Development of sapphire diaphragm gauge (Model V8):

A diaphragm vacuum gauge designed to meet the evolving needs of semiconductor process equipment by solving deposition shift problems and providing a compact design along with high-temperature and high-speed capabilities

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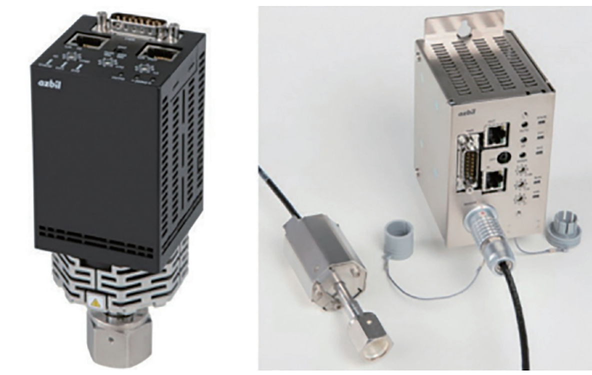
1. Introduction

Diaphragm vacuum gauges used in semiconductor deposition and etching processes must provide robust corrosion and heat resistance. Azbil has been developing and marketing MEMS sensor chips that use sapphire as the base material for over 10 years. However, the rapid advancement of semiconductor processes has increased the demand for higher temperature resistance and faster response times. In response to these changes, we have completely redesigned the architecture and features to develop the new sapphire diaphragm gauge (Model V8).

2. Model V8 lineup

The external appearance of the newly developed Model V8 is shown in figure 1.

We developed two variations: the integrated model (Model V8C), which combines the sensor and measurement circuit in a single enclosure—similar to the current product (Model SPG)—and the separated model (Model V8S), which houses the sensor and measurement circuit in separate enclosures.



Integrated model (Model V8C) Separated model (Model V8S)

Fig. 1. Model V8 appearance

3. Sapphire diaphragm gauge overview

3.1 Sapphire material

Table 1 compares the heat and corrosion resistance of sapphire and other materials. Sapphire exhibits superior resistance to both corrosion and heat compared to silicon and even other corrosion-resistant ceramics. It is also resistant to highly corrosive gases used in semiconductor processes, such as fluorine and chlorine, and retains these properties in high-temperature environments.

Table 1. Heat and corrosion resistance of sapphire and other materials

		Heat resistance	Corrosion resistance	
		Operating temp. (°C) under atmospheric conditions	Acid resistance	Alkali resistance
Sapphire (Al_2O_3)		1950	Excellent	Excellent
Silicon (single-crystal Si)		Up to 400	Not good	None
Fused quartz (SiO_2)		1200	Not good	Not good
Ceramic	Al_2O_3	1400-1750	OK	OK
	SiC	1600	OK	Not good
	Si_3N_4	1200	OK	Not good

3.2 Sapphire sensor chip

A cross-sectional view of the sapphire sensor chip is shown in figure 2.

The sensor chip consists of a pressure-sensitive diaphragm and a pedestal with a cavity for forming capacitors, both of which are made of sapphire. The diaphragm and pedestal are directly bonded, maintaining their corrosion- and heat-resistant properties. The size of the sensor is approximately 10 square mm, with the diaphragm having a diameter of approximately 8 mm.

Within the diaphragm and pedestal, two pairs of metal electrodes are positioned opposite each other, forming two types of capacitance: pressure sensitive capacitance C_X and reference capacitance C_R. The pressure sensitive capacitance, formed inside the diaphragm, changes its value in response to pressure variations. By using both the pressure sensitive capacitance C_X and the reference capacitance C_R, as given in equation (1), it is possible to effectively cancel temperature characteristics due to material thermal expansion and measure pressure with minimal error.

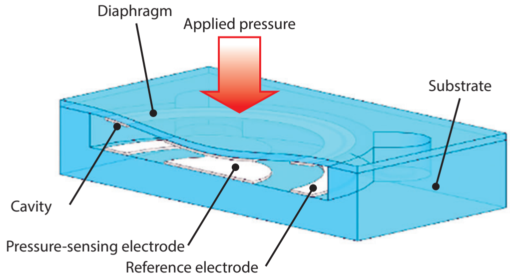


Fig. 2. Cross-sectional view of the sensor chip

$$\frac{C_X - C_R}{C_X} = \frac{\varepsilon \cancel{F} \frac{\cancel{S}}{\cancel{d}(1-\alpha P)} - \varepsilon \cancel{F} \frac{\cancel{S}}{\cancel{d}}}{\varepsilon \cancel{F} \frac{\cancel{S}}{\cancel{d}(1-\alpha P)}} = \alpha P \quad \text{Equation (1)}$$

ε: Permittivity in Cavity
F: Thermal expansion coefficient of sensor material
S: Area of electrode
d: Distance between electrodes
α: Deflections coefficient of diaphragm
P: Applied pressure

3.3 Sensor package

The structure of the sensor package is shown in figure 3. The sapphire sensor chip is bonded to the metal ring using a diffusion bonding technique, which ensures corrosion and heat resistance. Additionally, a chemical getter pump is employed to maintain a high vacuum in the reference vacuum chamber. The pressure inlet is equipped with a flat baffle plate that protects the sensor chip from solid matter.

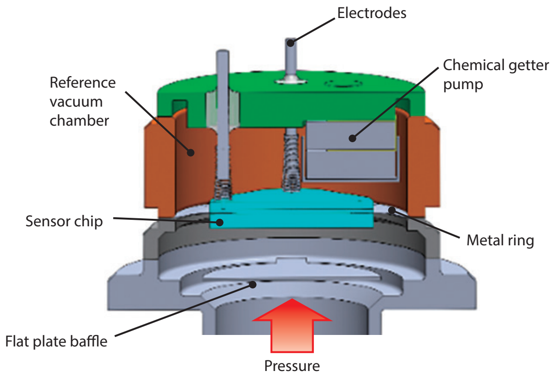


Fig. 3. Sensor package

4. Product features

4.1 Solution to deposition shift problems

Vacuum gauges used in semiconductor manufacturing experience zero-point shifts when by-products from deposition or etching processes adhere to the diaphragm. In the Model V8, we employed MEMS technology to develop a diaphragm with two structural features, described in sections 4.1.1 and 4.1.2, that significantly enhance resistance to deposition compared to the current product (Model SPG)[1].

4.1.1 Fine uneven structure

We created fine grooves on the diaphragm, each approximately 6 µm wide, as shown in figure 4. Since the mean free path of gas molecules during a typical deposition process is around 50 µm, it is highly unlikely that the molecules will enter the much narrower 6 µm spaces. This structure effectively inhibits deposition within the grooves, facilitating separation of the deposited film and reducing its impact on the diaphragm.

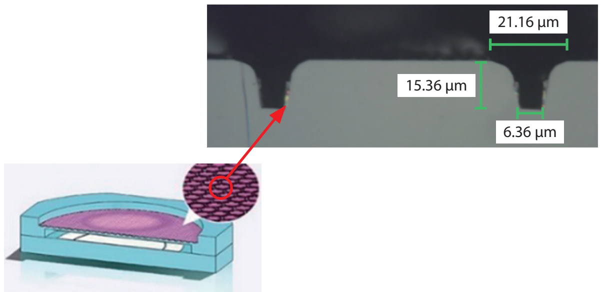


Fig. 4. Cross-sectional view of the uneven sensor diaphragm

Figure 5 shows the results of deposition shift testing in a SiO_2-CVD process. The new diaphragm with the fine uneven structure reduces deposition-induced shifts to less than one-tenth that of the previous flat diaphragm.

This structure is particularly effective for deposited films with the following characteristics, such as those formed during CVD processes:

- Viscous films
- Films composed of weakly bonded molecules
- Films that deposit relatively unevenly

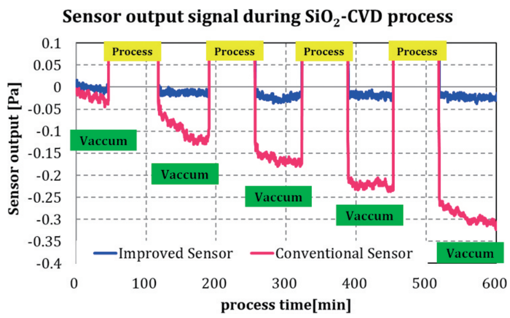


Fig. 5. Comparison of zero point behavior during the SiO_2-CVD process

4.1.2 Flat diaphragm

We simulated the stress applied to the diaphragm by deposited films in order to develop mechanical countermeasures that reduce deformation. When the radius (R) of the gas-contacting side of the diaphragm exceeds the base radius (R_0), stress-induced displacement is reduced, as shown in figure 6.

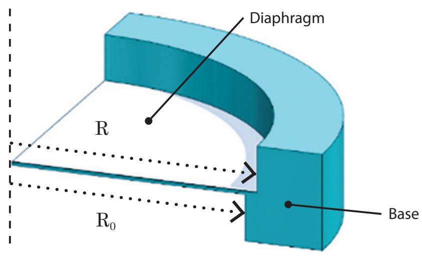


Fig. 6. Moment-balanced structure

The deposition resistance of the knurled diaphragm was verified through experimentation. Specifically, we simulated an Al_2O_3 deposition process using ALD by alternately introducing TMA (trimethylaluminum $(CH_3)_3Al$) and H_2O. The zero point was continuously measured throughout the process. Figures 7a and 7b show the results for sensor chips with and without the moment-balanced structure, respectively. The sensor chip with the moment-balanced structure successfully mitigated zero-point shifts throughout the process.

This structure is particularly effective for deposited films with the following characteristics, such as those formed during ALD processes:

- Firm films
- Films composed of strongly bonded molecules
- Films that deposit uniformly

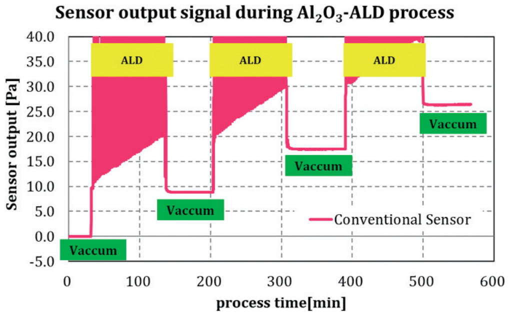


Fig. 7a. Zero point behavior after the Al_2O_3 ALD process (Without the moment-balanced structure)

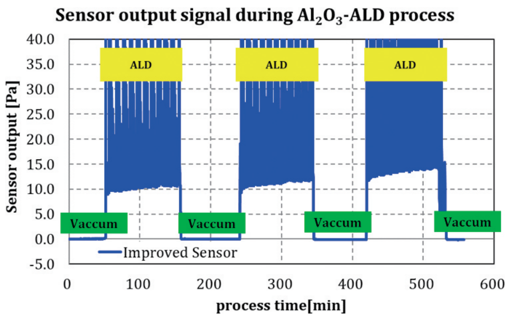


Fig. 7b. Zero point behavior after the Al_2O_3 ALD process (With the moment-balanced structure)

4.2 Separated model (Model V8S) for high-temperature applications

As semiconductor processes advance, gas materials are increasingly heated to higher temperatures, creating the need for a diaphragm vacuum gauge that can withstand these elevated temperatures.

To meet this requirement, we developed the separated model (Model V8S), which supports temperatures ranging from 10 to 250 °C. In this model, the measurement circuit is separated from the sensor, which is built with heat-resistant components.

Figures 8a and 8b show the results of temperature characteristic testing for the Model V8S sensor. Azbil's proprietary temperature correction algorithm enables measurement across a wide temperature range (10–250 °C) while minimizing error.

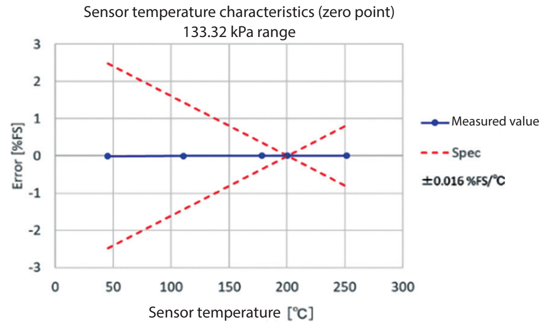


Fig. 8a. Sensor temperature characteristics (zero point) of the separated model (Model V8S)

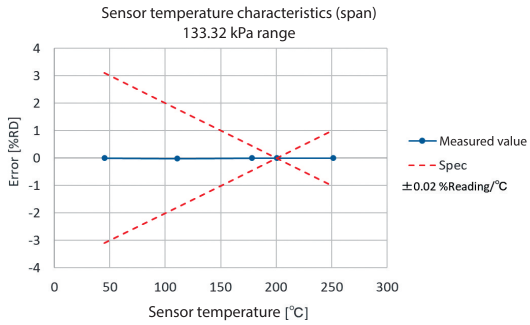


Fig. 8b. Sensor temperature characteristics (span) of the separated model (Model V8S)

4.3 Integrated model (Model V8C)

4.3.1 Product size

Figure 9 shows the current vacuum gauge (Model SPG) alongside the integrated vacuum gauge (Model V8C). The Model V8C adopts a rectangular design, unlike the cylindrical shape of the previous model, to reduce overall height while efficiently securing space for the measurement circuit. It maintains the same footprint as the current model to ensure easy replacement.

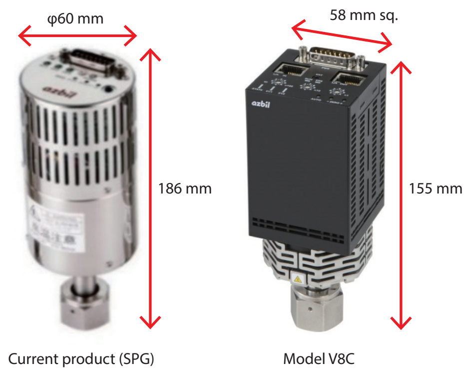


Fig. 9. Model V8C size (comparison with the current product)

4.3.2 Addition of the self-heating temperature adjustment function

The integrated model (Model V8C) includes the variable self-heating temperature function, an additional feature that allows flexible adjustment of the sensor's self-heating temperature, from 45 to 200 °C, via communication or contact input.

This function enables the self-heating temperature to adapt to different processes, such as deposition and cleaning. It also eliminates the need for customers to maintain spare gauges for each self-heating temperature setting. As a result, inventory requirements are reduced, and gauge management becomes easier.

Figures 10a and 10b show the temperature characteristics of the sensor integrated into the variable self-heating model (Model V8C). The gauge maintains high accuracy across a wide temperature range (45–200 °C), with minimal measurement error.

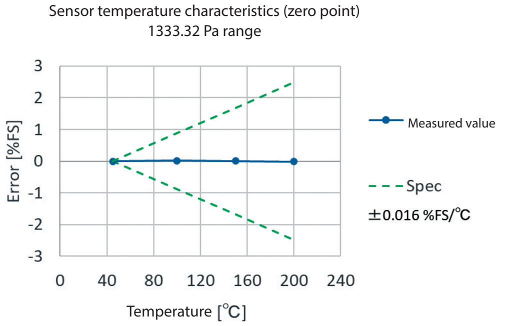


Fig. 10a. Sensor temperature characteristics (zero point) of the model with variable self-heating temperature

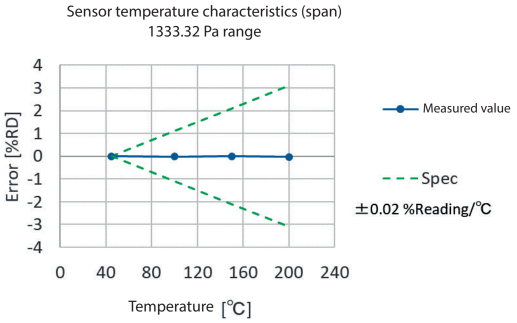


Fig. 10b. Sensor temperature characteristics (span) of the model with variable self-heating temperature

Fast response to temperature changes and excellent controllability are achieved through Azbil's PID temperature control technology. Figure 11 shows the results of the sensor's temperature control characteristics testing.

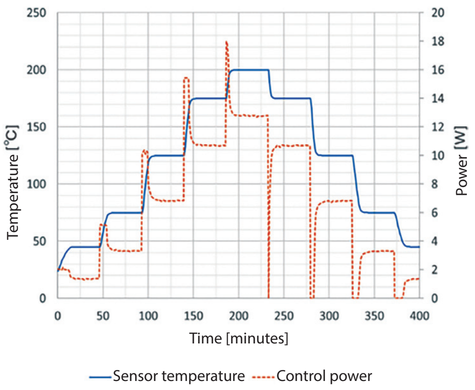


Fig. 11. Sensor temperature control characteristics of the model with variable self-heating temperature

4.4 Faster response speed

ALD and ALE processes involve rapid changes in chamber pressure on the order of milliseconds, which has increased the demand for vacuum gauges with faster response times.

The new vacuum gauge features a high-speed measurement circuit and signal processing system, achieving a response speed of 1 ms or less at a 63 % response rate, and a pressure update cycle of 0.27 ms. Figure 12 compares the response speeds of the current product (Model SPG) and the Model V8 against a high-speed reference device. While the current product (SPG) responds within 40 ms at a 63 % response rate, the Model V8 responds within 1 ms.

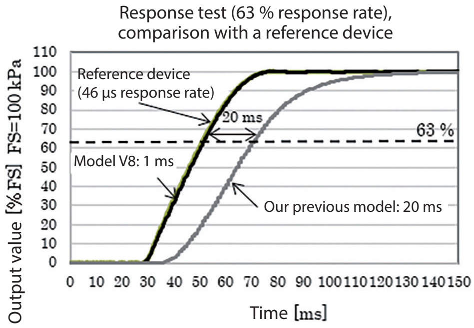


Fig. 12. Response test results
(comparison with a response reference device)

5. Conclusion

The sapphire diaphragm gauge (Model V8) was developed to deliver value while meeting the evolving demands of semiconductor process equipment. Looking ahead, Azbil remains committed to delivering value to customers through the development of more innovative products.

References

[1] Takuya Ishihara. "Upgrading a sapphire-based capacitance manometer for reduced size and enhanced anti-deposition characteristics." *azbil Technical Review*, 2023, Vol. 64, pp. 9-15, Azbil Corporation

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