Inertial Sensors for Automotive Applications

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SUMMARY

There are two distinct automotive applications for inertial sensors: safety and chassis control systems. In the former the dominant technology is surface, in the latter bulk micromachining. The large proof mass and rigid structure make bulk micromachining optimum for low g-ranges. The ultimate limitation is sticking due to adhesion forces. The state of the art bulk micromachined accelerometer is a five-layer sandwich of silicon and glass. Wet etching and anodic bonding are the key technologies. Inertial switches and angular rate sensors can also be produced in the same process. DRIE, SOI wafers and advanced glass processing can further improve bulk micromachined sensors.

Keywords: Automotive, accelerometer, inertial.

INTRODUCTION

The automotive industry has led the way to high volume applications of micromachined sensors. The examples are absolute pressure sensors for intake manifold pressure, accelerometers for several control systems and most recently angular rate sensors. The information gathered from the inertial sensors is used to determine the state of the motion of the vehicle in order to initiate control measures, which aim to maximize the safety and comfort.

It has been recognized that MEMS is not a single technology or a single market but several distinct ones [1]. A surprising variety of technologies are used to build sensors within such a narrow area as automotive motion measurement. Surface micromachined devices dominate air-bag systems. Bulk micromachined capacitive accelerometers have the major part of the business in low-g applications. The dominant angular rate sensor technology is based on quartz. Silicon rate sensors have not yet achieved performance comparable to quartz devices and cost targets expected.

This paper describes automotive applications where low-g accelerometers and angular rate sensors are used, presents the state of the art in bulk micromachined low-g accelerometers and discusses some developments.

AUTOMOTIVE APPLICATIONS

Automotive chassis control systems aim at controlling the motion of the vehicle in normal driving conditions beyond the limits of human capabilities or beyond the limits of passive suspension. In these applications there is a market for up to over 10 million accelerometers and several million yaw-rate sensors. Economically this business is comparable to the air-bag sensor business and is growing more rapidly.

Electronic stability systems

In antilock braking systems (ABS) the hardware is not utilized to full capability. If brakes were applied asymmetrically the vehicle could be forced to follow a predetermined trajectory. Over or under steering, rotation and fish tailing could be prevented. To accomplish this additional sensors are needed: a yaw-rate sensor, a transverse accelerometer and a steering angle sensor. The wheel speed sensors of ABS are still needed and in a 4-wheel drive vehicle a longitudinal accelerometer. The accelerometers are for ±1 to ±2 g range with total error over operating conditions and lifetime less than ±60 mg. The angular rate sensor has a 50 to 100 °/s range with a zero point error less than ±2 °/s. The sensors are placed at the center of gravity as stand-alone modules or integrated with the controller.

Suspension systems

The vertical movement of an automotive chassis is controlled by a passive spring-shock absorber combination. The aim is to isolate the chassis from the irregularities of the road. A trade-off is to be made between safety and comfort. The result is better if the spring or the shock absorber is made dependent on the motion. Controlling the damping is easier. The most sophisticated systems contain up to six accelerometers, which measure the motion of the chassis and the wheel hubs. The chassis accelerometers are for ±1.5 g on top of the 1 g bias due to gravity. The wheel hub accelerometers are for ±12 g range. The accelerometers are stand-alone devices located close to the springs and the shock absorbers.

BULK MICROMACHNED LOW-G ACCELEROMETERS

The most common accelerometers in automotive low-g applications are silicon capacitive bulk micromachined devices. The main reason is performance. A large proof mass, thin etched springs and large value capacitances enable to achieve the required high zero point stability, low noise and controlled damping. The ultimate limiting factor when increasing the sensitivity is sticking at overload. Adhesion force remains constant while the inertial force and the restoring spring force are scaled down. A large proof mass (Figure 1) guarantees high margin to sticking.

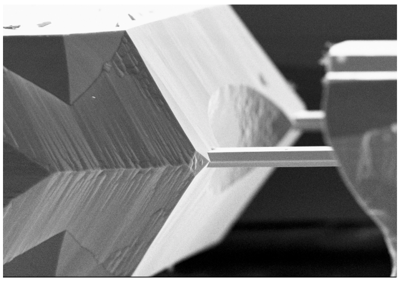

Fig. 1: *A large proof mass utilizing the entire wafer thickness enables to measure very low g-ranges with high accuracy and without sticking.*

Sensor structure

The leading low-g accelerometer is a five-layer structure of silicon and glass (Figure 2). The center layer of silicon contains the proof mass and springs. It resembles the one presented in [2]. It has been in mass production for 11 years with a couple of re-designs for smaller size. Currently the size is 2.6x2.8x1.9 mm^3. The cantilever beam spring is 20 µm thick. The dielectric gap between the proof mass and the electrodes is 2 µm. The capacitance is 8 pF. The cavity is filled with argon gas at a chosen pressure for controlling the frequency response as discussed in [3].

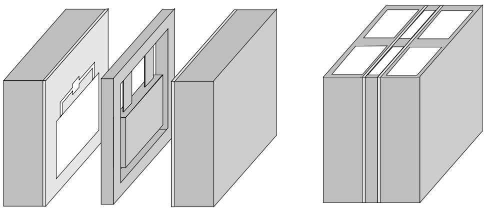

Fig. 2: *The accelerometer is a five-layer sandwich of silicon and glass*

Manufacturing process

Annually 7 million accelerometers with the above design are processed on 150 mm wafers. The outer wafers are 800 µm thick. They are coated with a 100 µm thick layer of borosilicate glass. The glass is deposited by melting, grinding and polishing to a surface finish adequate for anodic bonding. The double side polished middle wafer is anisotropically wet etched to form the proof mass and the springs. No etch stop technique is used. The uniformity of the spring thickness is limited by the TTV of the wafer. The stack of three wafers is anodically bonded in a single step at reduced pressure. Finally the stack is diced and contact pads are evaporated on the side of the sensor by vacuum evaporation through a stencil mask

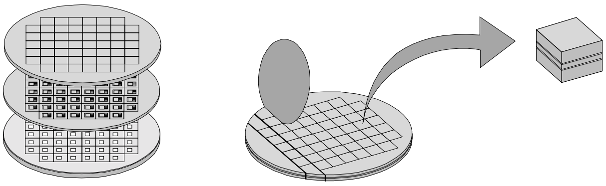

Fig. 3: *Three wafers are bonded into a stack, diced and finally contact pads are deposited.*

AUTOMOTIVE SENSOR PACKAGING

Low level packaging

Lowest level packaging aims at protecting the sensitive parts of the MEMS device and providing means for electrical contacting. In the sensors discussed here this is achieved by enclosing the proof mass, springs and electrodes hermetically with anodic bonding and depositing land areas directly on silicon. The sensor can be wire bonded or used as SMD directly on organic PWB with excellent reliability as in Figure 4.

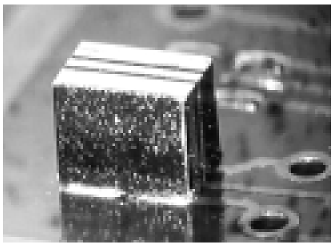

Fig. 4:*A bulk micromachined accelerometer can be used as SMD with excellent reliability*

Next in the packaging hierarchy is the component level. The sensor is combined with an interface circuit and some environmental protection. The aim is to produce a device with a high level output, remove the unit to unit variation and provide means for assembling with standard microelectronic means (like SMT).

In theory the whole system could be combined to the final, application specific package. This would be an optimum choice for a very large volume small sized product. But usually the same component is used in many different applications and in large sized end products, which would be uneconomical to test and calibrate. Finally, it is the sensor manufacturer who shall be responsible for the measurement accuracy.

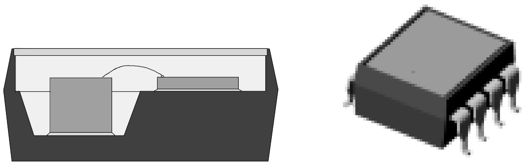

Fig. 5: *Pre-molded plastic DIL-type package is used for bulk micromachined accelerometers*

Bulk micromachined sensors are extremely sensitive to mechanical stress and humidity and have bulky size and shape. Typical packages look awkward when compared to state of the art microelectronic packaging. A transfer molded or pre-molded die cavity plastic package (Figure 5) guarantees functionality and reliability. The capacitive sensor and an interface circuit are assembled in the cavity and wire bonded to each other and to the leads. Silicon gel is molded over for humidity protection and a lid is sealed. The sensor has to withstand severe environmental testing like 2000 thermal shocks between –40 and +125 °C.

Stand-alone Modules

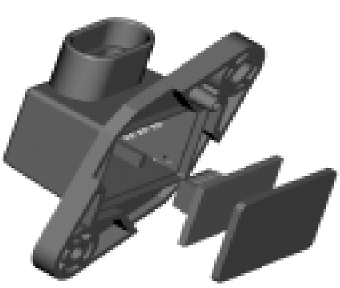

Fig. 6: *The component level packaged sensor is assembled with other components to an application specific stand-alone housing*

The final application specific packaging for automotive low-g accelerometers and angular rate sensors vary greatly even within the same application. The sensors may be integrated with the controller. More often they appear as independent stand-alone modules or sensor clusters where several sensors share the same housing. A stand-alone sensor is typically a plastic package with dimensions well below 50 mm and with an automotive platform dependent mechanical mounting and electrical connector. In addition to the sensor the package contains components for over and reverse voltage protection and EMI shielding on a small PWB. This assembly is soldered or welded to the connector terminals and the housing is filled with polyurethane.

OTHER INERTIAL SENSORS

Inertial switch

Launching of the air-bag in a non-crash situation is to be avoided by all possible means. A redundant inertial sensing device, an inertial switch that doesn't share failure modes with the primary device is used.

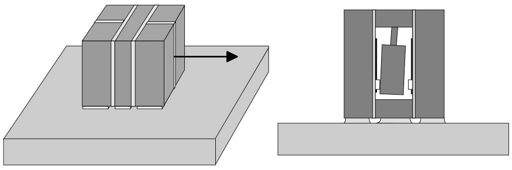

Fig. 7: *Micromachined trigger switch is based on the low-g accelerometer*

The inertial switch is a low-g device since the triggering level is in the order of 5 g. The bulk micromachined accelerometer described earlier was converted to a switch by adding a contact point to both sides of the proof mass. The capacitor plates are used for electrostatic self testing. The contact resistance is better than 300 ohms. More than 10^5 closure cycles have been tested succesfully. The switch can be directly soldered in a standard SMT process as in Figure 4.

Angular rate sensor

There are two general problems with silicon angular rate sensors: the lack of an efficient force generating mechanism and the extreme requirement for orthogonality of the vibration axes. Difficulty of matching the capacitive detection electrodes to external circuits and acceleration and vibration sensitivity due to flexibility of the structures or spurious mechanical resonances are also typical for silicon sensors and depend on the technical choices.

In [4] the first results from an angular rate sensor (Figure 8) based on largely the same manufacturing process as the low-g accelerometer were presented. After some re-designs the performance has been verified and is within the automotive requirements. The noise level is 0.02°/s/√Hz. The zero point is stable within ±10 °/s over the temperature range without compensation. There are no vibration effects below 5 kHz.

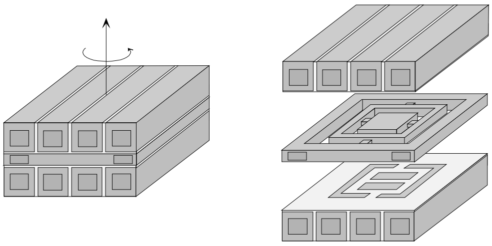

Fig. 8: *Silicon angular rate sensor with electrostatic excitation and capacitive detection*

DEVELOPMENTS IN BULK-MICROMACHINING

SOI and DRIE

While bulk micromachining is a 20 years old technology one doesn't have to limit the concept to the traditional processes. The anisotropic wet etching of silicon wastes area due to sloped side walls and severely restricts the shapes that can be produced. DRIE through the wafer enables to create arbitrary shapes while maintaining the proof mass thickness and rigidity of bulk micromachining. SOI wafers can be utilized to produce springs with the oxide layer acting as an etch stop. Figure 9 shows a proof-mass spring structure obtained by combining DRIE and wet etching.

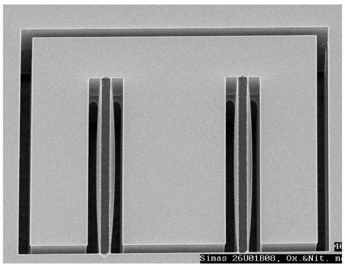

Fig. 9: *Combination of DRIE and wet etching enable to create mass-spring structures with optimum usage of area.*

Glass technology

Capping the sensitive mechanical structures (or so-called 0-level packaging) will always be a necessity for inertial sensors. External hermetic package can provide the protection but is costly. It is difficult to use deposited films for capping on large area structures. Capping by joining a second wafer or glass plate is currently the best approach. Then the remaining problem is how to get electrical access into the capped space.

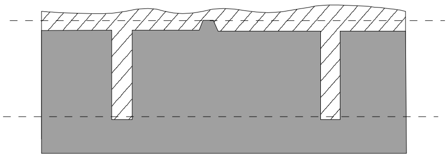

Fig. 10: *Glass is melted on the surface and into the grooves, ground on both sides and repolished for anodic bonding.*

A glass inlay method (figure 10, [5]) has been used in several inertial and pressure sensor prototypes. Glass is melted on a machined silicon wafer. Both sides of the wafer are ground and the side to be anodically bonded is polished. The horizontal glass layer thickness is typically 100 µm and the vertical inlays are 200 µm wide. The resulting wafer contains thousands of mutually isolated silicon islands in a glass matrix. Each island functions as an isolated hermetic feed through to the enclosed cavity.

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