Pressure Sensor for Exhaust Systems

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ABSTRACT

Exhaust gas regulations for motor vehicles are becoming stricter year-after-year, and as internal combustion engines are being made more efficient and their exhaust gas reduced, there is increased demand for pressure sensing in the exhaust systems of diesel engine vehicles. Applying a single-chip semiconductor pressure sensor fabricated by a CMOS process, which has been successfully used for manifold pressure measurement, Fuji Electric has developed an exhaust system pressure sensor capable of withstanding an exhaust gas environment containing corrosive substances. The newly developed sensor, in a DIN standard SO_2 gas test, exhibited the ability to withstand corrosion that is more than 2.5 times greater than that of conventional sensors, and is suitable for use in absolute pressure sensing and relative pressure sensing applications.

1. Introduction

Industrial development and expanded distribution in the BRIC countries (Brazil, Russia, India and China) and elsewhere are ongoing. The associated increase in economic activity on a global scale is acerbating the problems of global warming caused by the emission of greenhouse gases such as carbon dioxide (CO_2) and acid rain and air pollution caused by nitrogen oxides (NO_x) and sulfur oxides (SO_x).

As exemplified by the Green New Deal policies in the US, and Japan's announced intent to reduce CO_2 exhaust emissions by 25% by the year 2020, environmental issues are being addressed as national and global problems. With the establishment of strict targets for emission regulation, the development of new environmental technologies and the accompanying economic activity are expected to provide opportunities for environmental businesses.

In particular, environmental measures implemented by the automobile industry, which account for a major portion of the economic activities relating to industry and distribution, are being watched closely. In order to meet the exhaust emission regulations which are being strengthened from year to year, automobile manufacturers have concentrated their efforts on increasing the efficiency and realizing cleaner emissions of combustion engines, and on developing hybrid vehicles and electric vehicles.

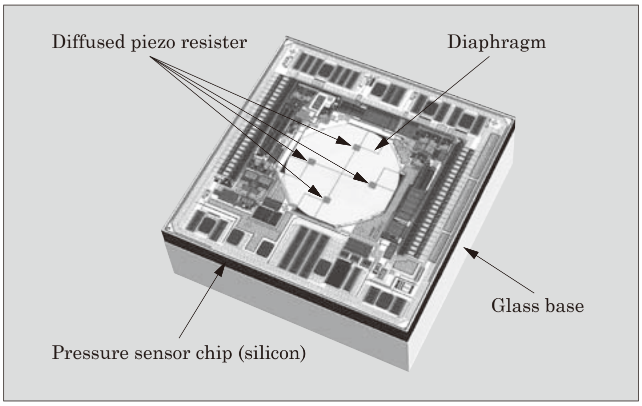
2. Fuji Electric's Pressure Sensors

To achieve cleaner emissions and more efficient fuel consumption of automobiles, the engine control must be made more accurate. In present-day automobiles, engine information such as the load status, aspiration and temperature acquired from sensors installed at various locations in the engine is used to control combustion electronically to realize an optimal air-fuel ratio.

Automotive pressure sensors attached to the intake manifold of an engine and used primarily for measuring intake pressure have helped to make engine control more efficient. Also, in addition to intake pressure measurement sensors, multiple other pressure sensors, such as boost pressure sensors for turbo chargers and super chargers, clogging detection sensors for air filters and barometric pressure sensors[(1)] for compensating the intake pressure at higher altitudes at which the air becomes thinner, are being used.

Fuji Electric began mass-producing manifold absolute pressure (MAP) sensors for automobile engines in 1984. The first sensor had many parts, including a circuit for adjusting the characteristics of a piezo-resistive gauge and a circuit board on which SMDs (surface mounted devices) for dealing with EMC (electromagnetic compatibility) such as chip capacitors, chip resis-

Fig.1 Sensor unit of pressure sensor



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tors and the like are mounted, and the parts had many electrical contacts(2).

To enhance the reliability by reducing the number of parts, Fuji Electric developed a pressure sensor in which the sensing unit, amplifier circuit, temperature characteristic compensation circuit and EMC protection devices are integrated into a single chip using a standard semiconductor CMOS (complementary metal-oxide-semiconductor) process. This single-chip type of pressure sensor has been deployed in the market mainly as a MAP sensor since 2002.

Figure 1 shows an overview of the sensor unit of this pressure sensor, and Fig. 2 shows the cross-sectional structure of this pressure sensor.

Diffused piezo-resistors are fabricated on a diaphragm at the same time as the IC process is performed, and a Wheatstone bridge is configured with four diffused piezo-resistors. The diaphragm ensures a high burst pressure and is formed, using Fuji Electric's proprietary silicon etching process, in a precise round shape.

When the application of pressure causes the diaphragm to flex, the resistance values of the diffused piezo-resistors come to change due to the piezo-resistive effect, and the output of the Wheatstone bridge changes. As a result of this principle, the pressure quantity can be converted into a voltage. Moreover, a high precision amplifier for amplifying the signal output from the Wheatstone bridge and an adjustment circuit for compensating the sensor characteristics are built on a single chip. Additionally, protection devices for protecting internal circuits from surges generated by the automobile engine control system, and from static electricity during the assembly process and electromagnetic noise from external sources, and so on, are all provided on a single chip(3).

Fig.2 Cross-sectional structure of pressure sensor unit

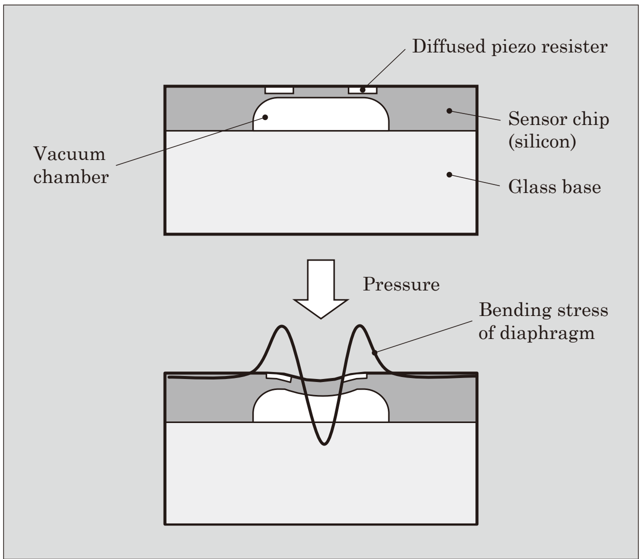
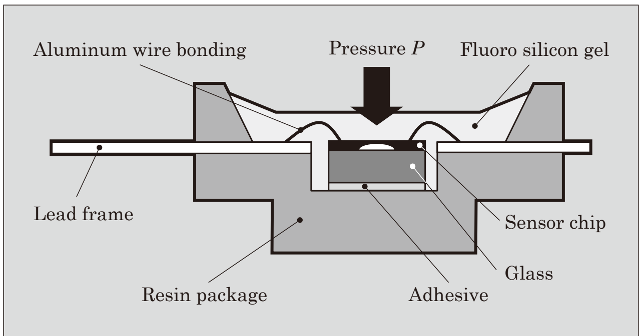


Fig.3 Structure of pressure sensor cell

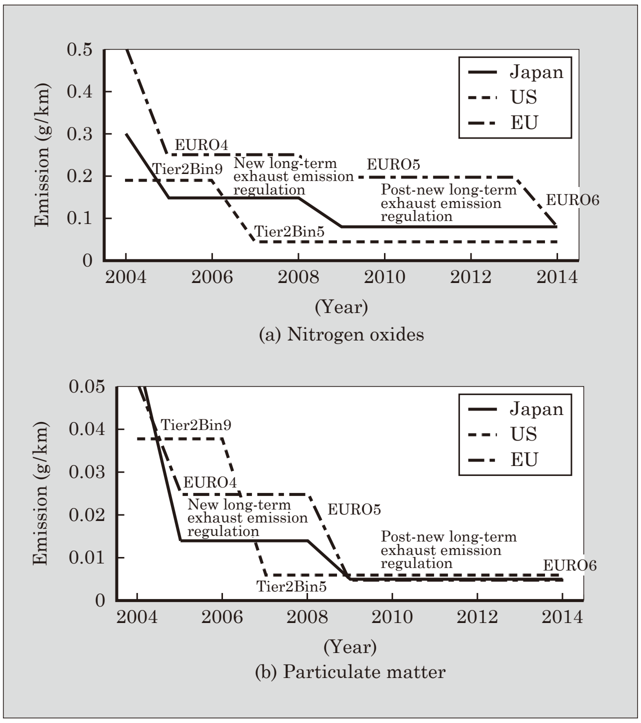


As shown in Fig. 3, the sensor unit is embedded in a resin package, and electrical and mechanical connections are made to the exterior. The sensor cell package is made from PPS (polyphenylene sulfide), which is used for automotive parts and has excellent resistance to acid, and the sensor chip unit, lead frame and wires are coated with fluoro silicone gel, which has excellent chemical resistance and oil resistance.

3. Application to Pressure Sensors for Exhaust System

Exhaust emissions regulations for automobiles have been strengthened year after year since the Muskie Act in the 1970s, and in Japan, Post-New Long-Term exhaust emission regulations came into effect in 2009. In Europe, the EURO5 emission regula-

Fig.4 Changes in NO_x and PM exhaust emission regulations for diesel passenger cars
(Prepared by Fuji Electric and based on documents from the Japanese Ministry of Land, Infrastructure and Transport, the Japanese Ministry of Economy, Trade and Industry, and Japan Automobile Manufacturers Association)



tions came into effect in 2009, and the EURO6 regulations are slated to come into effect in 2014. Figure 4 shows the changes in exhaust emission regulations for diesel passenger cars.

Aiming to improve fuel economy and to reduce CO_2 greenhouse gas emissions, diesel automobiles are in high demand chiefly in Europe and account for more than half of the total number of automobiles sold in Europe. Diesel automobiles have much better fuel economy and lower CO_2 emissions than gasoline-powered automobiles, but the NO_x emissions that accompany their higher combustion temperature and PM (particulate matter) emissions due to imperfect combustion are problems.

Recently, a DPF (diesel particulate filter) used to remove PM contained in exhaust gas has begun to be installed mainly in diesel automobiles. A pressure sensor is used to sense clogging of this filter. Additionally, an EGR (exhaust gas recirculation) system in which a portion of exhaust gas is recirculated to the intake side so as to control combustion has begun to be utilized, and pressure sensors have come to be used to measure the pressure of exhaust gas (Fig. 5).

The sensors used in these exhaust systems must be protected from corrosive matter such as acid caused by the NO_x and SO_x contained in the exhaust gas, and incompletely combusted fuels and oils.

Fuji Electric's newly developed pressure sensor for exhaust systems uses a conventional intake pressure sensor and implements the "corrosion free design" required for exhaust system pressure sensors (Fig. 6).

Fig.5 Engine intake/exhaust system and pressure sensor

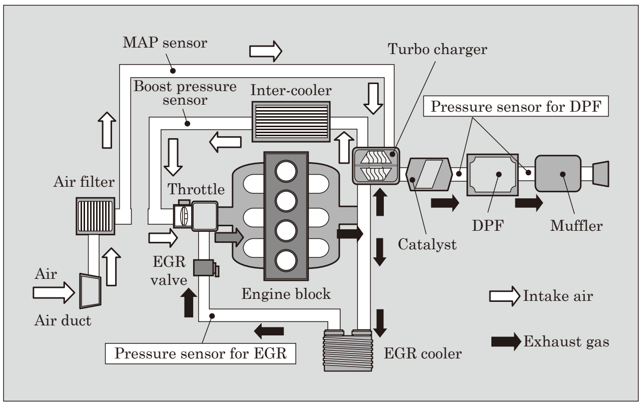
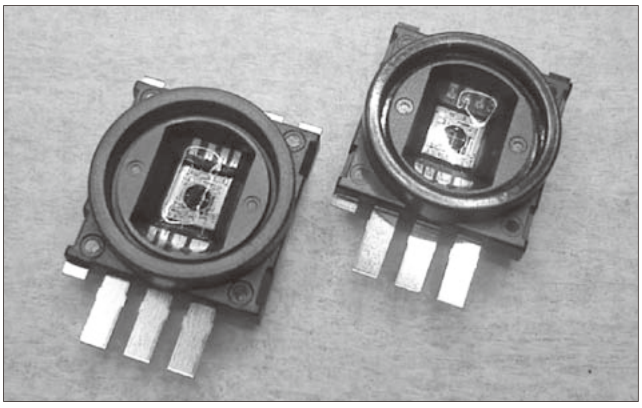


Fig.6 Exhaust system pressure sensor



4. Corrosion Resistant Design to Protect Against Corrosive Matter in Exhaust Gas

The corrosion resistance required of exhaust system pressure sensors has been achieved by implementing the following.

(1) Gold plating of electrode pads on the chip
(2) Gold wire bonding between the chip and lead frame
(3) Gold plating of lead frame for the resin case

Details of these techniques and their evaluation results are described below.

4.1 Corrosion resistant design of sensor chip

The electrode pads of the semiconductor chip, which is fabricated by Fuji Electric's standard CMOS process, are made from an aluminum alloy. If SO_x gas and steam contained in the exhaust gas permeate into the fluoro silicone gel on the chip, sulfuric acid is generated by the mechanism listed below, and the aluminum corrodes.

$$2SO_2+O_2 \rightarrow 2SO_3$$
$$SO_3+H_2O \rightarrow 2H^++(SO_4)^{2-}$$
$$2Al+6H^+ \rightarrow 2Al^{3+}+3H_2$$

Therefore, the electrode pads of the chip are coated with a gold plating layer to form a corrosion resistant structure. Figure 7 shows the cross-sectional structure of the electrode pads and the gold plating on the chip. In order to prevent aluminum and gold from diffusing between the aluminum alloy layer and the gold plating layer, a barrier layer of a titanium-tungsten (Ti-W) alloy is provided (for the purpose of explanation, the proportion of horizontal and vertical length in the figure differs from that of an actual chip).

Moreover, conventionally, the chip and lead frame were bonded together by aluminum wire, but because the same chemical reaction would cause the wire to corrode and possibly break, gold wire was used for the

Fig.7 Corrosion resistant structure of sensor chip electrode pads

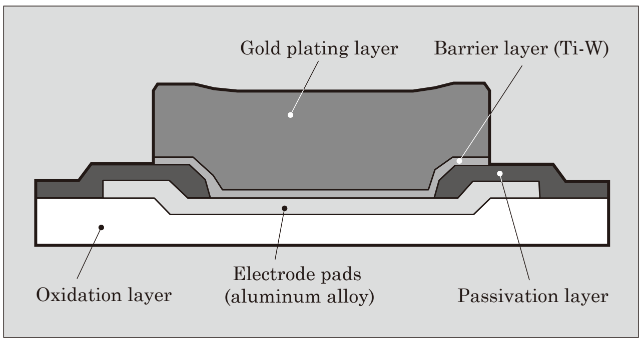


Fig.8 Structure of exhaust system pressure sensor

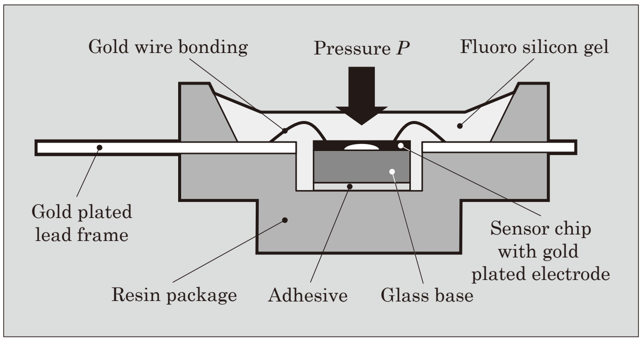


Fig.9 SO_2 gas test results

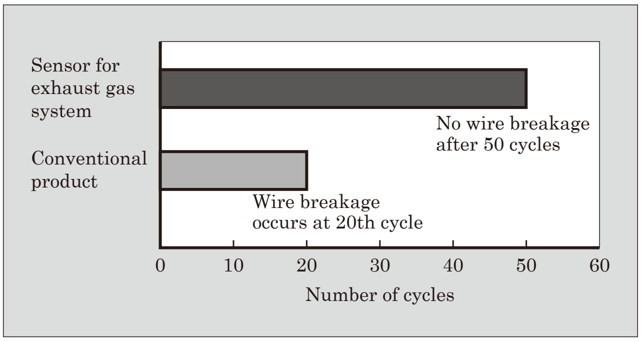


Table 1 SO_2 gas test conditions (DIN50018-SFW1.0S)

Theoretical SO_2 concentration at start of cycle (vol. %)			0.33*
Condensate climate			DIN50018-SFW 1.0S
Cycles	1st test process (h)		8 (including heating)
	2nd test process (h)		16 (including cooling) (test box is open or ventilated)
	Total (h)		24
Test room conditions	1st test process	Temperature (˚C)	40 ± 3
		Relative humidity (%)	Approximately 100 (forming condensation on the test material)
	2nd test process	Temperature (˚C)	18 to 28
		Relative humidity (%)	75 (max.)

* : The theoretical SO_2 concentration, in the case of a test box having a 300 L volume, corresponds to 1.0L of SO_2 added for each cycle.

new sensor.

4.2 Corrosion resistant design of the package

In an existing pressure sensor cell package, the lead frame is plated with nickel, but depending on the surface condition of the plating, the leads may become corroded by acid that has formed from the exhaust gas, resulting in a break in the electrical connections to the exterior. Therefore, a gold layer is plated on top of the nickel plating to create a structure that prevents corrosion.

Since acid formed from corrosive gas reaches the interface between the lead frame and resin, the side surfaces, i.e., the cut surfaces, of the lead frame that are implanted into the resin must be corrosion-resistant. After press-cutting of the lead frame, a gold plating process is performed, and the cut edge surfaces are gold-plated (Fig. 8).

4.3 Corrosion resistance test results

To evaluate the corrosion resistance, an SO_2 gas test was performed based on the DIN standard DIN50018-SFW1.0S. The test conditions are listed in Table 1. This test exposes the product surface, on which condensation is formed, to SO_2 gas and is more severe than the exhaust gas environment of an actual automobile, but is used as an accelerated test for verifying the lifetime until reaching the failure mode of wire breakage due to corrosion of the product.

Figure 9 compares broken wire failure modes of the chip electrode pads and case lead frame caused by corrosion in the SO_2 gas test for a conventional product and the newly developed exhaust system pressure sensor. We verified that the newly developed exhaust system pressure sensor has more than 2.5 times that corrosion resistance of a conventional product (where 1 cycle is defined as the time from product condensation until exposure to SO_2 gas).

Table 2 Basic specifications of the exhaust system pressure sensor

Item	Units	Specification	Comments
Over-voltage	V	16.5 V	1 min
Proof Pressure	kPa abs.	600	
Storage temperature	˚C	−40 to 150	
Usage temperature	˚C	−40 to 135	
Power supply voltage	V	5.00±0.25	
Pressure range (absolute pressure)	kPa abs.	50 to 400	*1
Type of pressure used (gauge pressure)	kPa gauge	50 to 400	*1
Output range	V	0.5 to 4.5	
Interface	kΩ	300	Pull-up
		100	Pull-down
Diagnostic output	V	<0.2, >4.8	*2
Accuracy	%F.S.	< 1.2	10 to 85°C
	%F.S.	< 2.0	−40/135°C
Standards that have passed EMC verification		JASO D00-87, CISPR 25, ISO11452-2, ISO7637	

* 1 : Full-scale pressure can be changed freely
* 2 : Detect open mode at Vcc and/or Vout

5. Basic Specifications

Basic specifications of the newly developed exhaust system pressure sensor are as listed in Table 2. The sensor chip circuitry directly reuses a configuration having a history of past success as a MAP sensor, and features a diagnostic function for detecting breakage of the wiring and an over-voltage protection function, and is resistant to electromagnetic noise. Either absolute pressure or gauge pressure can be selected for the pressure measurement.

6. Postscript

Fuji Electric's new exhaust system pressure sensor was developed mainly for automotive applications, but at present, efforts to reduce the exhaust gas from automobiles are targeting not only the exhaust from automobiles, but the entire process from the production to scrapping of automobiles. For example, since heavy machinery equipped with diesel engines that emit large quantities of exhaust are used in mining the iron or raw material from which automobile bodies are fabricated, and in the mining of rare metals used to make reduction catalysts and batteries, there is a movement to establish regulations for this exhaust gas and to reduce the amount of these emissions.

If the newly developed pressure sensor is to be applied to non-automotive engines, such as engines in heavy machinery and the like, then according to such conditions as the type of engine, location of sensor installation and type of fuel used, significant variations will exist in the quantity of corrosive matter contained in the exhaust gas, and in the exhaust pressure and ambient temperature, and it is important that product development be advanced with familiarity of the upper-level applications.

Fuji Electric will continue to develop world-class technology, aiming to develop products that will please our customers and contribute to environmental protection measures.

The authors wish to take this opportunity to express their gratitude to Hitachi Automotive Systems, Ltd. for their cooperation in conducting the SO_2 gas test.

References

(1) K. Saitou, Latest Trends of Automotive Sensors. CMC Publishing Co., Ltd. 2009, p.38-51.
(2) T. Takahama, et al. Semiconductor Pressure Sensors. Fuji Electric Journal. 1986, vol.59, no.11, p.707-710.
(3) K. Uematsu. About Automobile Pressure Sensors. Material Stage. Technical Information Institute, Ltd. 2009, vol.9, no.1, p.26-30.