Feature Article

Compact Capacitance Manometers

Takehisa Hataita

Sensing technology, which captures data on physical phenomena and states and converts them into signals, is one of the most fundamental and important contemporary industrial technologies for today's multi-functional, highly advanced and complex industrial products. In particular, manometers are an essential and integral part of manufacturing processes for semiconductors, flat panel displays (FPD), light emitting diodes (LED) and solar panels, as a wide range of gases and liquids must be controlled during these processes. HORIBA STEC Co., Ltd. has developed a compact, low-cost, highly reliable capacitance manometer that can be mounted on mass flow controllers and many other types of flow and pressure controlling devices.

Introduction

In multi-chambered semiconductor manufacturing devices developed in recent years, changes in pressure often have serious effects on the flow accuracy of mass flow controllers. These effects have been controlled by line regulators and manometers individually installed on gas lines preceding the mass flow controller. However, due to the need for compact, lightweight gas lines with high performance and low cost, there is a growing demand for mass flow controllers that are not affected by changes in pressure. In response to this demand, HORIBA STEC has released next-generation mass flow modules, the SEC-Z700 series and CRITERION D200 series, which are insensitive to pressure changes. These series both have a built-in compact manometer. In particular, the SEC-Z700 series modules are equipped with a capacitance manometer that HORIBA STEC has developed independently.

There is no doubt that the demand for built-in manometers as well as their importance will greatly increase in the future, as these manometers will be mounted not only on commercially-sold pressure controllers, but also on mass flow controllers, which are HORIBA STEC's principal products.

The capacitance manometer developed by HORIBA STEC is designed to be compact, highly sensitive, pressure-resistant and perfectly safe to use. It meets all major requirements for a built-in manometer and is expected to be used in various types of products. The capacitance manometer is therefore a key component for the HORIBA Group, which aims to be the world's top supplier in the fields of fluid measurement and control.

In this article, the author will provide an explanation of the principles of measurement by capacitance manometer and describe the features of the manometer developed by HORIBA STEC as well as the manufacturing technologies that provided the key to mass production.

About Capacitance Manometers

The Capacitance Manometer

A capacitance manometer is a pressure sensor that measures the displacement of a diaphragm caused by pressure changes as changes in capacitance and converts these changes into pressure. Its structure, which is designed to measure pressure directly from the displacement of a diaphragm regardless of the type of gas used for measurement, makes it suitable for measuring the pressure of a number of different gases or mixed gases.

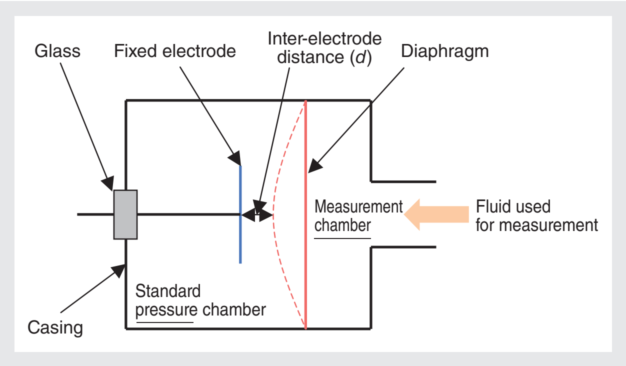

Figure 1 Model Diagram of the Internal Structure of a Capacitance Manometer

Structure

Figure 1 shows the structure of a typical capacitance manometer.
The main unit of a capacitance manometer is composed of two chambers separated by a diaphragm: a standard pressure chamber and a measurement chamber. The standard pressure chamber, in which a fixed electrode is installed at a microscopic distance (*d*) from the diaphragm, is insulated from the casing by glass sealing. With an absolute pressure sensor, the standard pressure chamber is sealed off from the outside to avoid the effects of changes in atmospheric pressure. If the pressure on the side of the measurement chamber is higher than that of the standard pressure chamber, the diaphragm bends toward the standard pressure chamber, thereby reducing the distance between the fixed electrode and the diaphragm and increasing the capacitance between the two. As the pressure of the measurement chamber decreases, the bending of the diaphragm becomes smaller, causing a decrease in capacitance. The manometer measures pressure by converting this change into a change in voltage.

The following equation indicates the relationship between capacitance and inter-electrode distance:

$$C = \varepsilon S/d$$

C : Capacitance
ε : Permittivity of the standard pressure chamber
S : Electrode area
d : Inter-electrode distance

As the above equation shows, capacitance varies in direct proportion to the electrode area S and in inverse proportion to the inter-electrode distance d. This means that in order to make a sensor with high output power, it is necessary to make the electrode area S as large as possible and the inter-electrode distance d as small as possible.

The relationship between a round diaphragm and bending is given by the following equation, which indicates the bending of a flat disk with a fixed perimeter:

$$W = 3P \cdot a^4(1 - v^2) / (16E \cdot h^2)$$

W: Bending of the diaphragm at its center
P : Pressure
a : Radius of the diaphragm
h : Thickness of the diaphragm
v : Poisson's ratio of the diaphragm
E : Young's modulus of the diaphragm

A model diagram showing the bending of a flat disk with a fixed perimeter is presented in Figure 2:

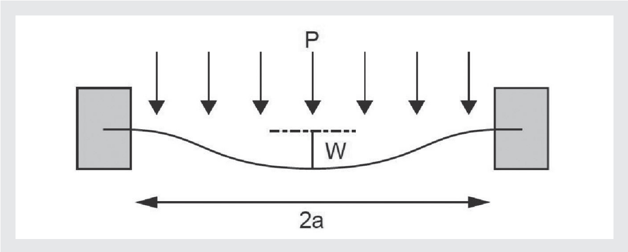

Figure 2 Bending of a Flat Disk with a Fixed Perimeter

The bending of a diaphragm varies in direct proportion to its radius raised to the fourth power and in inverse proportion to the square of its thickness. Therefore, in order to produce large displacement, it is necessary to increase the diameter of the diaphragm and decrease its thickness, which, however, also increases the internal stress caused by applied pressure. Since an internal stress exceeding the resistance of material causes plastic deformation and reduces the reproducibility of the manometer, it is necessary to design the diaphragm to be suitable for the range of pressures to be measured. It is also of great importance to choose materials with sufficient strength to withstand internal stress.

Features of the Pressure Sensor Developed by HORIBA STEC

Figure 3 shows the outward appearance of the capacitance manometer mounted on the mass flow module Z700 series. Its major specifications are presented in Table 1.

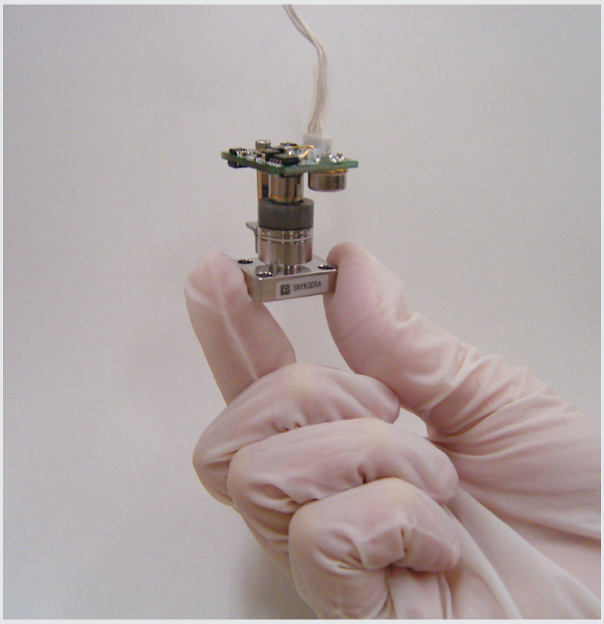

Figure 3 Appearance

Table 1 Major Specifications of the Pressure Sensor Mounted in the Z700 Series

Full scale	700 kPaA
Span width	≥ 1.5 V
Accuracy*	±1% of the full-scale capacity
Guaranteed pressure resistance*	Twice the full-scale capacity
Burst pressure	Five times the full-scale capacity
Effects of temperature*	≤ 0.5% of the full-scale capacity (20 °C to 50 °C; standard output at 20 °C)

*: Output power specifications of the manometer mounted on the Z700 series

Compact Size and High Sensitivity

By adopting a design with a very simple structure, we succeeded in developing a super compact sensor head with an outside diameter no greater than 13 mm. In addition to being a capacitance manometer, which has higher output power than other types of manometers such as bending-type manometers, the newly developed nanometer is designed to be highly sensitive despite its compact size by reducing the distance between the electrode and the diaphragm to the bare minimum using the glass sealing technology developed by HORIBA STEC.

High Pressure Resistance and High Reliability

A special high-performance alloy with high material strength is used for the diaphragm, thereby providing the manometer with high pressure resistance as well as great stability in performance, despite its compact size and high sensitivity. Metal diaphragms have a longstanding proven track record and are known to be highly reliable. In particular, diaphragms made of special alloys with high material strength exhibit sufficient pressure resistance even when their thickness is reduced to match their compact size. They also have excellent corrosion resistance and are suited to be used in the manufacture of semiconductors, which involves the use of various corrosive gases.

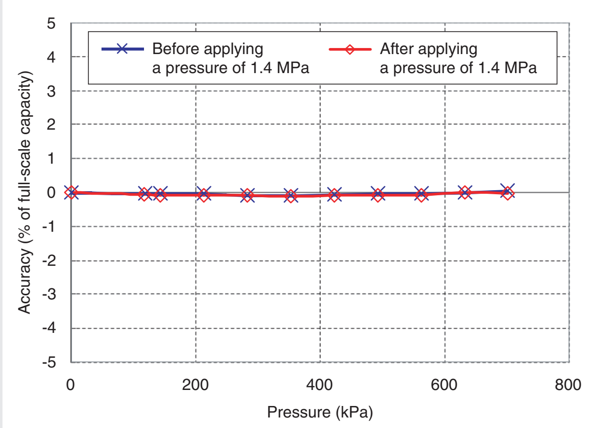

Figure 4 Change in Accuracy Before and After Applying a Pressure of 1.4 MPa (twice full-scale capacity)

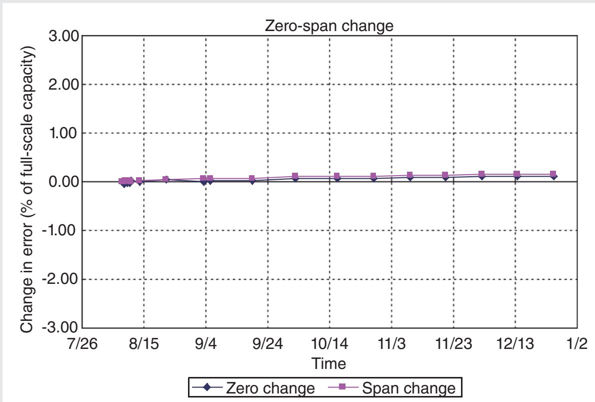

Figure 5 Stability Test by Repeated Application of Pressure (2.5 million times of pressure change between 0 and 700 kPa)

Oil-less Structure

Many compact, low-cost manometers with bending diaphragms use oil inside the medium that transmits power. In contrast, the manometer developed by HORIBA STEC is designed to measure capacitance without using oil. It is therefore very safe to use in gas lines and chambers.

Establishment of New Manufacturing Technologies (Semiconductor laser welding and glass sealing)

Due to their structural design, capacitance manometers tend to be more expensive than bending-type manometers containing oil. In order to reduce manufacturing costs as much as possible while maintaining the advantageous features of a built-in manometer, HORIBA STEC independently developed certain new manufacturing technologies. In this article, the author will focus on semiconductor laser welding and glass sealing technologies, which play particularly important roles in ensuring product quality.

Semiconductor Laser Welding

One of the most important technologies for the manufacturing of capacitance manometers is the technology for welding the diaphragm and the main device unit. Although Tungsten inert gas (TIG) welding, electronic beam welding and laser welding are available as welding methods for semiconductor-related parts that require an accurate and perfect finish, HORIBA STEC adopted semiconductor laser welding, which is likely to be widely used in the future, as the welding method for the manometer.

Structure of the semiconductor laser welder

The output power of a single semiconductor laser element (laser diode: LD) is several watts, which is far smaller than that of CO_2 laser or Neodymium-doped yttrium aluminium garnet (Nd: YAG) laser. In order to use semiconductor laser for the processing of materials, there is a need to arrange several dozen laser diodes horizontally to form a laser diode bar and to assemble a dozen laser diode bars together into a laser stack. An image of the interior of a semiconductor laser stack is presented in Figure 6. Laser beams emitted from laser elements are condensed by a condensing lens until they have sufficient energy density to be used for welding.

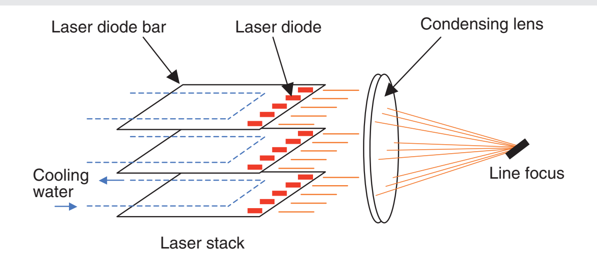

Figure 6 Image of the Interior of a Semiconductor Laser Welder

Features of semiconductor laser welding

The most essential feature of semiconductor laser welding is its high efficiency in energy transformation. In comparison with CO_2 laser welding and Nd: YAG laser welding, which have a system efficiency that does not exceed 10%, semiconductor laser welding has a much higher system efficiency (about 30%). Since semiconductor laser also has a wavelength shorter than those of CO_2 or YAG laser, its laser beams are absorbed by metals more quickly. Designed with a simple structure that collects laser beams directly from semiconductor laser elements, a semiconductor laser welder is highly reliable and requires low maintenance costs. Due to its structure that collects laser beams from laser diodes and laser diode stacks using an optical system, it emits horizontally spread beams. However, rather than being a disadvantage, this feature makes semiconductor laser welding particularly suitable for welding diaphragms and other thin films along their periphery. These features of semiconductor laser welding provide great advantages in the mass production of manometers.

Glass Sealing

The nanometer developed by HORIBA STEC is manufactured using glass sealing technology for the insulation of the fixed electrode. Glass sealing technology, which joins metals and glass together, has a long history and has been used for the manufacture of many devices and units with vacuum chambers or sealed chambers. Air-tight insulated terminals manufactured using glass sealing technology are sold by many manufacturers, and standard products are commercially available at low prices. However, in order to manufacture a compact manometer with high sensitivity, there is a need to make the distance between the fixed electrode and the diaphragm (inter-electrode distance) as small as possible and to control the distance at a microscopic level. By independently developing the glass sealing process technology, which not only has decisive effects on the inter-electrode distance but also directly affects product quality and yields, HORIBA STEC has made it possible to manufacture a low-cost manometer with high sensitivity and high quality.

Concluding Remarks

The capacitance manometer presented in this article is a compact and highly sensitive pressure sensor equipped with a diaphragm made of a special high-performance alloy and a sensor head designed with a very simple structure. By developing a unique manufacturing technology within our company, we succeeded in providing a stable supply of manometers with high performance.

The manometer presented above will be mounted on the mass flow module Z700 series models developed for pressure-insensitive systems. These models are considered to be HORIBA STEC's principal next-generation products. The nanometer is also expected to be further developed for the mass flow module Criterion series models, which use a new pressure difference detection system for the flow measurement unit on a pressure basis, and various types of pressure controllers.

The semiconductor laser welding and precision glass sealing technologies, which have been created in the process of the development of the manometer, are basic technologies that can be applied in a wide range of areas in which the HORIBA Group is engaged. Therefore, these technologies will contribute to the development of new products with advanced functions and high quality in the future.

Takehisa Hataita

VEGA Project,
Development Headquarters
HORIBA STEC Co., Ltd.