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Tri-Axial Piezoresistive Accelerometer

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A tri-axial piezoresistive accelerometer capable of detecting tri-axial acceleration components (Ax, Ay, Az) in the directions of X, Y, and Z axes has been developed. The sensor, which consists of three sets of gauge resistors for detecting the tri-axial components of acceleration on a surface of silicon chip, is derived from semiconductor and micro-machining technology. Each set of resistor is configured as a bridge circuit so as to detect the acceleration on each axis independently.

1. Introduction

Recently, there is an increasing demand for high performance accelerometers in industry, centered particularly on the automotive industry, typified by the air bag system, chassis control, etc, for controlling vehicle safety and comfort. In response to this demand, various accelerometers (1)-(3) have been offered, based on the piezoresistive effect and variation in elecrtostatic capacitance. Notwithstanding the fact acceleration is a vector quantity having direction as well as magnitude, nearly all accelerometers currently being developed are so-called uni-axial accelerometers, that is, they detect acceleration in one axial direction. We have developed a piezoresistive accelerometer shown in Fig. 1 which is capable of detecting tri-axial acceleration components (Ax, Ay, Az) in directions of the X, Y and Z axes. The sensor consists of gauge resistors for detecting the tri-axial components of acceleration on a surface of silicon chip. A diaphragm is formed at the back of silicon chip, and a seismic mass and a pedestal are attached to the center and periphery of the back. The seismic mass and pedestal are made originally of a single sheet of glass substrate, and the seismic mass and pedestal are separeted by dicing the glass substrate after it has been bonded to a silicon wafer. When the seismic mass is accelerated, the diaphragm is displaced. Three sets of gauge resistors are alighed on the surface of silicon substrate so that resistors are exercised a marked effect by displacement, each set is configured as a bridge circuit so as to detect the acceleration on each axis independently. In this paper, we discuss the principle of detection, output characteristics and method of eliminating cross-axis sensitivity in the tri-axial piezoresistive accelerometer.

2. Constructions and Priciples

The force and moment sensors (4) which detect tri-axial and hexa-axial forces (and momen) have already been announced. The

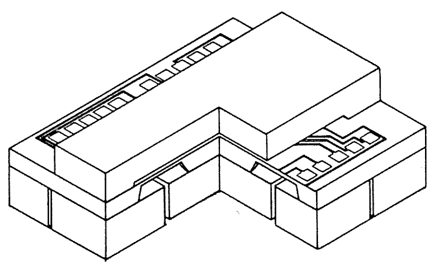


Fig. 1 Cross sectional structure of tri-axial piezoresistive accelerometer

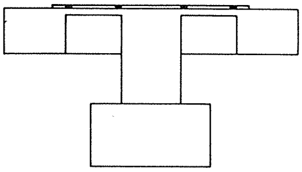


Fig. 2 Tri-axial force sensor and accelerometer

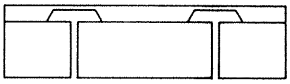


Fig. 3 Cross section of accelerometer

construction of tri-axial force sensor is shown in Fig. 2. The silicon chip is bonded to a strain generative body. Forces on the strain generative body cause a distortion of the piezoresistor which is formed on the silicon chip. Owing to the piezoresistive effect, the electrical resistance of the piezoresistor varies in proportion to the distortion. The variation in resistance is used to detect the forces. From Newton's equation ($F = m \times a$), if a seismic mass is connected to the force sensor in Fig. 2. It functions as a tri-axial accelerometer. However, for considerations of produciti-vity, price and size, the accelerometer constructed as shown in Fig. 2 would not be practical. This problem is solved by forming a diaphragm into the silicon substrate as shown in Fig. 3, the strain generative body plus silicon substrate configuration are transformed into the single grooved silicon substrate. As shown in Fig. 4, three sets of gauge resistors are formed on the surface of the silicon substrate in order to detect the tri-axial components of acceleration. The diaphragm is formed on the back and the seismic mass and pedestal are joined to the center and periphehry. The seismic mass and pedestal are made initially of a single sheet of glass, and seismic mass and pedestal are separeted by dicing the glass substrate after it has been bonded to diaphragm side of silicon wafer. This metod of assembly is conductive to batch handling and the manufacturing process can be automated. In the case of the actual accelerometer, as shown in Fig. 1, a stopper substrate limiting the upwards displacement of seismic mass is joined to the surface of silicon substrate, while the downwards displacement is limited by the surface of the package. Fore and aft and lateral displacements of seismic mass are limited by the dicing surface of the glass substrate.

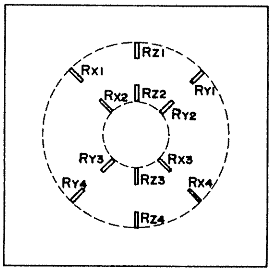


Fig. 4 Top view of silicon substrate

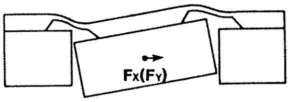


Fig. 5 Displacement of diaphragm in the X (or Y) direction

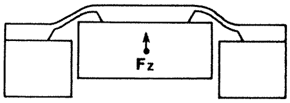
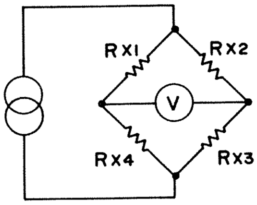


Fig. 6 Displacement of diaphragm in the Z direction

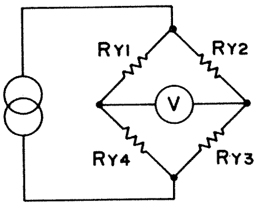
Fig. 5 shows how the diaphragm is displaced due to acceleration in the X (or Y) direction, Fig. 6 shows the same for acceleration in the Z direction. At this time, the gauge resistances formed on the silicon substrate vary as shown in Table 1. In this table, "+" indicates an increase, "-" indicates a decrease, and "0" indicates no change. Owing to the configuration of the bridge circuit as shown in Fig. 7, each axial acceleration is detected independently without cross-axis sensitivity.

	Rx1	Rx2	Rx3	Rx4	Ry1	Ry2	Ry3	Ry4	Rz1	Rz2	Rz3	Rz4
Ax	+	-	+	-	0	0	0	0	+	-	+	-
Ay	0	0	0	0	+	-	+	-	+	-	+	-
Az	-	+	+	-	-	+	+	-	-	+	+	-

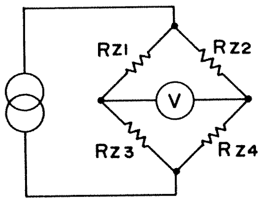
Table 1 Change of piezoresistor



(a) Circuit for X-axis



(b) Circuit for Y-axis



(c) Circuit for Z-axis

Fig. 7 Circuit diagram of accelerometer

3. Elimination of cross-axis sensitivity

The tri-axial accelerometer is shown in Fig. 8, Fig. 9-11 show its output characteristics. Fig. 9 shows the output characteristics under 1 G (acceleration due to gravity) in X direction, and Fig. 10 and 11 show the same for Y and Z directions respectively. As can be shown by the following Equation (1), the relationship between tri-axial acceleration (Ax, Ay, Az) and output voltages (Vx, Vy, Vz) are tabulated by a compliant matrix [ℂ].

$$\begin{bmatrix} Vx \\ Vy \\ Vz \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \begin{bmatrix} Ax \\ Ay \\ Az \end{bmatrix} \quad \text{———————(1)}$$

$$\begin{bmatrix} Ax \\ Ay \\ Az \end{bmatrix} = \begin{bmatrix} \mathbb{C} \end{bmatrix}^{-1} \begin{bmatrix} Vx \\ Vy \\ Vz \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{bmatrix} \begin{bmatrix} Vx \\ Vy \\ Vz \end{bmatrix} \quad \text{-(2)}$$

The non-diagonal components of the compliant matrix indicate cross-axis sensitivity. The acceleration for each axis are calculated from a inverse matrix [𝕂] of the compliant matrix as shown in Equation (2). These operation can be performed by using the arithmetic circuit of Fig. 12 or a micro-computer. The compliant matrix of sensor given from Fig. 9 to 11 is shown in Table 2. As shown in Table 3, it can be seen that the cross-axis sensitivity is reduced to about 1/10th by processing these with the arithmetic circuit of Fig. 12. The newly developed sensor can detect tri-axial acceleration, and can almost completely eliminate cross-axis sensitivity.

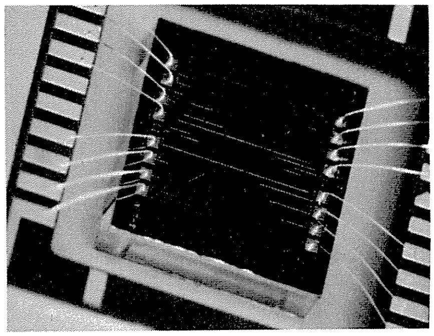


Fig. 8 Tri-axial piezoresistive accelerometer

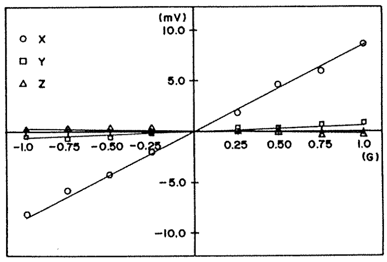


Fig. 9 Output voltage in case of X-axis acceleration

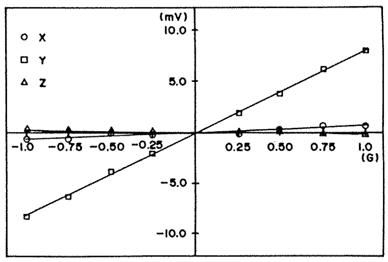


Fig. 10 Output voltage in case of Y-axis acceleration

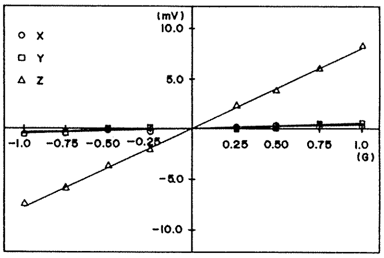


Fig. 11 Output voltage in case of Z-axis acceleration

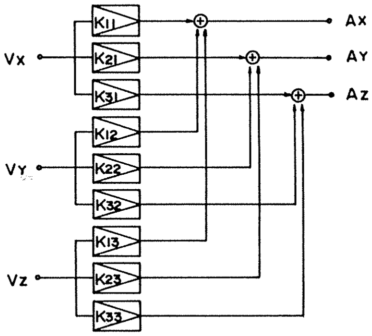


Fig. 12 Arithmetic circuit for elimination cross-axis sensitivity

(mV)

	Ax	Ay	Az
Vx	8.52	0.42	0.11
Vy	0.31	8.07	0.17
Vz	-0.14	-0.19	8.15

Table 2 Compliant matrix

(%FS)

	Ax	Ay	Az
Vx	100.0	0.5	0.1
Vy	-0.5	100.0	0.4
Vz	0.3	-0.6	100.0

Table 3 Out put characteristics with elimination cross-axis sensitivity

4. Performance

The main performances of the tri-axial piezoresistive accelerometer are shown in the following;

·Detecting range		: ±2 ~ ±50 G
·Frequency response		: 300 ~ 1500Hz
·Sensitivity (FS)		: 30 ~ 50mV
·Cross-axis sen.		: 5%FS
·Non-linearity		: 0.5 ~ 1.0%FS
·Temp. drift -sen.-		: 0.03%FS/℃
·Temp. drift -off.-	(X,Y)	: 0.10%FS/℃
	(Z)	: 0.20%FS/℃

Detection sensitivity and frequency response are determined mainly by the thickness of the diaphragm and the seismic mass. The temperature drift of the Z-axis offset is worse than for the X and Y axes. This is thought to be caused by distortion in the Z direction with temperature variation, due to differences in the thermal expansion coefficient. This is because the X and Y axis detection circuit have been made insensitive to distortion in the Z axis.

5. Conclusion

The tri-axial piezoresistive accelerometer has been developed using semiconductor technology and micro-machining technology, which is capable of detecting three dimentional acceleratin, and we make sure that it satisfies the basic performance as the accelerometer. With excellent features such as compactness, high performance and low cost, it can be expected to have a wider acceptance than previous industrial measurement devices as a vehicle mounted sensor for crash detection, chassis control and anti-lock braking system.

Reference

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