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Chip-Scale Packaging of a Gyroscope Using Wafer Bonding

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The chip-scale packaging of a micromachined gyroscope is discussed. The angular rate sensor requires the micropackaging of a resonating element in a vacuum. To fabricate and package the angular rate sensor, Lithographie Galvanoformung Abformung (LIGA)-like electroformed micromachining is integrated onto a complementary metal oxide semiconductor (CMOS) slice, which is wafer-bonded to a silicon micromachined capping slice. Reliability issues and applications of these devices are discussed.

1. Introduction

Motion sensors have a wide variety of uses. In the automobile industry, accelerometers have seen the widest application in crash detection.(1,2) Frontal accelerometers process 35 g to 250 g inputs for firing driver and passenger air bags. Side impacts are monitored using 250 g to 500 g sensors. Lower acceleration values in the 1 to 5 g range are employed for ride control purposes. Consumer demand has created a market for low-cost angular rate sensors. Potential automotive applications for these sensors include yaw chassis control, roll-over detection, adaptive cruise control and turn-by-turn navigation. At this time, the high cost of properly performing angular rate sensors restricts applications to the luxury vehicle market. Angular rate sensors can also be used for the stabilization of camcorders, wireless remote controls, virtual reality equipment as well as conventional aerospace applications. Advances in micromachining technology will provide the manufacturing breakthrough necessary for widespread use of angular rate sensors.(3)

Micromachined motion sensors have been packaged in TO cans, and plastic and ceramic cavity packages.(1,4,5) These packages often include an integrated circuit (IC) for purposes of amplifying the sensor output and compensating it over a wide temperature range. ICs have seen increasing use of flip chip bonding, chip on board, and other chip-scale packages.(6,7) Therefore, it seems logical that micromachines also employ these extremely small packaging concepts to save board space and cost. One problem with this packaging approach for micro electromechanical systems (MEMS) is the presence of movable micromachined parts. Dust, passivation and underfill materials can damage exposed micromachines.

Wafer bonding is a technique that has been used by the MEMS industry for many years to bond different materials, buffer against packaging stress, provide damping and protect movable parts.(1,8,9) Many of these features make wafer-to-wafer bonding an ideal tool for forming chip-scale packages for microsystems. Piezoresistive and capacitive pressure sensors as well as various motion sensors have been formed using these bonding techniques. Figure 1 shows examples of silicon to glass and silicon to silicon bonded pressure sensors, accelerometers and angular rate sensors. In this paper, the bonding of micromachined wafers together to form micropackages will be presented, for angular rate sensors.

2. Fabrication

2.1 *Historical background: accelerometer fabrication*

To understand how the micropackaging of the angular rate sensor developed, it is important to know how accelerometers have been fabricated. The accelerometers shown in Fig. 1 have been produced in high-volume manufacturing since 1993. Millions of these piezoresistive devices are made each year for automotive crash detection purposes. Figure 2 shows the process flow and a cross-sectional schematic of the triple wafer stack employed to make these sensors.

Standard integrated circuit processes are first used to create piezoresistors and the sensor circuit, as shown in Fig. 2(a). An electrochemical etch process is used to etch a cavity into the back of the wafer, Fig. 2(b), forming a thin diaphragm of the epitaxial layer. At this point, the device is essentially a pressure sensor. Millions of high-reliability pressure sensors are produced each year using this basic process.(4,9)

A silicon backplate wafer is bonded to the back of the sensing slice, forming a two-wafer stack. Virtually any kind of wafer-to-wafer bonding process can be used with the smooth surfaces. Table 1 lists the type of wafer bonding methods that have been employed in the industry.

After bonding, a dry or plasma etch process is used to cut through the diaphragm from the front, forming a cantilevered beam of a paddle shape. The piezoresistive sensing element is now free to move.

A separate cap wafer is made using wet etch processes, and is bonded to the two-wafer stack, as shown in Fig. 2(f). Since silicon steps are to be covered, traditional anodic and silicon fusion bonding cannot be employed. This top cap protects the accelerometer during

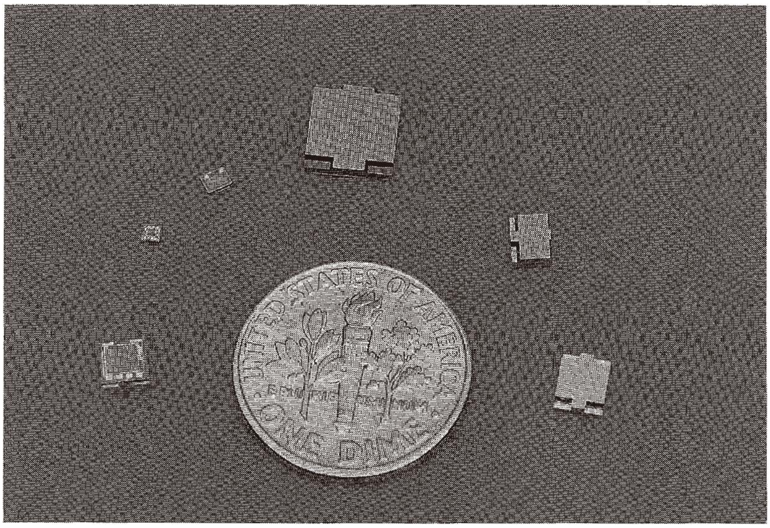

Fig. 1. Various sensors made using wafer bonding. From left to right: A silicon-to-glass bonded piezoresistive pressure sensor, a silicon to silicon bonded piezoresistive pressure sensor, a silicon-to-silicon bonded capacitive pressure sensor, two triple stacked silicon accelerometers and an angular rate sensor.

the harsh wafer dicing process. Without this top cap the silicon cantilevers may be broken off under the high-pressure water spray used during wafer saw .(2) Reducing the saw water flow can prevent breakage; however, it leads to silicon particle adhesion to the exposed aluminum bond pads.(10) Any kind of particles near micromachined sensors can present a quality problem for unprotected devices in cavity packages. Exposure to particles can continue during packaging and assembly. The complete packaging of a micromachine at the wafer level in a clean room minimizes the chances of particle contamination. Not only does the top cap prevent particle contamination and breakage, it also is used for damping cantilever motion to improve sensor performance, and enables the die to be mounted directly to a circuit board.

2.2 *Angular rate sensor fabrication*

Rate sensor fabrication is more complex than accelerometer fabrication. Processing begins with a mature, high-volume, dual-level polysilicon, dual-level metal CMOS process. After the final conventional CMOS processing step, pad etch, the micromachining begins. The micromachining process is a modular add-on to an existing production CMOS process. The first step in the LIGA-like micromachining process is the deposition of barrier and plating seed metals onto the open CMOS bond pads. A sacrificial layer is then applied as shown in Fig. 3(a). The sacrificial layer allows for the eventual motion of the structure by providing a space between the ring structure and the IC. The thick photoresist

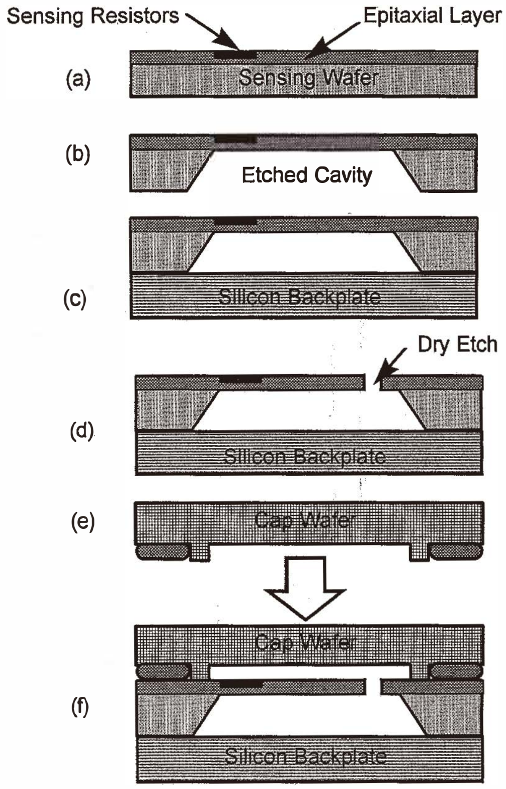

Fig. 2. Diagram of the accelerometer fabrication process sequence.

Table 1
Wafer to wafer bonding processes.

Electrostatic or anodic
Organic adhesive
Glass reflow
Solder reflow
Silicon direct or fusion

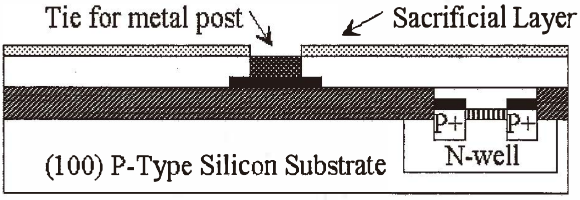

Fig. 3a. Sacrificial layer applied.

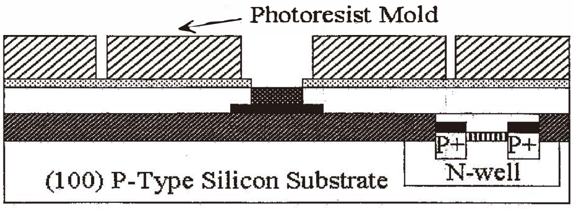

Fig. 3b. Photoresist mold on sacrificial layer.

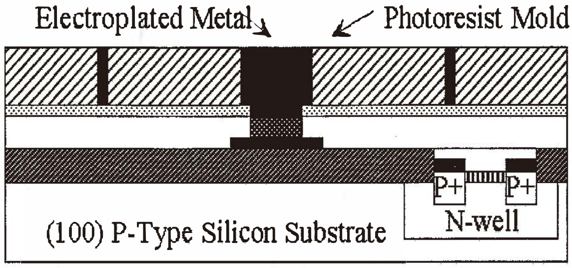

Fig. 3c. Metal ring electroplated into photoresist mold.

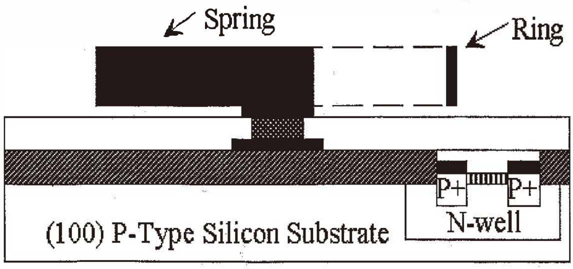

Fig. 3d. Free-standing ring, mold and sacrificial layer removed.

mold layer is then put down and patterned, Fig. 3(b). Vertical photoresist side walls 15 to 25 μm thick are used to form the plating mold for the metal micromachine. A thick metal layer is selectively electroplated into the open portions of the mold to create the ring structure. The mold is then removed, followed by the etching of the sacrificial layer, leaving the free-standing micromachine as shown in Figs. 3(d) and 4.

At this point in the processing step, the resonating surface micromachined device must be packaged. Early on in the development of this sensor, ceramic dual in line packages (DIPs) were employed.(11) Kovar lids were soldered to the DIPs under vacuum. This is where a derivative of the wafer bonding technology developed for micromachined accelerometers is applied to angular rate sensor micropackaging. A bulk etched top cap wafer, very similar to that used in the accelerometer, is bonded to the surface micromachined CMOS wafer. Since vacuum is required to produce a properly resonating device, and CMOS metal steps must be covered, only the glass frit or solder bonding process could be utilized. Glass bonding has been used to produce millions of accelerometers. Solder bonding has an advantage over glass bonding in that a variety of temperatures can be employed by changing the solder alloy composition. The disadvantage to using solder bonding is that a metallized top cap wafer is required. For the CMOS-integrated sensor, a third slice is not needed, in contrast to the bulk-etched piezoresistive accelerometer. Figure 5 shows a photograph of a bonded, CMOS-integrated angular rate sensor. Figure 6 illustrates the cross section of the capped micromachines in the final form. The process used to produce this angular rate sensor, CMOS-integrated LIGA surface micromachining, bulk-etched silicon micromachining and wafer bonding, is unique.

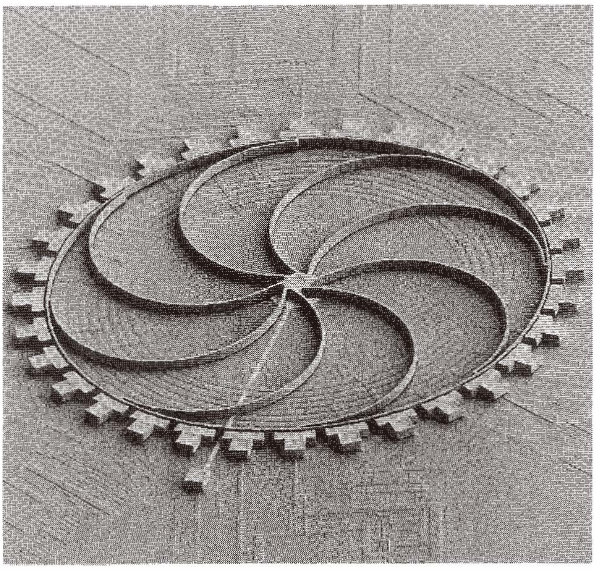

Fig. 4. SEM of the electroformed surface micromachined ring.

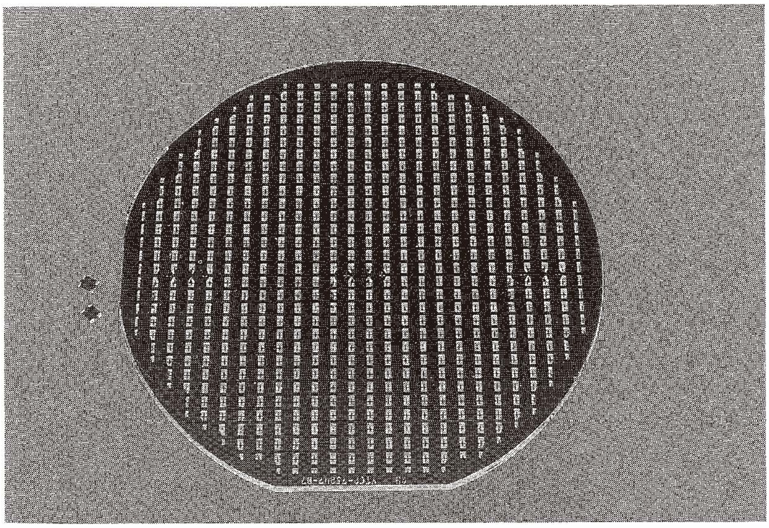

Fig. 5. The angular rate sensor slice after wafer bonding in vacuum.

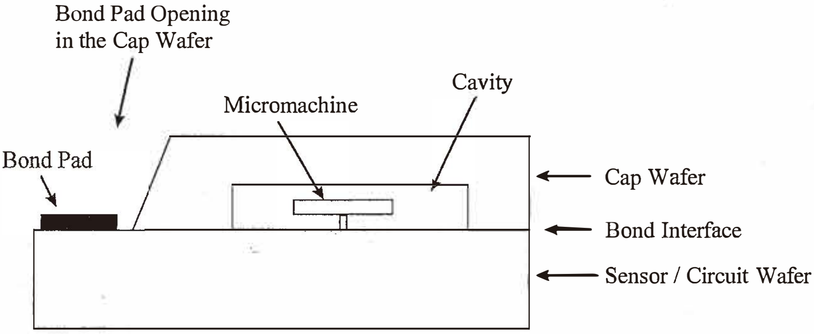

Fig. 6. Cross section of the package formed using wafer bonding.

3. Angular Rate Sensor Performance

Figure 7 shows the linearity of the angular rate sensor output. The sensitivity, rate range and bandwidth are programmable. Typical bandwidths selected are between 15 and 50 Hz. Nonlinearity is less than 0.2%. The noise is less than 0.8°/s root mean square (RMS). The device can operate between –40 °C and 85° C. Power requirement is 35 mA at 5 V. This level of performance is typical of that required for an automotive yaw rate sensor.

The most important device parameter related to chip-scale packaging in vacuum for this sensor is the quality factor, Q, of the device. The Q value of a resonant peak was determined by dividing the peak frequency by the 3 db peak width. In open air, the Q values of the ring structure range from 100 to 200. In vacuum, the Q values can go up to 2,000. Figure 8 shows a typical distribution of Q values for several slices that use a wafer-bonded stack. The Q data are automatically measured during wafer probing. Most of the Q values exceed 1,000. The Q values compare favorably with previous data taken when the die were individually vacuum packaged in ceramic DIPs with soldered Kovar lids.(11) Automotive life tests have been successfully performed on these micromachined systems, and the reliability of this wafer level bond looks very good. Modules have been run on automobiles, vans and trucks without failure. A 4.3 g, 2 h vibration test was completed with no effect on sensor performance. This test simulates 1,000 h of vehicle vibration. Excellent performance has been obtained under rough road conditions (vibration) without the need for external package dampening. In a previous study (11), the metal rings were electrically driven for over 1,000 h with no change in Q or frequency. Completed modules, shown in Fig. 9, have been continuously operated without failure for over 6,500 h at room temperature. Five gyroscope modules have also been operated for over 1,000 h at 125°C without failure or significant output shift. Wafer-bonded parts have been temperature

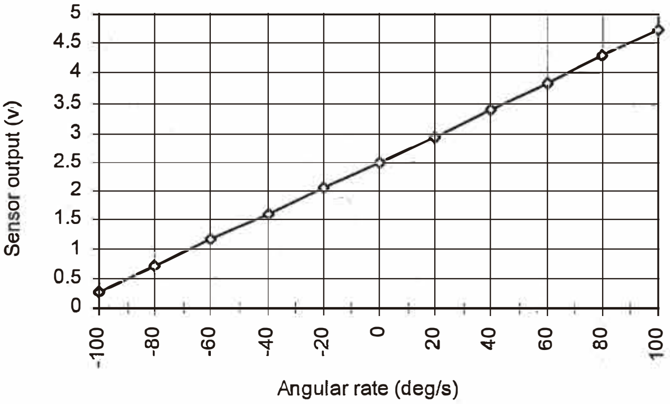

Fig. 7. Angular rate sensor output.

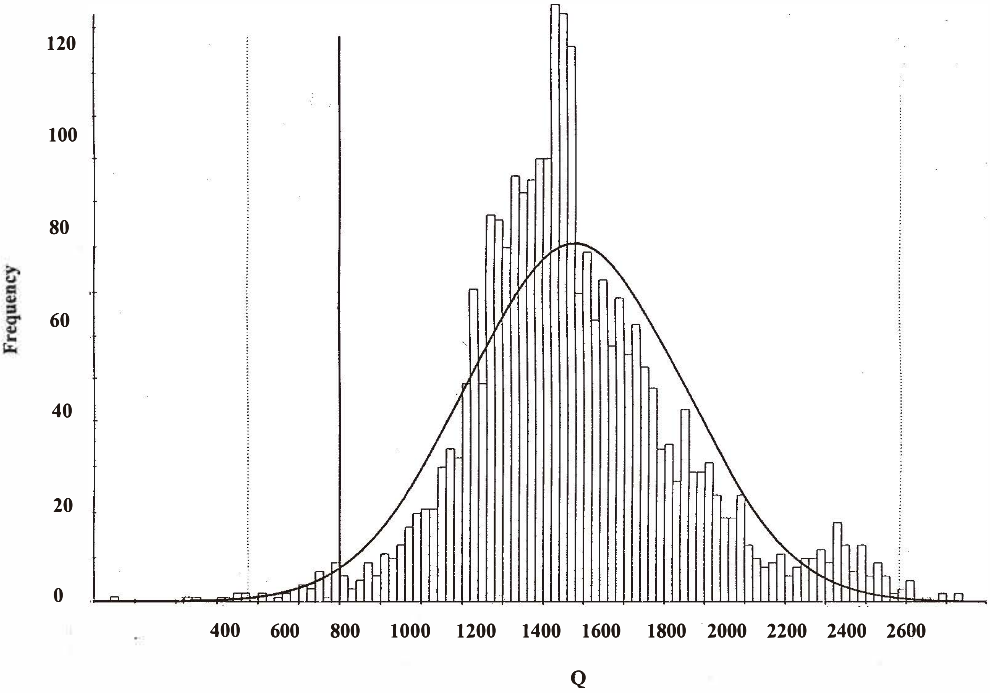

Fig. 8. Q histogram of several wafer-to-wafer bonded angular rate sensor.

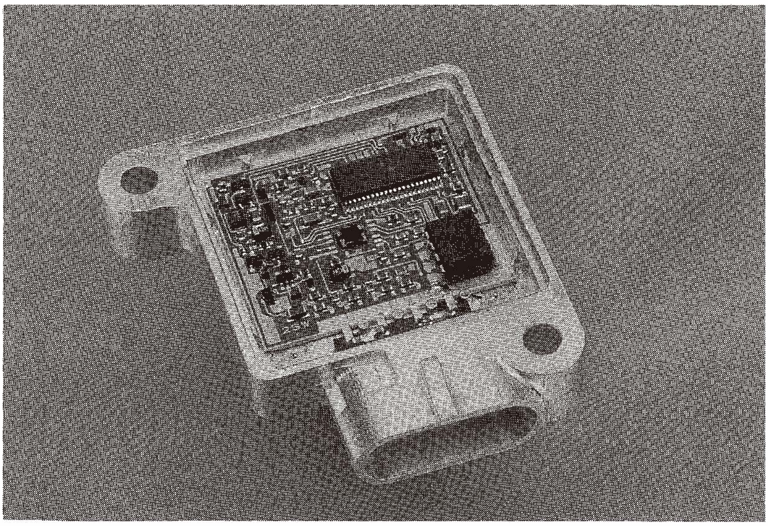

Fig. 9. Chip-scale packaging of micromachined motion sensors on a ceramic circuit board.

shocked from –40°C to 150°C, temperature cycled between –100°C and 125°C while undergoing 50 g vibration, and stored for prolonged periods of time at temperatures between 150°C and 240°C with no statistically significant change in Q. This indicates that the die level bond is strong, hermetic and stable. A resonant sensor using such a high Q value lends itself to performing continuous self-testing. Circuitry has been designed so that if the Q value changes significantly, a fault signal will be registered in the angular rate sensing system. Since the sensor is continuously vibrating, this self-test feature is always operating.

The capability of efficiently packaging micromachined devices in vacuum is needed by other sensors and technologies. These techniques could be applied to the chip-scale packaging of tunneling devices to improve both performance(12) and package size. Resonating accelerometers, emission displays and microvacuum tubes are other areas that could employ these fabrication techniques.

4. Chip-Scale Packaging

With a completely enclosed gyroscope, chip-scale packaging of these microsystem elements is now possible. Figure 9 shows how these MEMS chips can be placed on a circuit board along with integrated circuits and other discrete components to form a more complex system. In the example shown in Fig. 9, thick film elements, soldered discretes, integrated circuits and a chip-scale packaged micromachined motion sensor are combined. Like older accelerometer modules, this motion sensor is electrically connected to the circuit board by wire bonding. A passivating silicone gel is used to cover the board elements, further protecting them from the aggressive automotive environment. Millions of these modules that employ chip-scale MEMS have been produced and are in use on vehicles around the world.

5. Conclusions

Accelerometers and angular rate sensors have been fabricated by micromachining and packaged at the die level using wafer-to-wafer bonding. A resonating, electroformed, surface micromachined, CMOS-integrated gyroscope has been merged with bulk-etched silicon wafer-to-wafer bonding in vacuum to ultimately package this device at the chip level. The ability to use chip-scale packaging of MEMS along with integrated circuits has also been demonstrated in high-volume automotive applications.

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