A differential pressure sensor with ultra-overpressure resistance and an integrated overload protection system utilizing MEMS technology

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Key words

Pressure sensor, overload protection system, Bosch process, surface activated bonding (SAB), grayscale photolithography

Utilizing MEMS technology, including grayscale photolithography, wafer-level surface activated bonding (SAB), and a combination Bosch and non-Bosch processing technique, we have developed a differential pressure sensor with a revolutionary structure capable of resisting differential pressures approximately 630 times higher than those used at the sensor chip level. Additionally, this single sensor chip can make high-precision measurements of both differential pressure (DP) and static pressure (SP), and can measure differential pressure and pressure even when pressure exceeding the DP range is applied.

1. Introduction

Differential pressure/pressure transmitters are versatile industrial instruments widely used throughout the world for measuring pressure, flow rate, liquid level, and the like. Differential pressure/pressure transmitters can be used in extremely harsh environments where the applied static pressure can be several hundred times the measured differential pressure, and therefore require considerable pressure resistance. In the pressure sensors mounted on these transmitters, on the other hand, the differential pressure sensitivity and pressure resistance are in a tradeoff relationship. The pressure resistance can be anywhere from several times to as high as several tens of times the differential pressure that is measured. For this reason, differential pressure/pressure transmitters have an overload protection system to protect the sensor, but it comes with disadvantages that include deterioration of performance, increase in the product size and weight, and higher cost. For these reasons we have developed a differential pressure sensor with a revolutionary structure capable of resisting differential pressures approximately 630 times higher than those used at the sensor chip level by utilizing Azbil's microelectromechanical systems (MEMS) technology (fig. 1). Another noteworthy feature of this sensor is that it is capable, using a single chip [1], of independently detecting static pressure in two directions in addition to the differential pressure.

Φ7.5 × 5.52 mm in size and 0.3 g in weight.

Fig. 1. Exterior view of the sensor with ultra-overpressure resistance

2. Overview of the sensor

2.1 Measurement principle of a piezoresistive pressure sensor

This sensor uses piezoresistive sensing. Stress generated by the deflection of the diaphragm on the sensor chip is detected by a bridge circuit as a change in the resistance of the diffusion piezoresistors formed on the sensor's surface, as shown in figure 2. The relationship among the generated stress, resistance change rate, and bridge output voltage is shown by equation (1).

$$V_{out} = \tfrac{1}{2}(\sigma_l - \sigma_t)\,\pi 44 \times V_0 = \Delta R/R \times V_0 \quad \text{Equation (1)}$$

($\pi 44$: piezoresistive coefficient of <110>)

As this equation shows, voltage V_{out} accompanying the resistance change rate $\Delta R/R$, which is proportional to $\sigma_l - \sigma_t$, the difference between stress σ_l generated in the radial direction and stress σ_t generated in the tangential direction of the diaphragm, is output [2] [3].

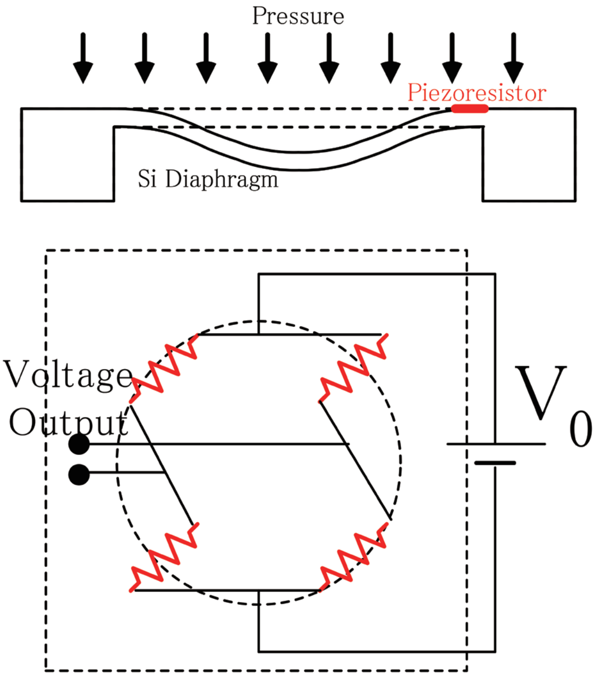


Fig. 2. Measurement principle of a piezoresistive pressure sensor

2.2 Structure and concept of the overload protection system

Our first sensor overload protection concept is illustrated in figure 3. In the sensor element, the diaphragm on which the piezoresistive elements are formed is sandwiched by two aspherical stoppers, and glass bases are connected to its top and bottom. The diaphragm does not come in contact with the aspherical stoppers within the range of operating conditions. However, if an overload is applied, the sensor diaphragm will reach the aspherical stopper, which prevents deformation of the sensor diaphragm and suppresses generation of excessive stress, thus preventing destruction of the diaphragm.

Therefore, the aspherical stoppers are shaped along the displacement of the sensor diaphragm when a certain pressure (the landing pressure) greater than the operating pressure is applied, so that the diaphragm does not have an abnormal deformation when it contacts the stoppers. In addition, there is a honeycomb pattern on the aspherical surfaces (fig. 4) that prevents sticking at the time of diaphragm contact. However, we know that, with a structure like this, stress is concentrated at one point at the end of the joint between the aspherical stopper and sensor diaphragm when diaphragm deformation occurs. Moreover, if there is displacement between the upper and lower aspherical surfaces, the amount of stress generated increases significantly. Therefore, we prevent an excessive concentration of stress by selectively forming an unbonded portion with a 50 μm width, as shown in figure 5. This succeeds in reducing generated stress by at least 50 %.

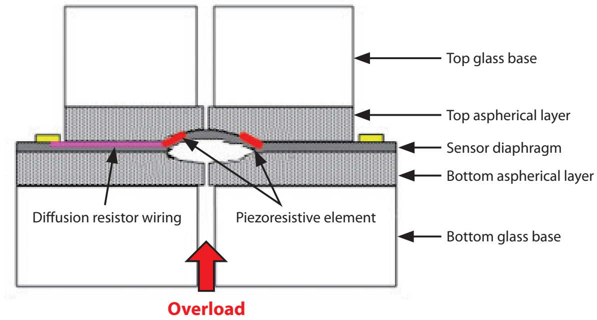


Fig. 3. First overload protection system concept

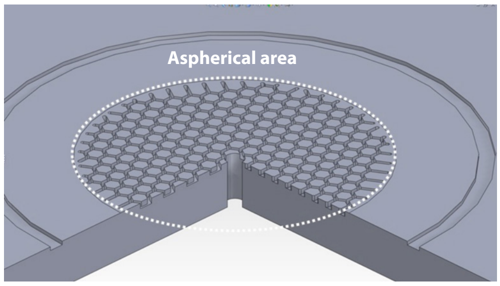


Fig. 4. Honeycomb pattern on aspherical surface

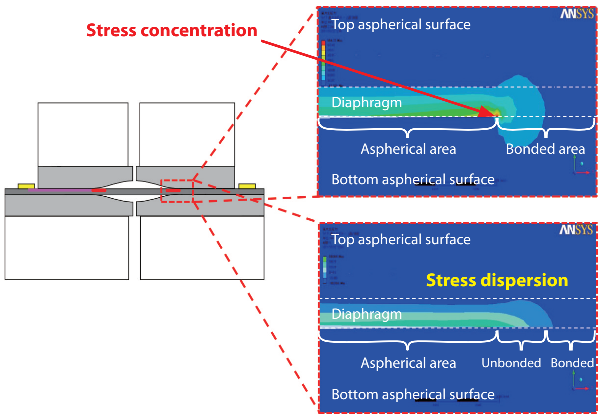


Fig. 5. Stress dispersion by selective bonding (result of FEM analysis)

However, if stress increases further, the entire sensor chip, including the stoppers, will be deformed. In such a case, excessive tensile stress is concentrated on the support sections of the aspherical surface and diaphragm, leading to destruction of the sensor (fig. 6).

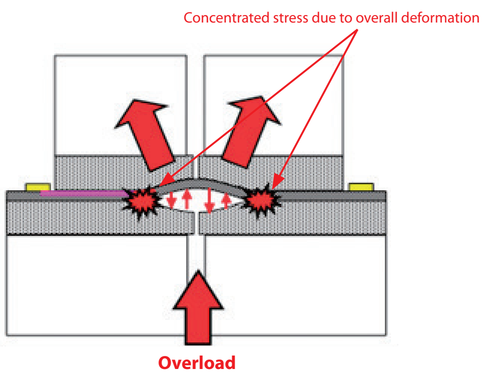


Fig. 6. Problems with the first concept

To prevent this, a second concept became necessary, resulting in the structure shown in figure 7. Here the sensor element consists of a sensor diaphragm, two aspherical stoppers, two silicon bases, and two glass bases.

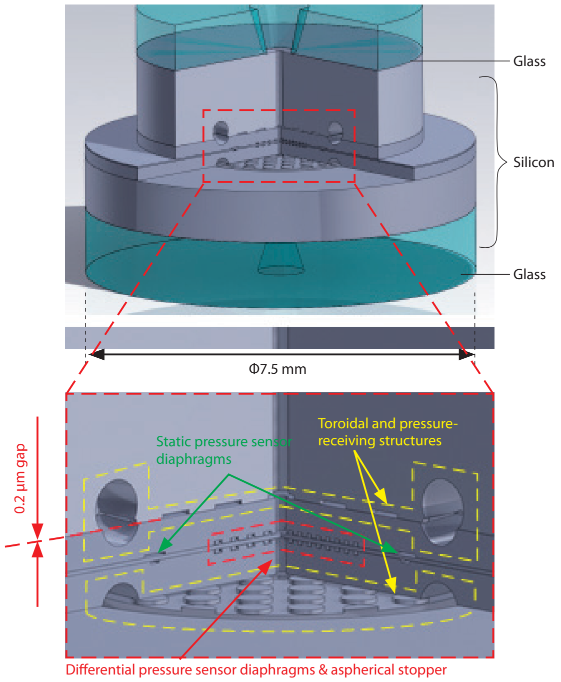


Fig. 7. Basic structure of the second concept

In addition to the first concept, a fine gap of approximately 0.2 µm is formed between the aspherical surface and the base layer connected to the back side of the aspherical surface, with the purpose of forming a pressure-receiving surface larger than the aspherical surface. In this area there is a pillar structure that prevents sticking and ensures the flow of the pressure-transmitting oil. Moreover, a unique toroidal structure formed by the stopper layer and base layer is provided at the end of the pressure-receiving surface. This structure makes the sensor multi-variable, with one differential pressure sensor and two independent static pressure sensors.

Figure 8 illustrates overload protection by the second concept. When overpressure is applied to this sensor element from the bottom, an upward force is generated on the bottom stopper layer because the pressure-receiving area formed on the base layer is larger than the aspherical surface area. The top stopper layer contacts the pillars, which suppresses deformation; therefore, compression stress, not tensile stress, is generated at the location that was the origin point of destruction due to excessive tensile stress in the first concept model. Instead, excessive tensile stress occurs in the toroidal structure sections on the outer periphery of the pressure-receiving area, but it is dispersed and relieved.

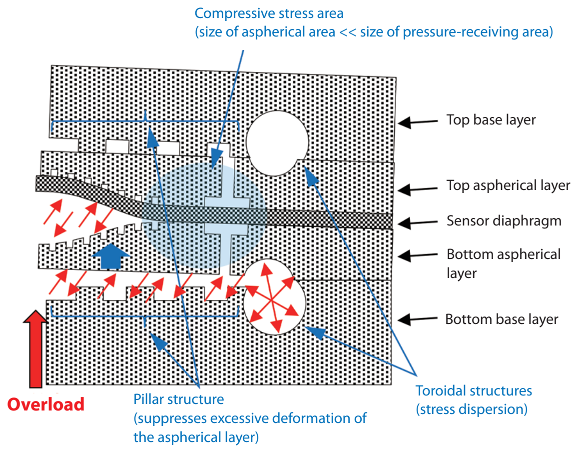


Fig. 8. Overload protection by the second concept

Figure 9 shows the result of FEM analysis of the toroidal structures' stress dispersion effect. The unique structure shown here is the result of optimization in stress dispersion and miniaturization by FEM, implementing the second overload prevention concept [4].

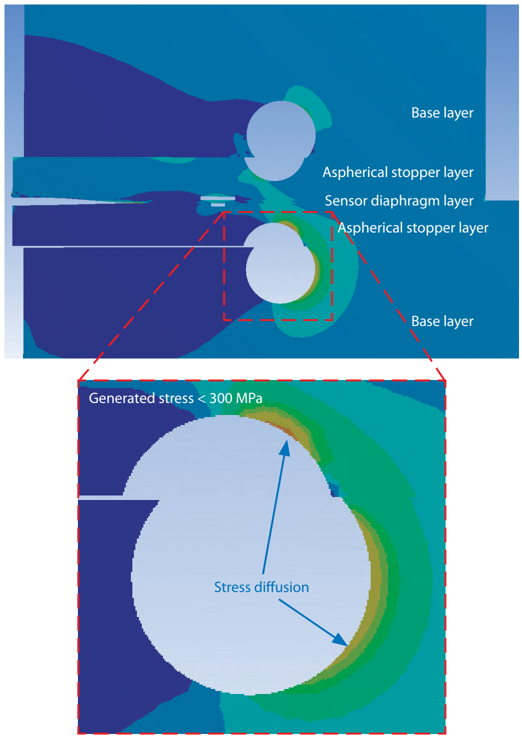


Fig. 9. Stress dispersion in toroidal structures during excessive pressure application (FEM analysis result)

3. Fabrication method

A schematic diagram of the stopper layer fabrication process is shown in figure 10. First (a), the aspherical shape is formed in the stopper layer made of a (100)-oriented silicon substrate with a thickness of 250 µm using grayscale photolithography and isotropic etching (Non-Bosch process) by reactive ion etching (RIE). Next (b), a ring-shaped trench structure with a depth of 20 µm for forming the diaphragms for static pressure (SP) is formed on the same surface using anisotropic etching (Bosch process). On the same surface, a trench structure with a depth of 100 µm (c) is formed using the Bosch process in order to avoid interference from the sensor electrode on the opposite side when bonding the wafer. On the back surface (d), a ring-shaped trench structure with a depth of approximately 130 µm, width of approximately 345 µm, and curvature of approximately 360 µm is formed using the Non-Bosch process.

As is shown by figure 11, there are two steps in the etching process. In the first step, etching uses SF6 gas only. In the second step, etching is done with SF6 and C4F8 gas. This makes it possible to increase the curvature while maintaining a shallow etching depth.

Lastly (e), a through-hole is formed as an opening for introducing pressure into the differential pressure (DP) and static pressure (SP) sensor diaphragm using the Bosch process.

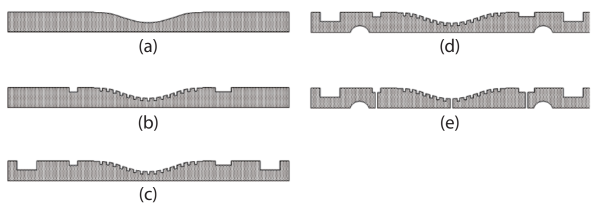
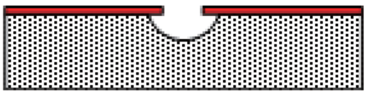


Fig. 10. Aspherical stopper layer fabrication process

(1) *The first etching result utilizing SF6 only*



(2) *The second etching result utilizing SF6 and C4F8*

Fig. 11. Two-step etching process

A schematic diagram of the base layer fabrication process is shown in figure 12. First (a), a pressure-receiving section with a depth of 0.2 µm or less is formed on the base layer consisting of a (100)-oriented Si substrate with a thickness of 1,500 µm by RIE. After that (b), pillar structures with a depth of 20 µm are formed at equal intervals using the Bosch process in the same area. Next (c), toroidal structures are formed on the outer periphery of the pressure-receiving section using a technology combining the Bosch and Non-Bosch processes. Etching is done in two steps as illustrated in figure 13.

The Bosch process is used in the first step, and then the Non-Bosch process in the second. This causes the etched portion to change from a slit to a circular shape, resulting in a unique structure with a depth of approximately 300 µm, an opening of approximately 315 µm, and curvature of approximately 385 µm. Lastly (d), a through-hole is formed as an opening for introducing pressure into the pressure-receiving section using the Bosch process.

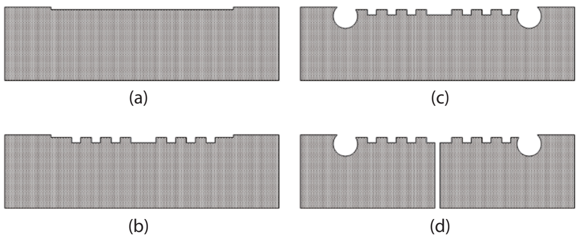
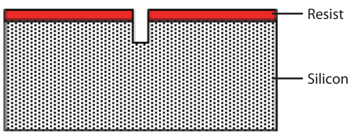
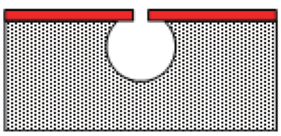


Fig. 12. Base layer fabrication process



(1) *The first etching result utilizing Bosch*



(2) *The second etching result utilizing Non-Bosch*

Fig. 13. Two-step etching process

A schematic diagram of the laminate bonding process is shown in figure 14. The sensor wafer consists of two stopper wafers, two base wafers, and piezoresistive elements fabricated with silicon-on-insulator (SOI) wafers bonded by means of wafer-level surface activated bonding (SAB). First (a), the top base layer and top stopper layer are bonded. Next (b), the first bonded wafer and sensor wafer are bonded. After that (c), the substrate layer of the SOI wafer is completely removed by the Bosch process, and the buried oxide (BOX) layer of the SOI wafer is also completely eliminated using the buffered oxide etch (BOE) process. Next (d), the bottom base layer and bottom stopper layer are bonded. Lastly (e), the bottom bonded wafer and top bonded wafer are bonded.

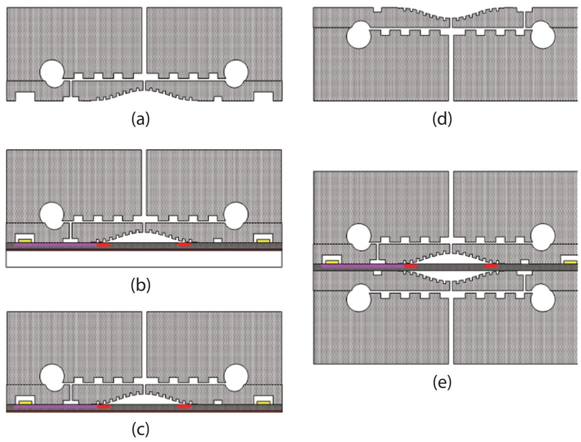


Fig. 14. Laminate bonding process

Figure 15 shows a cross-section of the fabricated sensor chip, and figure 16 shows the result of observation from above with an IR microscope. This structure protects the differential pressure (DP) sensor even when excessive differential pressure is directly applied to the chip, making it possible to independently measure static pressure (SP) from either direction.

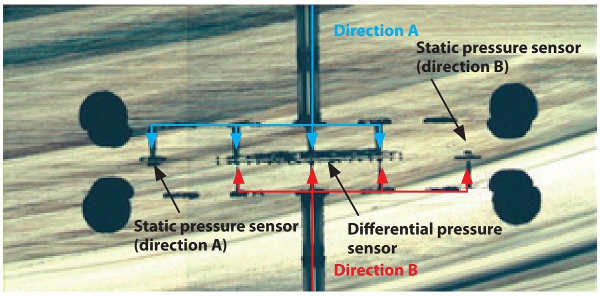


Fig. 15. Cross-section observation with a microscope

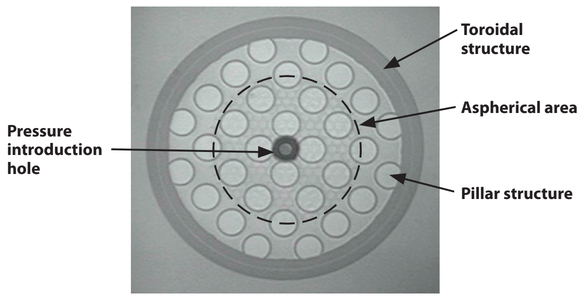


Fig. 16. Cross-section observation with IR microscope (top view)

4. Experimental results

The sensor output characteristics in the low differential pressure range and high differential pressure range are shown in figures 17 and 18. With one chip we were able to obtain differential pressure measurements from both the high and low pressure sides and independent static pressure measurements in two directions. We demonstrated that the sensor has pressure resistance (10 times greater than that of a conventional sensor) sufficient to withstand pressure 630 times the standard operating pressure range.

In addition, we were able to demonstrate pressure measurement by the outputs from the independent static pressure sensors in two directions because pressure is applied to the sensor chip while the differential pressure diaphragm is protected.

Moreover, in repeated pressure resistance testing the pressure resistance performance at 42 MPa was demonstrated 50,000 times.

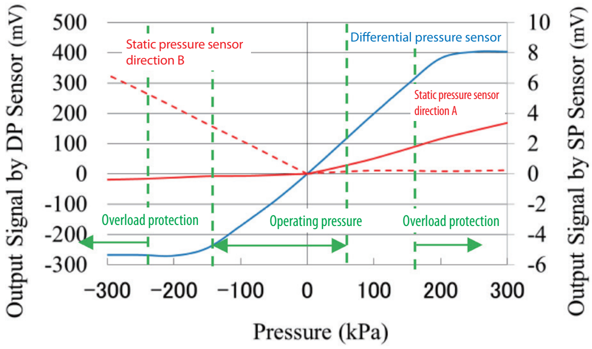


Fig. 17. Sensor characteristics in the low differential pressure range

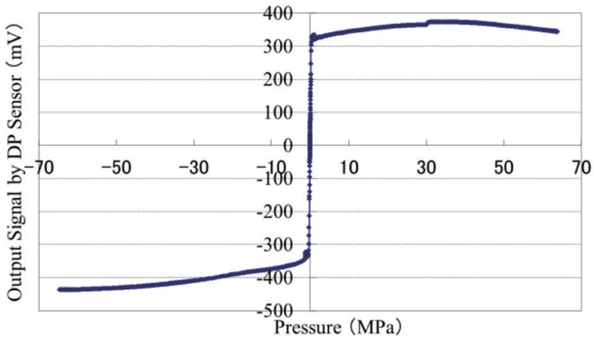


Fig. 18. Sensor characteristics in the high differential pressure range

5. Conclusion

A differential pressure sensor with an overload protection system equipped with ultra-overpressure resistance capacity due to a unique revolutionary structure has been realized utilizing Azbil's proprietary MEMS technology.

On the other hand, since the structure of this sensor is extremely complex, it has a high level of processing difficulty, and therefore mass production would be difficult. Utilizing this technology, we intend to introduce new products by creating a new sensor with the same functionality and a simpler structure that is suitable for mass-production, so as to provide value to customers through improved durability and reduced size and weight.

References

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