Sensor packaging technology maximizes MEMS sensor capabilities

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Keywords

MEMS sensor, sensor packaging, measurement and control

For the development of MEMS sensors, which is essential measurement and control technology, Azbil possesses both the MEMS sensor chip technology and the sensor packaging technology required. These capabilities enable Azbil to develop superior measurement and control devices not easily emulated by competitors. Sensor packaging must compensate for the characteristics of the MEMS sensor chip that are disadvantageous for commercialization, such as variations in film thickness across the wafer and a thermal expansion coefficient that is different from that of metals, while at the same time fully utilizing the superior characteristics of the MEMS sensor chip materials. In this paper, we report on Azbil's sensor packaging technology.

1. Introduction

In the development of microelectromechanical systems (MEMS) sensors, which are a cornerstone of measurement and control technology, the development of manufacturing methods and production equipment specialized for sensor packaging, which is needed for achieving stable production processes, is among Azbil's core competencies. MEMS sensor chips are made by forming micromechanical structures and electric circuits on silicon, glass, sapphire, and other materials. These sensor chips make it possible to accurately measure physical quantities like pressure and flow rate. In order to do so, however, it is necessary to minimize any negative impact of the mechanical and thermal characteristics of the material on measurement accuracy. MEMS sensor chips are mass produced on a thin disk-shaped plate called a wafer as shown in figure 1. Even a slight difference in the thickness of a metal film, insulating film, etc., on the wafer surface can cause a change in the characteristics of individual sensor chips. In order for MEMS sensor chips to have consistent and high measurement accuracy, it is important to ensure their performance level by absorbing and adjusting the impact of such material characteristics and the differences among individual sensor chips before incorporating them into measuring devices.

In the case of MEMS sensor chips using sapphire, it is possible to achieve distinctive measuring devices that can be applied in previously difficult environments if one can ensure utilization of their full measuring performance without compromising their excellent material characteristics, which include high resistance to heat and corrosion.

The technology for physically and electrically connecting a MEMS sensor chip or microdevice to the electric circuit of a measuring device to form a sensor module is called "sensor packaging." Azbil's sensor packaging technology not only connects the chip to an electric circuit, it also compensates for characteristics of the MEMS sensor chip that are disadvantageous for product development and modularizes the chip as the sensor of a measuring device that can take advantage of its excellent characteristics.

The fact that we have both MEMS sensor chip development technology and sensor packaging technology for the development of a MEMS sensor enables us to develop excellent measurement and control devices that other companies cannot easily compete with.

This article introduces some of Azbil's sensor packaging technology.

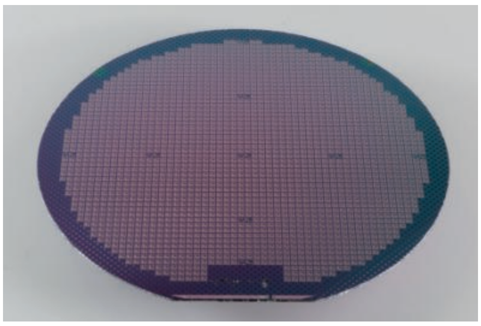

Fig. 1. Sensor chip groups formed on a silicon wafer

2. Challenges in the use of MEMS sensor chips in products

Sensor packaging technology adjusts MEMS sensor chips to have uniform characteristics so that they can be physically and electrically connected with measuring devices as sensor modules. Section 2 describes challenges actually encountered in the development of two products in which Azbil sensor packaging technology demonstrated its main functions of compensating for disadvantageous characteristics of MEMS sensor chips and making use of their excellent characteristics in the course of product development.

2.1 Piezoresistive pressure sensors

This section describes two challenges in using a piezoresistive pressure sensor as an example.

2.1.1 Impact of chip distribution on the wafer on MEMS sensor characteristics

A differential pressure flowmeter is the most common type of sensor for measuring the flow of process fluid. A differential pressure flowmeter employs a method in which an orifice (restrictor) is installed in the flow channel to intentionally cause a pressure loss. The pressure upstream and downstream of the orifice is measured and the difference between them (the differential pressure) is used to calculate the flow rate. Differential pressure flowmeters can measure liquids, gases, and high temperature/high pressure fluids, are unlikely to fail, and have other merits. The simplest way to measure differential pressure is to use two pressure sensors, but in that case obtaining high measurement accuracy is difficult due to individual differences in sensor chip characteristics attributable to their original position on different parts of the wafer.

2.1.2 Impact of thermal stress on temperature characteristics

A piezoresistive pressure sensor formed on a silicon wafer is capable of high-resolution stable measurement. In order to incorporate the sensor into a product, it is necessary to bond the sensor chip with stainless steel or another metal as shown in figure 2. However, doing so generates thermal stress that affects measurement accuracy, because the thermal expansion coefficient of the sensor chip is different from that of the metal. To mitigate the impact of stress, an intermediate material such as glass with a different thermal expansion coefficient from the sensor chip and the metal part is bonded between them. The sensor is bonded to the intermediate component, and they are then bonded to the metal part with adhesive. Due to design restrictions, however, sometimes the intermediate component is not long enough to mitigate the stress, or the stress generated when the adhesive cures may create a new problem.

In the conventional bonding method, epoxy adhesive is thermally cured at 135 °C. Then, it is cooled slowly to mitigate the stress generated during curing. Epoxy adhesive causes a shrinkage in volume as its molecules polymerize during curing. If there is a difference in temperature between the surface and the inside of the resin, there will be a large amount of residual stress due to the difference in volumetric shrinkage during curing. This is why the temperature difference between the surface and inside of the resin is reduced by cooling slowly to mitigate the stress. By cooling the adhesive slowly, a sufficient mitigation effect was observed in the conventional structure.

For the pressure sensor installed on the motorized control valve with flow measurement and control functions shown in figure 3, the length of the intermediate component is 2 mm shorter than on the conventional product due to the need to reduce the size of the sensor module. We found that during slow cooling of the new structure with the shorter intermediate component, the output voltage changed when no voltage was applied as shown in figure 4, suggesting that stress mitigation was insufficient. For that reason we needed a sensor packaging technology that could achieve both a smaller size and a sensor module capable of highly accurate measurement at the same time.

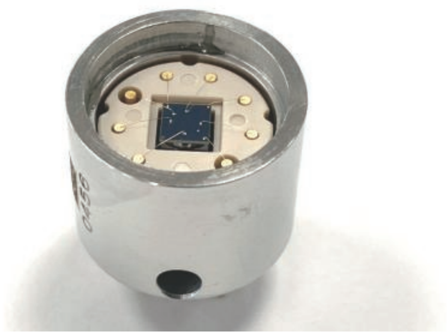

Fig. 2. Example of a piezoresistive pressure sensor module

Fig. 3. Motorized control valve with flow measurement and control functions

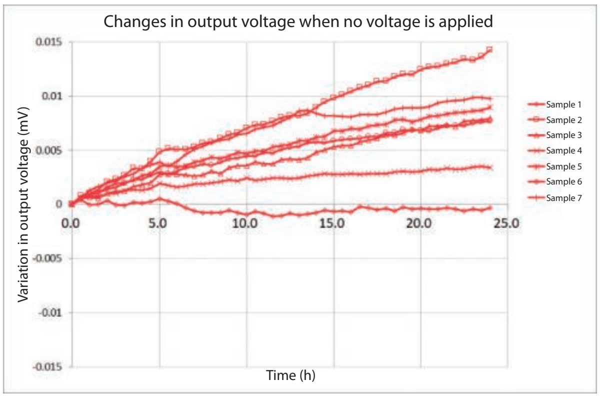

Fig. 4. Changes in the output voltage when left for 24 hours without applying voltage

2.2 Sapphire sensors

This section describes the challenges that arise when attempting to take advantage of the excellent characteristics of sapphire—high thermal resistance and corrosion resistance—for capacitance diaphragm gauges.

2.2.1 Establishment of an airtight bonding method for sapphire sensor chips

The sapphire capacitance pressure sensor used in sapphire capacitance diaphragm gauges can measure pressure in severe environments like the corrosive gas atmospheres used in semiconductor manufacturing processes, thanks to sapphire's high resistance to heat and corrosion. Figure 5 shows sample gauges.

However, in order to use the sensor in the sensor module of a product without ruining the excellent material characteristics of sapphire, it is necessary to develop a sensor packaging technology for bonding a metal with the same high thermal and corrosion resistance as sapphire.

For sapphire capacitance diaphragm gauges we decided to use a Ni-based alloy that has the necessary properties.

Since the thermal expansion coefficients of the sapphire sensor chip and the Ni-based alloy differ, we used a structure like that shown in figure 6, in which the sensor chip is bonded to a thin ring-shaped film of the Ni-based alloy to mitigate the impact of thermal stress caused by bonding.

Diffusion bonding is used, but it required establishing a process for evenly applying a certain amount of pressure to the surfaces under a high temperature of approximately 1,000 °C in a high vacuum [1].

Fig. 5. Sapphire capacitance diaphragm gauges

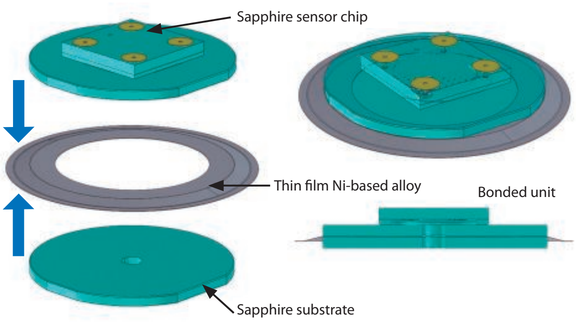

Fig. 6. Schematic cross-section of a bonded sapphire sensor chip

2.2.2 Establishment of an inspection process for airtight bonding

A sapphire capacitance diaphragm gauge is an instrument used to measure extremely low near-vacuum pressures.

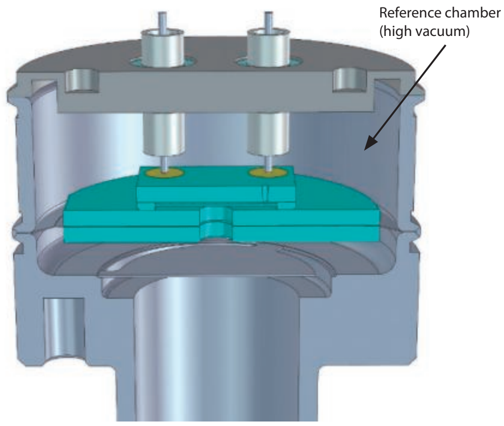

Fig. 7. Cross-section of a sapphire sensor module

As shown in figure 7, pressure is measured by maintaining a reference chamber containing the sapphire sensor chip in a high vacuum and determining the difference in pressure between it and the atmosphere being measured. Naturally, the bonded unit consisting of the sensor chip and the Ni-based alloy, which forms part of the reference chamber, requires high airtightness. Process engineering to inspect the airtightness of the bonding surface between the diffusion-bonded sapphire and the Ni-based alloy before mounting it in the reference chamber is needed. This inspection also serves to prevent passing a nonconforming item to a downstream process.

If a sapphire sensor chip that is not airtight is mounted in the reference chamber, the pressure of the atmosphere being measured and the output of the sapphire sensor chip will not match, so this can be easily checked. However, if a defect is found after the unit is mounted in the reference chamber, not only the sapphire sensor chip, but also all the components of the reference chamber and the sensor package need to be discarded. In order not to put pressure on the production cost, a process for inspecting airtightness following diffusion bonding is needed.

Thus, at Azbil, ensuring the quality of a produced item, including the inspection process, is considered to be part of sensor packaging technology.

3. Solving the challenges

Regarding solutions to the challenges of using MEMS sensor chips in products as described above, section 3.1 tells how compensation was made for MEMS sensor chip characteristics that are disadvantageous for product development in order to improve measurement accuracy.

Section 3.2 describes a sensor packaging process—and also the related inspection process—for mounting a MEMS sensor chip on a product without ruining the chip's excellent characteristics.

3.1 Solutions for piezoresistive pressure sensors

This section describes solutions for the two challenges mentioned above related to piezoresistive pressure sensors.

3.1.1 Elimination of the problem of chip distribution on the wafer by means of the structure receiving differential pressure

Since obtaining high measurement accuracy is difficult when using two pressure sensors in the measurement of a pressure difference due to individual differences in sensor chip characteristics, accuracy can be improved by a structure in which pressure is applied to both sides of the sensor chip within a single pressure sensor. Figure 8 shows the structure of the pressure sensor module. This module structure has two pressure-receiving diaphragms, and the pressure propagation path is connected with a pipe so that the pressure received is applied to the sensor chip. The space inside the pipe is filled with pressure-propagating liquid.

If a thick pipe is used for pressure propagation, the junction may break due to the thermal stress or stress generated when pressure is applied. Therefore, an extra fine pipe with an outer diameter of 0.45 mm and inner diameter of 0.23 mm is used to connect the two sections. Instead of directly bonding the pipe to the body, a washer is interposed, and they are welded individually. Reliable bonds are ensured by this structure.

A fiber laser is used to weld the pipe and the washer. The laser is applied in a way that penetrates sufficiently for welding but does not cause clogging of the pipe.

The washer is bonded to the structure by resistance welding instead of adhesion to prevent deterioration due to humidity and the like. This structure also withstands long-term use. If an air bubble enters the liquid for pressure propagation, the response when pressure is applied will be delayed and an abnormal sensor output may be caused due to the effect of temperature. Therefore, a process of encapsulating the liquid in a high vacuum to prevent air bubbles from entering was established.

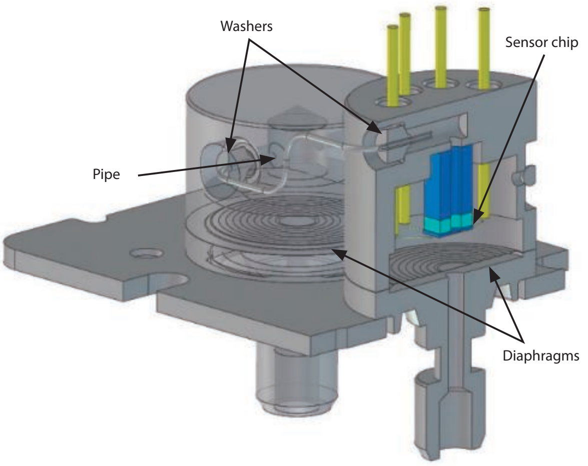

Fig. 8. Cross-section of a pressure sensor module

3.1.2 Elimination of thermal stress to the sensor chip

The volume of thermosetting adhesives during the curing process expands in a liquid-phase state due to a rise in temperature as a result of heating. The curing reaction initiates two-dimensional cross-linking of the resin, which reaches the gel point as it contracts. The behavior of the thermosetting adhesive shifts from that of a liquid to that of a solid at the gel point. Then, the cross-linking shifts to three-dimensional cross-linking and reaches its end point, the curing point. Next, cooling brings the temperature of the adhesive back to room temperature. In the curing process of the thermosetting adhesive, the difference between the volume at the gel point where the adhesive turns to a solid and the volume after cooling leads to stress [2].

To reduce it, we focused on the thermal curing temperature. Figure 9 shows that when the adhesive is heated in the liquid state, it arrives at the gel point as its volume expands from the heat. We thought, therefore, that if the curing temperature was lowered, the amount of change in the volume after curing will also be lowered, reducing the stress from contraction. Figure 10 shows changes in the output voltage when no voltage is applied by setting the curing temperature to 95 °C instead of the conventional curing temperature of 135 °C. The graph suggests that lowering the curing temperature mitigates the stress during curing and reduces changes in the output voltage when no voltage is applied.

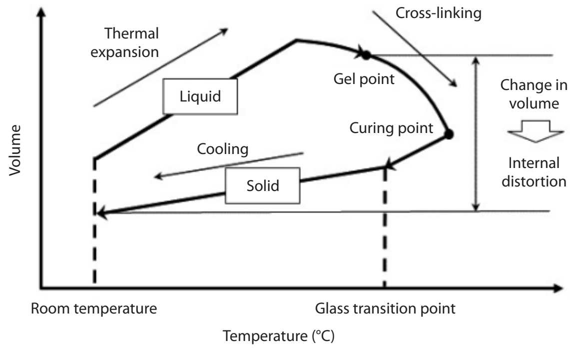

Fig. 9. Changes in volume when adhesive cures

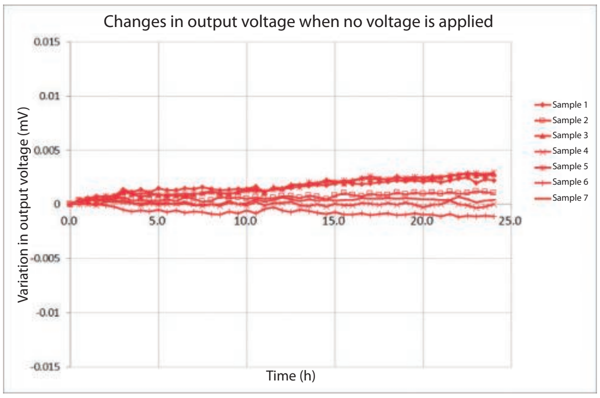

Fig. 10. Changes in the output voltage when left for 24 hours without applying voltage

3.2 Solutions for sapphire sensors

Next, we describe our solutions to the two challenges with sapphire sensors.

3.2.1 Diffusion bonding with a Ni-based alloy, a highly corrosion-resistant metal

Diffusion bonding, which is used to bond the sapphire sensor chip and the Ni-based alloy, is a method in which the same or even different materials are heated to a temperature up to the melting point of the materials, followed by bonding by diffusion generated on both contact surfaces as a result of applying pressure [3]. Diffusion bonding is known as a widely used bonding technique for MEMS sensors.

In order to achieve good diffusion bonding between the sapphire sensor chip and the metal foil of a Ni-based alloy, it was necessary to develop a bonding system with the following three main features.

(1) A chamber where materials can be kept in a vacuum of 1.0×10^{-5} Pa or less

Because the process uses diffusion on the contacting surfaces, any impurities on the surfaces will impede the process. The generation of oxides on the surfaces when they are heated is an especially serious hindrance. Therefore, the system must have a vacuum chamber suitable for heat treatment under a high vacuum to prevent oxidation of the nickel alloy foil.

(2) A pressing mechanism that can evenly apply the desired amount of pressure to the surfaces

For a sapphire capacitance diaphragm gauge, uneven stress on the surfaces being bonded must be prevented to the maximum extent possible so that the sapphire sensor chip is not affected by strain, and to ensure high airtightness. Since this system will be used on production equipment, it must be able to bond multiple sensor chips at once. For this reason, a die that can apply the same pressure to each sensor chip was also developed.

(3) A mechanism for heat treatment at a temperature of 1,000 °C or more

We undertook the development of various basic technologies to enable diffusion bonding of the sapphire sensor chip and the metal foil of a Ni-based alloy and completed fabrication of bonding equipment with these three features. Figure 11 shows photographs of the diffusion bonding system.

Fig. 11. Diffusion bonding equipment

The system has several monitors for checking whether bonding is taking place under the proper conditions. In addition to monitoring the heat treatment temperature and applied pressure, the system is equipped with a gas analysis device to check for the entry of impurities or contaminants that hinder diffusion bonding. As shown in figure 12, the system constantly monitors for unwanted elements and elements that are detected in a quantity beyond the allowable amount for the process. This makes it possible to check that the process is implemented according to the set conditions in the diffusion bonding system.

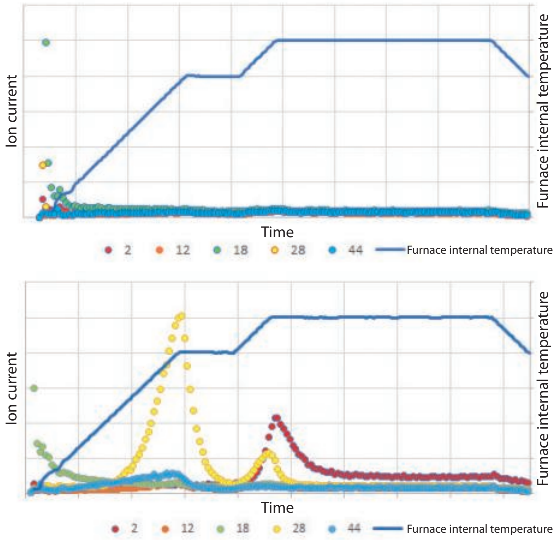

Fig. 12. Results of gas analysis during processing (top: normal; bottom: abnormal)

3.2.2 Establishment of an inspection process for airtight bonding

Although we can monitor whether diffusion bonding takes place under the proper conditions, we believe that quality inspection of the actual products is also essential.

Helium leak detectors are often used to inspect high airtightness. They are capable of quantitatively measuring and evaluating the amount of leakage. The space inside a pressure container, etc., is brought to a vacuum state with a turbo molecular pump and helium is injected from the outside. The detector then measures the amount of helium that enters inside.

However, the bonding of the sapphire sensor chip and the Ni-based alloy foil takes place in an open-air space. To use a helium leak detector, it would be necessary to assemble the parts up to the stage of the sensor module, which would serve as a container for the sensor chip as shown in figure 7. However, if defective airtightness was found at that stage, the sapphire sensor chip along with all the components of the sensor package would have to be discarded. Also, a fundamental rule of production processes is that a defective part must not be passed to the next process.

This means that after diffusion bonding, an inspection process was needed to ensure the soundness of bonding. What we focused on at this point was differences in light reflected from the bonded portion. By lighting the bonded surface and observing it with a special microscope, we are able to distinguish successful and unsuccessful bonding because, in the case of failure, there is a slight space in the interface that causes a difference in brightness. Figure 13 shows an example of such a case.

By photographing the bonded portion and processing the image, it is possible not only to detect the path of a leak, but also to evaluate the quality of bonding, as to whether there is a sufficiently large and even joint.

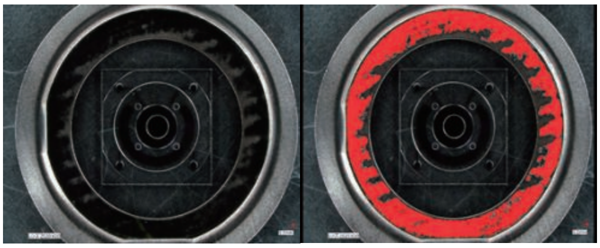

Fig. 13. Evaluation of diffusion-bonded surfaces using image processing

With the development of this technology, airtightness inspection of the bonded surfaces can now be performed without assembling the sensor module.

Azbil's sensor module production processes include one more inspection process to ensure that quality can be maintained even after a long period of use in the actual industrial environment. In this inspection, after the sensor module is assembled as shown in figure 7, it is exposed to an argon atmosphere at a certain pressure for a certain period of time. Then, by measuring the sensor output, we can check whether argon has entered the sensor module.

During this inspection, not only the diffusion-bonded surfaces, but also the airtightness of all bonded portions of the enclosure comprised of a Ni-based alloy are checked. If there is a portion where airtightness is lost even slightly, an abnormality in the output of the sapphire sensor occurs due to the effect of argon inside the sensor package. By means of our "argon aging" process, we are able to provide sapphire capacitance diaphragm gauges that customers can use in severe environments with confidence for a long time.

As seen above, for sensor packaging it is important to develop not only basic technologies for bonding and so on, but also methods of inspection to ensure the quality of the processes.

4. Achievements

The following is a report on our achievements with piezoresistive pressure sensors and sapphire sensors.

4.1 Sensor packaging technology that compensates for characteristics of MEMS sensor chips that are disadvantageous for product development

The development of a mechanism for applying pressure to the sensor has enabled sensor packaging that is not affected by differences between individual sensor chips, allowing us to provide pressure sensors that satisfy the products' specifications.

In addition, by relieving stress during the curing of adhesive through process control, a stable output voltage can now be obtained when no voltage is applied.

4.2 Sensor packaging technology that takes advantage of the excellent characteristics of MEMS sensor chips

We developed the basic technology and equipment for achieving good diffusion bonding with the nickel-alloy foil, as required in order to take advantage of the excellent corrosion resistance of the sapphire sensor chip.

We also devised means of monitoring the processes to ensure the soundness of diffusion bonding and to prevent defective items from being passed to subsequent processes, including an inspection process using image processing and an argon aging process to check whether the bond will be maintained even after long use. With these multiple inspection processes, which were developed along with the basic sensor packaging technology, we can now provide sensors that can be used for a long time even in severe environments.

5. Conclusion

This article reported on Azbil's sensor packaging technology for MEMS sensor chips, one of its core competencies.

We are now in the process of developing even higher sensitivity and higher accuracy MEMS sensor chips. At the same time, we are working to develop production technology so that the excellent characteristics of Azbil's MEMS sensor chips can be utilized by assessing the characteristics of MEMS sensor chips that are disadvantageous for product development in addition to the excellent characteristics, and by developing sensor packaging technology that both compensates for and takes advantage of the chip's characteristics. We are continually enhancing our development skills in order to continue to provide excellent measurement and control devices.

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