3D MEMS Accelerometers for Building Applications

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Abstract

As Health and Usage Monitoring Systems (HUMS) are gaining wide acceptance to build effective predictive maintenance strategies in many domains, civil engineering will benefit from advanced technologies and data management. Among the different sensing functions that are required for HUMS, one can find the accelerometers. In many aspects, micro-electro-mechanical system (MEMS) technology can benefit and help democratise Health and Usage Monitoring Systems in civil engineering structures. In this paper, we will present what are the most commonly used transducing principles for MEMS accelerometers. The different means of implementing the 3D sensing functionality are also compared and a description of the fabrication process of what is thought to be the best candidate i.e. a single die 3D capacitive accelerometer is given. In particular, the wafer level packaging (WLP) technique, which drastically simplifies the implantation of the out of the wafer plane acceleration sensing is described.

Keywords: Health and Usage Monitoring Systems, Building monitoring, MEMS acceleration transducers, 3D MEMS accelerometers, Wafer level packaging

1. Context

As Health and Usage Monitoring Systems (HUMS) are gaining wide acceptance to build effective predictive maintenance strategies in domains as wide as avionics, electrical networks or train transportation, civil engineering will benefit from advanced technologies and data management. Continuous monitoring of large and complex structures like bridges, roads, buildings, or amusement park rides require monitoring and control functions, communication functions, and sensing functions.

Sensing functions are obtained with numerous different types of sensors among which one can find accelerometers. The specifics of such accelerometers rely in their ability to detect low noise signals, with appropriate accuracy, ultra low power consumption and to sustain harsh environments. Price of such device is also one of the key additional requirements in order to deploy systems at a large scale and to multiply the number of sensors per infrastructure.

An accelerometer is an inertial sensing device that measures the rate of change in velocity. The technology which is currently used for making accelerometers for civil engineering applications is quite traditional and accelerometers are then bulky and expensive. In many aspects, MEMS technology can benefit and help HUMS in civil engineering structures become more accessible. Over the past decades and very last years, MEMS accelerometers have made a large intrusion in our everyday life.

The primary market item in terms of unit sales are high g accelerometers used in the automotive market. Airbags represent one of the most successful examples for the implementation of microsystems-based components. In such safety systems, a microsystems technology based (MST) motion sensor detects frontal impacts resulting from large changes in acceleration (up to 100 g) and triggers the inflation of airbags in the driver and passenger seats. Due to the much smaller crumple zone, side impact sensors operating up to 250 g and reacting within a few milliseconds have also become widely used.

Portable consumer products also offer large opportunities for the deployment of low g accelerometers. A small change in force (1 - 2 g) occurs when a handheld device (cell phone, MP3, PDA, etc) is either tilted or in motion. The resultant signal has a signature that can be sensed using a MEMS based accelerometer. This signature can be programmed as an interface command, allowing gestures to control the functionality of cell phones and other similar personal devices.

Another interesting application for accelerometers is for their use in "freefall" detection of hard disc drives (HDD) of portable devices such as MP3 players, but also IT peripherals such as notebooks. A multi-axis accelerometer senses when the instrument is in a free-fall (or zero g) mode. When this state is detected, a command is sent to park the head in order to avoid damage to the disc.

Whereas all the above market segments have entered (or are entering) a maturity stage in the product lifecycle, manufacturers of MEMS accelerometers are very much attracted with new high potential market segments with quite different technical requirements though.

MEMS accelerometers are small, robust, feature low power consumption and are sufficiently inexpensive to enable significant value added sensing functionality in a wide variety of applications. The incredible material properties of single crystal Silicon combined with batch processing and ultra-small size of the MEMS accelerometers make them one of the best candidates to address the civil engineering market and its requirements.

This paper highlights the pros and cons of each potential MEMS technology in order to address the specific needs for structural health monitoring.

2. MEMS Accelerometers

2.1. Overall system

Within the MEMSCON project a 3D accelerometer is required for the measurement of accelerations during an earthquake. The accelerometer will be rigidly mounted on the finished building. Therefore the requirements concerning the size are uncritical. The accelerometer will be mounted as a discrete component together with the ASIC and other components on a PCB board to form the RFID Tag (Fig. 1).

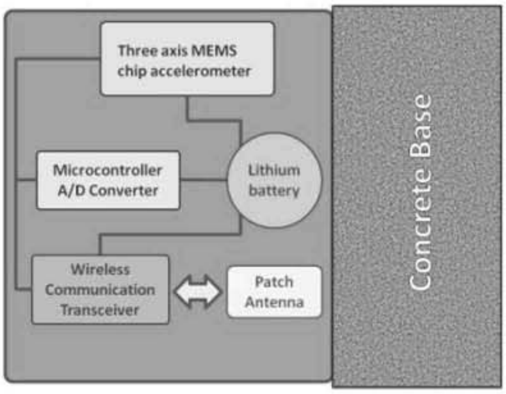

Fig. 1. Schematic representation of the 3D accelerometer RFID tag

2.2. Accelerometer specifications

The major requirements are summarized in the following table (Table 1). The most challenging requirement is the low power consumption to achieve the required battery lifetime of the complete accelerometer RFID tag. Although the main power consumption is expected to be in the wireless communication part of the RFID tag, the selection of the measurement principle must consider this requirement.

Table 1
Accelerometer end-user specifications

Parameter	Value	Unit
Acceleration during earthquake	0.01- 2	g
Frequency of acceleration during earthquake	0.1-10	Hz
Estimation of the average duration of an earthquake	15	s
Size constraint for acceleration sensor / whole module	uncritical	-
Operating temperature	-20 to +50	℃
Operating humidity	0 to 100	%RH
Vibrations (15g)	1000	Hz
Shocks	2000	g
Battery lifetime	2	years

2.3. Possible transducing principles

For high end applications the so called vibrating beam accelerometers (VBAs) are used. They are based on the fact that a frequency driven oscillator exhibits a frequency shift which is a function of acceleration applied to a proof mass.

However, most accelerometers are based on a spring mass system (Fig. 2). The acceleration applies a force on the mass. As a result the mass moves and the displacement generates a counterbalancing force in the spring. At equilibrium, the force generated by the spring equals the force generated by the acceleration, and the acceleration can be calculated from the displacement. Therefore an accelerometer is a mainly a displacement measurement system.

Displacements can be detected either directly by using e.g. an interferometer, or indirectly by measuring the effect of the displacement. Most commercial accelerometers are using nowadays the indirect measurement approach. MEMS are mainly using three methods:

- the piezoelectric effect
- the piezoresistive effect
- or, the capacitive detection

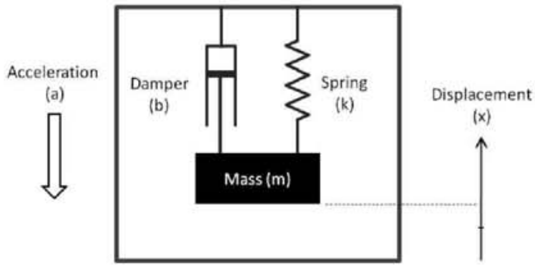

Fig. 2. Schematic representation of the 3 D accelerometer RFID tag

2.3.1. Piezoelectric detection

Many crystals generate an electric charge when subjected to a mechanical load. This correlation is known as the piezoelectric effect. Piezoelectric measuring technology is the perfect tool for carrying out measurement tasks with extreme requirements in terms of geometry, temperature range and dynamics.

Piezoelectric accelerometers consist essentially of three basic elements: the sensor body, the piezoelectric sensing element and the seismic mass. Initially piezoelectric accelerometers incorporated a compression design whereby the compression cut, quartz crystal sensing element is preloaded between the base plate and seismic mass. Because of the constant seismic mass, the force acting on the measuring element is proportional to the acceleration in accordance with Newton's second law F=m*a. An electrical charge is generated proportional to the force (hence the acceleration).

Application of force to a crystal deforms its lattice structure. For a crystal to exhibit the piezoelectric effect, this structure has to lack a center of symmetry. Synthesized quartz (SiO2) is therefore very suitable. The deformation forces its positive silicon and negative oxygen ions towards each other. The resultant shift in the centre of positive and negative charge generates an electric charge on the surface of the crystal.

The piezoelectric effect can only happen in non-conducting materials. Piezoelectric materials for sensor elements must exhibit very high mechanical strength and rigidity above all else. Other requirements include stable mechanical and electrical properties over a wide temperature range and a long service life. High sensitivity, good linearity, negligible hysteresis (that is identical rising and falling calibration curves) and high electrical insulation resistance are further advantageous characteristics. The most important materials used for measurement solutions are quartz, the quartz-like crystals and piezoceramics.

Piezoelectric measuring systems are active electrical systems. The crystals produce an electrical output only when they experience a change in load. For this reason, they cannot perform true static measurements.

However, quartz sensors exhibit remarkable properties which justify their large scale use. They are extremely stable which makes them an excellent candidate for Vibrating Beam Accelerometers (state of the art of navigation accelerometers in military and avionics applications for standalone IMUs).

Silicon has no piezoelectric effect, and the deposition of piezoelectric materials (e.g. PZT, BaTi) is difficult, and not IC compatible. Therefore the use of the piezoelectric effect is almost exclusively limited to quartz accelerometer. These types of accelerometers are extremely accurate with very low drifts, but expensive. They are mainly used for application with extreme requirements for low drifts e.g. in high end navigation application.

2.3.2. Piezoresistive detection

The resistivity of certain materials (e.g. silicon) changes when the material is strained. The effect of the piezoresistance is similar to the strain gauge effect in metal material, but the differences between the two effects are fundamental:

- the effect of metal strain gauges is caused by the geometric deformation of the resistor, whereas the piezoresistive effect is caused by the change of resistivity of the material,

- the piezoresistive effect is anisotropic, metal strain gauges are isotropic

- the piezoresistive effect can be much larger that the strain gauge effect.

Implanted and deposited gauges are historically available processes in the MEMS industry since decades. Implanted gauges are made of doped single crystalline silicon, whereas deposited gauges are made of doped polysilicon. Implanted gauges are based on p/n junction that degrades typically above 120℃ (order of magnitude) whereas deposited gauges can withstand approximately up to 180℃.

The gauges are typically located in the spring areas which hold the seismic mass. They are placed in the area with the highest stress in case of bending. Commonly four piezoresistive elements are used, connected in a Wheatstone bridge configuration. The inertial force on the mass due to acceleration forces the springs to bend and causes stress in the springs. This stress, in turn, causes a change of the resistance of the piezoresistors in the beam. The Wheatstone bridge becomes unbalanced, and the output voltage is proportional to the acceleration. Typical output levels of piezoresistive accelerometer are 10 -100mV full-scale output.

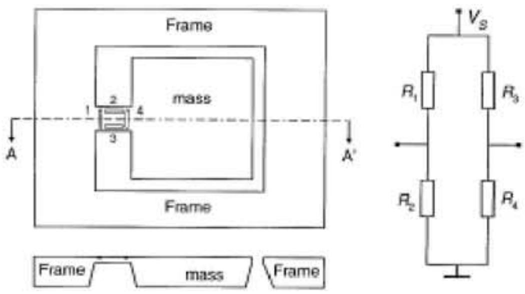

Fig. 3. Piezoresistive accelerometer with a cantilever beam-mass mass

Integrated circuit technology allows extremely small resistor networks to be integrated on the silicon chip. The main advantages of this technology over conventional metal strain gauges are high sensitivity, compactness, and high natural frequency.

Piezoresistive measuring cells made of silicon have excellent static measuring characteristics. Silicon is a single crystal and remains elastic up to its breaking point. It does not undergo any plastic deformation. For this reason, silicon cells are very stable and their properties do not change even over a long period of time.

Piezoresistive accelerometers are widely used nowadays thanks to the high sensitivity, good linearity, and easy signal processing. Nevertheless there are some drawbacks:

- The piezoresistive effect has a large temperature coefficient (typically 2000ppm/℃). Therefore temperature calibration and compensation is mandatory for most applications.

- Piezoresistive sensors are highly stress sensitive, and any mechanical thermal stress induced by the package can cause large offsets and thermal drifts.

The realization of 3D accelerometers with piezoresistive pick up is difficult to realize. As explained above, the resistors need to be placed at locations with high mechanical stress. For out of plane sensors this is achieved by placing the resistors on the surface of the spring. For in plane accelerometer, the point of high stress in a spring would be the side wall of the spring. Unfortunately it is almost impossible with standard IC technologies to realize resistors in that area.

2.3.3. Capacitive detection

The capacitive pick-off technique has several advantages e.g. higher output levels, excellent linearity and a low sensitivity to temperature drift. However, the electronics for the signal processing are more complex, because differential capacitances down to a few fF need to be measured, which makes the devices very sensitive to parasitic capacitances. A typical design of an accelerometer with capacitive pick-off is shown in Fig. 4. A mass centred between two electrodes forms the seismic mass of the spring mass system. The gap between each electrode and the central mass creates a repeatable electrical capacitance. When the mass is forced off-centre by an imposed acceleration, a differential capacitance exists between the two initially equal capacitors C1 and C2. This differential capacitance is (in first order and for small displacement) linearly proportional to the applied acceleration within the specified amplitude range of the accelerometer. The differential approach creates immunity or common mode rejection to environmental influences since both capacitors react similarly and the difference is quasi negligible.

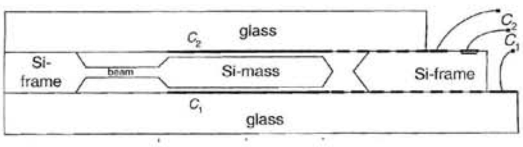

Fig. 4. Schematic cross-section of a bulk micromachined capacitive accelerometer [1]

Both modern bulk micro-machining processes and Deep Reactive Ion Etching (DRIE) techniques produce very high accurate and repeatable elements that are required for high precision sensors. They allow the combination of a "large" mass and a "large" capacitor (from 1 to 10 pF range). For applications with large dynamic ranges, or large measurement bandwidth, closed loop operation can be implemented. Within these systems the position of the central mass is restored to its origin by presenting an electrostatic force to the appropriate electrode. Self test features are also easy to implement via electrostatic test signal.

2.3.4. Vibrating beam accelerometer

The VBA principle relies on the fact that a vibrating beam behavior is changing under the effect of a stress that is applied along its axis. Its natural frequency changes with the traction, or compression, force (see Fig. 5). This principle can be compared as tuning a violin string. The acceleration sensing is usually done by means of an inertial mass M at the end of the beam.

VBAs are currently made of Quartz, and using piezoelectric detection of the frequency shift. Quartz technology is an expensive fabrication technology, and therefore these components are exclusively used for inertial navigation systems, where the long time stability is of high importance.

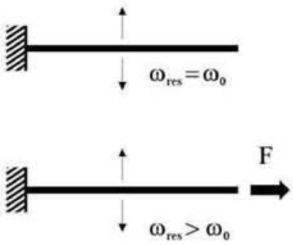

Fig. 5. VBA principle. Under the effect of an axial force, the resonance frequency of the beam varies. The resonance frequency increases when tensile stress is applied, and it decreases when compressive stress is applied.

In order to achieve a "low cost" VBA a transfer into silicon could be possible. That would imply also to use a capacitive detection instead of using the piezoelectric effect as the transducing mechanism for devices made in Quartz.

Therefore for the MEMSCON project the Silicon VBA has no clear advantages over use of a simple spring mass system.

2.3.5. Conclusion of transduction principles

Table 2 summarizes the advantages and disadvantages of the different transduction principles. The capacitive sensing is thought to be the most suitable principle for building monitoring application.

2.4. MEMS technologies for accelerometer

2.4.1. Bulk micromachining

Historically, MEMS accelerometers have been manufactured with a technique called "Bulk Micromachining". This technique allows to etch the bulk part of a wafer typically using wet etch techniques (batches of wafers are put in a bath of chemical solutions) and according to some crystal planes of the Silicon. A typical shape obtained is a pyramidal etch at 54.7° corresponding to the (111) planes of Silicon. This technique, combined with wafer level bonding allows building "large" seismic mass structures. Fig. 6 below illustrates this approach.

The thickness of the wafer and the angle of 54,7° makes each die relatively large compared to other types of etching.

Yield is a common problem due to the difficulties to align properly the multiple wafers for the bonding steps (typical alignment accuracy in these steps is 2 to 10 microns). The other problem which affects yield is the fragility of the wafers: the number of holes weakens the wafers for all the manipulation steps, especially since holes are aligned with crystal planes of Silicon due to the etching technique used.

Even though this technique is taking advantage of batch processing, still relatively large costs are occurring due to low yield, and relatively low number of devices one can make on a single wafer.

Typically, bulk micromachining techniques provide with low noise components since the large seismic mass reduces the Brownian noise. On the other hand the cross talk can be high due to wafers misalignment diring the bonding steps.

Table 2
Comparison of transduction principles

Principle	Advantage	Disadvantage
capacitive	Small sensing elements Good resolution Good stability Low temperature dependency Easy implementation of closed loop operation and self test possible Low power consumption	-Complex circuitry needed
piezoresistive	Simple electronics Simple system behaviour Excellent linearity	Sensing element sensitive to the packaging stress Difficult to design and manufacture for reliability Difficult to realize 3D accelerometer
piezoelectric	High accuracy Low drift	Complex manufacturing Expensive Difficult to integrate with Silicon
Silicon VBA	High accuracy Low drift High SNR	Complex circuitry needed Sensing element sensitive to packaging stress Difficult to realize 3 D accelerometer “Exotic” solution with more development efforts

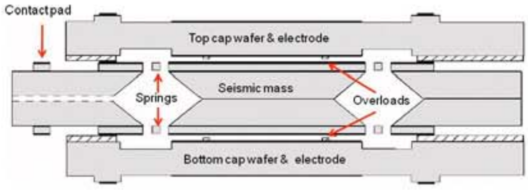

Fig. 6. Bulk micro machined capacitive accelerometer (Colibrys)

2.4.2. *Surface micromachining*

In contrast to bulk micromachining surface micromachining is using the silicon wafer only as handle wafer. The MEMS structures are built on top of the wafer by subsequent deposition and etching steps of thin films. Sacrificial layers are used to almost completely remove certain layers, allowing the fabrication of movable structures.

In the beginning, the thickness of the movable structures was limited to a couple of microns thus limiting the achievable capacitance values. To overcome the problems with dominating parasitic capacitances, a monolithic integration of the electronics (i.e. the electrical structures are realized on the same chip as the MEMS) was necessary, and the technology accessible only to companies with IC technology. Fig. 7 show the first commercial available monolithic integrated accelerometer from Analog Devices Inc.

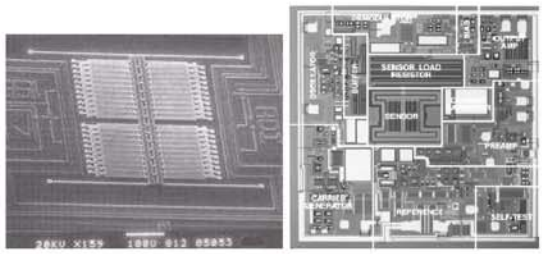

Fig. 7. Analog Devices accelerometer: mechanical element (left) and full sensor (right)

In the 90’s, Deep Reactive Ion Etching (DRIE) revolutionized the world of inertial MEMS. This technique, initially developed by Bosch, allows to anisotropically etch structures with a very high aspect ratio (up to 70), and smooth side walls. Combined with Silicon On Insulator (SOI) wafers with thick device layer (from 15 to 100 microns), DRIE allows MEMS manufacturers to increase the size of the seismic mass compared to thin Silicon available so far (a few microns), and dramatically increases the nominal capacitance of the devices.

That new technology opens the path to capacitive sensors with reasonable capacitance values in the range of 10pF and enables the hybrid integration of these sensors with the ASIC. Fig. 9 shows a hybrid integrated accelerometer from Robert Bosch Company as example.

Fig. 9. Examples for hybrid integration of MEMS and ASIC (Bosch)

The advantage of hybrid integration over monolithic integration is the decoupling of the MEMS fabrication from the ASIC process. MEMS and IC processes can be chosen independently, and both parts of the sensor can be optimized. Development costs are lower, and the adaptation to different application areas is simpler.

Surface micro machined accelerometer for in plane accelerations are typically built as interdigitated differential capacitive accelerometer as shown in Fig. 10. A movable proof mass is building the movable plate of a differential capacitor. Fixed fingers are building the fixed plate of the capacitor. In case of an in plane acceleration along the longitudinal axis of the structure the mass hence the movable capacitor plate is forced to move. The resulting change of the two capacitors is a measure for the deflection, which is proportional to the acceleration. The size of the mass and the supporting spring allows the adaptation of the acceleration to be measured.

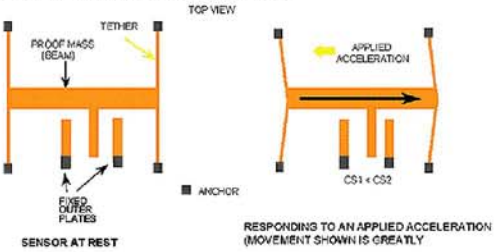

Fig. 10. Functional principle of an interdigitated capacitive accelerometer

2.4.3. *Conclusions on MEMS technologies*

The following table (table 3) gives a summary of the advantages and disadvantages of the different technologies.

Table 3
Comparison of MEMS micromachining technologies

Technology	Advantages	Disadvantages
Bulk	Large seismic mass results in low noise	Large devices Complex process with stacks of wafers Difficult to realize 3D accelerometers
Surface	Small devices Well suited for capacitive sensors In combination with DRIE, large capacitors	Higher noise due to smaller mass

2.5. Concept of 3D accelerometer

For the realization of 3D accelerometer three different concepts are possible which are described below.

2.5.1. *Mounting of three 1D accelerometers*

The simplest solution to realize a 3D accelerometer is the mounting of three 1D sensors accordingly (Fig. 11). The disadvantages of this approach are the possible misalignment among the different sensors, the relative high cost of the assembly and the large size of the final 3D sensor.

Fig. 11. Two 1D Accelerometers mounted on a block to form a 2D accelerometer (Colybris)

2.5.2. *3-axis sensitive mechanical structure*

Mechanical elements are more or less always sensitive to accelerations in all directions. For a 1D sensor, the design goal is to reduce this cross sensitivities to a minimum by making the mechanical element very rigid in all directions except the desired one. But it is also possible to use this effect to get a 3D accelerometer as shown in Fig. 12. The biggest disadvantage of this approach is the large cross sensitivity between the different axes.

2.5.3. *3 independent structures on the same die*

Both in bulk micromachining and surface micromachining, elements can be designed in a way that they are sensitive to accelerations in and out of plan. Fig. 13 shows an example for a 3D capacitive accelerometer from VTI in bulk micromachining technology which is using 4 elements that are deflecting in case of acceleration. Data treatment is necessary to back calculate to the acceleration in the three basic directions x, y and z.

For surface micromachining technologies, the use of two structures shown in Fig. 10 rotated by 90degree allows the realization of a 2D accelerometer. For the third axis for the out of plane accelerations, different designs are possible. Fig. 14

shows the solution of Motorola, where a plate supported via four springs is covered by a counter plate and forming a parallel plate capacitor with one movable plate.

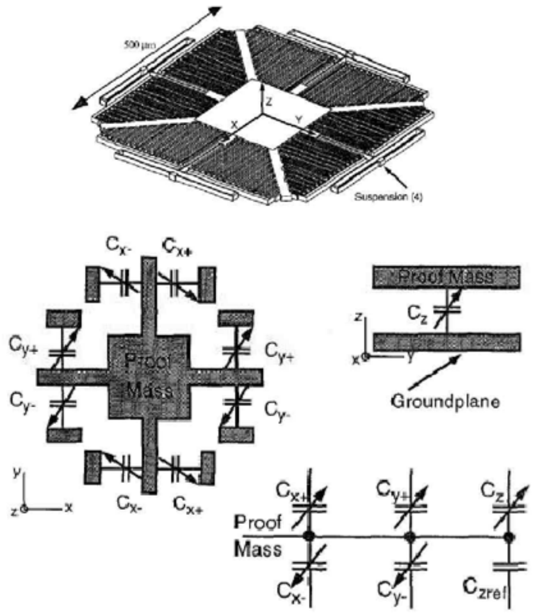

Fig. 12. 3D accelerometer with common proof mass [2]: 3D sensing element (top), and capacitor schematic (bottom)

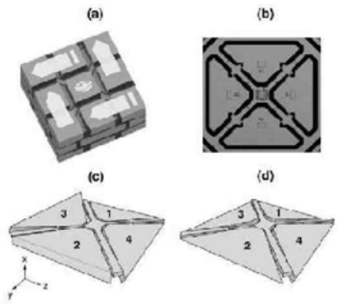

Fig. 13. 3D accelerometer [3], (a) encapsulated accelerometer, (b) top view structural element of the accelerometer, (c) z-directional, and (d) x-directional acceleration.

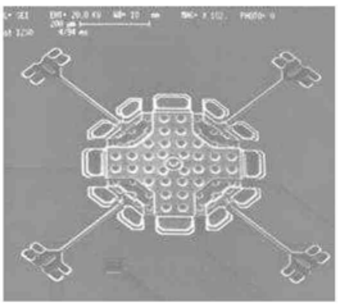

Fig. 14. Z-axis accelerometer of Motorola

In another design a pendulum that is supported via two torsion bars is building the movable plate of the capacitor, and the fixed counter electrodes are located underneath the pendulum on the substrate. The advantage of this approach is the fact, that the cross sensitivities can be very small as each element can be designed very stiff in all undesired directions.

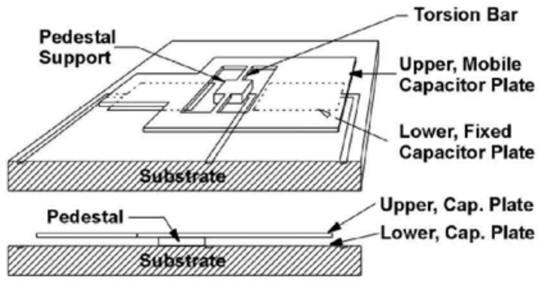

Fig. 15. Pendulum type z-axis accelerometer

2.5.4. Conclusion of the 3D concept

The following table gives a summary of the advantages and disadvantages of the different 3D concepts.

Table 4
Comparison of 3D concepts

Principles	Advantages	Disadvantages
Mounting of 3 1D accelerometers	Simple Not yield sensitive	Large final device Expensive assembly to achieve sufficient alignment accuracy
One mechanical structure sensitive in all 3 axis		Large cross sensitivities
3 independent mechanical structures on the same die	Low cross sensitivities Easy assembly Low manufacturing cost	Yield sensitive

2.6. Description of the selected sensor concept

Based on this evaluation, a capacitive sensing principle with mechanical elements realized in a surface micromachining technology is selected for the MEMSCON accelerometer. The sensor will use independent mechanical elements for each axis. For the in plane sensing, interdigitated comb structures as shown in Fig. 10 and for the out of plane sensing a pendulum as shown in Fig. 15 will be realized. The fabrication technology for the three elements is identical; therefore the three elements can be placed on one die as shown in the next figure.

Fig. 16. Concept for the 3D accelerometer

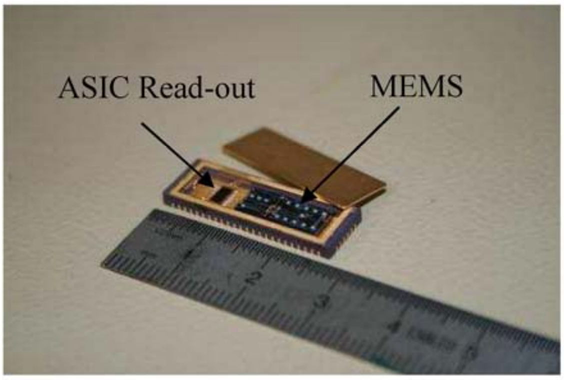

Fig. 17. 1st accelerometer prototype with MEMS and ASIC dies in a ceramic leadless carrier.

3. Fabrication

3.1. Wafer level packaging

Under normal environmental pressure conditions, the MEMS would run into an overdamped regime. In that case the functionality of the accelerometer could not be guaranteed especially regarding the linearity in the bandwidth. Therefore, vacuum is needed. It appears from simulation that the pressure level must be controlled in the vicinity of the moveable elements and that it should be about 1Torr.

The wafer level packaging (WLP) technique consists in bonding a cap wafer onto the MEMS wafer once the moveable structures are released. This technique offers several advantages compared to traditional packaging techniques. First, it allows the protection of the fragile MEMS structures from the early stages of the manufacturing process and eases the problematic step of the singulation of the MEMS dies. Furthermore, since the bonding step can easily be performed under controlled pressure, the vacuum inside the MEMS accelerometer is set at the desired value. And finally, WLP takes full advantage of the parallel manufacturing to drastically reduce the cost associated to the packaging. With traditional packaging techniques the cost of the packaging can be as high as 50% of the final sensor manufacturing cost.

In addition, WLP simplifies the implementation of the out-of-plane acceleration sensor since the counter electrode can be integrated into this cap layer.

Therefore, the WLP technique is used for the realization of these accelerometers.

3.2. Fabrication process

As previously explained, the proposed concept uses three separate mechanical elements, one for each axis. For the in plane accelerations (x and y directions) the sensor is using interdigitated comb structures, which form a differential capacitor. The fixed plates of the differential capacitor are formed by fingers attached to the substrate, whereas the movable part is a mass with fingers attached. Two of these structures rotated by 90 degree's are placed on the die. For the measurement of out of plane accelerations (z axis) a pendulum with asymmetric mass distribution is used, which is forming the movable part of a differential capacitor (Figure 16). The fixed part is realized by counter electrode on top of the mechanical element (figure 18). Although the basic structure of the x- and y-sensors and the z-sensor is different, an appropriated design allows the achievement of similar sensor parameters. A sensor SOI wafer is used for the MEMS sensors. The device layer is 85um thick, the buried oxide 2um and the handle silicon 635um. The mechanical structures are defined by a combination of DRIE etching and sacrificial layer etching.

The cap is formed by two silicon wafers bonded together. The top wafer of the cap stack is etched with KOH to allow the electrical contact to the cap bottom wafer. For the bottom part of the cap, deep trenches are etched all around the different areas to ensure the electrical isolation. For the top part, the isolation is guaranteed by a thick surface oxidation (1-2um) of the silicon wafer (green area in the figure 18). The cap itself is mounted to the MEMS wafer by using a metal-silicon eutectic bonding process. The metal for the sealing ring is also used to realize the electrical connections between the cap and the MEMS wafer.

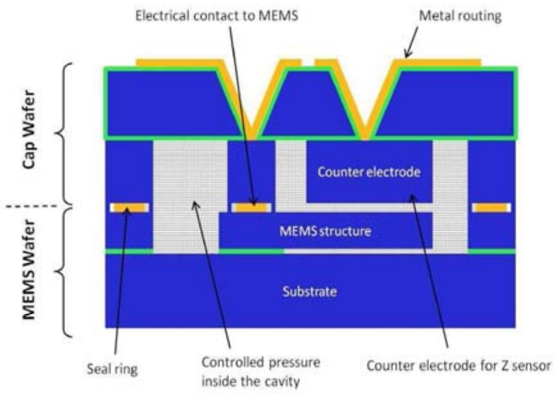

Fig.18. Schematic sensor cross section

4. Conclusion

In this paper, we presented the different transducing principles that are commonly used for the realization of accelerometer MEMS sensors. The capacitive sensing is thought to be the most suitable principle for building monitoring applications. The implementation of the 3D functionality has also been analysed and a description of the MEMS 3D acceleration sensor fabrication process is given.

Acknowledgements

The authors would like to thank Juan M. Santana and Richard Van den Hoven from IMEC-NL for the fruitful collaboration in developing the accelerometer module (MEMS + ASIC). MEMSCON is a FP7 funded project.

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