6th Generation Small Pressure Sensor

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ABSTRACT

A pressure sensor is a critical device for improving the precision and efficiency of engine management in order to reduce the environ-mental impact of cars. Fuji Electric has developed a 6th generation small-size digital trimming-type pressure sensor. High precision diaphragm processing is implemented using an anisotropic etching technique and the area of the sensor unit is reduced. Additionally, the design rules were revised, and as a result, the sizes of the circuitry and protective devices were reduced. Accordingly, the chip area was reduced by 70% while maintaining the equivalent functions, precision and EMC protection as conventional 5th generation products.

1. Introduction

The automobile industry is actively implementing environmental initiatives as regulations are strengthened in Europe, United States, Japan and Asia and elsewhere throughout the world. To comply with these stricter regulations, the industry is moving ahead with the development of hybrid electric vehicles (HEV), electric vehicles (EV) and the like. Meanwhile, for conventional gasoline vehicles and diesel vehicles, the air-to-fuel ratio is being controlled more finely to improve fuel economy and increase efficiency, and technical development to make exhaust gas cleaner is being accelerated.

A pressure sensor is one key device used to administer engine management to make engines run more efficiently and cleanly, and its importance has been increasing each year.

Fuji Electric has been mass-producing automotive pressure sensors since 1984. Since then, in response to changes of needs for reliability and detection accuracy pursuing strict environmental efficiency, Fuji Electric has proposed proprietary high-efficiency circuit technology and high-level MEMS (micro electro mechanical systems) technology so that these sensors are used in automobiles and motorcycles both in Japan and overseas. Since 2007, Fuji Electric has been mass-producing 5th generation digital trimming-type pressure sensors using a CMOS (complementary metal oxide semiconductor) process.

This paper introduces 6th generation small-size digital trimming type pressure sensors that have been realized in a smaller size while maintaining the functions, performance (detection accuracy), and EMC (electro magnetic compatibility) protection function of

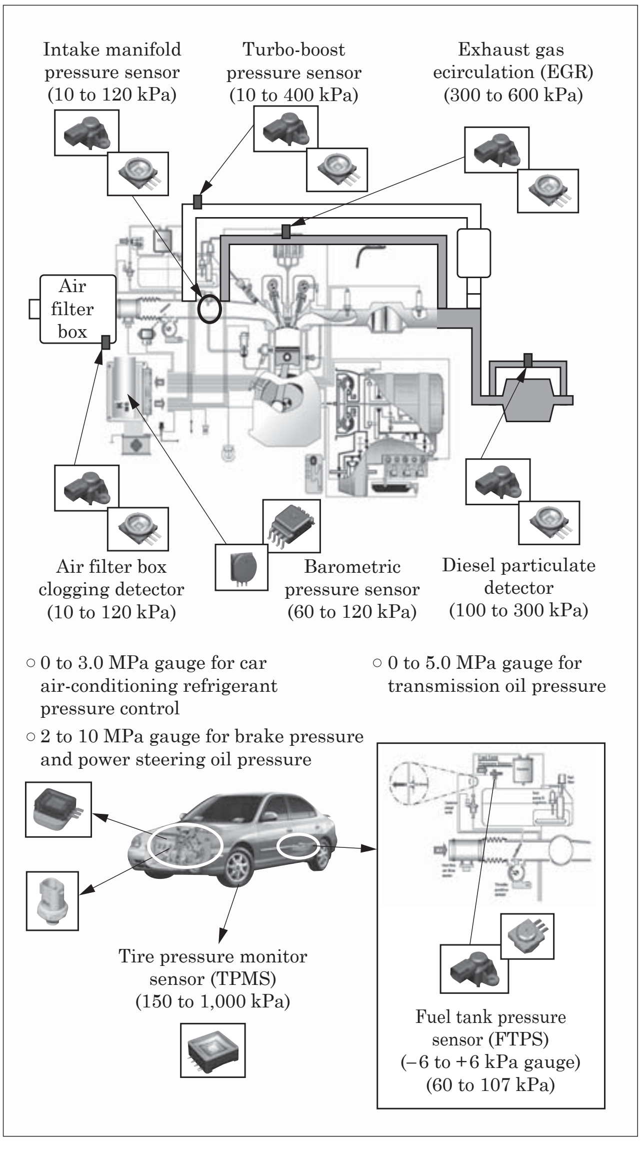

Fig.1 Applications of automotive pressure sensors

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the 5th generation digital trimming-type pressure sensors already being mass-produced.

2. Pressure Sensors for Automotive Applications

Fig. 1 shows applications of pressure sensors in automobiles. To improve the fuel economy of engines, electronic control of the fuel injection system has been promoted. In an electronic control fuel injection system, a MAP (manifold absolute pressure) sensor that measures the intake manifold pressure and a TMAP (temperature manifold absolute pressure) sensor equipped with a temperature sensing function are used. Such electronic control fuel injection systems are now being used often in motorcycles, and demands for even smaller size are intensifying. To improve fuel economy, pressure sensors are additionally used in many places, including an atmospheric pressure sensor used to perform advanced compensation so that fuel economy does not deteriorate when an automobile travels at a high elevation, a pressure sensor for detecting clogging of the air intake filter box, a pressure sensor for the turbo-boosting used in a turbo system that reuses exhaust gas, and a sensor for EGR (exhaust gas recirculation).

Furthermore, a pressure sensor for detecting clogging of a DPF (diesel particulate filter) is an example of a sensor used in response to the strengthening of exhaust gas regulations as typified by the Post New Long-term Regulation (2009) in Japan and Euro5 (2009) and Euro6 (2016) in Europe.

Pressure sensors applications for complying with safety regulations include a tank pressure sensor for detecting fuel leakage (FTPS: fuel tank pressure sensor) that is used in Europe, the United States and South Korea, and accompanying the establishment of the TREAD law (transportation recall enhancement accountability and document act) in the United States, a tire pressure monitoring system (TPMS) that monitors the tires for insufficient pressure.

In addition, there is increased demand for pressure sensors to control air-conditioning refrigerant and to control oil pressure of the transmission and elsewhere. Accordingly, the applications and demand for automotive pressure sensors are expanding rapidly.

3. Changes in Pressure Sensor Technology

Fig. 2 shows the technical progress of Fuji Electric's pressure sensors over time. In 1984, making full use of bipolar-integrated circuit technology and its surge tolerant capability, Fuji Electric commercialized a 1st generation of pressure sensors mainly for automotive engine control.

The subsequent 2nd and 3rd generations utilized single-chip integration techniques and thin-film resistor trimming (i.e., a method for laser-trimming thin-film resistors on a chip).

For the 4th generation, the world's first CMOS process-based single-chip digital trimming type automotive pressure sensor were mass produced.

The 5th generation, responding to market requests for smaller size and higher reliability, inherited the 4th generation's basic concept of an "All in one chip,"

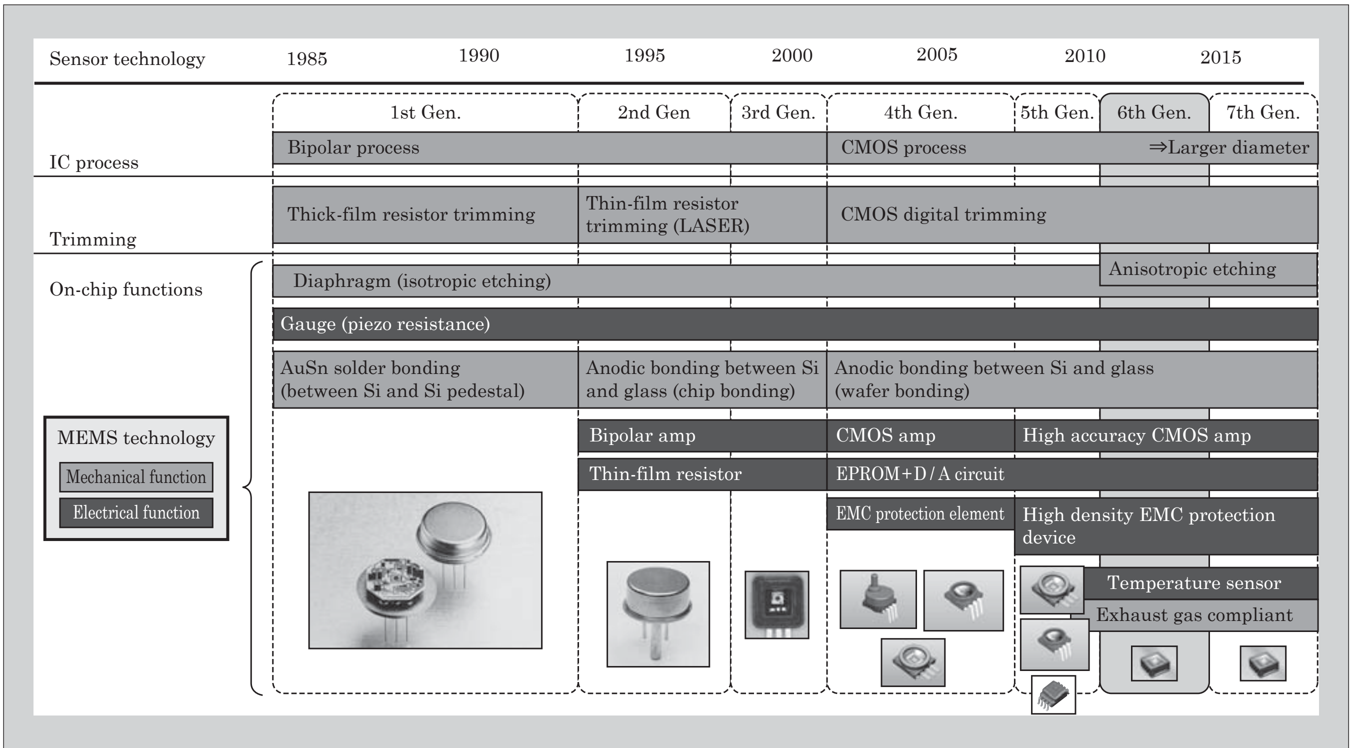

Fig.2 History of Fuji Electric's pressure sensor technology

and aimed to realize smaller size.

4. Characteristics of 6th generation small-size pressure sensors

Fig. 3 shows the appearance of a newly developed 6th generation small-size pressure sensor and a prior 5th generation pressure sensor.

The main feature of the 6th generation small-size pressure sensor is that the chip was fully optimized and that a limit design was carried out so as to maintain comparable functions and performance as the 5th generation pressure sensor but in a chip area that has been reduced to 70%.

Introduced below are three specific examples of the optimized designs incorporated into the 6th generation small-size pressure sensor: “diaphragm design,” “integrated circuit design (digital/analog (D/A) converter)” and “protection device design.”

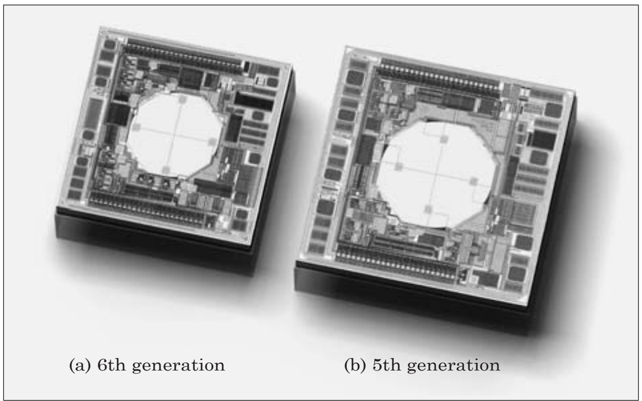

Fig.3 Appearance of pressure sensors

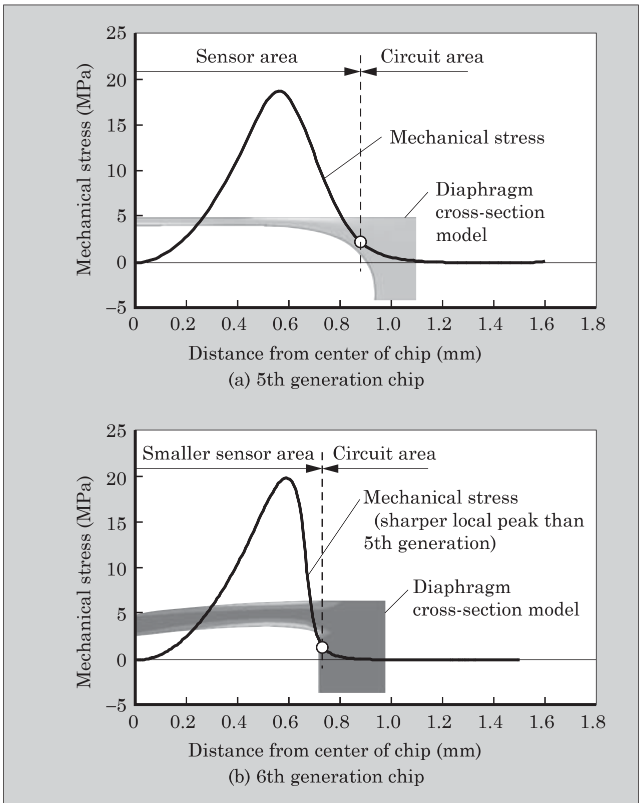

Fig.4 Example of diaphragm design based on FEM analysis

4.1 Diaphragm design

The diaphragm that forms the pressure sensor was optimized and designed using finite element method (FEM) analysis.

One example of the diaphragm design is shown in Fig. 4. Up until the 5th generation, pressure sensors had adopted an arch-shaped diaphragm as shown in Fig. 4(a). This shape was characterized as having a moderate distribution, without local concentrations, of mechanical stress (lines on the graph) when pressure was applied to the diaphragm. Thus, although an extremely rigid mechanical strength is obtained against applied pressure, the stress does have an effect, and there is an enlarged region in which analog circuits and devices other than the pressure sensor cannot be placed. That is, there were constraints on integration and miniaturization.

To remove these constraints, the 6th generation small-size pressure sensors adopted a diaphragm shape having a perpendicular cross-section that closely resembles Fig. 4(b), whereby the generated peak mechanical stress is sharper and more locally distributed. As a result, the mechanical stress that extends up to the circuit area side concentrates in the vicinity of the diaphragm unit, and there is an enlarged region in which devices can be placed on the circuit area side. Thus, by changing the cross-sectional shape, the diaphragm area could be reduced to approximately 60% of the size of the 5th generation while maintaining the same sensor sensitivity.

Fig. 5 shows a comparison of actual diaphragm cross-sectional shapes. 5th generation pressure sensors were manufactured using isotropic etching tech-

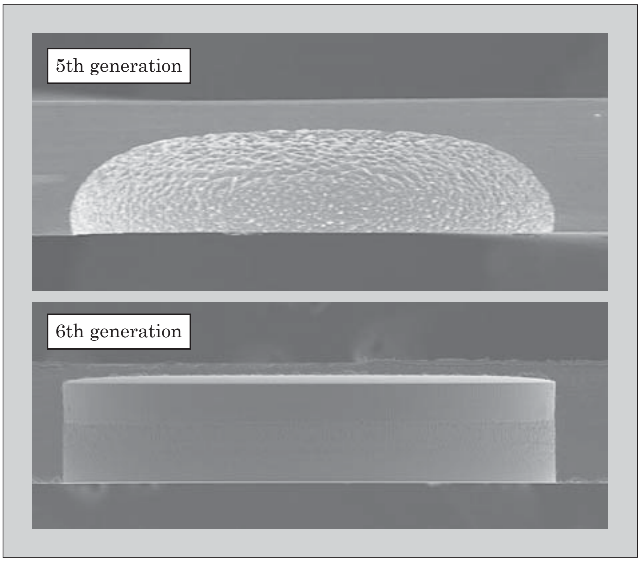

Fig.5 Comparison of diaphragm cross-sectional shapes

nology, but 6th generation small-size pressure sensors use anisotropic etching technology and achieve a cross-sectional shape that is nearly perpendicular. Through the application of Fuji Electric's proprietary process conditions, uniformity within ±2% of the in-plane depth of etching was achieved, and variation in the sensor detection sensitivity was reduced.

As an example of the sensor prototype results, Fig. 6 shows a graph of the nonlinearity. Nonlinearity indicates the amount by which the relationship between input (pressure) and output (voltage) deviates from a straight line, and a value closer to zero indicates greater linearity, i.e., a characteristic that is closer to the ideal.

In the 6th generation of small-size pressure sensors, in addition to changes in the cross-sectional shape, the diameter and thickness of the diaphragm, positioning of the sensing resistor, and the like were optimized. As a result, the 6th generation achieved an improvement from nonlinearity, compared to the 5th generation, over the entire range of diaphragm thicknesses as shown in Fig. 6.

4.2 Circuit design

Fig. 7 shows the circuit block diagram of a 6th generation small-size pressure sensor. This configuration has been inherited from the 4th generation, without eliminating any functions. In reducing the size of the circuit, based on experience gained in the 5th generation, criteria for the design of automotive pressure sensors was revised in order to realize higher integration with finer line widths.

Additionally, in the analog unit, especially for op-amps in the signal amplifier circuit, the sensitivity adjustment circuit, and the offset adjustment circuit, the device layout has been optimized without reducing the device size of MOS transistors and the like.

As a result, the circuit area could be reduced to approximately 80% that of the 5th generation. Furthermore, as shown in Table 1, the same functions, performance and trimming accuracy as the 5th generation could be maintained.

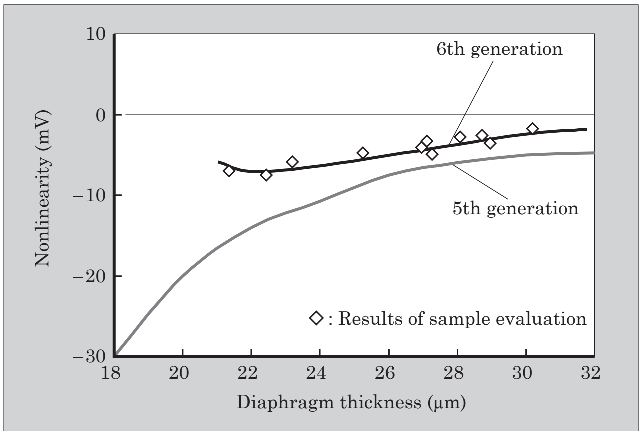

Fig.6 Nonlinearity of sensor output

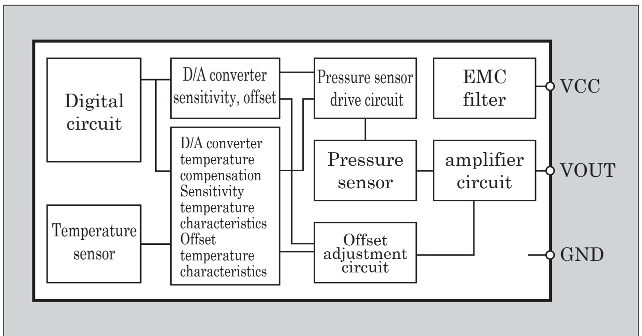

Fig.7 Circuit block diagram of 6th generation small-size pressure sensor

4.3 Protection device design

The protection devices in 6th generation small-size pressure sensors have also been subjected to a thorough review of their design criteria, and have been miniaturized. The device area has been reduced to approximately 80% of the size of 5th generation devices, while realizing the equivalent surge protection and noise protection. Specific performance characteristics are listed in Table 1. For example, by ensuring at a tolerance of least ±600 V in the case of a machine model (0 Ω/ 200 pF) ESD (electrostatic discharge) test, and so on, the highest level of surge protection and noise protection for automotive applications is realized with a single chip.

Table 1 Comparison of main performance characteristics of pressure sensors

Item	6th generation	5th generation
Chip size (area ratio)	70%	100%
Diaphragm size (area ratio)	60%	100%
Pressure range	60〜500 kPa	
Absolute max. pressure	Pressure range×3	
Supply voltage	5±0.25 V	
Output range (when supply voltage is 5 V)	0.5 to 4.5 V	
Output error (at 25 °C/125 °C)	1%FS/1.5%FS	
Nonlinearity (diaphragm thickness of 30 μm, 255 °C)	−2.5 mV (typ)	−5 mV (typ)
Sink/Source current	Sink 1 mA Source 0.1 mA	
ESD (external interface pin)		
MM (0 Ω, 200 pF)	±1 kV or greater	
HBM (1.5 Ω, 100 pF)	±8 kV or greater	
ISO 7637 (Pulse1, 2, 3a, 3b)	Clears LEVEL-IV	
Impulse	±1 kV or greater	
Latch-up (current injection method)	±500 mA or greater	
EMS (G-TEM) (100 V/m)	Fluctuation: 1%FS or less	
Over voltage protection (between VCC-GND)	16.5 V (max)	
Reverse connection (between VCC-GND)	0.3 A (max)	

5. Postscript

This paper has presented an overview and described the characteristics of 6th generation small-size pressure sensors. With “global warming” being the keyword, stringent requirements for improved environmental performance and product performance are expected to continue to accelerate as products are deployed widely throughout Japan and overseas. Fuji Electric intends to continue to respond to market needs and to develop products deemed essential by the market.