A Modular MEMS Accelerometer Concept

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A quasi-monolithic MEMS concept setting up a new family of MEMS-based sensors is presented. The concept combines the advantages of hybrid MEMS with respect to optimal technology choice, and of monolithic integrated MEMS with respect to system integrity, on chip signal conditioning, self-calibration and size.
A sensor signal conditioning circuit and a micro-mechanical sensing element are joined face-to-face by eutectic bonding on wafer level. This sealed system can be used as is, or can be assembled in standard SOIC plastic package. Using this approach, austriamicrosystems AG has developed high performance, low-cost accelerometer sensors.
The accelerometer micro-system consists of the mechanical component die with a single clamped poly-silicon cantilever and an ASIC die with counter-electrodes to measure the distance between cantilever and IC surface. The operation in closed loop mode yields high linearity and large bandwidth. Specific advantages of the concept are: (1) the modular approach is open for advanced sub-micron technologies, (2) the hermetic seal approach paves the way to new vacuum-on-chip MEMS products.

Introduction

Accelerometers gained a significant market share within the multi-billion microsystem market (2002: 90-100 Mio units expected representing a turnover in the range of 400-500 Mio US$ [1]).

Presently, main applications can be found in the automotive market segment (e.g. front and side airbag sensors, ESP respectively chassis stabilization, active suspension, roll over detection). However, low-g sensors enter also new application areas like inclinometry and vibration sensing for instance for anti-theft devices or activity monitoring for pacemaker control. Like in the microelectronics RAM market the 50 g airbag sensor market has been ruined by a prestigious price war. Presently the low-g sensor market, which partially covers also the Inertial Measurement Module (IMM) market, is gaining weight and speed.

Automotive components are high volume products (some million units per year). Beside stringent performance, environmental and reliability requirements, cost became the decisive factor for success in this market. The manufacturing costs consist of

- fabrication cost for the core microsystem including signal conditioning,
- packaging cost, and
- test cost including quality assurance tests.

[1] austriamicrosystems AG, with headquarter in Unterpremstaetten near Graz (Austria), is one of the world's leading designers and manufacturers of custom specific mixed signal ICs. The company has 940 employees and offices in 14 countries worldwide. Despite the semiconductor downturn austriamicrosystems' sales grew in 2001 by 20% to approximately EUR 147 million.

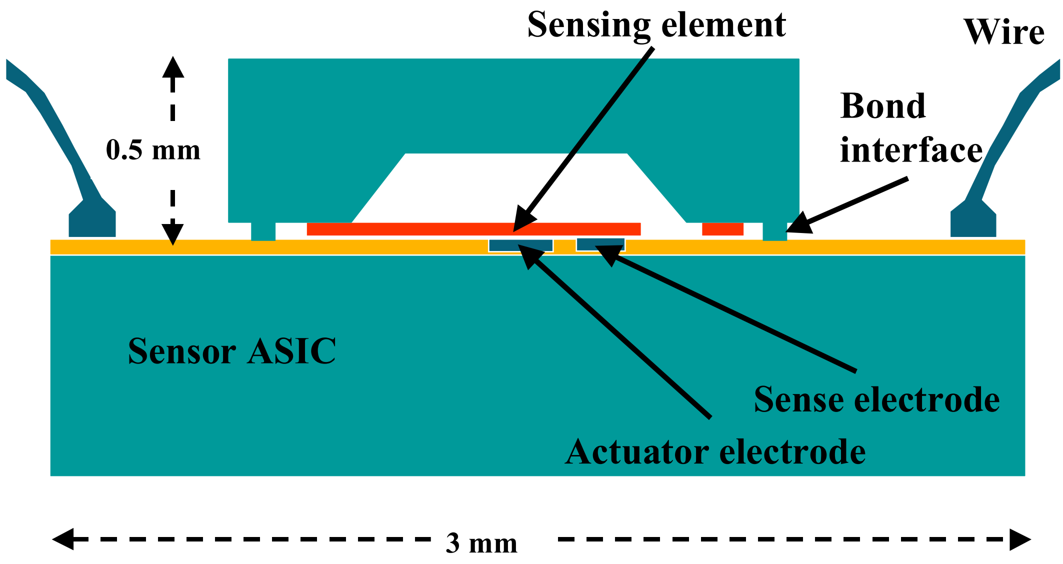

Fig. 1: Schematic view of the accelerometer.

Packaging and test are very often the cost determining factors. Generally, highly efficient designs for manufacturability, packaging and testing are required. Desirably, they should include harmonically integrated first level packaging methods and extensive self-test as well as cheap calibration. The latter should be based on single temperature measurement. However, a highly efficient design is not sufficient. Very often, effort and time needed for the industrialization of a properly chosen design constitutes the main barrier for coming up with the right product at the right time (i.e. time to market). One of the deeper reasons for the difficulties of industrialization of new MEMS is the very sensitive interdependency of performance and technology parameters. This becomes especially important in situations where the technology is not yet mature and stable enough to guarantee the finally required small process tolerances.

Design Approaches and Products on the Market

The first monolithically integrated, commercially available accelerometer sensor was industrialized by Analog Devices [3]. It is based on the capacitive detection of the in-chip-plane movement of a comb structure. The monolithic concept requires a trade-off in IC technology (feature size) and mechanical performance. Therefore, the complexity of signal conditioning on-chip is limited. This affects self-test and diagnostic functions, fine adjustments and calibration. This forces to keep complexity of signal processing at a lower level. The non-modular concept asks for long development times for new design options and, moreover, is yield critical. A ceramic or metal can package is needed.

Industrialized concepts of hybrid accelerometers are available, comprising comb like sensor elements as well as out-of-plan movable beam/cantilever like structures made from dedicated MEMS processes (e.g. Bosch, Motorola [6], VTI [7], [10], Sensonor [8]). They are based on piezoresistive or capacitive measurement principles. Signal processing is placed on a separate IC. Sensor elements and signal processing ICs are packaged in one body, forming the hybrid system. Hybrid systems allow optimized sensor structures as well as the signal processing part to be realized by dedicated and well established manufacturing processes. Larger size and still a considerable packaging effort are the weak points of the hybrid concept. Bosch´s hybrid accelerometers are based on Surface Micromachining using EPI-poly Silicon with DRIE and cap for first level packaging. The concept requires larger sensing elements due to the less sensitive external signal conditioning. This concept is well suited for high performance accelerometers and also supports special applications (e.g. angular acceleration sensor), however the cost structure is an issue and the concept is not suitable for high vacuum applications due to out-gassing of glass seal ring. Similar concepts are used by a number of other MEMS companies (e.g. ST).

Motorola released a hybrid sensor for the ±8 g range. A low-g accelerometer development is ongoing as well, but information on the actual status was not available to the authors.

VTI is currently market leader for automotive low-g acceleration sensors. The hybrid sensor has probably costs advantages over Bosch like surface micro machined hybrid concepts at similar sensor performance but seems to be still a rather high cost technology. The sensor requires dedicated package that is significantly thicker compared to standard.

Some new principles are becoming interesting for commercial applications. Memsic has developed a sensor based on a thermodynamic principle with a hot gas bubble. The sensor is limited to applications with close to horizontal mounting for lateral acceleration measurement, z-axis measurement is not possible. No data on the impact of vibrations in the z-axis direction were reported which may be a critical issue for some applications.

The number of accelerometer developments (and corresponding publications) following the described concepts is huge. Only few of them have successfully entered the market.

Sensor Design

The quasi-monolithic concept of austriamicrosystems represents a unification of the monolithic and the hybrid approach. The movable out-of-plane sensing element is formed by simple bulk micromachining on a second, so called top wafer and can be designed easily for different acceleration ranges. The basic wafer carries the dies with measurement and actuation electrodes as well as with the whole signal processing part. This wafer is processed in standard CMOS technology. Joining the two parts on die (soldering) or wafer level (eutectic bonding), a quasi-monolithic system is created which combines the advantages of the monolithic and hybrid approaches.

To a large extent the concept was the solution and consequence of the following, quite conflicting development goals:

- High performance accelerometers for low, medium and high g applications
- Cost efficient solution for high volume production
- Usage of available CMOS technologies with
- low cost add-ons
- Modularity of sensor design and signal conditioning part
- Usage of standard packaging technologies

The accelerometer concept is demonstrated in Fig. 1. The top die is forming the mechanical sensing component and the bottom die carries the actuating and sensing electrodes and the ASIC. The joined dies are packaged as a single unit. As mentioned, the mechanical sensor module is customizable for different g ranges. The corresponding control and signal-conditioning module can be adapted to the different ranges from a low-g sensor (1 or 2 g for electronic chassis stabilization) to high-g applications (up to 200 g and more for airbag release).

The sensing element is a single clamped poly-silicon cantilever, which forms the mass loaded spring of the accelerometer (see Fig. 2). It is fabricated by photolithography and reactive ion etching followed by a subsequent release step using anisotropic wet etching in KOH solution. This yields a very robust, cost efficient sensing element with most simple shape and practically no cross-axis sensitivity.

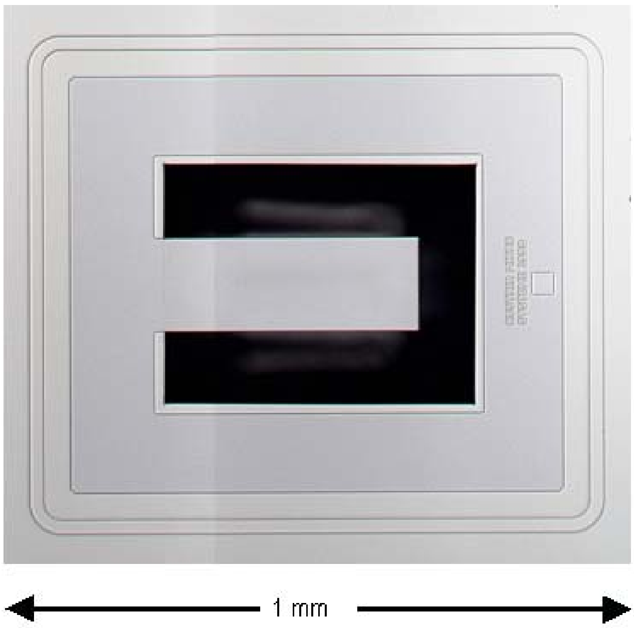

Fig. 2: Mechanical component with poly-silicon cantilever (Top view).

The sensing element die is joined face to face to a CMOS ASIC using a eutectic bonding procedure on wafer level. Thus, the cantilever is hermetically sealed and electrically shielded. In this way, a first level package for the movable cantilever is simultaneously provided, allowing for standard plastic injection molding of the composite structure. An air gap of a few micrometers between cantilever and the ASIC is formed.

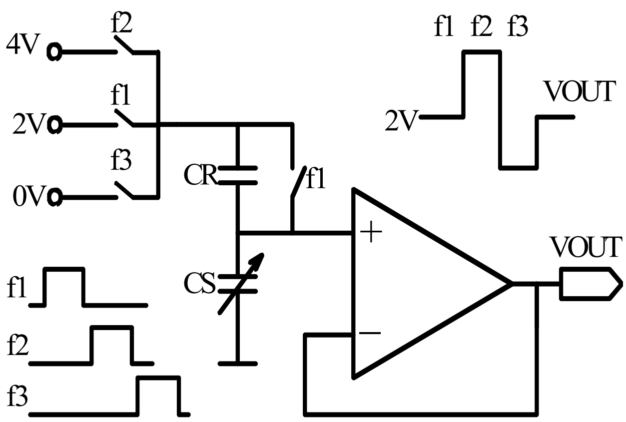

Fig. 3: Sensor Front End: the reference capacitor CR is connected in series with the variable sensing capacitor CS.

The ASIC contains the counter electrodes for the actuation and capacitive position sensing of the cantilever, and the electronics for signal processing and trimming (0.8 µm double poly, double metal CMOS). The patented integrated capacitive distance sensing circuit is capable to measure changes down to <0.5 atto-farad/√Hz. To achieve such high resolution, parasitic cancellation techniques have been extensively used. This involves low capacitance switches, dedicated architecture for low input capacitance buffers, and shielding techniques. The schematic in Fig. 3 shows the basic principle of the measurement front end.

The measurement cycle is a good example for the inherent feedback of any capacitive measurement system. The applied measurement voltages should be large enough in order to increase the signal to noise ratio (in our example short pulses of 2 V, 4 V and 0 V within one system cycle). They create electrostatic force pulses inversely proportional to the square of the actual distance between the cantilever and the counter-electrode. These forces cannot be neglected. Assuming a pulse time much shorter than the response time of the cantilever, an average DC force is created by the measurement pulses which will bend the cantilever and becomes part of the offset signal setting. This can be demonstrated by the simulation results of the transient behavior of the cantilever movement shown in Fig. 4. For demonstration purpose a highly unrealistic thin cantilever was chosen where the nonlinear electrostatic feedback of the measurement forces can drive the cantilever into the instability region.

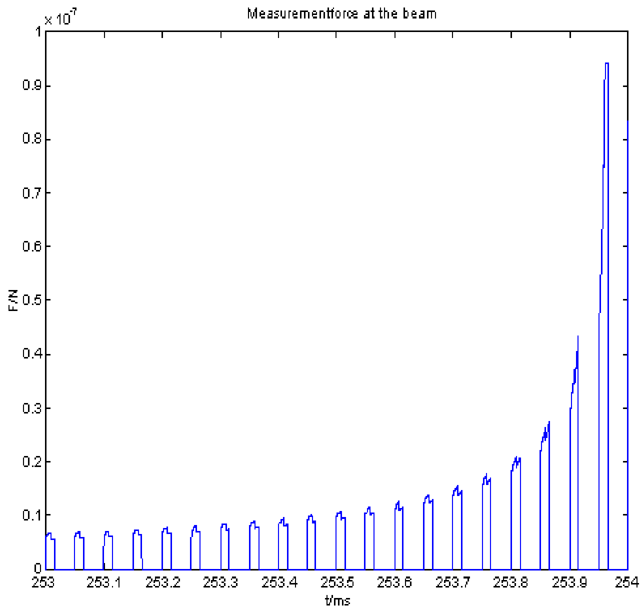

Fig. 4: Transient behavior of a very thin cantilever with too large measurement force

The developed simulation system can be used for the analysis of the overall system behavior and of specific effects in different applications. Additional FEM analyses were used for the determination of key parameters of the SIMULINK model.

For excellent linearity and large bandwidth up to some kHz (depending on the configuration of the cantilever for the different full-scale ranges), the system is operated in closed loop mode. The actuating force is a PWM modulated signal in order to generate a force that linearly depends on the capacitance change. This electrostatic actuation keeps the mechanical cantilever close to its initially adjusted position.

Loop stability is ensured by the uncritical modal behavior of the cantilever and overcritical squeezed-film damping in the air gap. The bandwidth of the output signal is limited by outside loop filtering (typically 100 Hz for low g and 1 kHz for high g application).

The microsystem is packaged in a standard low-cost plastic injection-molded package (SOIC 16). A decapsulated device is shown in Fig. 5. For stress reduction, a silicon gel globe top spreading over the mechanical component is employed. 2D and 3D packages with orthogonal positioning of two or three sensors are in preparation.

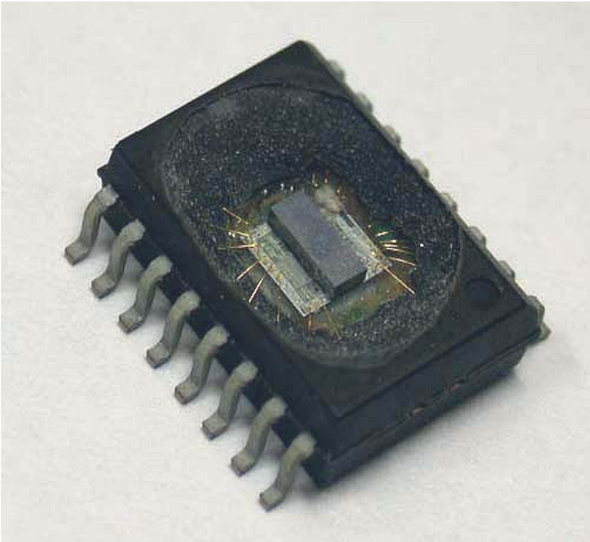

Fig. 5: Top view of a decapsulated sensor within SOIC 16 plastic package.

Main Performance Parameters

The typical sensor performance can be demonstrated for instance for a ±7 g z-axis sensor in PLCC28 package with a sensitivity of 250 mV/g is:

- Peak to peak noise at 140 Hz bandwidth <0.01 g
- Temperature coefficient of zero-g level <2 mg/K
- Zero-g stability over lifetime <0.15 g.
- Linearity better 1%

The sensors are fully calibrated for sensitivity, offset and self test. The ASIC provides a fully calibrated analog output signal, ratio metric to supply voltage with self-test function. Calibration is performed through a serial interface with one-time programmable Zener fuses.

Conclusion

The described technology is well capable to achieve the performance / cost expectations for automotive applications.

Exclusively mature technology modules are used like:

- Fully qualified standard CMOS process.
- Low temperature, one mask post processing for the bond interface.

- High yield, high performance micro-mechanical process utilizing only a few mask layers.
- Wafer bonding process similar as used in volume MEMS production
- Packaging with mechanical stress isolation.

The sensor design does not imply yield limiting factors known from other sensor concepts like fragile mechanical structures, dedicated cleaning technologies to avoid sticking of released sensing elements or more expensive process steps like deep trench etch technologies. Zero-level packaging is an intrinsic feature of the sensor device concept, and is not an additional cost factor as in present commercial sensor designs.

The on-chip sensing with atto-farad resolution enables orders of magnitude better resolution than competitors at equivalent sized sensing elements.

The accelerometer offers low noise, low drift, low cross-axis sensitivity, high linearity, combined with excellent robustness versus mechanical shock.

Basically with the same technology other MEMS devices like high performance capacitive pressure sensors can be built.

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