7th–Generation Automotive High-Pressure Sensors

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ABSTRACT

Automobiles are being strictly required to improve fuel efficiency and comply with environmental and safety regulations. Fuji Electric has developed 7th-generation automotive high-pressure sensors to help meet these stricter regulations. Since the sensors are used in high-temperature and high-pressure environments, they have new package structure using stainless-steel diaphragm system to improve pressure resistance and combined with a sensor chip that has better temperature characteristics through utilization of a newly developed dual gate MOS transistor. This expands the applicable pressure range, ensuring operation at 150 °C and increasing accuracy.

1. Introduction

In recent years, in addition to achieving better fuel efficiency, safety, and comfort, automobiles are being strongly required to reduce their environmental load through compliance with air pollutant emissions regulations and CO_2 emissions regulations. In order to meet these increasingly stringent regulations, the accuracy of various automotive systems is being enhanced. Sensing devices are essential for improving the accuracy of systems. In particular, there has been increased market demand for various sensors, such as acceleration sensors, rotation sensors and the pressure sensors introduced in this paper.

Fuji Electric started mass production of automotive intake pressure sensors in 1984, and has since expanded its business mainly in the low-pressure equipment field, which has a rich variety of automotive applications, and has commercialized products that meet the high accuracy and reliability demands of the market. In 2005, we provided improved detection accuracy with our 5th-generation of digital trimming type pressure sensors based on complementary metal oxide semiconductor (CMOS) processes. Since 2010, we have been mass producing 6th-generation pressure sensors that are miniaturized and improved in noise resistance. Furthermore, in 2018, we started mass producing 6.5th-generation pressure sensors featuring improved output characteristics at high temperatures. They have been utilized in the internal combustion engines of passenger vehicles and heavy construction equipment, trucks and motorcycles, as well as passenger vehicles, and have helped reduced environmental loads.

In order to achieve better fuel efficiency and lower emissions, it has been necessary to improve efficiency not only for internal combustion engines, but also for the drive transmission systems of vehicles .

In this paper, we will introduce our new 7th-generation automotive high-pressure sensors developed especially for transmission hydraulic pressure control systems.

2. Role of Automotive High-Pressure Sensors

Automobiles are equipped with sensors that measure various pressures. They can be broadly divided into low-pressure sensors for measuring approximately 300 kPa from vacuum pressure and high-pressure sensors for measuring larger pressures of 1 MPa or higher. Low-pressure sensors include intake pressure sensors used in electronic fuel injection systems as one of the essential engine control systems for improving fuel efficiency and lowering emissions, as well as pressure sensors for detecting exhaust gas pressure used in the exhaust gas recirculation (EGR) and diesel particulate filter (DPF) systems to comply with emissions regulations (see Fig. 1).

High-pressure sensors contribute to improved fuel efficiency, environmental performance and safety in the same way as low-pressure sensors: controlling the coolant pressure of air conditioners (1- to 5-MPa sensors); measuring the fuel pressure of direct fuel injection systems (GDI) that increase engine combustion efficiency and improve fuel efficiency (13- to 26-MPa sensors); controlling electronic hydraulic pressure of suspensions designed to increase comfort (1- to 10-MPa sensors); and measuring brake hydraulic pressure, such as those for ABS and side-slip prevention functions for electronically controlling the brakes (1- to 10-MPa sensors)(1). In addition, they are used in automatic transmissions that transmit engine power to

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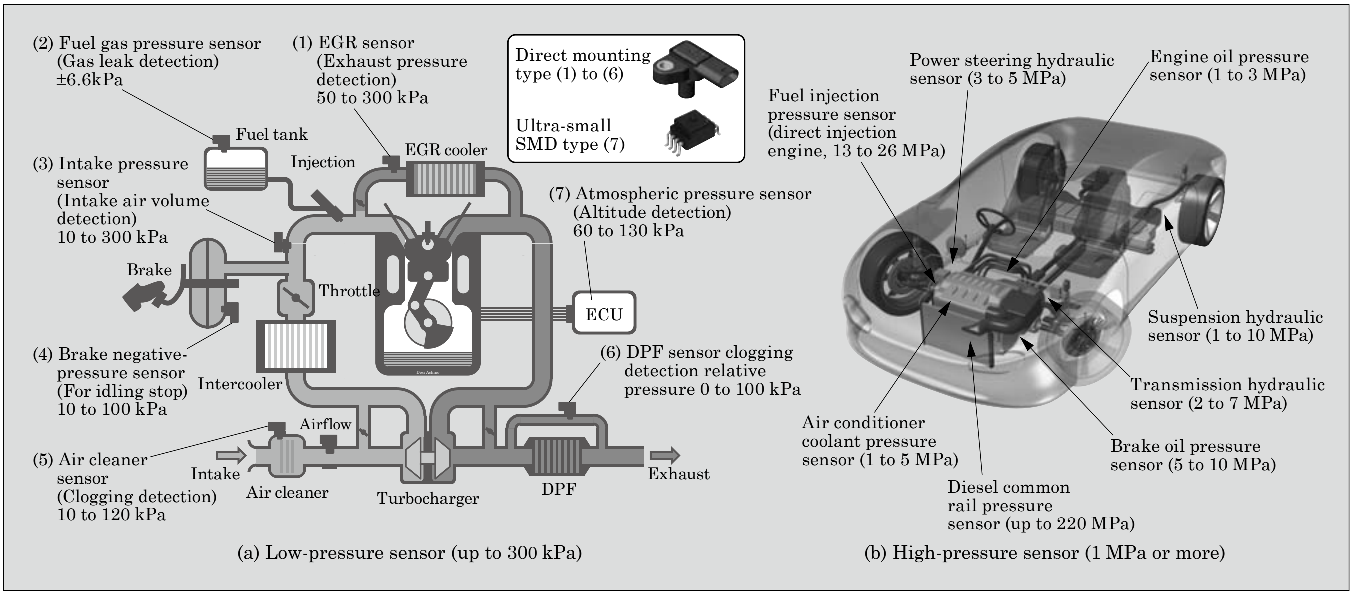


(a) Low-pressure sensor (up to 300 kPa)

(b) High-pressure sensor (1 MPa or more)

Fig.1 Example of a sensor application system

the drive wheel, as well as for measuring hydraulic pressure for continuously variable transmission (CVT) control functions capable of determining the optimal gear ratio while maintaining the most efficient engine speed.

The transmission mechanism of the CVT consists of two pulleys with V-shaped grooves and a metal belt sandwiched between the pulleys. The transmission is operated by moving the metal belt closer to or farther away from the rotation shaft of the pulleys by changing the groove width of the pulleys after increasing or decreasing the hydraulic pressure generated by the oil pump according to conditions related to accelerator opening and vehicle speed. Furthermore, engine power is transmitted by friction generated between the pulleys and metal belt, and transmission loss occurs when slipping occurs due to excessive engine power. To prevent slippage, it is necessary to increase the pulling load of the pulleys by increasing the working hydraulic pressure in such a manner that increases frictional force. At the same time, however, increasing friction leads to loss of power and degrades fuel efficiency. To solve these issue, it is necessary to control the hydraulic pressure so that it does not push the metal belt more than necessary or cause slippage, while also improving fuel efficiency by minimizing transmission loss. The pressure sensor used to control the hydraulic pressure needs a compact package that contributes to reducing the weight of the transmission, in addition to high precision.

Moreover, since automotive electrical control systems are becoming increasingly large scale, high precision, and miniaturization, techniques to achieve high-density mounting of components have been progressing. Therefore, the pressure sensor needs to operate properly in a transmission-mounted environment and is required to secure high-temperature operation, vibration resistance, pressure resistance, oil resistance and corrosion resistance. Furthermore, it also needs to have electromagnetic compatibility to be resistant to electromagnetic noise generated from various electronic devices.

In order to meet these demands, we have developed an automotive high-pressure sensor utilizing single chip technology, which combines sensing elements and a signal processing circuit, and a small package technology.

3. Overview of the 7th-Generation Automotive High-Pressure Sensor

Since this sensor is used in high-temperature, high-pressure environments, it utilizes a new package structure and a newly designed sensor chip.

In particular, it uses the combination of the structure that uses a stainless steel diaphragm for the pressure receiving part of the pressure medium with a sensor chip with improved high-temperature characteristics.

3.1 Package structure with a stainless diaphragm

Figure 2 shows the external appearance of the 7th-generation pressure sensor, and Fig. 3 shows a comparison diagram of the cross-sectional structures of pressure sensors. Up until now, Fuji Electric's high-pressure sensors have used an adhesive to bond the sensor chip to the metal base and the pressure is applied to the back surface of the chip through the metal hole. As a result, a force would be applied in the direction for detaching the sensor chip when applying a pressure. This would limit the measurement pressure range according to the adhesive strength fixing the chip, resulting in it not being suitable for high-pressure measurements. The double diaphragm struc-

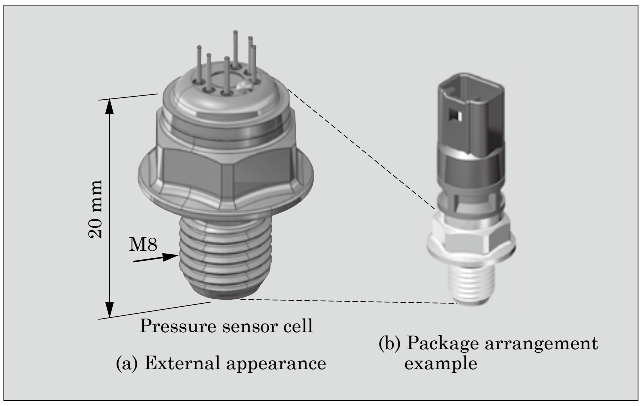


Fig.2 7th-generation pressure sensor

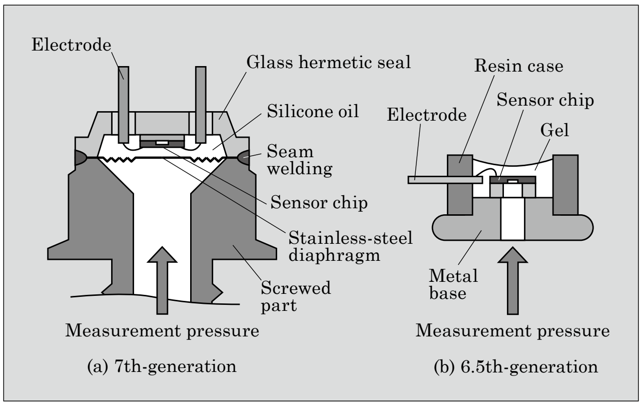


Fig.3 Comparison of cross-sectional structure of pressure sensors

ture used by our recently developed sensors comes equipped with a chip mounted inside a glass hermetic package. Furthermore, a stainless-steel thin film functioning as a pressure receiving part is sandwiched between the screwed part and hermetic part, with the three parts then being seam welded together at the same time. By sealing the space formed between the hermetic and stainless-steel thin film with silicone oil, the pressure received by the stainless-steel diaphragm is applied to the silicon diaphragm with micro electro mechanical systems (MEMS) structure formed on the sensor chip through silicon oil and distorts the diaphragm to enable pressure detection. This structure provides a better pressure resistance performance than conventional structures because it is a structure that receives pressure from all structural parts whose pressure resistance performance does not depend on the bonding strength of the chip adhesive. This has expanded the pressure range applicable to the system, as well as the application range.

This sensor is used for performing hydraulic measurements for transmissions and is designed to measure a maximum pressure of 6 MPa and destructive pressure resistance of 20 MPa. To design a package capable of withstanding this pressure, it was necessary to secure pressure resistance for the hermetic part and increase the pressure resistance strength of the seam welded part. Our basic concept for improving the strength involved the relationship “pressure × pressure receiving area = load,” whereby the load increases as the pressure receiving area increases. The pressure resistance is secured by using a structural part whose strength does not succumb to the generated load. In order to achieve this package, it is necessary to increase the thickness of the hermetic part, use a high-strength material and improve the strength of the seam weld. However, doing so was not feasible cost wise. To solve this problem, our recently developed sensor reduces the load (stress) generated on the package by decreasing the area of the pressurized part (i.e., decreasing the diameter) and ensuring overall pressure resistance performance. To achieve miniaturization for the sensor, we developed a glass hermetic part and incorporated special specifications into the assembly technology, such as those related to the mounting technology and equipment design. In addition, we have optimally designed the shape of the stainless-steel diaphragm waveform that needs thin-walled precision press working technology.

3.2 Optimized design for stainless-steel diaphragm

The diaphragm is capable of avoiding internal pressure rise even when the size of the stainless-steel diaphragm is reduced. In this section, we will describe the optimized design for diaphragm.

The stainless-steel diaphragm has the following main functions:

(a) Function to protect internal elements from measurement medium (corrosion resistance)
(b) Function to alleviate internal pressure rise due to temperature

For (a), stainless-steel materials with excellent corrosion resistance are selected. The materials are also used for the measurement equipment.

For (b), changes in the oil temperature or ambient temperature cause sensor temperature change ΔT to occur as shown in Fig. 4. The silicone oil sealed inside the sensor causes volume change ΔV to occur due to the thermal expansion coefficient α of the silicone oil. It is capable of absorbing the volume change using the springiness k possessed by the stainless-steel

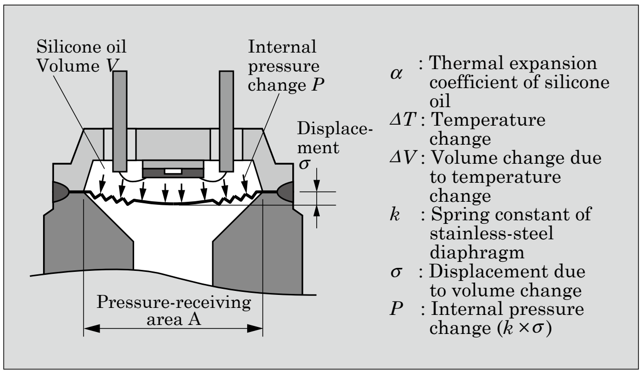


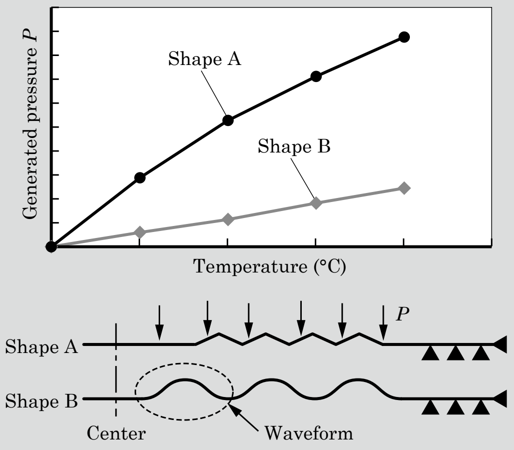
Fig.4 Internal pressure rise mechanism

diaphragm. At the same time, however, it serves as a mechanism for causing pressure change in the silicone oil through the springiness. These challenges are solved by optimizing the wave-shape processed into the stainless-steel diaphragm and the thickness of the diaphragm. Figure 5 shows an optimal analysis example. In order to achieve high accuracy, it is necessary to control the silicone oil pressure that is generated simultaneously with the volume change due to the temperature. We carefully considered the output characteristics of the sensor chip and created a 3D model of the diaphragm shape for various patterns. After this, we performed thermal deformation analysis (b) for the diaphragm. On the basis of the data obtained from the analysis, we developed a package that maximizes the performance of the 7th-generation pressure sensor chip by adjusting the linearity of the internal pressure rise and the internal pressure change characteristics required for the stainless steel diaphragm.

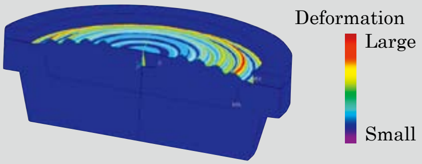
3.3 Sensor chip for high-temperature operation

Fuji Electric's pressure sensor chip is designed on the basis of the concept of being an "All in one chip" that integrates all basic functionality, such as pressure detection, characteristic compensation, signal processing, a protection circuit and fault diagnosis. In addition, we have been developing next-generation products that not only maintain these basic functions, performance and EMC protection, but also include cost reduction and accuracy technologies.

The basic operation of the pressure sensor chip is characterized by the diaphragm (which was formed by molding some of the silicon into the thin film using Fuji Electric's proprietary etching technology) creating deformation according to the applied pressure. When this happens, the resistance values of the 4 piezo resistors composed of the diaphragm's diffusion wiring change respectively, and this causes the balance of the Wheatstone bridge circuit consisting of the piezo resistors to collapse, resulting in a potential difference at the output. By amplifying and outputting this potential difference, the applied pressure is then converted to an electrical signal. Figure 6 shows an overview of the pressure sensor chip.



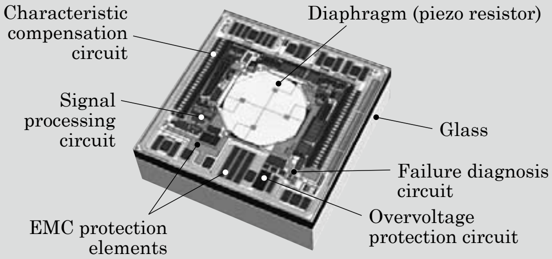
(a) Diaphragm characteristic (temperature and generated pressure)



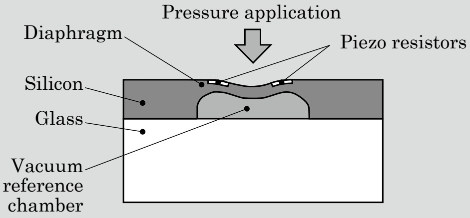
(b) Thermal deformation analysis

Fig.5 Optimal analysis example (diaphragm shape and internal pressure transition)

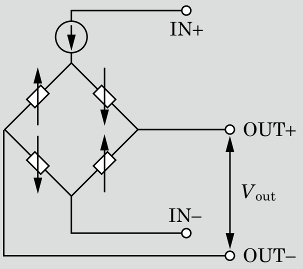
Our 7th-generation automotive high-pressure sensors make use of a newly developed dual-gate MOS transistor designed to provide better accuracy than conventional mass-produced products while increasing the working guarantee temperature to 150 °C. As shown in Fig. 7, dual-gate is technique employed to reduce the leak current in the channel directly below the gate by using different types of gate poly silicon formations for the negative-channel metal oxide semiconductor (NMOS) and positive channel metal oxide semiconductor (PMOS) of the MOS transistor. We developed a manufacturing process for our 7th-generation automotive high-pressure sensors that uses this dual-gate MOS while maintaining the same performance as



(a) Chip structure

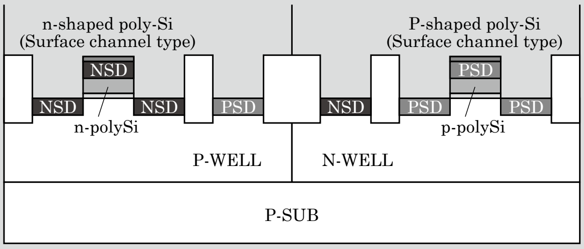


(b) Sensor chip cross-sectional view

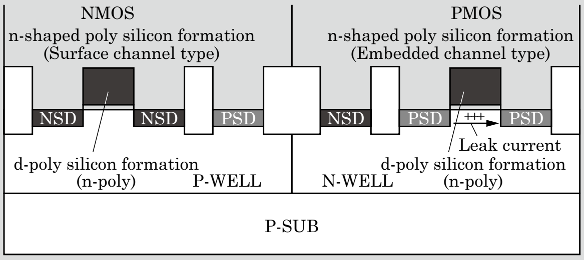


(c) Diaphragm circuit (Wheatstone bridge)

Fig.6 Overview of pressure sensor chip



(a) 7G: Dual gate



(b) Current mass production process

NSD: Negative Source Drain
PSD : Positive Source Drain

Fig.7 Dual-gate structure

conventional mass-produced products for devices other than MOS transistors. As a result, we have been able to improve the leak current in the high-temperature region using the same circuit configuration and circuit size as conventional mass-produced products. In particular, as shown in Fig. 8, the leak current of the PMOS transistor at 150 °C was able to be reduced to approximately one-fifth of that of the conventional process, thereby significantly contributing to improving the working guarantee and accuracy in the high-temperature region.

Figure 9 shows the temperature dependence of the output tolerance. The characteristic tolerance at high temperatures is reduced by approximately 40% compared with the 6.5th-generation product.

Table 1 shows the main performance of the recently developed 7th-generation automotive high-pressure sensors.

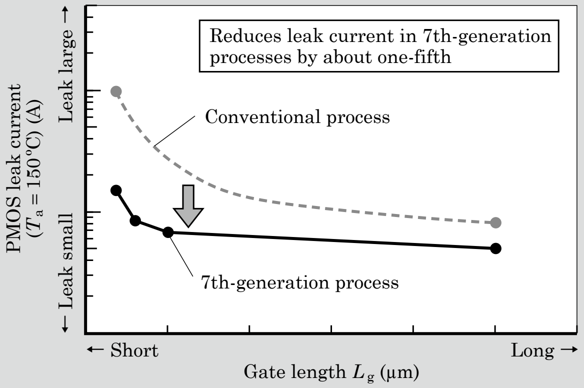


Fig.8 Effect of reducing dual-gate MOS leak current

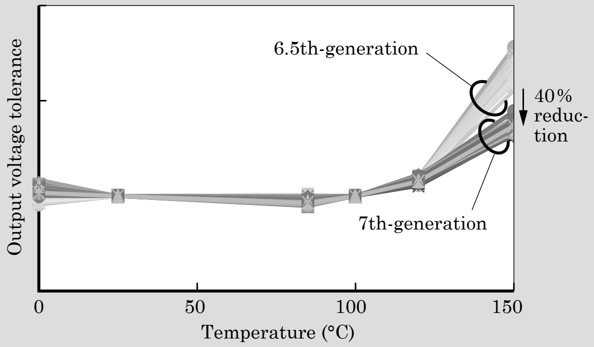


Fig.9 Output tolerance characteristic

Table 1 Main performance of the 7th-generation automotive high-pressure sensor

Item		Main performance and specifications
Product size (overall view)		ϕ15 × H20 (mm)
Pressure interface		M8 × 1.0
Operating temperature range		−40 °C to +150 °C
Operating pressure range		0.1 to 6.1 MPa (absolute pressure)
Destructive pressure		20.1 MPa
Rated pressure		9.1 MPa
Power supply voltage		5 ± 0.25 V
Output voltage (at 5-V power supply voltage)		0.5 to 4.5 V
Sink source capability		Sink 1 mA, source 0.1 mA
Clamp function		Clamp voltage 0.35 V/4.62 V (typ.)
Method		Surface pressure (absolute pressure)
ESD (external interface pin)		
	MM (0 Ω, 200 pF)	±1 kV or higher
	HBM (1.5 kΩ, 100 pF)	±8 kV or higher
Transient voltage surge		ISO 7637 (2011) standard Pulse1, 2, 3a, 3b LEVEL-III cleared

4. Postscript

In this paper, we introduced our 7th-generation automotive high-pressure sensors. As the demand for high-pressure sensors increases, it is expected that the number of stringent requirements on product performance will also increase in order to improve fuel efficiency and comply with environmental and safety regulations. We intend to continue developing products that meet the demands of various sectors in the market.

References

(1) Sato, E. et al. 6.5th-Generation Automotive High Pressure Sensors. FUJI ELECTRIC REVIEW. 2018, vol.64, no.4, p.215-220.

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