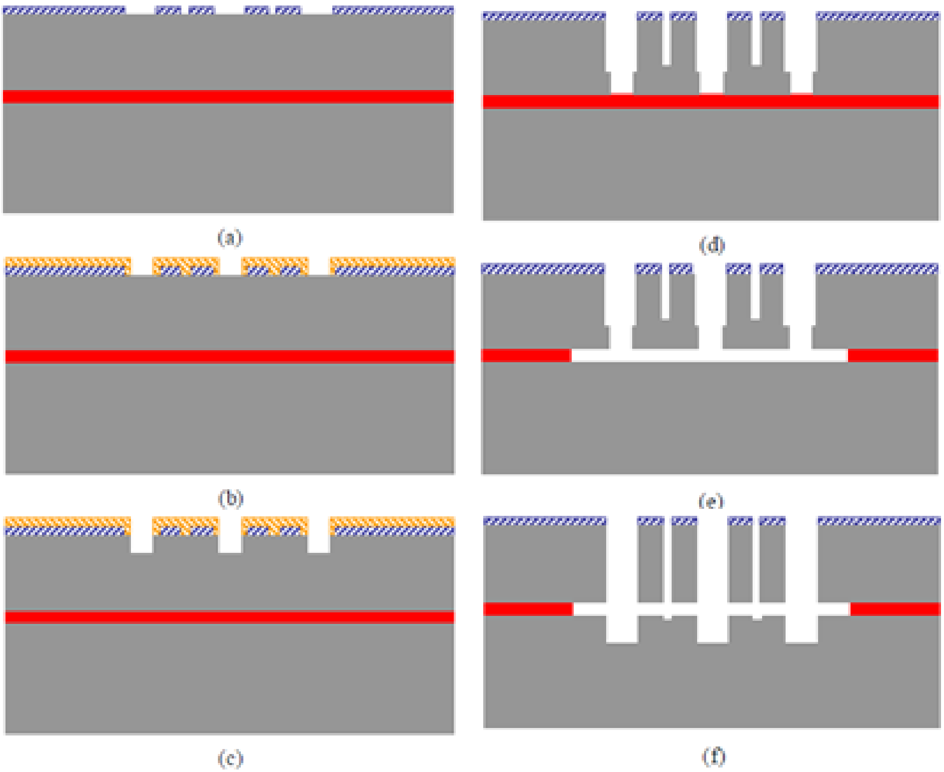

Fig. 7: Fabrication flow of dry release process (XU, 2009)

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The second device example (HAOGANG, 2009), it uses surface micromachining. . Instead of using Silicon as wafer, this design uses glass substrate as wafer. In previous design, the structure released by using a dry release process to avoid stiction but in this design it is dipped in isopropyl alcohol and then dried up (wet etching). Since the device structure is unique, the thickness of the device was measured by the electroplating time and supervised by a stylus profiler to get that precision structure. As for the mould and sacrificial layer, this design uses Positive photoresist.

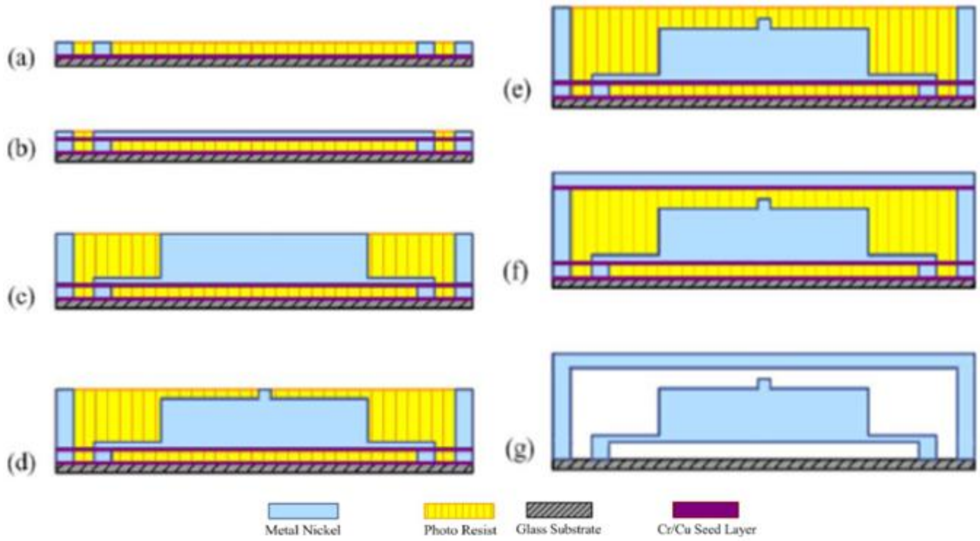

Fig. 8: Fabrication of Surface micromachining (Haogang, 2009)

As for the third design example [10], the type of micromachining uses is Bulk. It is a double-sided structure with N-type (100) plane oriented that uses two wafer; Silicon wafer and Pyrex glass wafers as substrate. For this design, it considers the micro loading effect to the device. So, to avoid it, a metal layer is deposited on top of the glass surface and it is electrically attached to the silicon substrate. Just like the first design, before releasing the structure, it uses a deep RIE process to etch through the silicon wafer and prevented from stiction problem.

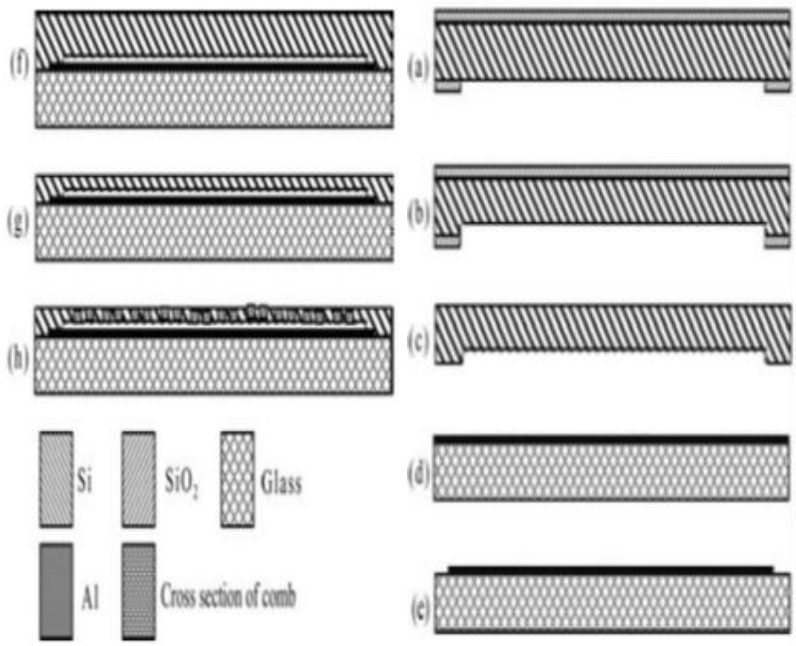

Fig. 9: Fabrication of two sided device using Bulk Micromachining (Dong Linxi, 2009)

Commencing from reviews of the entire device's process design, the pros and cons of the approach can be seen clearly.

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Pros and cons of the approaches:

For the first device, the design process can prevent the footing outcome by using the final releasing DRIE which portrayed below. For the structures with vertical sidewall (no undercut) to be constructed, structures will be weaken and then entirely removed. (Refer to Figure 2).

But the disadvantage of using this approach is that the substrate is not smooth and this causing the capacitance alteration of capacitive inertial sensors which reduce the sensitivity of the inertial sensor because it is etched during the final releasing DRIE. From the figure below, it is clearly shown the non-flat surface after final etching.

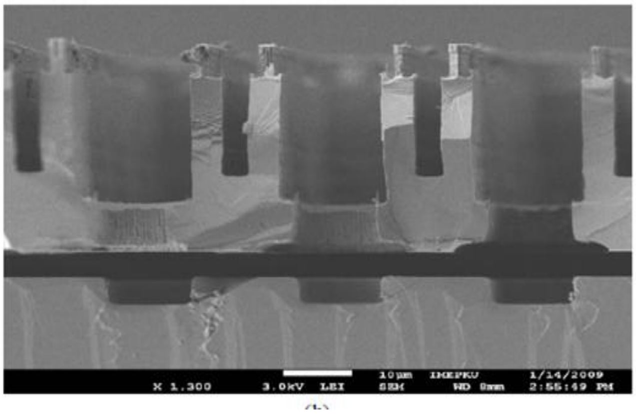

Fig. 10: Cross section view of SOI structure after final etching.

The advantage of the second device is the topmost of the proof mass is installed with a connection point on; it changes the effective contact part of the fixed electrode from its end to the center. During the connection process, it will bent and decrease the contact bouncy outcome and lengthens the switch-on time. But the drawback of the design, device was a little inflexible. This may be contributed from the fabrication deficiency and the ideal half-sine wave of the deviancy of the acceleration. (Refer to Figure 3)
As for the third device, it focuses on intensification the mass of the seismic to lessen the mechanical noise by using deep RIE process. But it will affect the oblique combs prompted by the DRIE process distress the capacitance and electrostatic force. As a result, it affects the reliable process of the micro-accelerometer

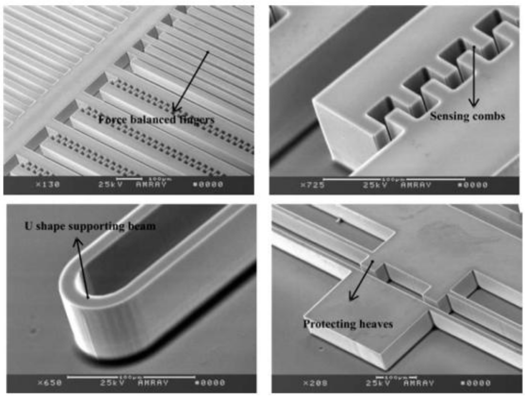

Fig. 11: SEM picture of the fabricated device.

Conclusion:

Based from reviewing these three designed device, to design and develop an efficient inertial sensor depends on what application that the inertial sensor will be used because different applications required different enhancement on its parameter. The second and third designed device mention that the sensor can be used shock and vibration detection for automation, great accuracy inertial triangulation, earthquake prediction, seismic sensing for geophysical and oil-field usage, and also healthcare application. But the first design did not mention on its application, so it be assume based on standard application like automation.

From studying all the designed, the third device gives the most complete report. It included a supported simulation result that can verified the fabricated design, and the fabrication method which is DRIE before releasing the device can avoid the stiction problem that certainly not allowable in fabricating an inertial sensor.

the sensitivity of the sensor also showed which the most important criteria for a sensor are very high which is 0.492 pf/g.

Any further improvement that can be done is to include the yield result of the sensor designed. This can help improved the next designed device.

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