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Commercial vision of silicon-based inertial sensors

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Abstract

This paper reviews current technology and market trends in silicon inertial sensors using micromachining technologies. The requirements for successful commercialization of the research results will be discussed. Commercial implantation requires involvement at the design, process, and manufacturing stages, so that low cost, reliability, and better performance can be achieved. It is also necessary to have a clear understanding of the market and IC mentality. The paper also forecasts the potential applications and future market values of silicon-based inertial sensors.

Keywords: Inertial sensors; Commercialization; Silicon micromachining; Accelerometers; Gyroscopes

1. Introduction

Micromachining is one of the most important emerging technologies for inertial sensors because of the advantages that it offers: small size and low cost. Although a variety of different materials can be applied for the micromachining technology, silicon has been the material of choice in micromachining, including inertial sensors, due to its many desirable mechanical and electrical properties and its compatibility with IC fabrication technologies. The main benefits that silicon-based microelectromechanical systems (MEMS) derive from their common base with the IC industry are low cost, mass-producibility, and monolithic integration. While the fabrication sequences of silicon sensors are similar to those used in IC processing, the mechanical nature of MEMS gives rise to additional requirements for commercial implantation that do not exist in IC processes, such as the releasing of the microstructures, handling of these released wafers or die, the packaging, and the testing of the devices.

The R&D on silicon-based inertial sensors has advanced quite far during the last decade. For transferring the research results to industry, however, a clear understanding of commercial applications and market trends as well as of the current technology is necessary. This paper will first briefly review the present R&D and commercial status so far and discuss the technological requirements to satisfy further approach to the market. It will then forecast the feasible application area and the future market.

2. Commercial status

Silicon inertial sensors have been developed rapidly during the last decade and are considered as the next mass-produced mechanical sensors after silicon pressure sensors. For sensing physical quantities such as acceleration or angular rate, a mechanical movable component converts the unknown quantity into a displacement that is then detected and converted to an electrical signal. The detailed operational principles of those inertial sensors will not be covered here and the reader is referred to the many reference materials available [1,2]. This paper will focus on the recent advances there have been in R&D of silicon-based inertial sensors, especially as it relates to commercialization.

One of the most successful microaccelerometers in the current market is the fully integrated monolithic ADXL50, which was released in 1993 by Analog Devices Inc. (ADI) [3]. This force-balanced accelerometer consists of a beam–mass mechanical structure using surface micromachining, a capacitive sensor for the position detection of the mass, the signal-processing electronics for the sensor by means of BiCMOS IC technology, and an electrostatic actuator to apply a feedback force to the seismic mass. The device achieves a noise floor around 10 mg Hz$^{-1/2}$ over an input range of $\pm 50g$ or more with a single 5 V power supply and with shock survival in excess of $2000g$. Although these specifications are aimed at applications for airbag release control, there are potential mass applications in a variety of motion-control systems, spurring significant interest and investment from

Silicon accelerometers in the $\pm 50g$ range are currently being supplied to vehicles in the USA by ADI, Motorola, and I.C. Sensors. In Europe, Bosch is the major player; in Japan, the supplier is Nippodenso. With the exception of ADI, all manufacturers are using multiple-chip configurations.

Micromachined gyroscopes have also received vigorous development efforts in recent years [4–6] due to their wide applications in motion control, including the automotive area. Most micromachined gyroscopes are exclusively of vibrating type consisting of two resonant modes: lateral and perpendicular. The main design issue for a vibratory gyroscope is how to detect the sensing amplitude, which is much smaller than the vibrating amplitude. For example, since the sensing amplitude is roughly at sub-atomic scale for a 10 μm driving vibration at $1° s^{-1}$ input, output signals are very sensitive to various error sources in the system. In order to improve the sensitivity of the devices it is necessary to match the resonance frequencies of lateral (driving) and vertical (sensing) modes, to minimize stray capacitance, and to reduce environmental vibration effects by keeping high resonance frequencies.

The noise equivalent rate of present gyroscopes announced by manufacturers including ADI, Motorola, GM, Benz, Bosch, Nippondenso, and Sumitomo is about $1° s^{-1} Hz^{-1/2}$ with the exception of $1° h^{-1} Hz^{-1/2}$ for military application by Charles Stark Draper Laboratory (CSDL). Out of the companies mentioned above, ADI adopted surface-micromachining technology for fabricating devices. It is generally known that surface micromachining has advantages over bulk micromachining: the fabrication of free-form, complex, and multi-component integrated electromechanical structures.

Recently Samsung has presented a surface-micromachined gyroscope representing prominent performance with a noise equivalent rate of $0.1° s^{-1} Hz^{-1/2}$ [7]. Fig. 1 shows an SEM view of the gyroscope fabricated by Samsung. The dimensions of this microgyroscope are 450 μm wide, 1200 μm long, and 7.5 μm thick. The gap between the resonator and the polysilicon electrode on the substrate is designed to be 1.5 μm. Samsung has improved the performance of the device in two ways. One is the effective reduction of noise level using differential driving voltage and electrical tuning by applying an inter-plate d.c. bias after fabrication. The other is to adopt a high-aspect-ratio polysilicon structure with 7.5 μm thickness as shown in Fig. 2.

Fig. 3 demonstrates another force-balanced surface-micromachined gyroscope presented by Samsung with high angular inertia momentum and compact size: 900 μm wide, 900 μm long and 7.5 μm thick [8]. To increase the linearity and dynamic range, a force-balancing method was used. This device features low fabrication cost since this structure has a new force-balancing torsional torque mechanism which does not require another top electrode layer to reduce the intrinsic nonlinearity in capacitive-type sensors. In order to remove cross-axis sensitivity from mechanical coupling, differential d.c. bises are applied to the torsional sensing mode and driving mode. This enables a resolution of $0.1° s^{-1}$ to be achieved at a maximum measurement range of $\pm 100° s^{-1}$ with 1% (FS) nonlinearity.

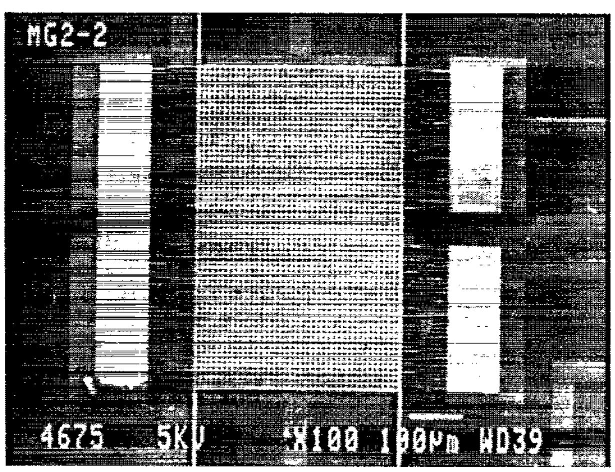

Fig. 1. SEM view of a tunable vibratory gyroscope using surface

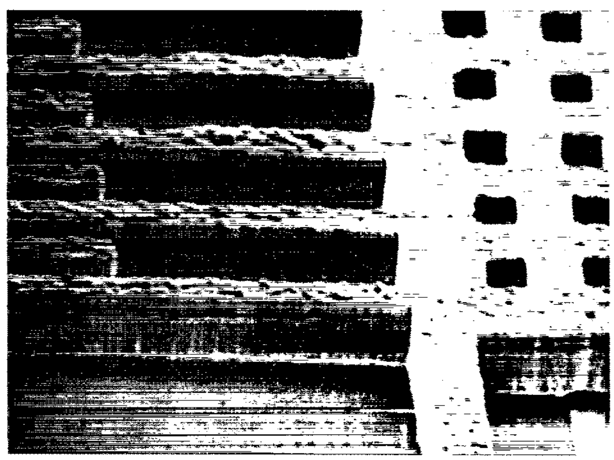

Fig. 2. SEM view of a high-aspect-ratio polysilicon microstructure with 7.5 μm height.

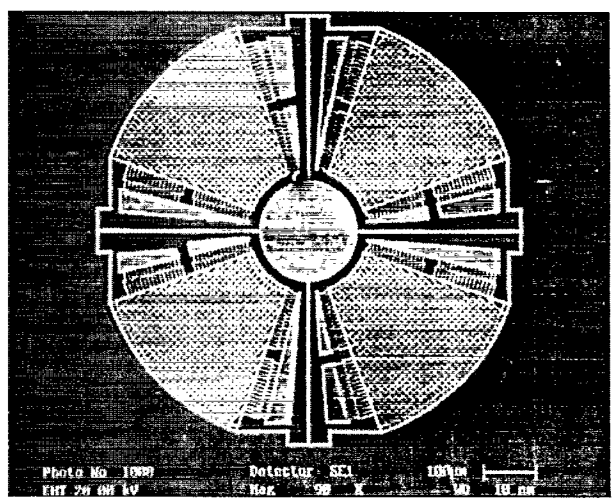

Fig. 3. SEM view of a force-balanced dual-axis microgyroscope using sur-

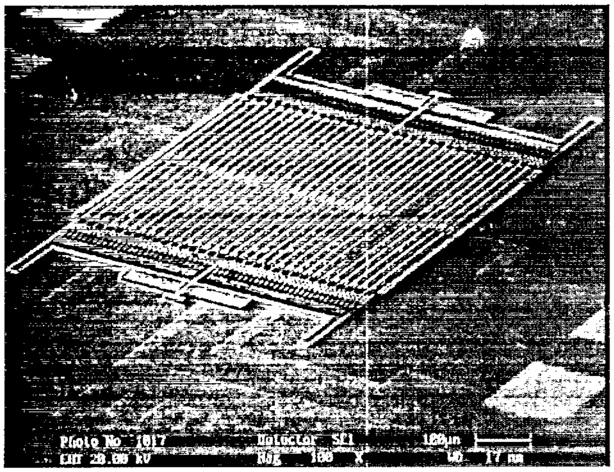

Fig. 4. SEM view of a laterally oscillated and sensed vibratory gyroscope supported by LT-shaped spring.

Fig. 4 also shows a force-balanced vibratory gyroscope designed by a new concept and fabricated by surface micromachining [9,10]. This gyroscope has a resolution of 0.1° s^{-1} at 2 Hz, a bandwidth of 100 Hz, and a dynamic range of 90° s^{-1}. Since the direction of the Coriolis motion occurs in the wafer direction, this device measures the angular rate of the vertical direction. For maximizing the ratio between the sensing and mass areas, LT-shaped electrodes as shown in Fig. 4 are introduced. The specially designed springs serve to match the first and second modes with the mass driving and position-sensing modes, respectively. The prominent shape of the comb-drive helps to improve the resolution by increasing oscillating displacement. A feature is that the resonance frequencies associated with lateral vibration modes are not likely to be varied by a change in thickness of the polysilicon structure, which guarantees the uniform sensitivity of products and requires less testing cost for tuning.

Samsung plans to create a micromachined inertial measurement unit (IMU) which consists of three gyroscopes: two tunable gyroscopes as shown in Fig. 1 for measuring two lateral directions and one laterally sensed gyroscope as viewed in Fig. 4 for measuring the vertical direction. This system enables the three angular rates along three axes to be measured. Though the R&D of these micromachined gyroscope has been moved up to the edge of the market, none of them has been commercialized yet due to the requirements that will be discussed in the following section.

3. Requirements for commercialization

An important requirement for commercialization of MEMS is that they should be low cost, offer better performance, be reliable, and be easily integrated with electronics and provide sufficient flexibility so that different types of sensors/actuators can be systematized without significant

3.1. Wafer-level testing

While functional testing of ICs is generally performed at the wafer level, that of MEMS is carried out currently at the die level and this is a source of cost increase. For lowering testing cost, the performance measurements such as resolution, sensitivity, linearity, and drift rate should be carried out at wafer level. Then, reliability testing should be done at packaged die level. Most difficulties in wafer-level testing of micromachined gyroscopes come from the tuning processes of two different resonance frequencies resulting from fabrication errors. The rest of the difficulty is that the device should be maintained in a vacuum environment, especially for gyroscopes. Therefore, the testing of inertial sensors requires the development of unique test facilities.

3.2. Wafer-level packaging

Packaging is one of the most expensive steps in the development of inertial sensors. For example, it costs over 80% of the whole price in the case of vacuum packaging using an Al_2O_3 ceramic case as shown in Fig. 5 [7]. A reasonable cost ratio between die and packaging for production is 1:1. For a gyroscope, the package should provide a vacuum inside with no leakage and easy interconnection with electronics by feedthrough. It should also be free of mechanical stress and should prevent external perturbations from reaching the device, protect the device from the harsh environment, and be small enough. In order to overcome all these problems, the package should be designed and fabricated at the same time as device fabrication, especially at the wafer level.

3.3. Manufacturability

The vast majority of companies currently involved in MEMS fabrication are performing their processing in facilities previously fitted-up for IC processing. The choice of bulk

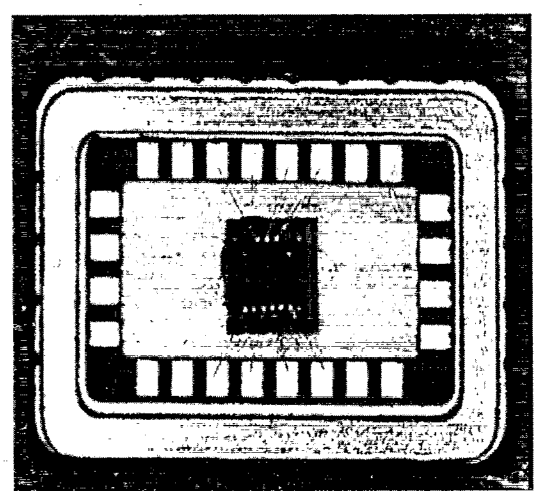

Fig. 5. Photograph of a vacuum-packaged gyroscope using Al_2O_3 ceramic case. The dimensions of the package are 8 mm × 12 mm.

or surface micromachining and integrated or hybrid devices depends on their accessible facilities and technical background. For example, ADI and Samsung can take advantage of integrated surface-micromachined sensors with reasonable support from existing IC infrastructures. However, the most important factor is how to minimize the process errors. Thus, better equipment such as deep-etching facilities and deposition furnaces for higher-aspect-ratio structures are required and this increases production cost. It is necessary to trade off between the process errors and process cost. The other factor that should be considered in manufacturing is the number of masks, since fewer masking steps offer a simple and cost-effective process.

3.4. Higher performance

The miniaturized advantage of MEMS is an important factor, especially in a battery-operated system which should have a power consumption as low as possible. However, any significant size reduction of inertial sensors is accompanied by a loss of their performance. The performance of a MEMS vibratory gyroscope is defined eventually by the minimum detectable angular rate. Therefore, this problem should be solved by optimal design: a selection of low-noise elements in the signal-transforming chain, providing favorable conditions for their maximal robustness to external noise, and increasing the output signal value at any given input angular rate. This will be possible by providing effective use of the favorable electrical and mechanical properties of silicon as design material, as well as providing near-resonant oscillations of the proof mass at high values of the Q-factor of exciting and sensing oscillation contours. The microstructure can also be made as thick and narrow as possible, justifying the need for high-aspect-ratio microstructures.

3.5. Reliability

One of the most challenging aspects of commercialization is the fabrication of reliable and reproducible devices. For example, the drift rate for temperature variation in the range −40 to +150°C has to be minimized and compensated for the inertial sensors in an automobile. The lifetime of the devices can be precisely predictable and the function should also be guaranteed for the whole lifetime.

4. Application and market

The overall market growth of MEMS is about 6% per year. The fastest-growing market segments include automotive/transportation sensors and smart sensors, with growth rates close to 20% per year [11]. Very rapid growth of inertial sensors is expected to occur primarily in the automotive and consumer market, as shown in Table 1. Silicon-based sensors will occupy more than 90% of all commercial inertial systems in 2000.

The future market of inertial sensors will be basically spurred in ways to satisfy all the requirements described above. First of all, the automobile market tends to substitute the expensive conventional 'fully active' ($5000) suspension or navigation systems based on total closed-loop control with low-cost MEMS or 'semi-active' systems [12]. However the 'semi-active' systems are still expensive ($2000), since the unit price of the existing angular rate gyros similar to Murata's piezoelectric vibrating cylinder or Matsushita's tuning fork is around $30–50. Thus, they will only be implemented in high-end models at this point. This price pressure pushes vehicle manufacturers to reduce system cost, making systems suitable for less expensive vehicles. The availability of a low-cost, MEMS-based angular rate sensor similar to those developed by ADI, GM, BEI Electronics, and Samsung

Table 1
Inertial sensors market projections in the year 2000. The expected requirements and performances are also shown (Samsung and MRI, June 1996)

Market area (requirement)	Applications	Estimated units (gyro/accel.)	Gyro performance; range/res. (° s^{-1})	Sales ($Bil.)
Automobile (low-cost, reliable, harsh environment, lifetime)	advanced airbags	3/6	200/10	0.8
	active suspension	2/4	50/2	0.4
	navigation	1/0	100/0.1	0.02
	ABS/anti-skid	3/4	50/0.5	0.6
Consumer/medical (low cost, low power, small size, lifetime)	camcorder	2/0	50/0.5	0.3
	3D mouse	2/0	100/2	0.3
	VR game/toys	2/2	100/0.1	0.6
	sports equipment	2/2	50/0.1	0.1
Industry (small size, reliable, harsh environment)	robotics	6/6	10/0.1	0.3
	machine monitoring	[a]	10/0.1	0.3
	attitude control	3/3	20/0.2	0.2
Military (reliable, higher resolution)	new weapon systems	[a]	[a]	[a]
	IMU	[a]	[a]	[a]
Total				3.92

is expected to be commercialized in the near future, probably in a year or two years, and will propel the adoption of these enhanced systems into less expensive vehicles over a period of time.

Secondly, only the reliable and robust devices that can survive in harsh environments will be adopted to the market. Moreover, the market also requires an order of magnitude better resolution at lower power consumption for a very large range of applications. Future accelerometers will have a noise level as low as 1 μg Hz$^{-1/2}$ at an input range of $2g$. Though the necessary accuracy of a gyroscope for the recent automobile GPS/INS is 50–300° h^{-1}, the next-generation devices for short-term military navigation systems are expected to have random drift of about 10° h^{-1} or better and the acceleration scale factor stability should be in the order of 0.05%. Several companies including CSDL, ADI, I.C. Sensors, Motorola, and Samsung will be likely to compete for these opportunities.

Finally, the capability of integration with electronics is getting more attention in the market since a one-chip system is of major interest for commercial devices, especially in automobile applications. The role of on-chip electronics becomes more important for intelligence and multiplicity: the combination of a large number of sensors, actuators, and electronics in one single unit. In addition, the demand for wireless telemetry technology for communicating with the outside is growing fast. Therefore, the compatibility of a single unit sensor with one-chip systems has to be considered from the beginning of the design and fabrication.

5. Conclusions

The demand for silicon-based inertial sensors is increasing, which promises a new wide market for many areas. In order to introduce inertial technology into these markets, it is necessary to meet a number of principal requirements: significant cost reduction by wafer-level testing and packaging, decrease of power consumption by miniaturization, enhancement of performance and reliability, and on-chip integration for multiplicity. Notwithstanding the many challenges discussed above, a great effort at developing inertial sensors will enable these devices to be commercialized, perhaps in as little as two years.

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Biographies

Cimoo Song received the B.S. and M.S. degrees in mechanical engineering from Yonsei University, Korea, in 1977 and 1982, respectively, and the Dr.-Ing. degree from the Technical University of Berlin, Germany, in 1987. From 1977 to 1982, he specialized in robotics at Korea Institute of Science and Technology, Korea. In October 1987, he joined Samsung Advanced Institute of Technology in Korea. Since then he has been engaged in the research and development of micro-mechatronics system technologies including microsensors and microactuators as a program manager.

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