6.5th-Generation Automotive High Pressure Sensors

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ABSTRACT

To respond to environmental regulations and fuel consumption improvement in recent years, high-precision control technology is being applied to internal combustion engines, namely gasoline and diesel engines, and high-density mounting is being adopted to achieve downsizing. As a result, automotive high-pressure sensors are required to achieve high precision and a high guaranteed operating temperature. To meet these needs, Fuji Electric has developed a 6.5th-generation high-pressure sensor for automotive applications. The product is characterized by its integration of a metal based package that ensures a high breakdown voltage with the sensor chip that guarantees operation and precision even under high temperature and pressure. The sensor has achieves miniaturization and guarantees operation at 150 °C using miniaturization technology and revised circuit layout.

1. Introduction

Today's automobiles not only need ensure safety and comfort, but are also increasingly required to reduce environmental burdens according to laws that regulate the emission of air pollutants and CO_2. In order to meet these regulations, there has been rapid development of control systems for electric-powered vehicles such as hybrid electric vehicles (HEV), electric vehicles (EV) and fuel cell vehicles (FCV). At the same time, conventional internal combustion engines are undergoing developments to reduce environmental burdens through high-precision control technology.

Automotive pressure sensors include low-pressure sensors with a measuring range of less than 1 MPa and high-pressure sensors with a range of more than 1 MPa. Low-pressure sensors are being increasingly used for systems that seek to improve fuel efficiency in internal combustion engines, such as gasoline and diesel engines, by precisely controlling intake volumes and fuel mixture ratios, as well as for systems that endeavor to clean exhaust emissions by recirculating gas after combustion in order to reduce the emission of air pollutants. High-pressure sensors are designed to improve fuel efficiency and safety and are used in the hydraulic pressure control units of automobile engines, transmissions, power steering and brakes.

Fuji Electric started mass production of automotive pressure sensors in 1984. Since then, our sensors have been utilized in automobiles throughout the world by improving detection accuracy and achieving a high level of reliability capable of withstanding harsh automotive environments. Starting in 2005, we were able to improve detection accuracy with our 5th-generation digital trimming type pressure sensors that utilized a complementary metal oxide semiconductor (CMOS) process. Furthermore, in 2010 we started mass production of 6th-generation pressure sensors designed for miniaturization and enhanced noise resistance[(1)].

In this paper, we introduce our 6.5th-generation automotive high-pressure sensor capable of ensuring precision in the high-temperature environments that have accompanied engine downsizing. This product has refined the conventional 5th-generation automotive high-pressure sensor for engine oil pressure.

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2 Overview of Pressure Sensors

2.1 Application of automotive pressure sensors

Figure 1 shows the applications of automotive low-pressure sensors, and Fig. 2, those of high-pressure sensors. The electronic fuel injection systems for improving fuel efficiency in automobiles make use of manifold absolute pressure (MAP) sensors for measuring intake pressure, as well as temperature manifold absolute pressure (TMAP) sensors that implement temperature detection. In addition, many other types of pressure sensors for improving fuel efficiency are also used, such as barometric sensors for assisting highland correction in prevention of fuel efficiency degradation during high-altitude travel, pressure sensors for detecting intake air filter box clogging, and sensors used with turbo engines for detecting supercharging pressure.

Furthermore, there are also pressure sensors for detecting diesel particulate filter (DPF) clogging and sensors for exhaust gas recirculation (EGR) in systems that reuse exhaust gases, both of which were designed to satisfy enhanced emissions regulations typified by Japan's exhaust gas regulations or Europe's Euro 6 regulations.

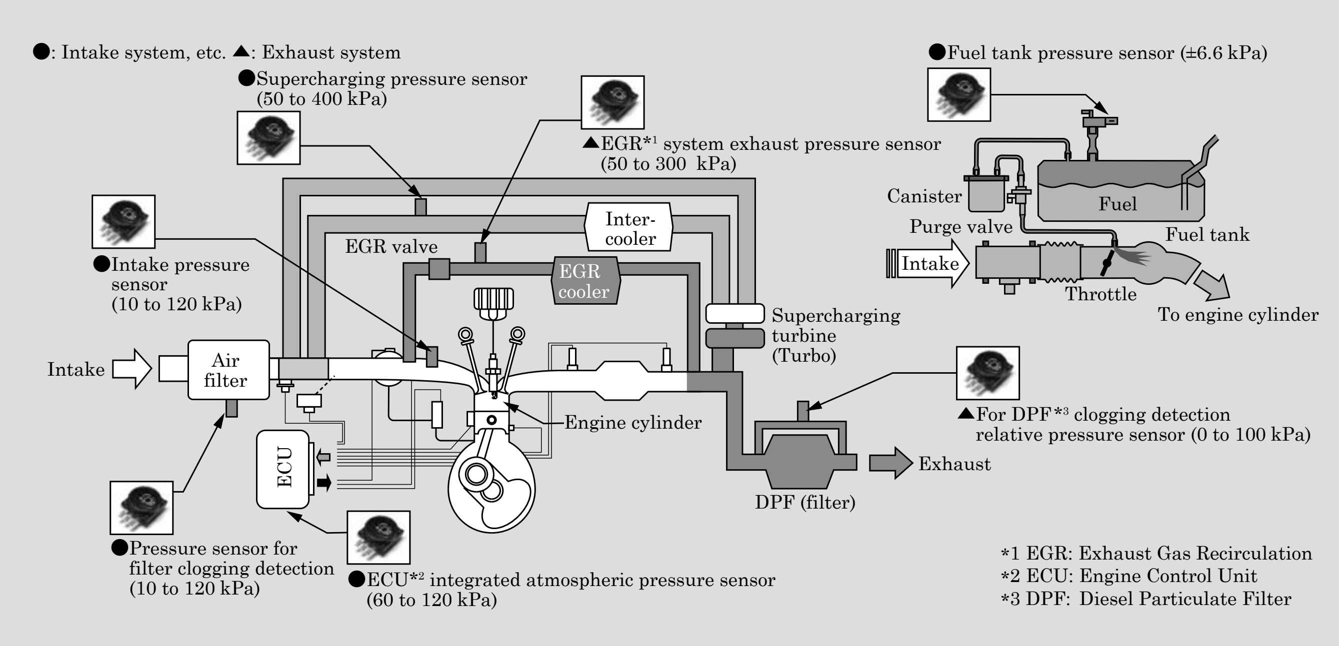


Fig.1 Automotive low-pressure sensor applications

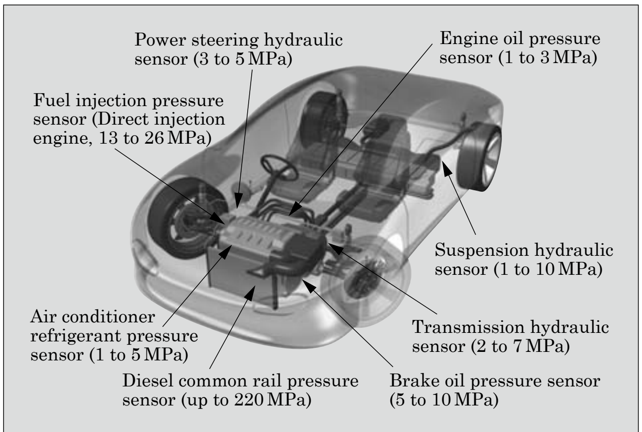


Fig.2 Automotive high-pressure sensor applications

Moreover, there are also fuel tank pressure sensors to detect fuel leakage used in Europe and the United States as pressure sensors required to meet safety regulations.

For high-pressure detection applications, the demand is increasing for fuel pressure sensors that can be mounted on diesel engines and direct-injection engines because automobile makers have become increasingly using downsized engines to improve fuel efficiency. In addition, transmissions have also advanced in compactness, lightweight, and function for high fuel efficiency, and they use multiple pressure sensors. Pressure sensors are also increasingly used for hydraulic systems, such as for measuring engine oil pressure (1 to 3 MPa). In this way, the demand for high-pressure sensors has thus been rapidly expanding.

2.2 Installation environments of automotive pressure sensors

In recent years, high-density mounting has been increasingly utilized as engines are downsized to achieve better fuel efficiency for automobiles. As a result, pressure sensors are required to ensure high-precision high-temperature operation and electromagnetic compatibility (EMC), that is, having durability in electromagnetic noise generated by other electronic devices. Furthermore, depending on their application, they also need to have high-pressure resistance, corrosion resistance and electrification characteristics.

3 Overview of 6.5th-Generation Automotive High-Pressure Sensors

Our 6.5-generation automotive high-pressure sensors have the structure shown in Fig. 3 in order to ac-

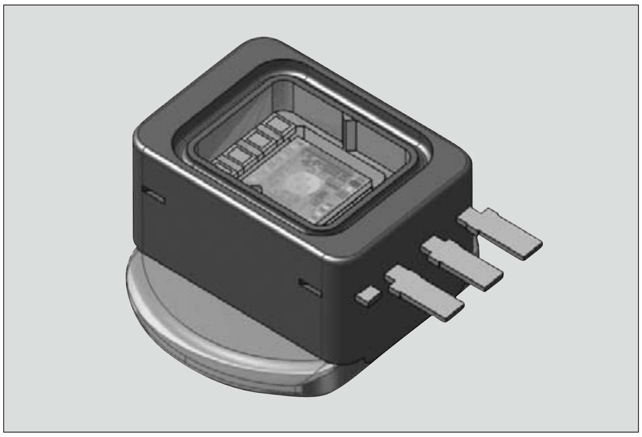


Fig.3 Automotive high-pressure sensor

commodate use in high-pressure and high-temperature environments.

In particular, these sensors have the feature of integrating a package that utilizes a metal base and ensures high pressure resistance with a sensor chip that guarantees operation and accuracy even when high temperatures and high pressures are applied.

3.1 High pressure resistant package with metal base

The package for low-pressure pressure sensors is characterized by integrally molding the lead frame for electrically connecting the sensor chip with a polyphenylene sulfide (PPS) resin. However, the pressure resistant strength of the PPS resin itself is insufficient when applied with a high pressure. In order to solve this problem with respect to automotive high-pressure sensors, a metal base is used for the section where pressure is applied in order to improve pressure resistance of the entire sensor structure. Figure 4 shows the high-pressure sensor structure and mounting state schematically. The drawing shows the parts subjected to pressure when pressure is applied (area A_o, A_s) and

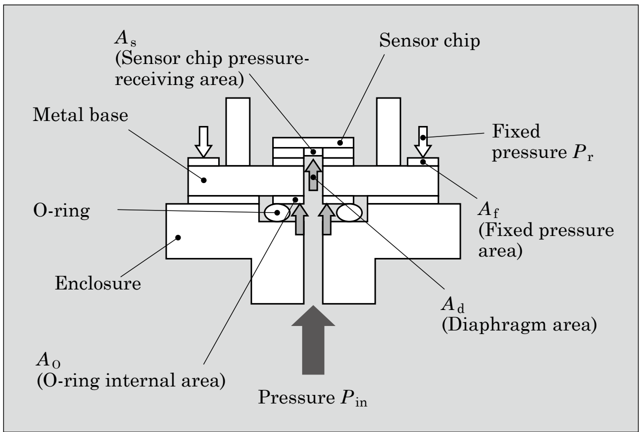


Fig.4 Schematic diagram of the high-pressure sensor and its mounted state

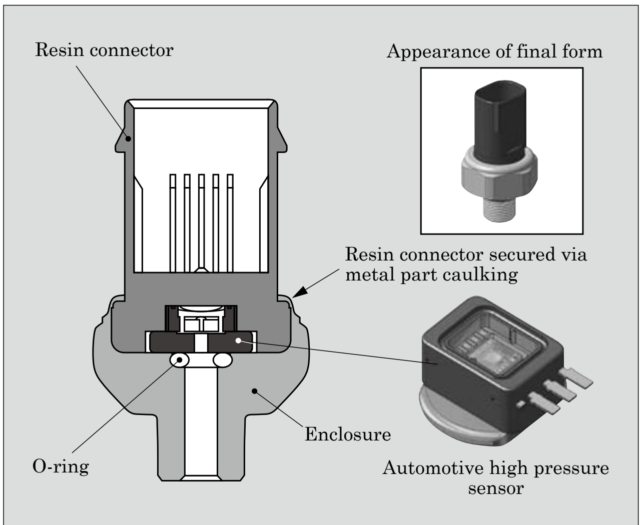


Fig.5 High-pressure sensor mounting example

the part with the counteracting reactive force (area A_f). Figure 5 shows an example of mounting the high-pressure sensor. The enclosure shown here represents the side to which the high-pressure sensor is mounted. The high-pressure sensor is secured by the enclosure and a fixture inserted from the top. Airtightness is ensured by an O-ring inserted between the enclosure and the high-pressure sensor.

Since the high-pressure sensor is secured with the help of the reactive force from the fixture, the relationship between the applied pressure and fixed load can be expressed by the following equation.

(1) Applied pressure and fixed load

$$F = P_{in} \cdot (A_o + A_s) = P_r \cdot A_f \quad (1)$$

F: Fixed load
P_{in}: Applied pressure
A_o: O-ring internal area
A_s: Sensor chip pressure-receiving area
P_r: Fixed pressure
A_f: Fixed pressure area

By rearranging Equation 1, fixed pressure can be expressed as $P_r = P_{in} \cdot (A_o + A_s) / A_f$. However, in the actual structure, $(A_o + A_s) / A_f$ is extremely small, and this means that fixed pressure P_r can be reduced and the size of the high-pressure sensor miniaturized, thereby contributing to the miniaturization of the entire structure.

In addition, the mechanical strength required for each member (adhesive between sensor chip and metal base, and the metal base itself) when the applied pressure P_{in} is generated can be expressed by the following equation that takes into consideration respective stress balances.

(2) Structural design for the applied pressure

$$P_{in} \cdot (A_d + A_s) < \sigma_m \cdot A_f \quad (2)$$

P_{in}: Pressure
A_d: Diaphragm area
A_s: Sensor chip adhesive area
σ_m: Metal base elastic limit stress
A_f: Fixed pressure area

$$P_{in} \cdot A_d < \sigma_s \cdot A_s \quad (3)$$

P_{in}: Pressure
A_d: Diaphragm area
σ_s: Bonded member breaking stress (i.e., the adhesive)
A_s: Sensor chip adhesive area

Since the temperature environment for automobiles ranges widely from −40 to +150 °C, it is necessary to employ a design that takes into consideration the stress generated by differences in the thermal expansion coefficients of each member. In particular, the selection of the adhesive and metal base materials is important with regard to the stress generated between the sensor chip and the metal base.

We created an FEM analysis model during the package design stage for the high-pressure sensor. In particular, we analyzed the deformation and stress distribution when applying pressure P_{in}, as well as the thermal stress deformation and stress distribution at the time of temperature change. Figure 6 shows the FEM analysis model diagram, and Fig. 7, the FEM analysis results. The material and structural dimensions of each member were determined on the basis of the results of this calculation.

3.2 Sensor chip for high-temperature operation

Fuji Electric has developed pressure sensor chips that incorporate high-precision technology on the basis of the principle "All in one chip" that combines all features such as pressure detection, characteristic compensation, signal processing, protection circuit, failure diagnosis and EMC protection.

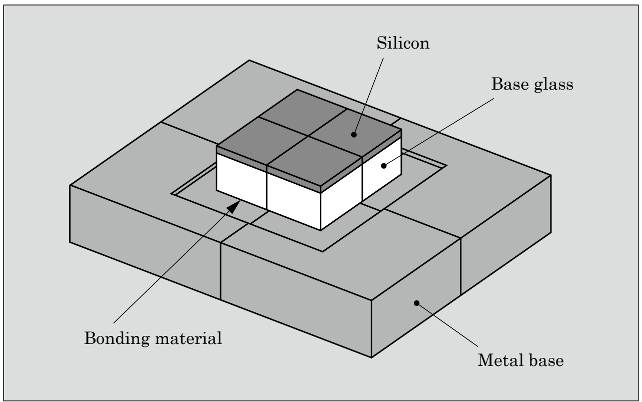


Fig.6 FEM analysis model diagram

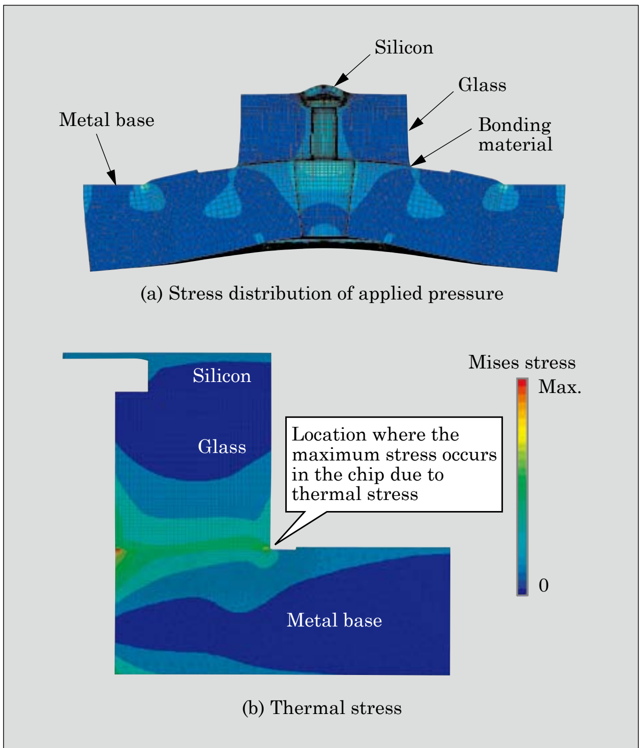


Fig.7 FEM analysis results

The basic operation of the pressure sensor chip is shown below. The diaphragm, which is formed by processing a portion of silicon into a thin film using Fuji Electric's proprietary etching technology, will deform in response to applied pressure. At such a time, there are changes in each of the resistance values of the 4 piezoelectric resistors, which are composed of the diffusion wiring arranged on the diaphragm. The balance of the Wheatstone bridge circuit composed of the piezoelectric resistors is lost, resulting in a potential difference in the output. By amplifying and outputting this potential difference, the applied pressure is converted into an electrical signal. Figure 8 shows an overview of the pressure sensor chip.

In order to reduce the size of conventionally mass-produced 5th-generation automotive high-pressure sensors and increase the guaranteed operating temperature to 150°C, we have recently developed a chip for 6.5th-generation automotive high-pressure sensors. Figure 9 shows the external appearance of the chip for the 6.5th-generation pressure sensor and 5th-generation pressure sensor.

The chip uses the technologies of CP processing and circuit miniaturizing developed for the 6th-

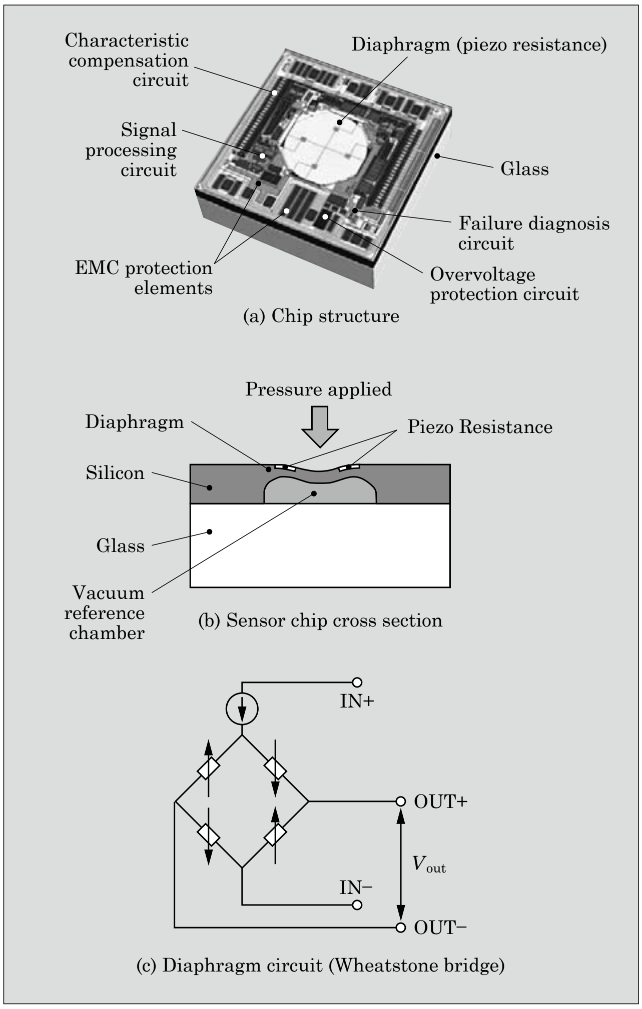
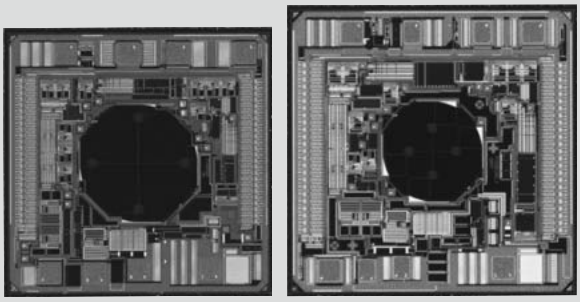


Fig.8 Overview of the pressure sensor chip



(a) 6.5th-generation (b) 5th-generation

Fig.9 Pressure sensor chip appearance

generation pressure sensors. As a result, it is 14% smaller than the 5th-generation chip (area ratio). Furthermore, the linearity of the output characteristic is improved by optimizing the diaphragm diameter and thickness and the gauge resistors position. Moreover, by optimizing the temperature characteristics of each circuit block shown in Fig. 10, characteristic degradation in the high-temperature operating region is suppressed and accuracy was ensured at 150 °C (see Fig. 11).

Figure 12 shows the pressure-output characteristic diagram for the product. By setting the output of the sensor to the diagnostic voltage region when the wire harness is disconnected, it becomes possible for the higher-level system to detect failures. On the other

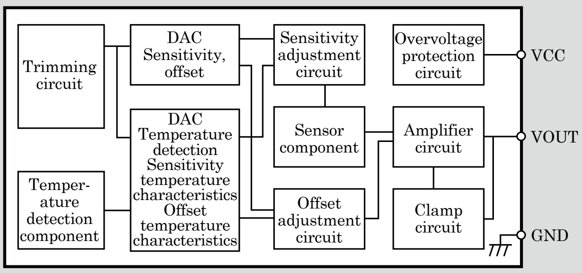


Fig.10 Circuit block diagram for the 6.5th-generation automotive pressure sensor

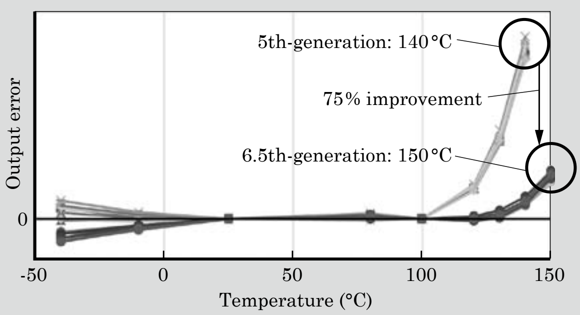


Fig.11 Output error temperature characteristic

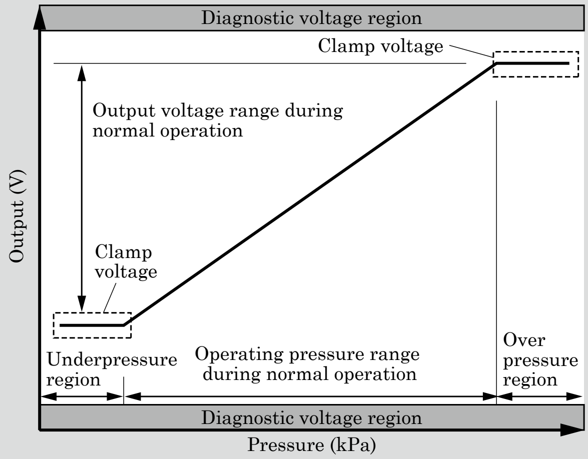


Fig.12 Pressure-output characteristic diagram for the 6.5th-generation automotive pressure sensor

hand, when too much or too little pressure is applied, the output may reach the diagnostic voltage region and lead to erroneous detection. However, this product is able to prevent erroneous detection because it comes with an output voltage clamping circuit and is able to reliably dissociate the diagnostic voltage region and normal output voltage range[(2)].

Table 1 shows the specifications for the 6.5th-generation automotive high-pressure sensor.

Table 1 Specifications of the 6.5th-generation automotive high-pressure sensor

Item		Specifications
Product size (resin section)		W7.5 × H10.0 × D5.6 (mm)
Operating temperature range		−40 to +150 °C
Operating pressure range (engine oil pressure)		0 to 1 MPa
Rated pressure		Pressure range × 3
Power supply voltage		5±0.25 V
Output voltage (at power supply voltage of 5 V)		0.5 to 4.5 V
Sink/source capability		Sink 1 mA, source 0.1 mA
Clamp function		Clamp voltage 0.35 V/4.65 V (typ.)
Pressure direction		Pressurized from back
ESD (external interface terminal)		
	MM (0 Ω, 200 pF)	±1 kV or higher
	HBM (1.5 Ω, 100 pF)	±8 kV or higher
Transient voltage surge		ISO 7637 (2011) standard Pulse1, 2, 3a, 3b Clears LEVEL-Ⅲ
Impulse		±1 kV or higher
Latch-up (current injection method)		±500 mA or higher
Overvoltage (VCC-GND)		16.5 V (max.)
Reverse connection (VCC-GND)		0.3 A (max.)

4. Postscript

In this paper, we introduced our 6.5th-generation automotive high-pressure sensor. In the future, we plan to further expand its application range to include other types of high-pressure applications (up to 4 MPa) in addition to engine oil pressure applications. As product development expands throughout the world, it is expected that pressure sensors will be increasingly required to meet harsh demands regarding enhanced product performance from the standpoint of better fuel efficiency and compliance with environmental and safety regulations. In this regard, we will continue to work hard to develop the products needed by the market in order to meet the requirements of the market.

References

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(2) Uzawa, R. et al. 6.5th-Generation Automotive Pressure Sensors. FUJI ELECTRIC REVIEW. 2017, vol.63, no.4, p.232-236.

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