MEMS applications of Ball Semiconductor Technology

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ABSTRACT: Instead of using conventional flat and rectangular chip technology, our idea is to make semiconductor devices and sensors on 1mm-diameter spherical silicon (Ball) substrates. This paper describes five key enabling process technologies to realize Ball devices such as 3-axis accelerometer.

1. INTRODUCTION

Conventional semiconductor industry focuses on making integrated circuits on flat-surface wafers. Instead of the conventional semiconductor industry, we are challenging to make semiconductor integrated circuits and sensors on 1-millimeter spheres as an alternative technology [1]. Roundness, smallness, symmetry, closed surface topology, 3-dimensional feature, and about 3 times larger surface area than a 1-milimeter square chip are unique aspects of the spherical shape. We are aiming to realize unique spherical devices using these features. Our internal goal for manufacturing is to reduce its cost and to shorten the production lead-time using novel continuous fabrication process. We call this technology Ball™ semiconductor technology.

In this paper, above five key enabling process technologies [2,3] are introduced and an electro-statically levitated 3-axis accelerometer and an omni-directional clinometer are described as unique applications of the Ball semiconductor technology for Micro-Electro Mechanical System (MEMS).

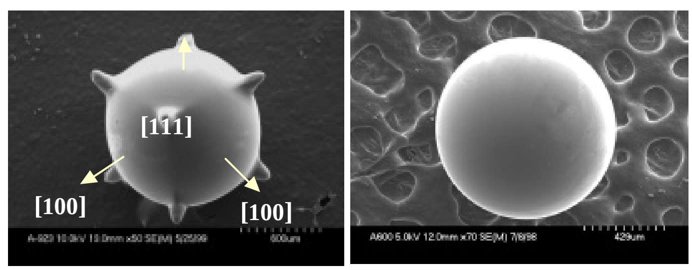
2. BALL PROCESS TECHNOLOGIES

The fundamental concept of the Ball mass production line is manufacturing the Ball in a continuous, enclosed tube like a chemical plant. Basically, balls are running through the tube during the process, except the exposure process and the bumping process. To realize this technology, we are developing a spherical single crystallization technology during free-fall through a plasma furnace, continuous processing technologies in small diameter tubes, a lithography technology for use on spherical surfaces, a layout design methodology, and a clustering technology to connect many Balls as a molecule.

2-1 Single crystallization

The first and foremost step in making Ball™ devices is the fabrication of single crystal spheres. This process consists of melting, solidification and polishing. In the melting step, polycrystalline silicon granules are preheated and melted in a high temperature atmospheric pressure plasma flame generated by Inductively Coupled Plasma (ICP) system. We have successfully generated a 1-meter length plasma flame in a 2-milimeters-diameter quartz tube. The melted granules are then dropped through a solidification tube, which is about 7 meters in height. During the free fall, the granules are solidified. The crystal shape depends on the heating and cooling conditions. Figure 1 (a) shows a shape of the spherical single crystal as grown. The crystal orientation of the horns is the [111] direction and 8 horns are an evidence of the single crystal.

After the single crystallization, the horned crystal is lapped to make the perfectly spherical crystal and then polished to make mirror-like finish with no surface defects and damages (Figure 1 (b)). The lapping accuracy is 1.0mm +/- 0.07um, and the polishing accuracy is about 1.0mm +/- 2um, which is a little bit worse than that of lapping.



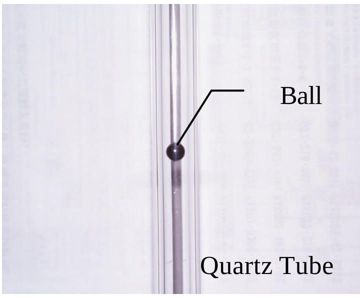
(a) As grown (b) After lapping and polishing

Figure 1. Shapes of single crystal sphere

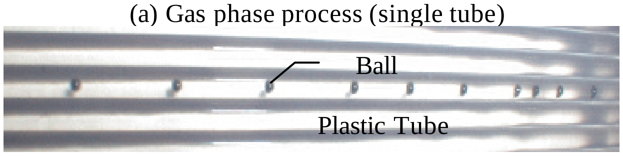
2-2 No-contact processing

The fabrication process of Ball™ involves deposition and etching of various types of films. Such processing requires that the balls do not hit the walls of the pipes, or each other, to prevent damage and contamination. As long as no damage and no contamination occurs, slight touching might be acceptable. To meet this requirement, we have developed two types of the process equipment. One is for the gas phase processes and the other is for the liquid processes.

In the prototype of gas phase process system, a ball is floating inside a quartz tube in atmospheric pressure as shown in Figure 2 (a). The inner diameter of the tube is about 2-millimeters. The carrier gas of the precursor suspends the ball itself. We have already built oxidation systems, diffusion systems, poly Si CVD system, oxide CVD system, metal CVD systems for Al, Cu and TiN [4]. A system, which has a concept of parallel processing with several hundreds of floating balls, is under development for mass production stage.



(a) Gas phase process (single tube)



(b) Liquid chemical process

Figure 2. Balls running through the tube.

In the liquid process system, balls are flowing with the liquid chemical(s) along the inside wall of the plastic tube (Figure 2 (b)), which is wrapped like a coil followed by a DI water rinse system. We have been developing wet etching systems, photo resist developing systems and so forth. In the case of the liquid process system, the processing time can be controlled by the tube length and by the pressure to pump the liquid out. The same concept with DI water is applicable to ball transportation between process and process for continuous fabrication.

2-3 Spherical lithography

One of the high hurdles in Ball Semiconductor technology is spherical lithography, because no conventional exposure system was available for curved surfaces.

We have recently developed a so-called mask-less lithography system, which is illustrated in Figure 3. This system includes two important concepts. One is the electrical pattern generation using Digital Micro-mirror Device (DMD)[5] instead of the quartz mask, and the other is a spherical focal plane using an original micro lens instead of a flat focal plane.

The DMD consists of an 800 x 600 micro-mirror array with 17μm pitch. Each micro-mirror can be individually addressed for two tilting positions, +10 or –10 degrees, so this device can be used as a pattern generator, which is driven by computer directly. Six micro lens systems with DMD will cover almost 100% of entire surface of a sphere. Even electrical fine alignment of the patterns becomes possible in the mask-less lithography system.

In general, it takes about a month and huge cost to make quartz masks. On the other hand, the mask-less lithography system could reduce R&D cycle time and cost dramatically. The flexibility of pattern designing and mapping has much benefit to produce small quantities and many varieties of devices even if it is the flat chip.

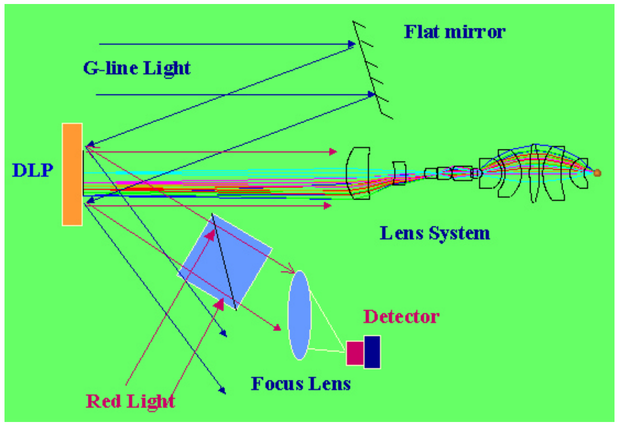


Figure 3. Schematic diagram of mask-less lithography system

2-4 Layout design on spherical surface

Designing circuits on a sphere is another unique aspect of Ball Semiconductor technology. There are two main issues in 3D design over conventional 2D design. The first is the closed surface topology with the inability to look at the entire design surface as a whole. The second is that there is no perpendicular grid system, which can cover the entire surface of the sphere. So we need a unique display system with a specifically ruled grid system.

Currently we have developed a 3-dimensional layout design tool for spherical surface, ABLE (Advanced Ball Layout Editor). ABLE was created to have high flexibility featured in (1) changing its viewpoint all the way around the sphere and (2) moving its relative perpendicular coordinate in any desired direction. A designer can draw parallel lines and spaces as same as conventional design tools and also can draw the shortest path between two specific points, which is a unique characteristic of the sphere called the great circle.

Recently, ABLE has been connected to the mask-less lithography system, so that designed patterns can be instantly exposed on the sphere. We are improving the tool by adding the functions of design rule check, electrical simulation capability and so forth.

2-5 Bumping and clustering

Instead of utilizing "system-on-chip" technology to achieve system integration, our approach is to cluster different function Balls together like atoms of a molecule.

To realize actual mechanical and electrical connection for input and output, a micro-ball bump technology[6] is applied on the spherical surface.

The material of the bump is currently gold and its size is about 80μm in diameter. The size and the position of the bumps are designed to match the requirement of the number of the pins and the height. Micro-balls are attached by a thermal press method. Figure 4 shows a SEM picture of a 3-axis accelerometer after patterning and bumping.

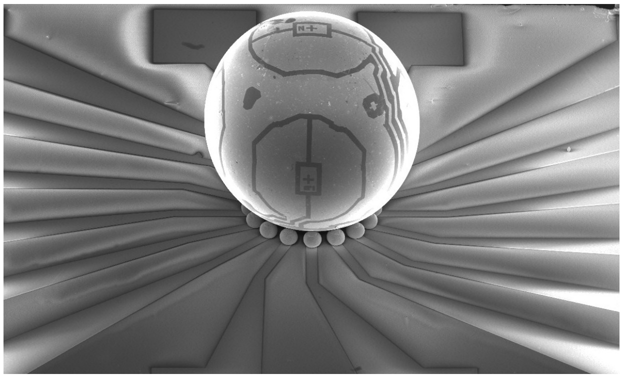


Figure 4. SEM picture of 3-axis accelerometer after patterning and micro-ball bump process

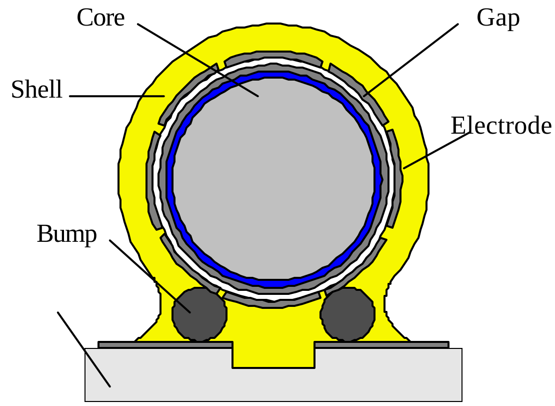


Figure 5. Cross section of 3-axis accelerometer

3. BALL PRODUCT TECHNOLOGIES

After successful development of the world first NMOS integrated circuit on the spherical surface in March 1999, we are exploring ball unique products utilizing the smallness, the roundness and other features of the Ball. Benefited by highly symmetrical 3D structure, closed topology of the ball, and surface process capability to fabricate a 3D structure, the MEMS device is one of the most interesting applications of the Ball technology.

We are currently developing an electro-statically levitated 3-axis accelerometer with Tohoku University and Tokimec [7]. The accelerometer consists of an outer shell and an inner core as shown in Figure 5. There is a narrow and precise gap between the shell and the core. Twelve electrodes for the electrostatic actuation and the capacitive sensing are placed at the inner surface of the shell.

The position of the core is controlled by a closed-loop servo system[8] to keep in the center and feedback intensity tells the acceleration. The mass of the 1-millimeter core is relatively large compared with the typical 2D surface micro-machined sensors.

Another inertia sensor, omni-directional clinometer is obtained by utilizing a similar structure. In this case, the inner core moves freely so that capacitance change tells us a tilting angle including up side down.

In the case that the inner core will be electro-statically levitated and rotated, a gyroscope can be realized. This principle of the gyroscope is well known to have the highest sensitivity among various gyroscopes [9].

A key process is a sacrificial layer etching using xenon difluoride (XeF2), which generates the gap. A beauty of the XeF2 etching is its extremely high selectivity between the Silicon and other materials. This etching process is performed at the final step of the process flow to avoid the damage of the shell from excessive stress of the micro-ball bump process.

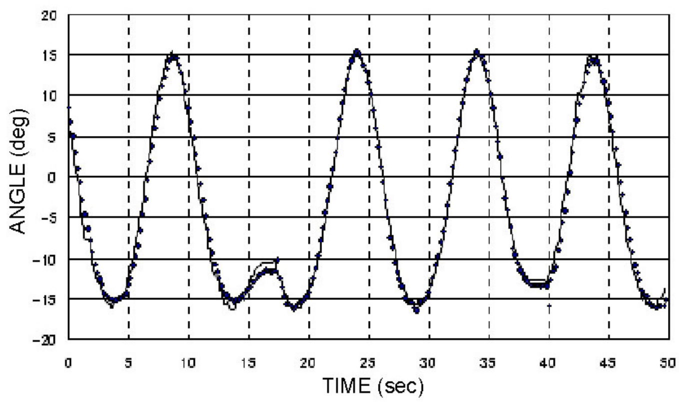


Figure 6. Detection of tilt angle using 2-axis electro-statically controlled Ball accelerometer[11].

The other interesting aspect is the gas permeable shell approach[10]. This shell enables to etch the sacrificial layer without any patterning on the shell. The structure can be sealed against the atmosphere easily after the sacrificial etching.

Figure 6 shows a detection of a tilt angle using the 2-axis electro-statically controlled Ball accelerometer. 3-axis control is now under development.

4. CONCLUSION

We have developed spherical single crystallization system, gas phase and liquid chemical process equipment using tubes and pipes, spherical lithography systems, 3D layout design tool and clustering technology to realize semiconductor devices and sensors on a 1mm sphere. We are currently developing an electro-statically levitated 3-axis accelerometer to utilize unique features of the sphere.

However these developments are halfway, all of expected technologies are present after three years research and development activities. Our efforts will be continued to explore unique processes and products such as integrated circuits and sensors so as to open up new markets utilizing the smallness, the roundness and the 3D features of the Ball.

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