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SEMICONDUCTOR PRESSURE SENSOR

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1 INTRODUCTION

As semiconductor pressure sensor utilizes a large piezo-resistance effect of silicon through adoption of IC technology, its size can be made smaller and its weight lighter as well as its aptitude for mass production and responsiveness more excellent, when we are to compre it with characteristics of mechanical type pressure sensor which is conventionally used or those of static capacity type pressure sensor that has been developed to more advanced stage recently.

On the other hand, sever control on exhaust gas and fuel to cost ratio have been imposed on automobile engines, and in order to cope with this problem, development of system that would control the engine using various sensors and microcomputers is rapidly progressing now.

As Fuji Electric has developed semiconductor pressure sensors that can fully withstand the severe environment of utilization on automobiles well as those of high-pressure field like refrigerating plant controllers as a pressure sensor for inlet air pressure indicators to be used for these engine control systems, we, authors, like to introduce the outlines of this newly developed semiconductor pressure sensors.

2 STRUCTURE AND PRINCIPLE OF OPERATION

The pressure sensors are classified into the following type according to their functions: absolute pressure indicator, gauge pressure indicator and relative pressure indicator.

The pressure sensors for automobiles used for measuring inlet air pressure, as their principal purpose is to calculate the suctioned air volume from the inlet air pressure they will have to be absolute pressure indicators. Also as they are to be used in a very severe condition as in automobile engine room, an excellent withstand characteristics to environment is required and further, as the gas to be measured contains gasoline and engine exhaust, the parts in contact with the measuring gas must be constructed with materials having sufficient anticorrosive properties. Still further, for those destined to refrigerating plants are required to have a high resistance to freon gas and a high electric insulation.

2.1 Structure

Fuji Electric semiconductor pressure sensor meets such severe requirement as mentioned above. Its outer view is as shown in *Fig. 1 (a)* , while the outer view of pressure

Fig. 1 Sensor and pressure sensitive diaphragm chip

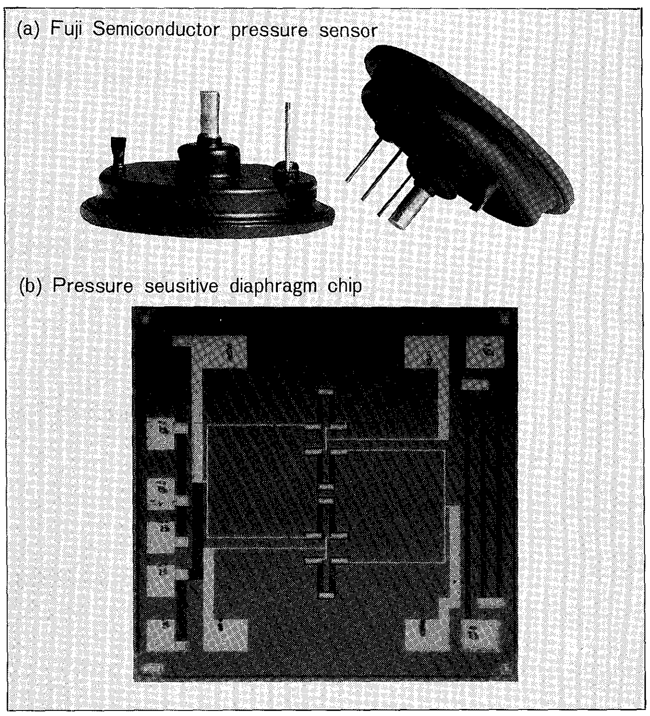
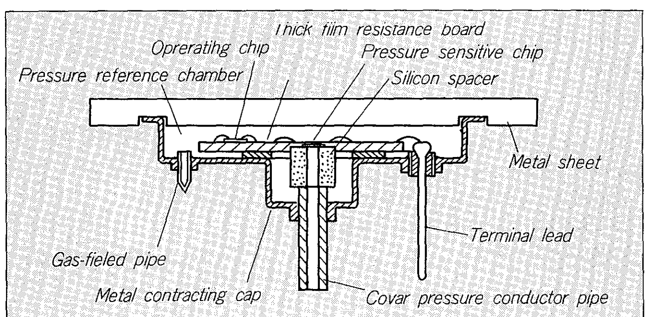


Fig. 2 Sensor structure



sensitive diaphragm chip, in *Fig. 1 (b)*. *Fig. 2* shows the sensor structure. The pressure sensitive diaphragm chip (hereinafter called "pressure sensitive chip") by which the diffusion type strain gauge (hereinafter called "gauge") converting pressure into electric signals is constructed, is soldered on the silicon spacer with a hole perforated in its center through anticorrosive gold based soldering; and on the other side of the silicon spacer, gold plated covar pressure conducting pipe is soldered also with gold based anticorrosive soldering, all these constituting pressure detecting element. This detecting element consitutes a hermetically closed space together with lead terminal and metal contracting cap having gas-filled pipe and metal sheet and this space forms a pressure reference chamber. This chamber houses all circuit components as pressure sensitive chip gauge, thick film resistance board, etc. And the space is filled with helium gas of specificed constant pressure.

This structure features in the following points:

(1) As the pressure sensitive chip which is the most sensitive to strains due to the external force and temperature change is mounted on the silicon space supported by covar pipe, the chip receives little influence from external force and thermal strains.
(2) As all circuit elements are housed in the metal housing, it has a strong defence against noise.
(3) For soldering part in contact with measuring gas, a based solder is used, so that anticorrosive properties are excellent.
(4) Including gauge, all circuit elements are in inert helium gas environment so that it is excellent in stability.
(5) Air tightness of the pressure reference chamber can be gauranteed by filled-in helium gas.

2.2 Principle of operation

The semiconductor pressure sensor operates on the principle of a large piezo-resistance effect (a phenomenon that the value of electric resistance changes in function of distortion) that a semiconductor has. In a concrete form, the pressure is converted into electric signals in the following manner.

(1) Diaphragm is formed by thinning a part of the chip.
(2) A gauge is formed in a predetermined position opposite to the convex surface of which the diaphragm is formed.
(3) Diaphragm receives pressure, resulting in diaphragm deformation.
(4) With this deformation, a strain is produced on the gauge formed surface of the diaphragm, and by this stress, the resistance value of the gauge changes.
(5) The gauge is incorporated into a Wheatstone bridge, and this change in resistance is taken out as electric signal.

The stress distribution of a circular diaphragm with uniform thickness in its fixed periphery can be expressed by the following equation, whereas,

a : diaphragm radius
h : thickness, and
P : applied pressure

$$\sigma_r = \frac{3P}{8h^2} \quad (1+\nu)a^2 - (3+\nu)r^2 \quad \cdots\cdots\cdots (1)$$

$$\sigma_\theta = \frac{3P}{8h^2} \quad (1+\nu)a^2 - (1+3\nu)r^2 \quad \cdots\cdots\cdots (2)$$

In the above formula, r represents distance from the diaphragm center; ν, Poisson ratio; and σ_r and σ_θ, stress components in radial and right-angle directions, respectively. *Fig. 3* shows σ_r and σ_θ.

The piezo resistance effect of the semi-conductors has a large anisotropy, and it differs according to the surface and orientation of crystal and the form of conduction. *Fig. 4* shows the dimensions of piezo resistance coefficient of p-type silicon in the typical crystal surface. The length from the original point represents the dimensions of the piezo resistance coefficient in the orientation. π_r and π_θ represent, respectively, the piezo resistance coefficient in case the distorsion direction coincides with that of current (lengthwise direction of the gauge), and the distorsion direction meets at right angles with the current direction. In the figure, full lines show the case the piezo resistance coefficient is positive, while the broken lines, the case of negative.

In general, the change rate of the resistance of the strain gauge is calculated by the following formula.

$$\frac{\Delta R}{R} = \pi_r \sigma_r + \pi_\theta \sigma_\theta \quad \cdots\cdots\cdots (3)$$

in this formula, R is the resistance when stress is not applied, ΔR is the change of the resistance due to the stress, and π_r and π_θ, piezo resistance coefficients in radial and rectangular directions in the gauge position.

Fig. 3 Stress distribution in a circular diaphragm

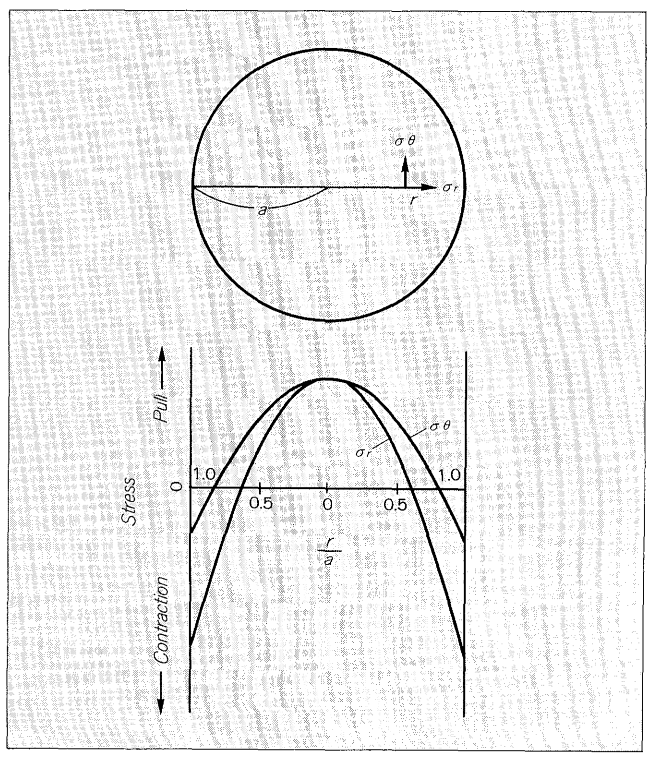


Fig. 4 Piezo resistance coefficient of p-type silicon

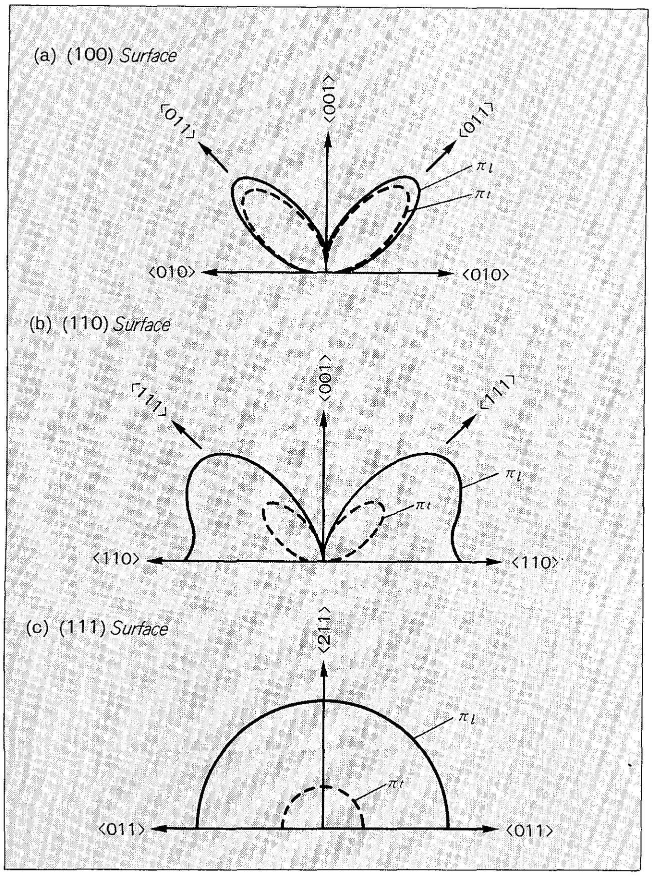
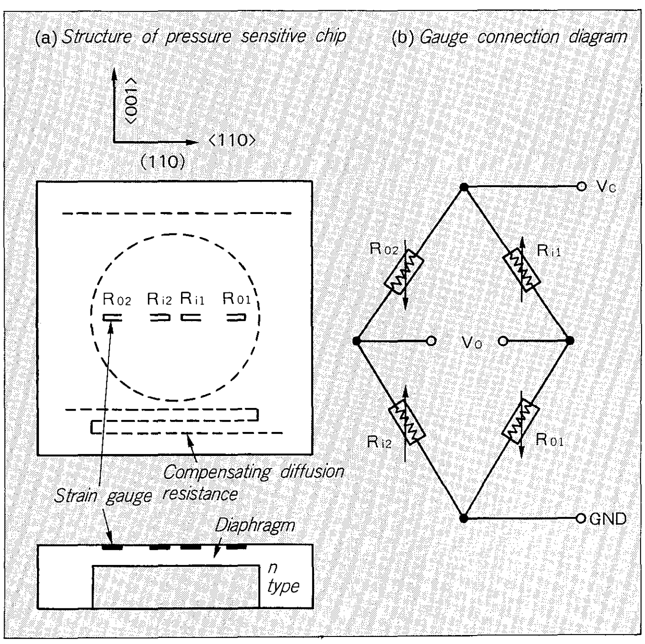


Fig. 5 Structure of pressure sensitive chip and gauge connection diaphragm



On <110> surface, when p-type gauge is formed to the radial direction with (110) orientation, as π_θ is extremely small, $\Delta R/R$ will be the first term of the formula (3) only, and the product will have an advantage of being high sensitivity, receiving little influence from the discrepancy of crystal orientation, and little influence also from the variation of the diaphragm diameter.

Fuji Electric's pressure sensitive chips use this crystal surface and crystal orientation, and set 2 gauges in the periphery of the diaphragm, and another 2 in the center, all these gauges having lengthwise orientation in the radial direction. *Fig. 5* shows the structure of the pressure sensitive chip and connection diagram of the gauges. Chips have dimensions of 3.5 mm in angle and about 200 μm in thickness and enhance the precision of control on diaphragm thickness.

The resistance value and piezo resistance coefficient of the semiconductor strain gauge vary greatly by temperature coefficient. It is by that reason, when the gauge is used in a wide temperature range as in the case of automobile pressure sensor, why it is necessary to compensate their temperature characteristics. In Fuji Electric's pressure sensors, in order to cope with the problem, a diffusion type resistance having a large temperature coefficient is used for them, and this diffusion resistance is integrally formed on the pressure sensitive chips.

3 CIRCUIT COMPOSITION

The circuit composition of this pressure sensor is shown in *Fig. 6*. Other circuit elements than gauge bridge and temperature characteristic compensating diffusion type resistance formed on the pressure sensitive chip are all formed on a single ceramic PCB.

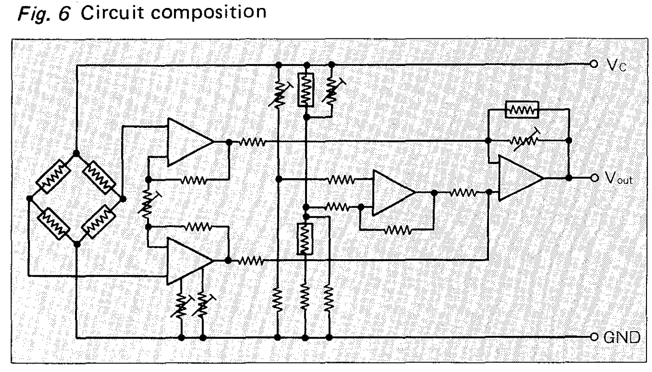
The temperature-dependency of the sensitivity is compensated by providing temperature-dependency to feedback resistance of post-amplification circuit. In this case a special consideration was taken for impurity concentration of the compensating diffusion resistance so as to minimize the curve component of temperature-dependent sensitivity.

Instability of sensitivity is adjusted in the degree of amplification in pre-amplifying circuit.

Zero point and temperature characteristics of zero point are compensated by adding the temperature-dependent voltage including compensating diffusion resistance generated in the bridge circuit to signals from the gauge bridge. And by adjusting the off-set voltage of the operation amplifier, voltage characteristics are also adjusted.

Adjustments in this amplification compensating circuit

Fig. 6 Circuit composition



are all carried out by trimming of print resistance and controlled by output voltage.

Main features of this circuit composition are the following:

(1) As the adjusting procedures are independent one from another, that is, later adjustment exerts no influence to the former ones, adjustment precision is very high.

(2) As the result of adjustment can be detected by output voltage, the adjustment operation is easily be made.

(3) As the gauge and compensating diffusion resistance are formed in the same single chip, the compensation precision of the temperature characteristics is high.

(4) Adjustment even on the curvature of the zero-point temperature characteristic is possible.

4 CHARACTERISTICS AND RELIABILITY

An example of characteristic specification of semiconductor pressure sensor is given in *Table 1* and *Table 2*. It is required to have a pressure range of 100 kPa for engine suction air, 200 kPa for supercharging of turbo and for refrigerating plant compressor, about 600 kPa.

4.1 Initial characteristics

Fig. 7 shows an example of precision distribution of initial characteristics at –30°C, 25°C and 100°C. *Fig. 8* is a distribution data on the linearity. The linearity is smaller than 0.3% FS. *Fig. 9* shows the relationship between diaphragm thickness and breakdown pressure, and as the figure indicates, a satisifsfactory value for rated working pressure is obtained.

Table 1 Absolute maximum rating of pressure sensor

Item	Rating			Unit
	EP2445	EP2705	EP2525	
Allowable pressure	450	550	1,200	kPa
Working pressure	20~112	20~200	98~590	kPa
Allowable voltage	5±1	5±1	5±1	V
Working voltage	5±0.25	5±0.25	5±0.25	V
Ambient temperature	–40~120	–40~120	–40~120	°C
Working temperature	–30~100	–30~100	–30~100	°C
Sink current	1	1	1	mA
Source current	0.1	0.1	0.1	mA

Table 2 Rating of pressure sensor

Item	Condition	Rating			Unit
		EP2445	EP2705	EP2525	
Temperature characteristic	25°C	1	2	2	%FS
	–30~100°C	1.5	4	4	%FS
Output impedance	V_{cc} = 5V 25°C	10			Ω
Consumption current		10			mA
Responsiveness	V_{cc} = 5V 25°C	5			ms

Fig. 7 Precision distribution of initial characteristics

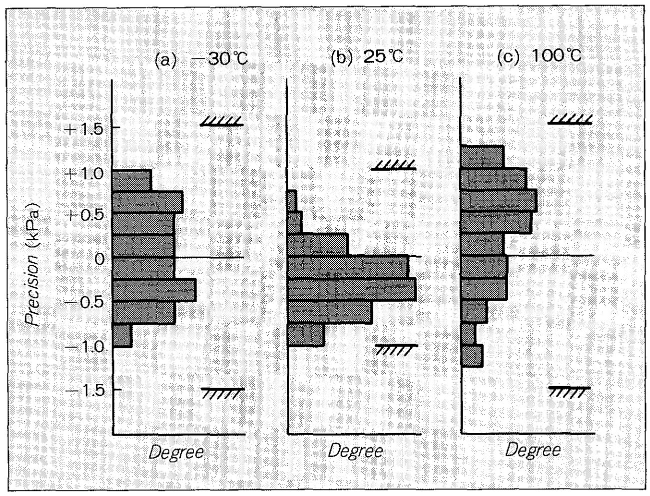


Fig. 8 Linearity

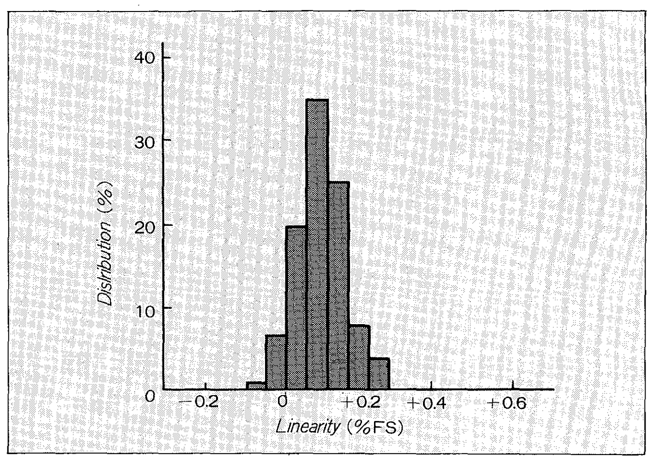


Fig. 9 Diaphragm thickness and breakdown pressure

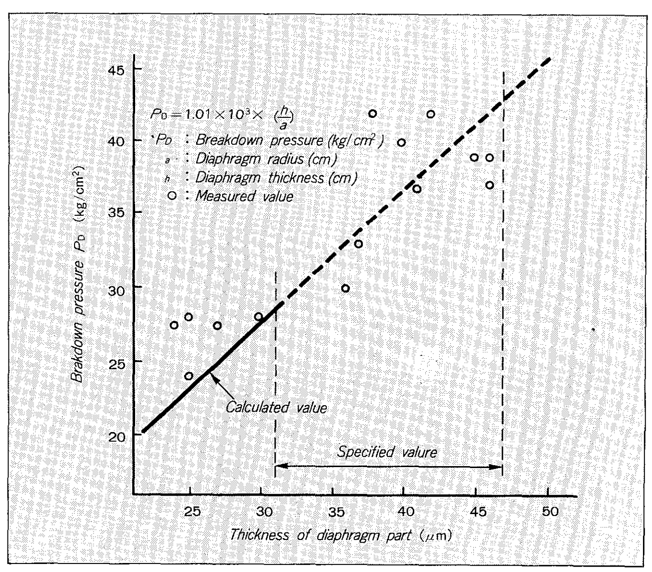
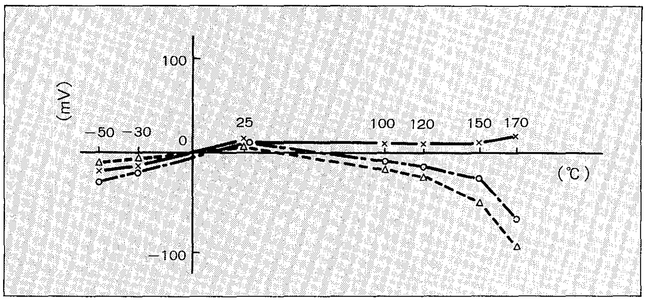


Fig. 10 Temperature limit



4.2 Reliability test

We have conducted a various durability tests in order to guarantee that +he products withstand severe working conditions as those in automobiles. The main test items have been: performance in high and low temperatures, performance in high temperature and high humidity, pressure cycles, resistance to thermal shocks, resistance to vibrations, shelf-state performance in high and low temperatures, shelf-state performance in high temperature and high humidity, watertightness, resistance to salt-water spray, water-splash resistance to gasoline, to LLC, to oil, anti-corrosiveness to exhaust gas, etc.

For these tests, when water component gets frozen in diaphragm, this may result in diaphragm breakdown, so that it is necessary to take special care for the mounting method and the product construction so as not to frozen water component in the diaphragm. The products had all withstood the tests by. setting them actually on the machines and vehicles and proved that they satisfy the specified requirement. Also it was confirmed that the products presented no problem for their practical use by electrical surge tests and electric wave noise tests. Further, an ample margin for the design value is proved by conducting various limitation tests. *Fig. 10* shows the resulting data the temperature limit test. As it can be known from the figure, the products withstand the conditions imposed by actual usage in the range of −30°C to 100°C with an ample margin, presenting no problem for their practical use.

5 CONCLUSION

We could develop products fit for use in the field of high pressure as measuring of suctioned and supercharged air pressure as well as compressor control, utilizing the special features of semiconductor pressure sensor. We expect that their range of application will be more and more extended and the range of their working pressure, wider in the near future. For example, the prospect of widening of their field of use is bright, in particular, in the domain of measurement and automatic control as home-use electronic blood pressure indicator, disposable blood pressure indicator for surgical operations, air conditioner control, as well as industrial measurement use and automatic control on plants and environment as accident prevention and for measuring gas pressure, and many others to cite a few. With this demands as a background, we like further to endeavor our effort for miniaturizing the product and for reducing the production cost, as well as improvement of their reliability. With a view to achieve this goal, we like to propel our plan further of putting the semiconductor pressure sensors into practical use, through making them IC's on one chip not only their gauge part but also peripheral circuit parts.

We like to express here our heart felt thanks to all personnel of Toyota Motor Corporation, Ltd. for their generous technical assistance and cooperation for developing our pressure sensors for automobiles.