Upgrading a sapphire-based capacitance manometer for reduced size and enhanced anti-deposition characteristics

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Key words

Capacitance pressure sensor, MEMS, sapphire, semiconductor manufacturing process, capacitance manometer

We have developed a new vacuum gauge that dramatically improves our previous sapphire capacitance diaphragm gauge model (SPG), which was developed for use in semiconductor manufacturing processes. The sensor chip and the peripheral package structure have been thoroughly reworked for compact size, smaller volume, and high pressure resistance. The specially designed diaphragm structure now has significantly improved resistance to deposition. Also, by separating the sensor element from the circuit boards we have been able to raise the operating temperature from 200 ºC to 250 ºC, allowing us to meet a great variety of customer needs related to continuously developing semiconductor manufacturing processes.

1. Introduction

For the deposition and etching processes in semiconductor manufacturing, capacitance pressure sensors—total pressure vacuum gauges without gas dependency, generally known as capacitance manometers—are widely used for pressure monitoring and control. Many of the gases used for these processes are very reactive and corrosive, such as halogen gases, and therefore the constituent materials of the sensor must have corrosion resistance. In addition, these sensors are often heated in a range from 100 to 200 °C to prevent adhesion of by-products inside the vacuum gauge, and the range of required maximum measurable pressure is also broad, from an ultra-low pressure of 13 Pa to 133 kPa, which is close to atmospheric pressure.

Azbil has developed a sapphire capacitance diaphragm gauge, model SPG_ _, that incorporates a MEMS sensor chip with sapphire as the base material, which gives it superior resistance to corrosion and heat. It is designed for use in semiconductor manufacturing processes, which require a broad range of gas types, operating temperature ranges, and pressure ranges [1]–[7]. Figure 1 shows the appearance of model SPG gauges. More than 10 years have passed since these gauges were put on the market, and various issues have arisen as they have been used. In particular, a major issue has been how to suppress the effect on output of process by-product accumulation inside the sensor, and specifically on the pressure-sensing diaphragm. Also, we have made various improvements to the structure of the SPG's sensor [3] [7]. In conversations with our customers it has also become clear that smaller products that do not take up much space, those with a smaller vacuum gauge internal volume for fast response, and those that operate at higher temperatures so as to support next-generation materials are in demand. Since the limitations imposed by the structure and size of the previous model SPG would make it impossible to satisfy these customer demands, we needed to fundamentally rethink the sensor chip's structure, the package, and the measurement circuit. For these reasons we began development of the model V8 sapphire capacitance diaphragm gauge.

Fig. 1. Appearance of model SPG

2. Overview of the pressure sensor

In section 2 the structure of the sensor chip and package of the V8 is compared with those of the SPG, and their features are explained.

2.1 Sensor chip structure

The structure of the SPG [1] [4] is basically used for the sensor chip. The sensor works by detecting outputs caused by changes in the capacitance, which are caused by deflection of the thin sheet called the diaphragm, as shown in figure 2. The basic structure is such that electrodes that form a capacitor are arranged above and below a cavity on the opposite side of the diaphragm from the process fluid whose pressure is being measured. The diaphragm is deflected when pressure is applied, and signals are read from behind the diaphragm.

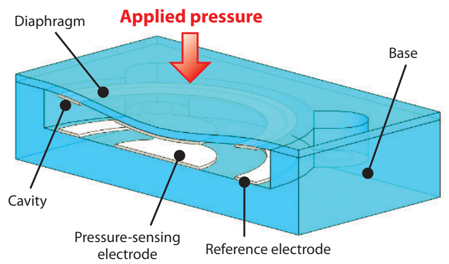
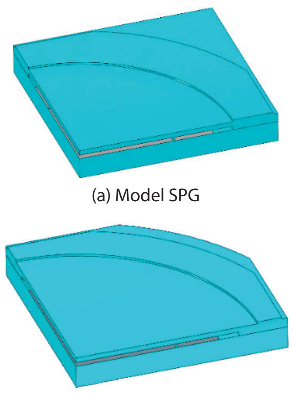


Fig. 2. Sensor operation principle

As shown in figure 3, the most radical change made to the V8 to improve it over the SPG is that the sensor chip is not a simple square but has rounded corners. This change made it possible to reduce the burden placed on the metal sheet (fig. 4) if a pressure overload is applied, improving the burst pressure to over 3 MPa, more than double the 1.5 MPa of the previous model. A high burst pressure like this is required especially for vacuum gauges installed in the gas supply side of process chambers.



(a) Model SPG

(b) Model V8

Fig. 3. Comparison of sensor chip shapes

2.2 First packaging

First packaging is a process in which the sensor element is bonded to a piece of sheet metal used as a bridge between the sensor element and the metal casing. Also in this step, the electrodes are led out from the back of the sensor. The linear expansion coefficient of sapphire, between 7 and 8 × 10^{-6} / K, is very different from that of nickel-based corrosion resistant alloys, between 12 and 14 × 10^{-6} / K, which are the casing materials. Bonding a sapphire sensor chip to metals like this would not only have a negative impact on aspects such as temperature characteristics and temperature hysteresis of the sensor, but would also impair the corrosion resistance of the overall sensor if a bonding material such as adhesive, brazing material, or low-melting-point glass was used. In the SPG, we avoided bonding the sensor chip directly to the metal sheet, instead inserting a type of intervening material called cover sapphire to prevent deterioration of the above characteristics. In addition, we adopted a thermal diffusion bonding technique that does not require inclusion to bond the metal and the sapphire. In this bonding method, the thermal stress generated by bonding is balanced by the structure, which consists of a metal sheet sandwiched between two pieces of sapphire [1]. In the V8, we sandwiched a nickel-based alloy sheet between a component called the balance sapphire (which is fabricated from a wafer like the sensor chip) and the sensor chip, without using a cover sapphire. Naturally, temperature-related characteristics are expected to deteriorate, as mentioned above, unless countermeasures are taken, since materials with different linear expansion coefficients are directly bonded to the sensor chip.

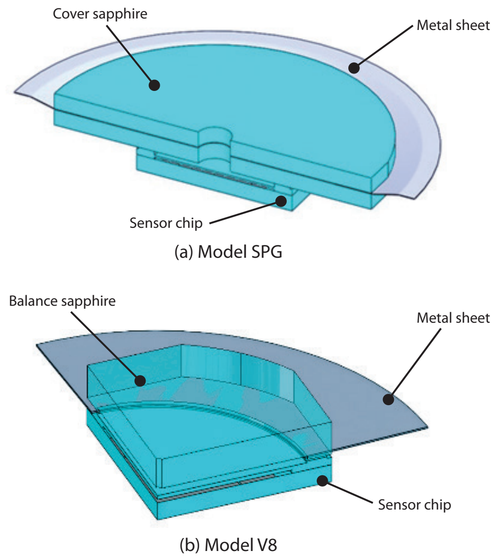
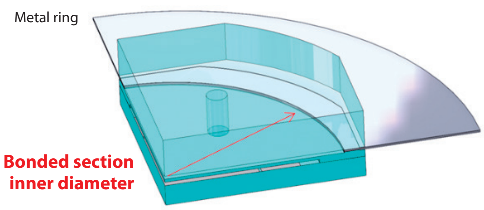


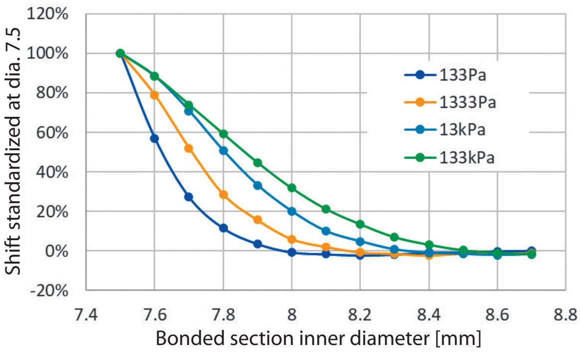
Fig. 4. Comparison of the structures of the first package

As a result of various simulations, we found that temperature characteristics were improved by making the inner diameter of the bonded section larger than the diameter of the movable part of the diaphragm. Calculations resulting from the simulations are shown in figure 5. The inner diameter of the bonded section is plotted on the horizontal axis and the shift in the output when the temperature is changed is plotted on the vertical axis, with 100 % as the value when the diameter of the movable part of the diaphragm matched the inner diameter of the bonded section (7.5 mm).

In sensors for any range, we found that the effect of bonding different materials can be suppressed by enlarging the inner diameter of the bonded section of the sensor. This is based on the principle that the deformation of the diaphragm can be prevented even when the overall sensor becomes deformed by placing the diaphragm on the neutral plane of the deformation caused by bonding different materials.



(a) Calculation model



(b) Calculation result

Fig. 5. Temperature characteristic simulation results

The temperature characteristics of an actual 1,333 Pa range sensor are shown in figure 6. The temperature characteristics in the 45–200 °C range are improved to 1/100 or less when the inner diameter is increased from 7.5 to 8.1 mm.

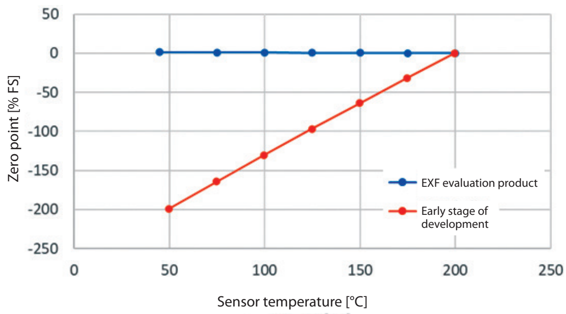
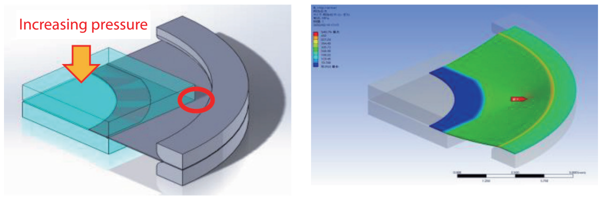
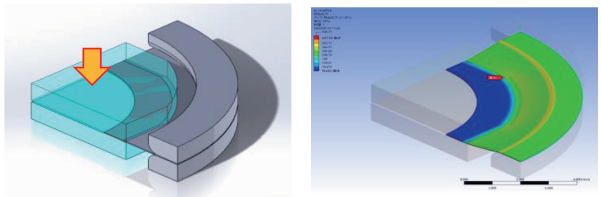


Fig. 6. Temperature characteristics

The results of simulations for pressure resistance explained in section 2.1, "Sensor chip structure" are shown in figure 7. In these simulations we used a nonlinear material model to calculate the stress at each location when a pressure of 1 MPa was applied to the sensor, and we examined whether the stress reached 540 MPa, which is the fracture stress of the metal sheet. In the case of a square chip, the maximum stress is generated at the location where the corner contacts the metal sheet, and it reaches the fracture stress when a pressure of approximately 0.8 MPa is applied. In the case of a rounded sensor chip, the maximum stress was 497 MPa and it did not reach the fracture stress, showing that a rounded chip could increase the pressure resistance.



(a) Square sensor chip



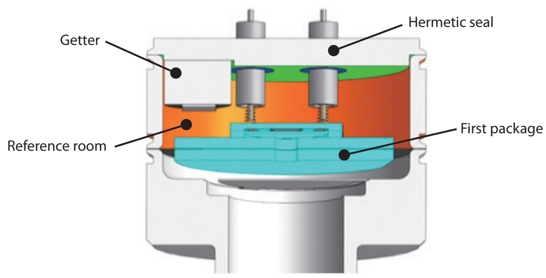
(b) Rounded sensor chip

Fig. 7. Results of pressure overload simulation

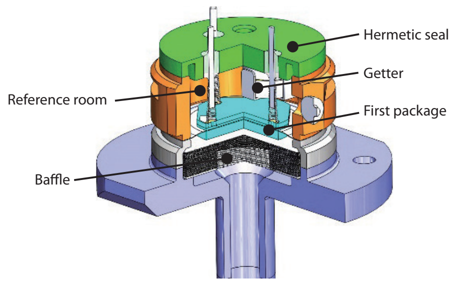
As mentioned above, we were able to reduce the overall sensor size while significantly reducing the internal volume of the sensor, which has a large impact on the stress response, by making the first package without the cover sapphire while still maintaining each characteristic.

2.3 Second packaging

Second packaging is a process in which the first package is welded to the metal casing together with the glass part of the hermetic seal section from which signals are received and a baffle for preventing accumulation of process by-products, all of which are then vacuum sealed. After vacuum sealing, the activated getter materials made of active metals maintain the degree of vacuum of the reference chamber at ultra high vacuum (up to 10^{-10} Pa), enabling the measurement of the absolute pressure. In this package, the basic concept of the SPG was used without modification, and the casing was designed to fit the downsized first package. A comparison of the structures of the SPG and V8 is shown in figure 8. A major change was eliminating the shielding of the signal lines of the hermetic seal provided in the SPG. Since capacitance measurement is sensitive to external electrical noise, it is necessary to shield the signal lines. However, as a result of various tests, it became clear that removing the shielding from the hermetic seal section had no impact on the noise resistance. Therefore, the structure was simplified.



(a) Model SPG



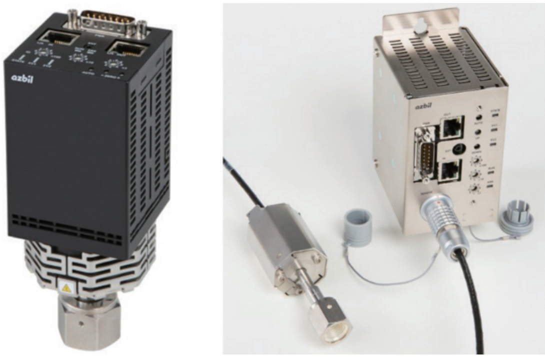
(b) Model V8

Fig. 8. Comparison of the second package structures of models SPG and V8

2.4 Product packaging

The structure and process of product packaging, which is the process after second packaging up to product completion, are variable according to the purpose. In developing the V8, we not only developed the shape of the coupling for attaching the product to the process chamber, but also developed a new model (fig. 9b) with the measurement circuit separated from the sensor. The separated model does not have a heater, unlike the integrated model (fig. 9a), and it is heated together with the piping of the customer's equipment. In the integrated model, the temperature cannot be raised above 200 °C because the circuit is located near the sensor. However, in the separated model the temperature can be raised up to 250 °C. This type of sensor is required not in the process chamber itself, but in the line on the gas supply side. In recent years, the process called atomic layer deposition (ALD) has made it necessary to supply various liquid materials or solid materials to the chamber after vaporizing or sublimating them. This has resulted in an increased need for pressure sensors, flowmeters, and valves that operate at higher temperatures.

Once the packaging of the product is complete, the sensor is characterized with the incorporated measurement circuit, and the product is shipped after an inspection of the characteristics. We have radically redesigned the measurement circuit as well and made improvements such as increasing its response speed.



(a) Model V8C integrated model (b) Model V8S separated model

Fig. 9. Separated model and integrated model

3. Sensor characteristics

In section 3, typical results of the characteristics evaluation for a 1,000 Pa range sensor are shown.

Figure 10 shows the pressure sensitivity of multiple sensors. The vertical axis shows the change in capacitance and the horizontal axis shows the applied pressure. The pressure sensitivity of all units clearly falls within the range of standard values specified based on the manufacturing tolerances of the sensors.

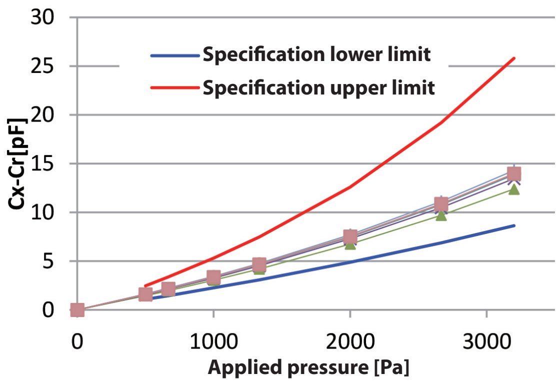


Fig. 10. Pressure characteristics

Figure 11 gives the thermal hysteresis measurements, which show the shift in the span when the sensor temperature is raised from 150 to 230 °C and then reduced to 150 °C again. The span is the difference between the output when pressure is applied and the output when the pressure is zero.

The results show that the shift in the zero point is less than 0.5 % full scale and that there was almost no shift in the span, indicating stable characteristics even when the temperature changed over a wide range.

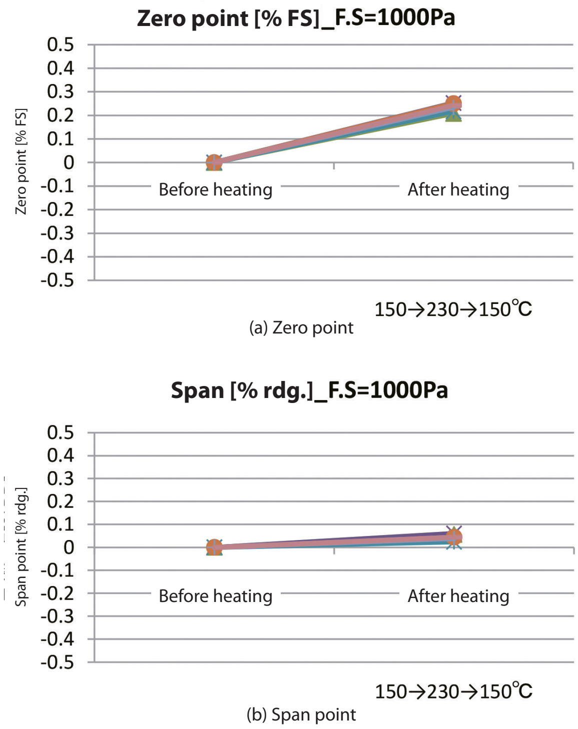


Fig. 11. Thermal hysteresis

Evaluation of the fluctuations in long-term output of the zero point at 230 °C is shown in figure 12. The output fluctuates by less than 0.1 % full scale even after 180 hours, indicating that it is extremely stable.

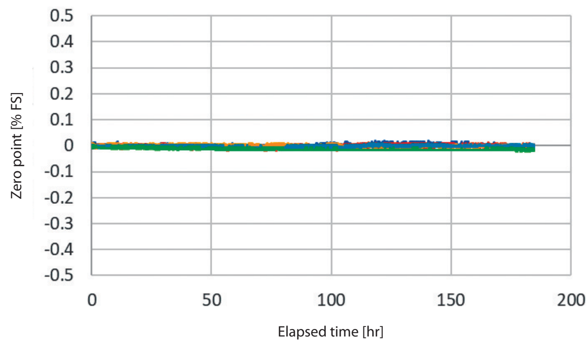


Fig. 12. Zero point drift at 230 °C

The results of the vapor phase thermal shock test between −20 and 80 °C are shown in figure 13. The shift in the zero point was 0.1 % full scale and the span was 0.02 % rdg., and there were no significant changes before and after the test.

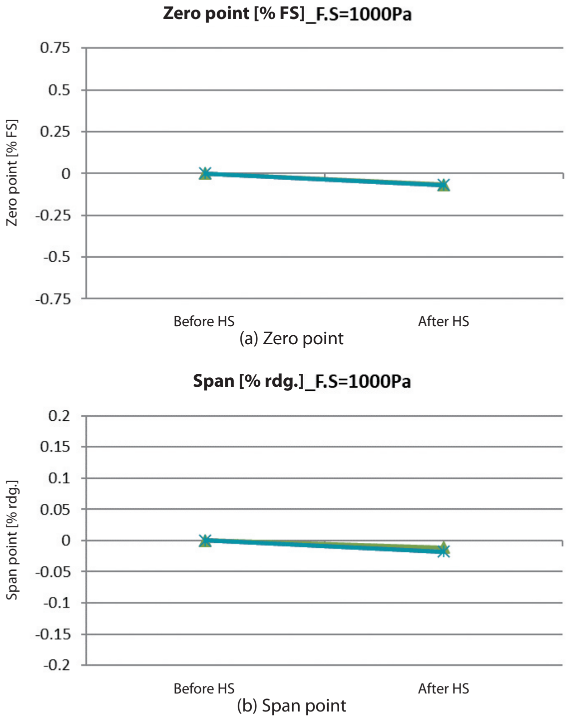


Fig. 13. Vapor phase thermal shock test

In figure 14, the results of an allowable pressure application test are shown. The changes in the zero point and span after a pressure of 300 kPa is applied 250 times at 230 °C are shown. There were no major changes in either value, indicating that no major characteristic changes occur even after excessive pressure is applied, such as opening the chamber to atmospheric pressure.

These results show that the characteristics of the V8 sensor we have developed are greatly superior to other sensors.

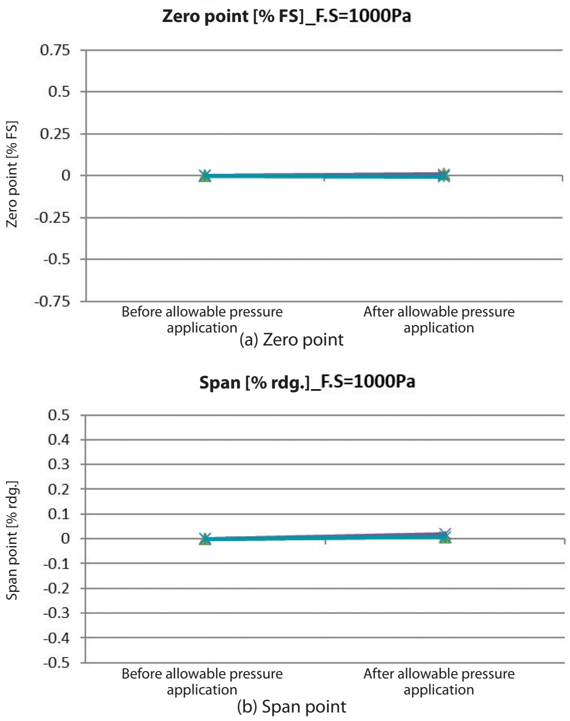


Fig. 14. Allowable pressure application test

4. Deposition resistance

Process by-products may accumulate in vacuum gauges used in semiconductor manufacturing processes, causing a shift in the zero point. This results in the need to stop the equipment to adjust the zero point or to replace the sensor. "Deposition resistance" refers to how well this deposition is prevented, and is the most important criterion used by equipment manufacturers in deciding whether or not to adopt a product. In actuality, this problem cannot be prevented simply by heating the sensor. Although various countermeasures were taken for the SPG, they were insufficient for various reasons. For example, processes like ALD that cause the generation of a large quantity of by-products became mainstream, and the amount of by-products increased due to increase of the gas supply in order to raise wafer throughput. The behavior of a typical SPG sensor is shown in figure 15. This is the result of an in-house re-evaluation of a 1,333 Pa sensor used in a chemical vapor deposition (CVD) process. It is characterized by shifting or drifting due to the application of heat or pressure, in addition to a shift in the zero point by 13 Pa. This sort of sensor behavior indicates that some kind of viscous material remains on the diaphragm and that countermeasures are necessary.

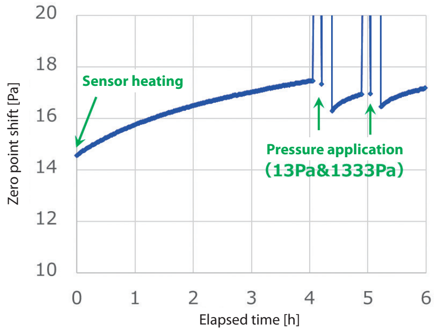
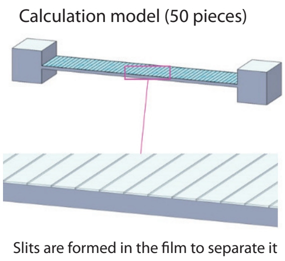


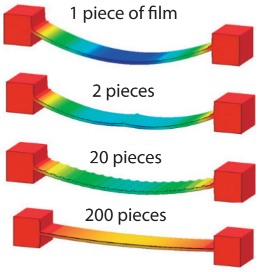
Fig. 15. Sensor behavior after CVD process

4.1 Basic deposition countermeasure concept for the V8

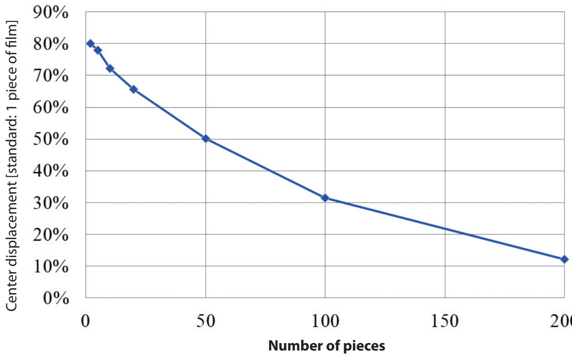
In developing the V8, a somewhat versatile countermeasure was taken that does not cause problems such as a shift of the zero point even if deposition occurs. The basic principle of this countermeasure is that, if the deposited film can be physically separated into pieces, stress generated from individual pieces will not cause the diaphragm as a whole to deflect. The results from verification of this principle by simulation are shown in figure 16. Depositional stress is placed on a one-dimensional model beam, which causes it to deflect. Slits are formed in the film to separate it, and the effect was checked. The results of these calculations indicate that the maximum deflection of the beam can be reduced to approximately 1/10 when the film is separated into 200 pieces compared to when it is not separated.



(a) Analysis model



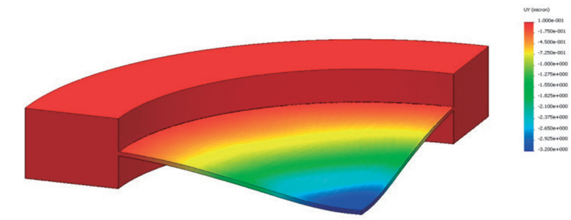
(b) Analysis result (displacement diagram)



(c) Analysis result (center displacement)

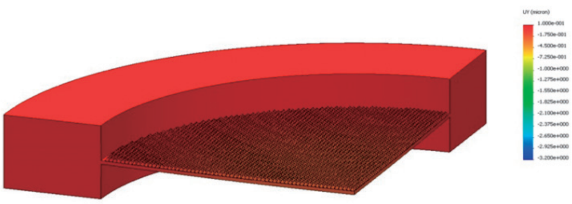
Fig. 16. Simulation of deposit film separation effect using a one-dimensional model

In addition, the results of calculation using three-dimensional disk models that are close to the actual shape are shown in figure 17. We found that the displacement in the model with separated film is 1/12 that of the model without film separation.



Center displacement 3.178 µm

(a) Displacement diagram for the model with continuous film



Center displacement 0.256 µm

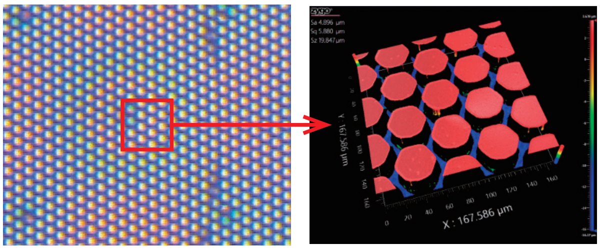
(b) Displacement diagram for the model with separated film

Fig. 17. Simulation of the effectiveness of deposited film separation using a 3D model

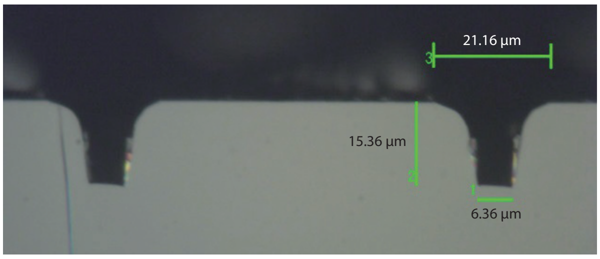
The simulations show that even if film is deposited on the sensor diaphragm, the effect of stress on the diaphragm can be suppressed if the film is separated into small pieces.

4.2 Knurled diaphragm as a deposition countermeasure

Next, we considered how to create a structure that separates the film. Our goal was to separate film that is deposited by utilizing MEMS processing technology to make fine grooves on the sensor diaphragm, causing differences in the ease of gas infiltration during deposition. Based on the temperature and pressure during the deposition process, the mean free path of gas molecules (the distance they can travel without colliding with other gas molecules) is approximately 50 µm. The probability of gas molecules infiltrating spaces smaller than this falls off sharply. As a result, the amount of film deposited inside and outside the grooves differs, and this is what is used to separate the film. The structure that was processed on the diaphragm is shown in figure 18.



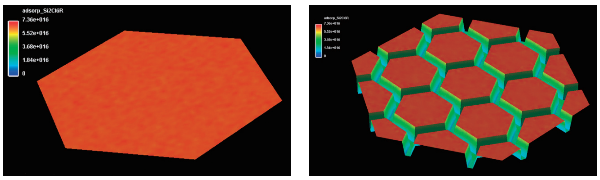
(a) Photo of diaphragm surface with finely knurled structure (left) and magnified view (right)



(b) Cross-sectional view of the finely knurled structure

Fig. 18. Finely knurled structure

In addition, the results of simulations of deposition using direct simulation Monte Carlo (DSMC) are shown in figure 19. A difference of approximately 3:1 in the amount of adsorption was generated between the outside and the bottom of the grooves, and the honeycomb pattern in which these grooves are arranged contributes to separation.



(a) Flat structure (b) Finely knurled structure

Fig. 19. Simulation of deposition by DSMC

4.3 Effectiveness of the deposition countermeasures

Lastly, the effectiveness of the knurled diaphragm's deposition resistance as verified by experiments is shown below. In figure 20, the results of an experiment in which a vacuum gauge with a simple flat diaphragm chip and one with a finely knurled diaphragm chip were placed in the latter part of the SiO_2 thermal CVD process. The zero point was continuously measured throughout the process. The range was 1,333 Pa, and there was a shift of approximately 0.3 Pa for the gauge with the flat chip, a small but clear difference.

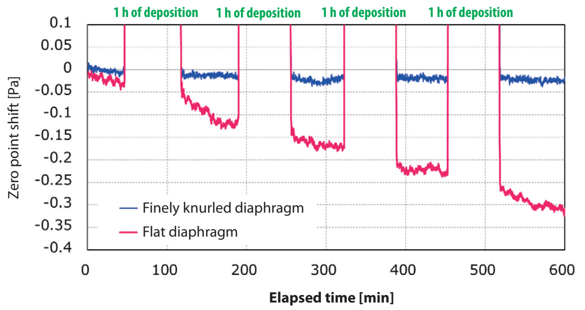


Fig. 20. Comparison of zero point behavior after the SiO_2 CVD process

Next, the result of a comparison of sensor behavior after the polysilicon CVD process with the two kinds of chip is shown in figure 21.

The figure shows that the chip with the finely knurled pattern had significantly improved performance in the case of polysilicon, unlike in the case of SiO_2. The flat chip had a zero point shift of about 14.5 Pa (corresponding to a little over 1 %), and there was also drift after heating and a shift after pressure application. The chip with the finely knurled pattern had a zero point shift of only 1.4 Pa (corresponding to 0.1 %), and the reading returned to 0 immediately after heating or pressure application. The drift and shift seen with the flat chip was not observed. Since the evaluation of deposition was conducted on these two sensors simultaneously, a clear, although relative, deposition resistance effect was confirmed.

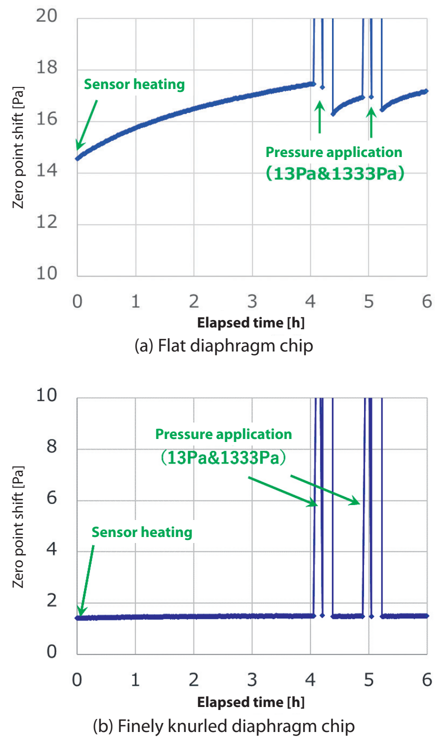


Fig. 21. Comparison of zero point behavior after the polysilicon CVD process

5. Conclusion

As devices are increasingly miniaturized or made three-dimensional, the methods and materials used for semiconductor manufacturing processes are advancing day by day, and so the functionality required of vacuum gauges used for pressure control in semiconductor manufacturing processes is also expanding. In particular, deposition resistance is an important characteristic that directly affects equipment operation conditions for end users. Therefore, it is necessary for gauges to support not only the SiO_2 and polysilicon CVD processes that were evaluated in this article, but also plasma processes and a wide range of others. We plan to offer models based on the V8 with enhanced functionality as needed by our customers.

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