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Sensors in Network (2) —Fabrication Technologies—

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1. Introduction

In the previous session,[1] the concept and current status of highly functional sensors were outlined. The technologies for realizing such sensors are discussed in this session. For details of individual technologies such as thin-film deposition, patterning, and etching, please refer to published textbooks.[2–6] In this session, I review the basic principle of frequently used technologies and their history.

2. Bulk Micromachining and Surface Micromachining

The methods for realizing micro-electromechanical systems (MEMS) devices are roughly classified into bulk micromachining and surface micromachining. The former is used to fabricate sensor structures by etching silicon wafers themselves, whereas the latter is used for patterning thin films with a thickness of 2–50 μm on wafers. Sensors that require cavities, such as pressure sensors and microphones, as well as those that should be thermally isolated, such as flow sensors and infrared sensors, are fabricated by bulk micromachining so that wafers of a large volume can be etched out to create cavities (Fig. 1). Previously, wet bulk micromachining using crystalline dependent etchants [*e.g.*, potassium hydroxide (KOH), ethylenediamine-pyrocatechol-water (EPW), and tetramethylammonium hydroxide (TMAH)][3] was frequently adopted to create deep cavities that penetrate substrates. However, dry bulk micromachining has been increasingly performed

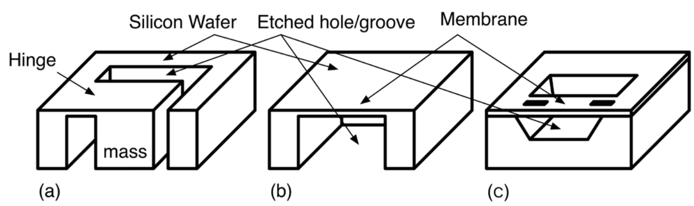

Fig. 1. Bulk micromachining for (a) movable structure (*e.g.*, acceleration sensor, gyro), (b) large cavity (*e.g.*, pressure sensor, microphone), and (c) thermal isolation (*e.g.*, flow sensor, infrared sensor).

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since the development of the Bosch process, which enables reactive ion etching of high-aspect-ratio trenches and through-holes, was put into practical use in 1995.[7] In surface micromachining, a sacrificial layer is formed on a substrate, and then a structural thin-film layer is formed on the sacrificial layer and processed to fabricate a sensor structure (Fig. 2). Subsequently, only the sacrificial layer is removed by selective etching to release the structure from the substrate. There are various methods of forming structural thin-film layers; for example, (1) directly bonding a silicon wafer to other wafer with a silicon dioxide film and polishing one of the wafers, (2) depositing a polysilicon film,[8] and (3) depositing an epi-polysilicon film.[9] MEMS manufacturers develop their own original techniques for obtaining fine structural thin-film layers and apply them to their sensors. Recently, surface micromachining has been frequently adopted to fabricate inertial sensors [*e.g.*, acceleration sensors, and angular rate sensors (gyroscopes)] because this technique can be applied to various sensors simply by changing the design of patterns without modifying the fabrication process. In surface micromachining, controlling the residual stress of the structural thin-film layer is essential. If a stress is generated between the substrate and the structural layer, the structural layer may buckle or become distorted depending on its shape. The magnitude of the stress may be dependent on temperature and varied if the substrate and the structural layer have different thermal expansion coefficients. Moreover, the structural layer may warp under a perpendicular nonuniform stress distribution (stress difference between top surface and bottom surface). MEMS manufacturers make an effort to establish fabrication techniques for structural layers with reduced stress by designing special structures that have as much tolerance to stress as possible.

3. Monolithic Integration (System on Chip; SoC) vs Hybrid Integration (System in Package; SiP)

As described in the previous session,[1] the integration of sensors and circuits has considerable merit. For examples, magnetic sensors and pressure sensors have long been fabricated by monolithically integrating analog-based peripheral circuitry, such as amplifiers and temperature

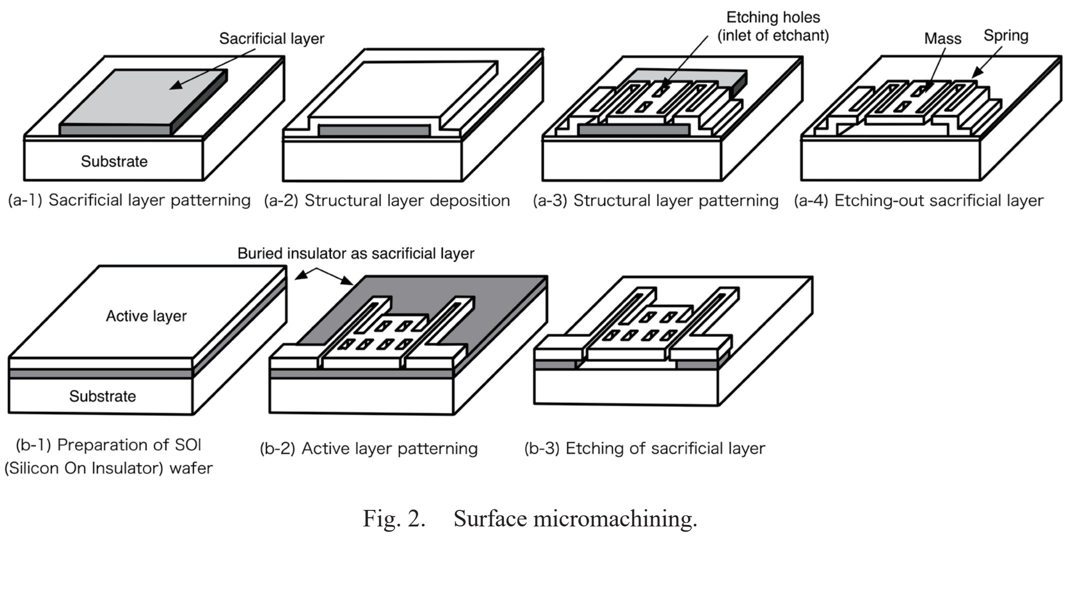

Fig. 2. Surface micromachining.

compensators, and sensor structures. There are two types of integration; monolithic integration and hybrid integration. As for the monolithic integrated sensor, the first sensor-integrated device with a MEMS-like structure—that has a movable structure with several degrees of freedom—was considered to be the ADXL series of accelerometers developed by Analog Devices, Inc. ADXL50,[10] released in 1993, was excellent and elegant considering the technical level at that time. This device was fabricated by polysilicon surface micromachining on a bipolar complementary metal-oxide-semiconductor (BiCMOS) integrated circuit. It realized completely monolithic (i.e., single chip) integration of a structure and peripheral circuitry, and was sold as the world's first monolithically integrated accelerometer. The feature of the ADXL series was the all-analog circuitry embedded into a monolithic sensor structure. At that time, mixed signal techniques (analog–digital mixed integrated circuitry) using the CMOS process were not yet mature, and common sensor systems were constructed using analog circuitry (in particular, bipolar circuitry). For the ADXL series, annealing (at ≥900 °C) was required to reduce the residual stress in polysilicon used for the structure. The BiCMOS technique of a 3 μm design rule, which was relatively large, even in those days, was used for the process tolerant to high temperatures. In 2002, Analog Devices released a gyro ADXRS300 developed using the same technique.[11] This device was the world's first monolithically integrated gyro obtained by realizing vibration-driven circuitry, weak signal detection circuitry, and various trimming and correction circuitry by the all-analog method (Fig. 3).

The above-mentioned acceleration sensor and gyro of Analog Devices are bipolar analog-based devices. However, high levels of digital integration and low supply voltage have been increasingly required for integrated circuits, and CMOS mixed-signal circuits have become mainstream today. As CMOS large-scale integration (LSI) chips of high levels of integration and a fine design rule have become used for interfacing sensors to integrated circuits, various problems have arisen in the formation of sensor structures and integrated circuits on a single chip: (1) LSI circuits of a fine design rule cannot withstand the high-temperature processes that are required to form and treat a movable polysilicon structure; (2) LSI wafers of high levels of integration are expensive in terms

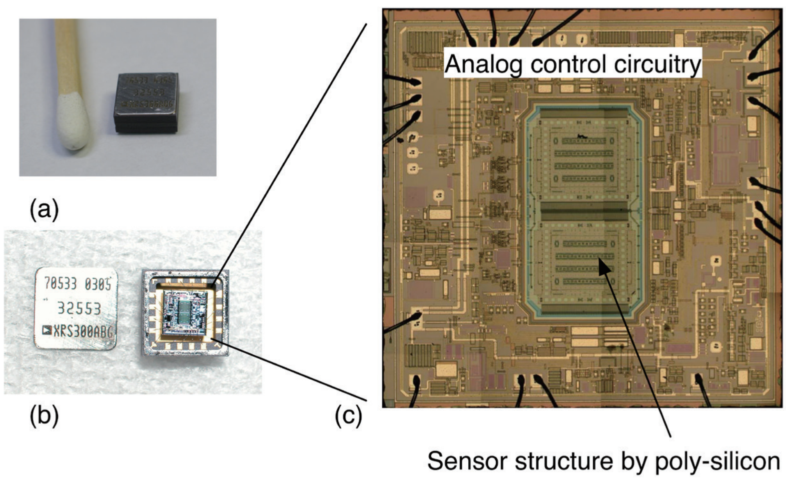

Fig. 3. (Color online) ADXRS300 (Analog Devices, Inc.), the first commercially available monolithic MEMS gyroscope.

of unit price per wafer area and are costly when a large mechanical structure (about a few hundred micrometer square for an inertial sensor) is embedded into a wafer; and (3) individual reworking or redesign of structures and circuits is not possible because they are on the same wafer, resulting in difficulty of frequent improvement of the device. To solve these problems, subsequent MEMS manufacturers have designed and manufactured sensor wafers and circuit wafers separately, and then connected them by wire bonding in a package or wafer level bonding[12] followed by dicing and packaging. This is known as SiP and has become the current mainstream method of manufacture. A schematic of the thus-obtained sensor chip is shown in Fig. 4(a). A sensor structure and a cap structure that protects the sensor structure are glued and attached to an LSI circuit with a package lead. The sensor and circuit as well as the circuit and package lead are connected using bonding wires and sealed with resin. Figure 4(b) shows another example device in which multiple chips are horizontally arranged and mutually connected in a package.

It is said that we will realize the so-called Trillion Sensor Universe in the near future. I think that monolithic integration of sensors is the ultimate goal in our society where a huge number of sensors are manufactured and used. However, this technique faces several problems, as mentioned above. If these problems are solved, monolithic integration will become more advantageous than hybrid integration because it is an elegant technique in terms of small size, high productivity and low cost. For example, if a thin-film structure that has no stress can be formed and processed directly on a CMOS LSI wafer with low temperature treatment, and a technique for forming a protective layer for the structure (currently, a cap structure) can be realized, devices that can strongly promote the realization of the Trillion Sensor Universe will become available. Recently, general electronic components have been increasingly required to be smaller, and increasing numbers of key devices, such as microprocessors, wireless devices, and field-programmable gate arrays (FPGAs), have been supplied in wafer-level chip-scale packages (WLCSPs) (Fig. 5). Advancing the technologies for the monolithic integration of MEMS sensors will enable the fabrication of sensor nodes in WLCSPs, which will lead to their reduced size and cost. Currently, node devices of sensor networks are fabricated by connecting individual devices such as sensors, controllers, wireless devices, and power sources. In the near future, versatile platforms in one-chip systems for sensor networks may be realized by advanced monolithic integration technology.

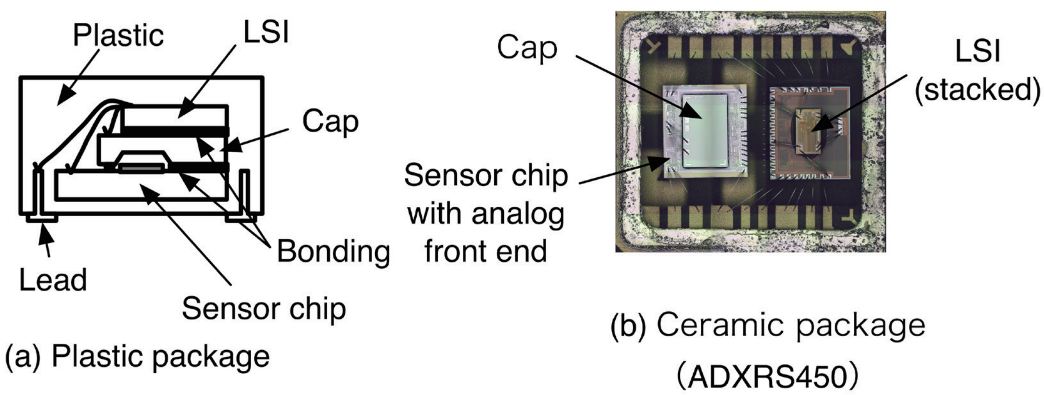

Fig. 4. (Color online) Examples of packaging. (a) Plastic package and (b) ceramic package (metal lid is removed).

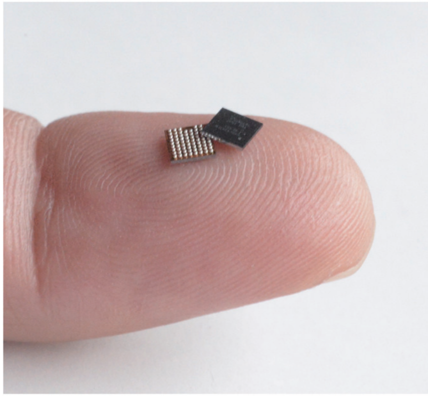

Fig. 5. (Color online) Example of WLCSP device (PSoC4 BLE, Cypress Semiconductor Corp.). Two devices are placed on a finger. These devices include programmable analog circuitry, a microcontroller with a memory, and a low-energy Bluetooth module. If these devices are integrated with sensors and a power source in the chip, a complete monolithic wireless sensor node can be obtained.

4. Summary

I have reviewed bulk micromachining and surface micromachining as techniques for the fabrication of MEMS sensors. These techniques are used differently depending on their purposes, and both are considered to be the main techniques for fabricating various sensors. I have introduced monolithic integration of sensors and circuits as an elegant technique in this session. Although the current mainstream is that sensors and integrated circuits are fabricated on different chips and are connected in a package, I suggest that monolithic integration is ultimately preferable, and await future solutions to the technical problems.

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