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Five-axis motion sensor with electrostatic drive and capacitive detection fabricated by silicon bulk micromachining

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Abstract

We have developed a five-axis motion sensor with electrostatic drive and capacitive detection by using silicon bulk-micromachining technique. This sensor has a seismic mass which is constantly vibrated along *Z*-axis by electrostatic force at the resonant frequency of 1875 Hz. Since the *Z*-axis acceleration (A_z) translates a mass parallel and the *X*-, *Y*-axis accelerations (A_x, A_y) tilt a mass, three-axis accelerations can be detected by capacitance change. Coriolis force induced by two-axis angular rates (Ω_x, Ω_y) makes tilting vibration of a mass synchronizing with driving frequency. Therefore, two-axis angular rates can be detected separating from the accelerations. Measured sensitivities of *Z*- and *X*-(*Y*-) axis accelerations were approximately 20 and 6 fF/G, respectively, and the cross-axis sensitivity was less than 5%. The sensitivities of two-axis angular rates around *X*- and *Y*-axis are approximately 3 aF/(deg/s). The cross-axis sensitivity of Ω_x against Ω_y was less than 3%, and that of Ω_z against $\Omega_x(\Omega_y)$ was not observed. The chip size of developed sensor is 8.4 mm × 8.0 mm × 1.4 mm.

Keywords: Five-axis motion; Three-axis acceleration; Two-axis angular rate; Electrostatic drive; Capacitive detection; Silicon bulk-micromachining

1. Introduction

In recent years, the multi-axis accelerometers and gyroscopes are required for wide fields, for example, automobile motion control, human-body motion monitoring and amusement equipments such as video game controllers and the commercialization is also making a progress gradually.

Under the existing circumstances, the combined units with accelerometers and gyroscopes are used for sensing multi-axis motions. In order to perform miniaturizing of the instruments, high yields and low cost production, one chip multi-axis motion sensor is required extremely. Micromachined multi-axis accelerometers [1,2] and vibrating gyroscopes [3–5] that were presented previously, had excellent performances which were high sensitivity and small size, but these sensors could detect either accelerations or angular rates with one chip.

The five-axis motion sensor with electromagnetic drive and capacitive detection has been already presented [6]. Although this sensor could detect both three-axis accelerations and two-axis angular rates with one seismic mass simultaneously, it is not suitable for miniaturizing of the sensor system because a large external electromagnetic force coil was used for driving of the mass.

This paper describes a new five-axis motion sensor with internal driving function fabricated by silicon bulk-micromachining. The seismic mass is driven by the electrostatic force, and five-axis motions can be detected by electrostatic capacitance change, simultaneously.

2. Structure and principle

Schematic view of the sensor structure is shown in Fig. 1. The sensor consists of two silicon layers (Si-1,2) and two glass layers (PX-1,2). A silicon seismic mass (4.0 mm × 4.0 mm × 0.2 mm) in the Si-2 is connected to a center pillar suspended with cross shaped four beams (2.2 mm long, 0.4 mm wide, 0.04 mm-thick). Four sensing plates (0.04 mm-thick) are also formed in the Si-1. The electrostatic driving electrodes (D1–4 and D_z) are fixed on the 7.5 mm etched surface of the PX-2, and the capacitive sensing electrodes (*X*+, *X*−, *Y*+, *Y*− and S_z) are fixed on the 7.5 μm etched surface of the PX-1.

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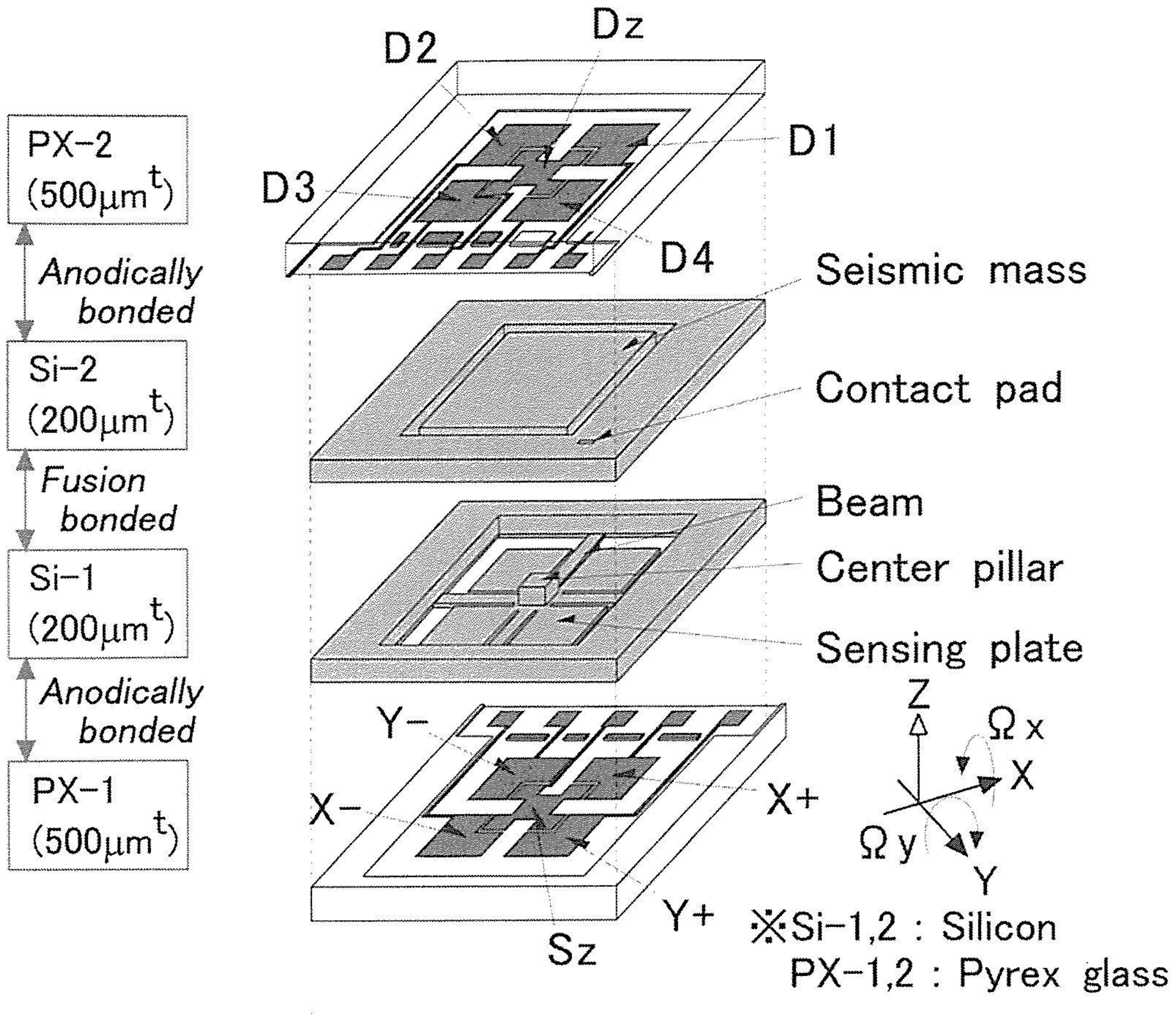


Fig. 1. Schematic view of the sensor structure.

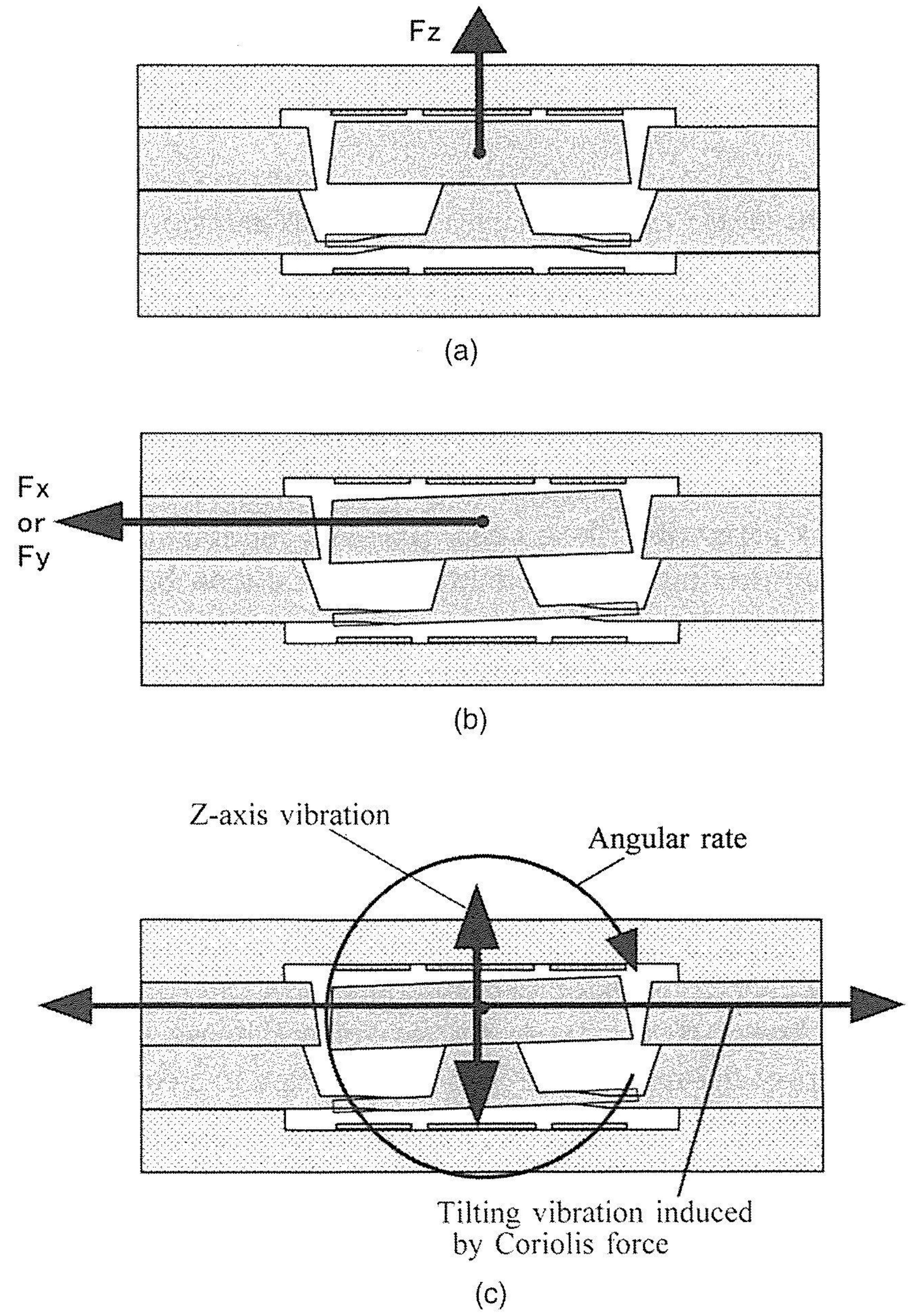


Fig. 2. Principle of operation. (a) *Z*-axis acceleration; (b) *X*- or *Y*-axis acceleration; (c) angular rate around *X*- and *Y*-axis.

The principle of operation is shown in Fig. 2. The mass is constantly vibrated by the electrostatic force along *Z*-axis at driving frequency. *Z*-axis resonant frequency which is nearly equal to driving frequency, is designed to be 1.9 Hz, and *X*-, *Y*-axis resonant frequency is designed to be 2.0 kHz. Frequency response to detect acceleration and angular rate is supposed to be from DC to several 10 Hz.

When *Z*-axis acceleration is applied, F_z force causes the parallel translation of the mass (Fig. 2(a)). And when *X*- or *Y*-axis accelerations are applied, F_x and F_y force tilt the mass(Fig. 2(b)), therefore, three-axis accelerations can be detected by sensing of capacitance change [1,2].

When two-axis angular rates around *X*-axis (Ω_x) and *Y*-axis (Ω_y) are applied, the tilting vibration along *Y*- and *X*-axis synchronized with driving vibration are induced by the Coriolis force, respectively (Fig. 2(c)).

Fig. 3 shows the block diagram for sensing five-axis motions. The sensing capacitance which are C_x+, C_x-, C_y+, C_y- are converted to each voltage of V_x+, V_x-, V_y+, V_y- with *C*–*V* converter. The subtract V_x- from V_x+ makes *X*-axis acceleration, the subtract V_y- from V_y+ makes *Y*-axis acceleration, and *Z*-axis acceleration is made from the sum of V_y+ and V_y- through an amplifier and a low pass filter (LPF).

Two-axis angular rates of Ω_x and Ω_y can be detected separating from the accelerations of low frequency from DC to several 10 Hz, with the high pass filter (HPF) and the synchronous detector. In the case of applying high frequency acceleration, angular rate can not be separated from acceleration sufficiently, because acceleration signal is not cut with the HPF. In order to detect angular rate without influence of high frequency acceleration, it is effective to mount the sensor as high frequency vibration is eliminated.

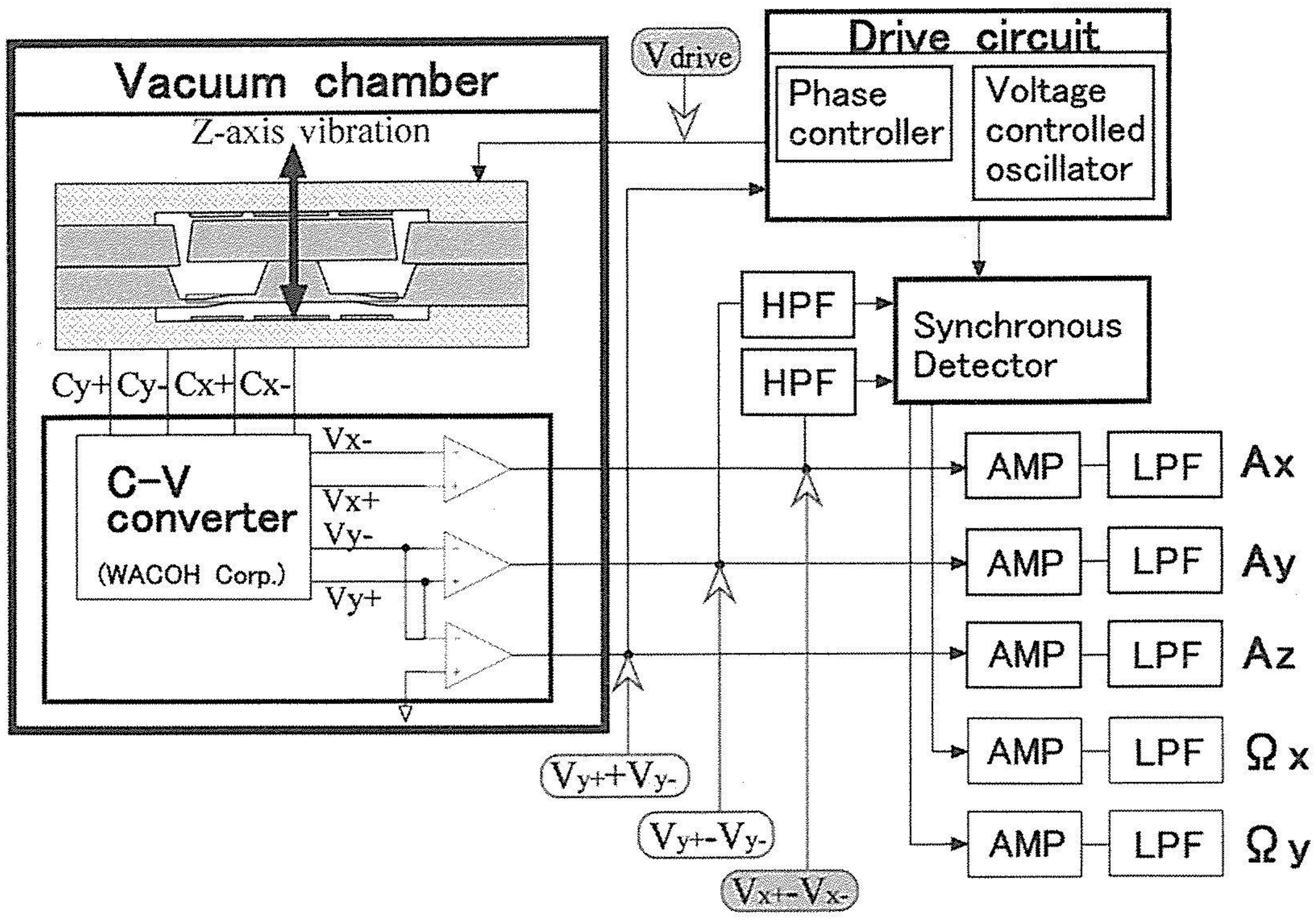


Fig. 3. Block diagram for sensing.

3. Fabrication

The fabrication process sequence of the sensor is shown in Fig. 4. (a) A (1 0 0) oriented silicon wafer (Si-1) was anisotropically wet-etched through with TMAH solution from both sides to form the center pillar, beams, and sensing plates; (b) a (1 0 0) oriented silicon wafer (Si-2) was fusion bonded to the Si-1 at 1100 °C for 120 min in nitrogen atmosphere [7,8]; (c) after thermal oxidation, the mass was released from the frame by anisotropic wet-etching using KOH containing IPA solution; (d) two glass wafers were etched by 7.5 μm and Pt/Cr layered electrodes (2.4 mm^2 in area) were formed on the etched surface. After that, two glass wafers were anodically bonded to the both sides of the Si–Si structure. Finally, grooves for chip-break lines were diced, and the wafers were separated to sensor chips.

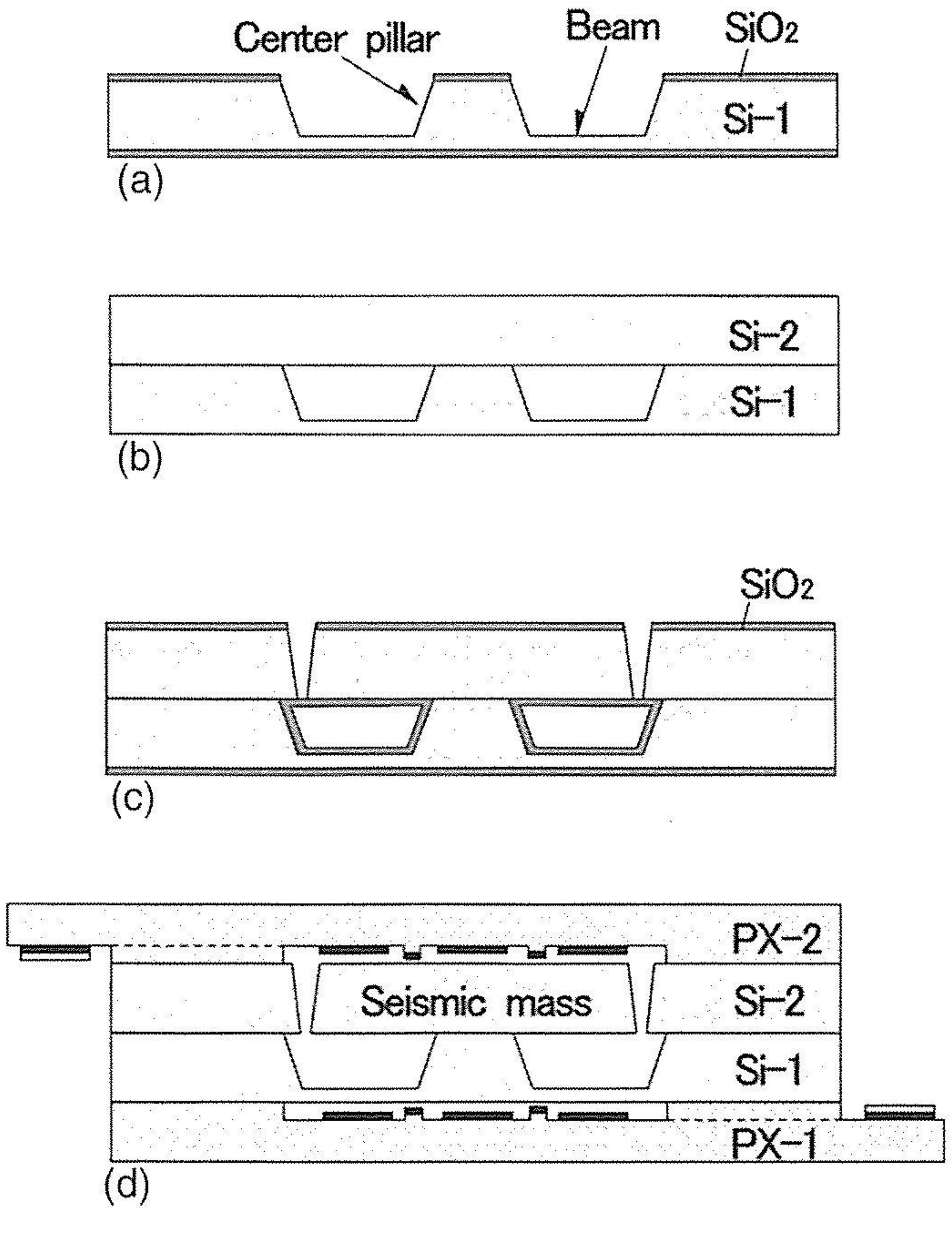


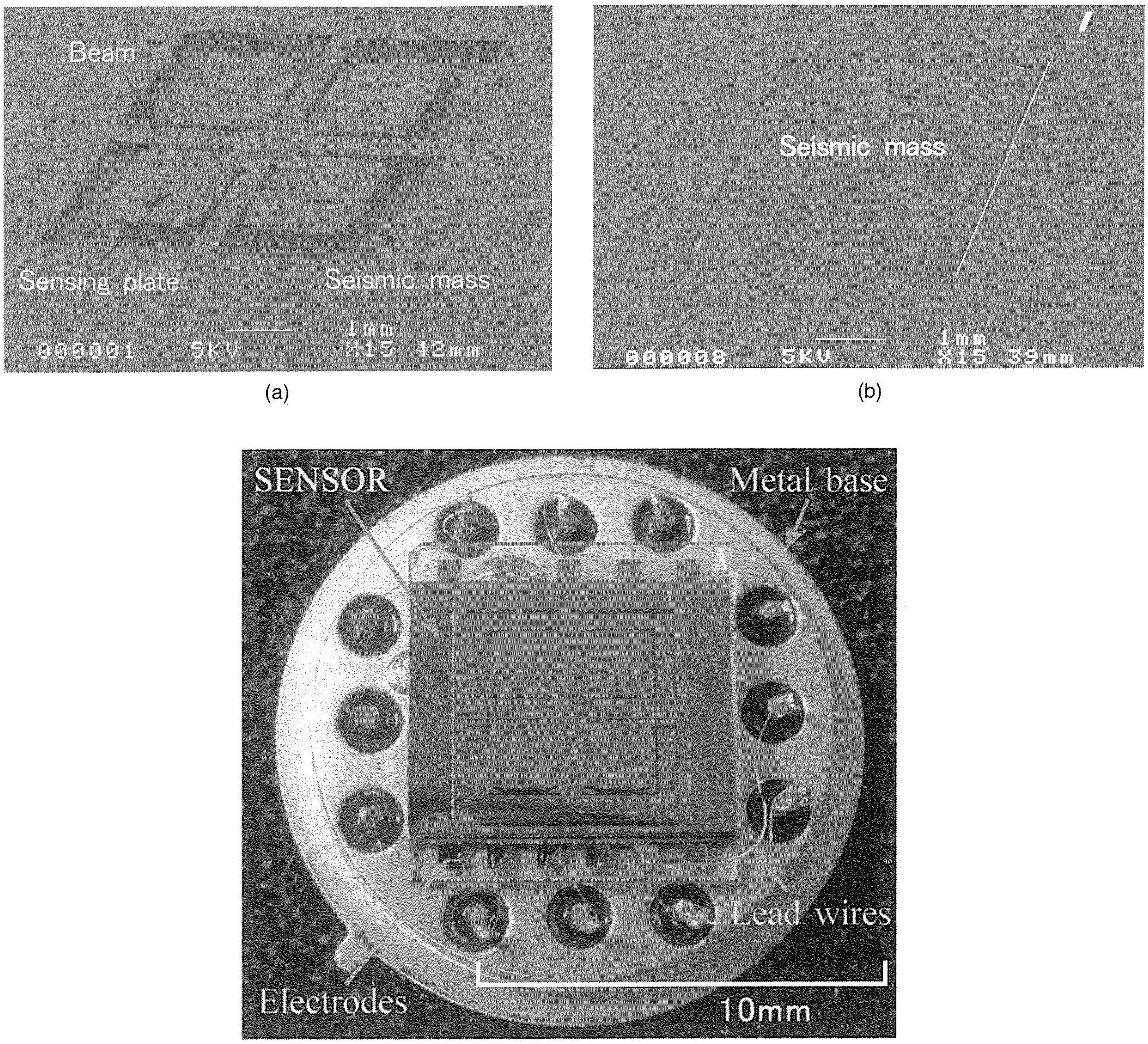
Fig. 4. Fabrication process sequence of the sensor. (a) Anisotropic wet-etching; (b) Si–Si fusion bonding; (c) anisotropic wet-etching; (d) anodic bonding and separation to sensor chips.

Fig. 5 shows photographs of the fabricated sensor. Fig. 5 (a) and (b) are SEM images of the Si–Si structure viewing from both sides. Through the wet process such as wet-etching and surface cleaning, the sensor could be fabricated successfully without damages on the beams and the sensing plates. The seismic mass could be electrically connected to the center pillar because of the Si–Si fusion bonding. Fig. 5 (c) is an optical image of the sensor chip mounted on a metal base. The chip size of the sensor is 8.4 mm × 8.0 mm × 1.4 mm.

4. Characteristics

4.1. Vibration characteristics

In order to improve angular rate sensitivity, the large amplitude of the driving vibration is so effective [4] that the vibration characteristics of the resonator was evaluated. The measurement system is shown in Fig. 6. The mass was driven in the direction of Z-axis (parallel vibration) and Y-axis (tilting vibration) by electrostatic force applying DC added sine-wave signals output from the network analyzer, and C–V converted signals were returned to the analyzer. The Z-axis vibration and Y-axis vibration were carried out by using the electrodes of D_z(drive)-S_z(sense) and D2(drive)–D4(sense), respectively. Measured vibration characteristics are shown in Fig. 7. The center frequency of a resonant peak



(a) (b)

(c)

Fig. 5. Photographs of fabricated sensor. (a) SEM image of Si–Si structure from beam side; (b) SEM image of Si–Si structure from mass side; (c) optical image of the sensor mounted on a metal base.

was approximately 1880 Hz in a case of Z-axis drive (Fig. 7(a)). In a case of Y-axis drive, two resonant peaks, their center frequency were 2030 and 2040 Hz, observed. Then the mass was driven in the direction along the beams, and in consequence we found these peaks were those of tilting vibration along the beams. This phenomenon seems to depend on the fabrication error which is mainly thickness error of the beams.

In order to obtain high angular rate sensitivity and stable vibration without phase shift, acceleration and angular rate characteristics were evaluated by driving at 1875 Hz which is 5 Hz lower than Z-axis resonant frequency.

4.2. Three-axis acceleration

Static acceleration characteristics were measured by rotating along each axis using gravitational 1 G. The mass was vibrated along Z-axis electrostatically at the resonant frequency of 1875 Hz, with applying 6 V_{pp} sine-wave and 4 V offset voltage to the electrodes of D1–4 commonly connected. Measured acceleration characteristics are shown in Fig. 8. The sensitivities of A_x, A_y, A_z acceleration were 3.2 V/G, which were equivalent to 5.9, 5.7 and 23 fF/G, respectively. The cross-axis sensitivity were less than 5%. These results were similar to the non-driven measurement results.

4.3. Two-axis angular rate

Angular rate characteristics were measured by rotating around X- and Y-axis using the turn-table with air bearing to eliminate the mechanical vibration noise. The applied angular rates were calibrated by a reference gyroscope set with the fabricated sensor. The mass was vibrated

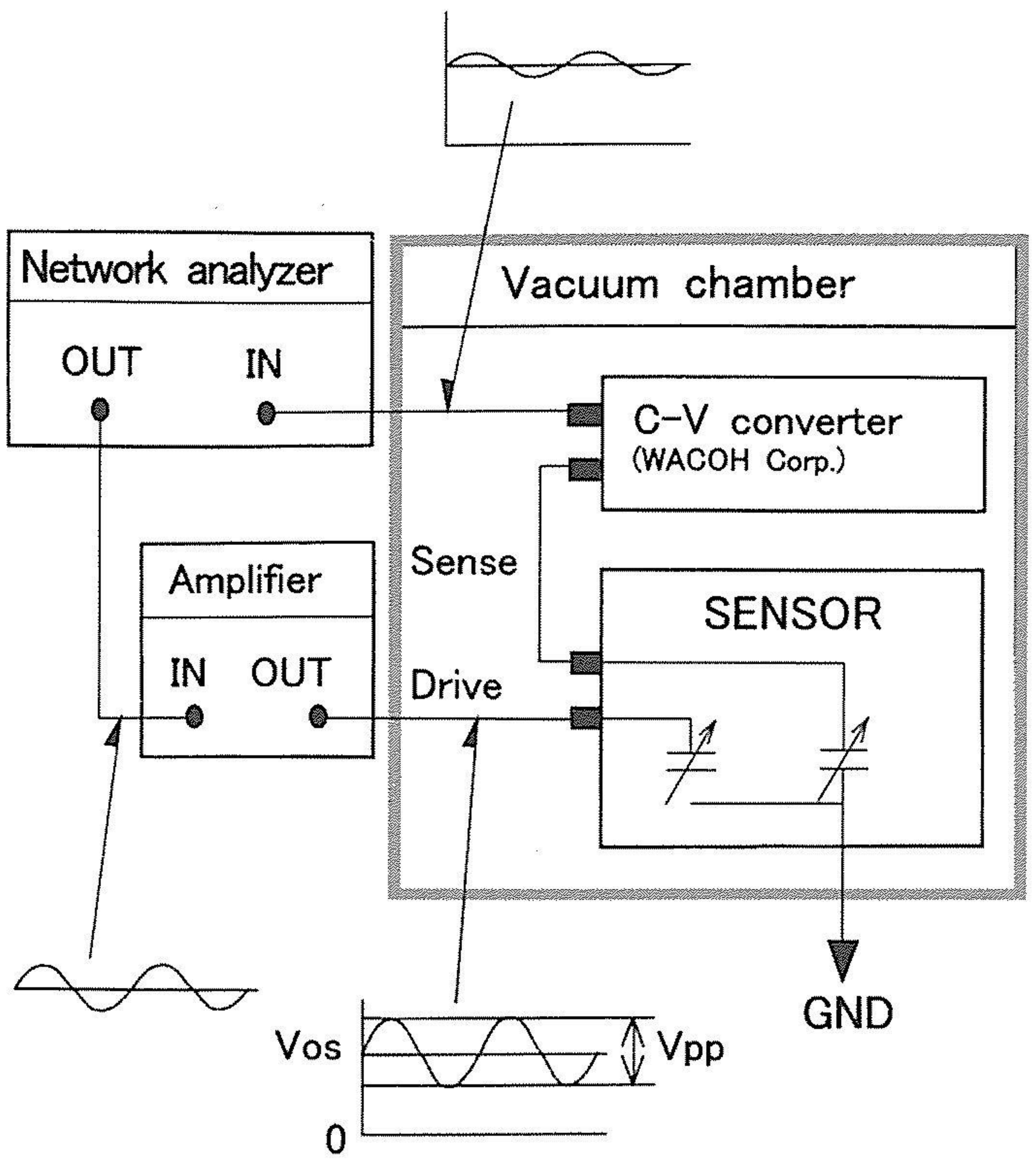


Fig. 6. Measurement system of vibration characteristics.

electrostatically with applying 6 V_{pp} sine-wave of 1875 Hz and 4 V offset voltage, to the electrodes of D1–4 commonly connected. Measured characteristics of angular rates around X- and Y-axis (Ω_x, Ω_y) are shown in Fig. 9. The sensitivity of Ω_x and Ω_y were 6.8 and 7.0 mV/(deg/s), which were equivalent to 2.7 and 2.8 aF/(deg/s), respectively. The cross-axis sensitivity of Ω_x against Ω_y were less than 3%, and that of Ω_z against Ω_x or Ω_y was never observed. These low cross-axis sensitivities seems that the amplitude of X- and Y-axis vibration are much less than Z-axis vibration, because the resonant frequencies of the tilting vibration differ from the Z-axis driving frequency sufficiently, and cross-axis mechanical couplings are reduced at low level [3].

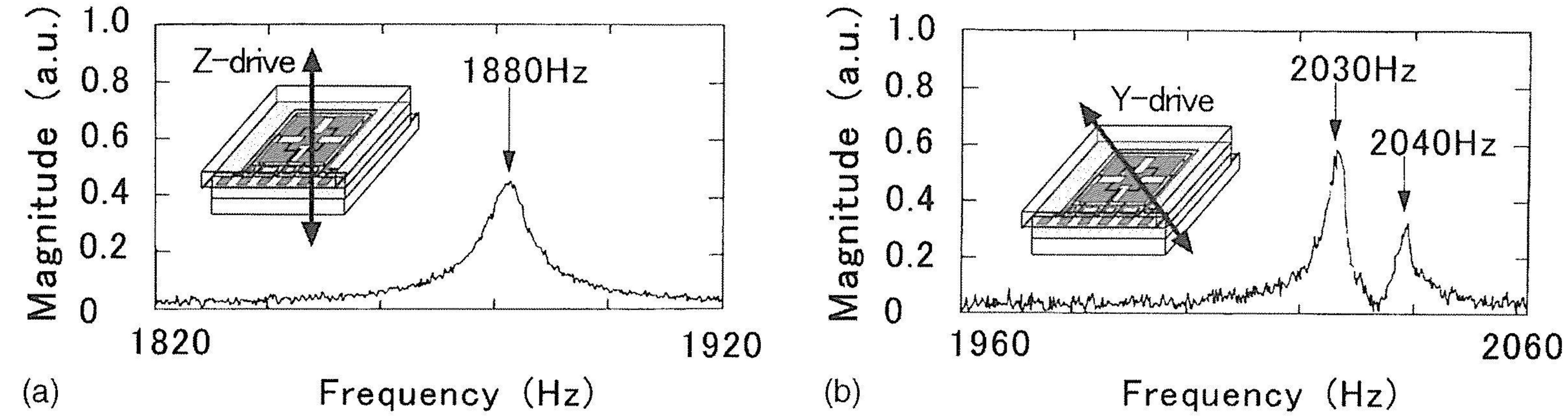


Fig. 7. Measured vibration characteristics: (a) Z-drive, drive: D_z ($2\,V_{pp} + 8\,V_{os}$), sense: S_z; (b) Y-drive, drive: D2 ($2\,V_{pp} + 2\,V_{os}$), sense: D4.

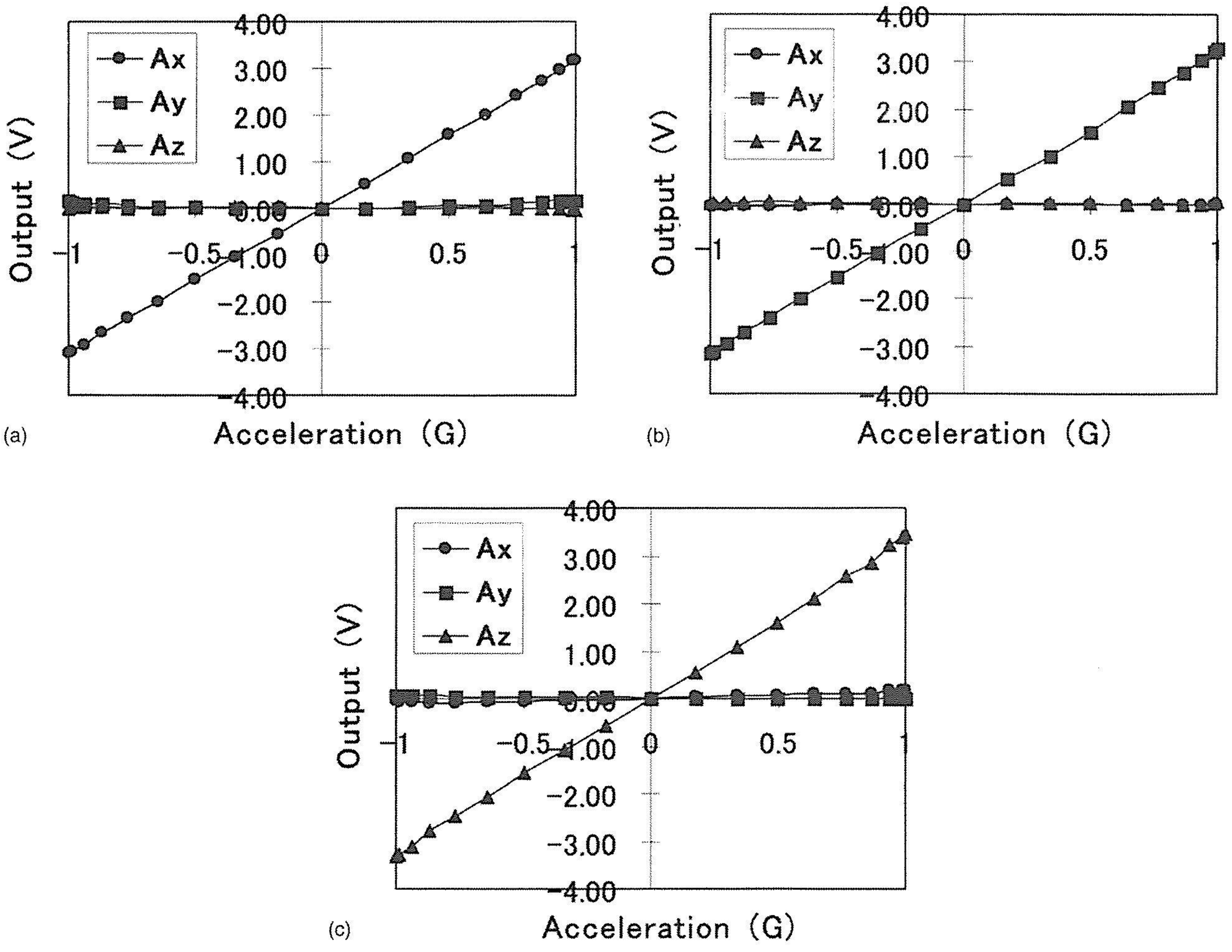


Fig. 8. Measured acceleration characteristics: (a) X-axis acceleration (A_x); (b) Y-axis acceleration (A_y); (c) Z-axis acceleration (A_z).

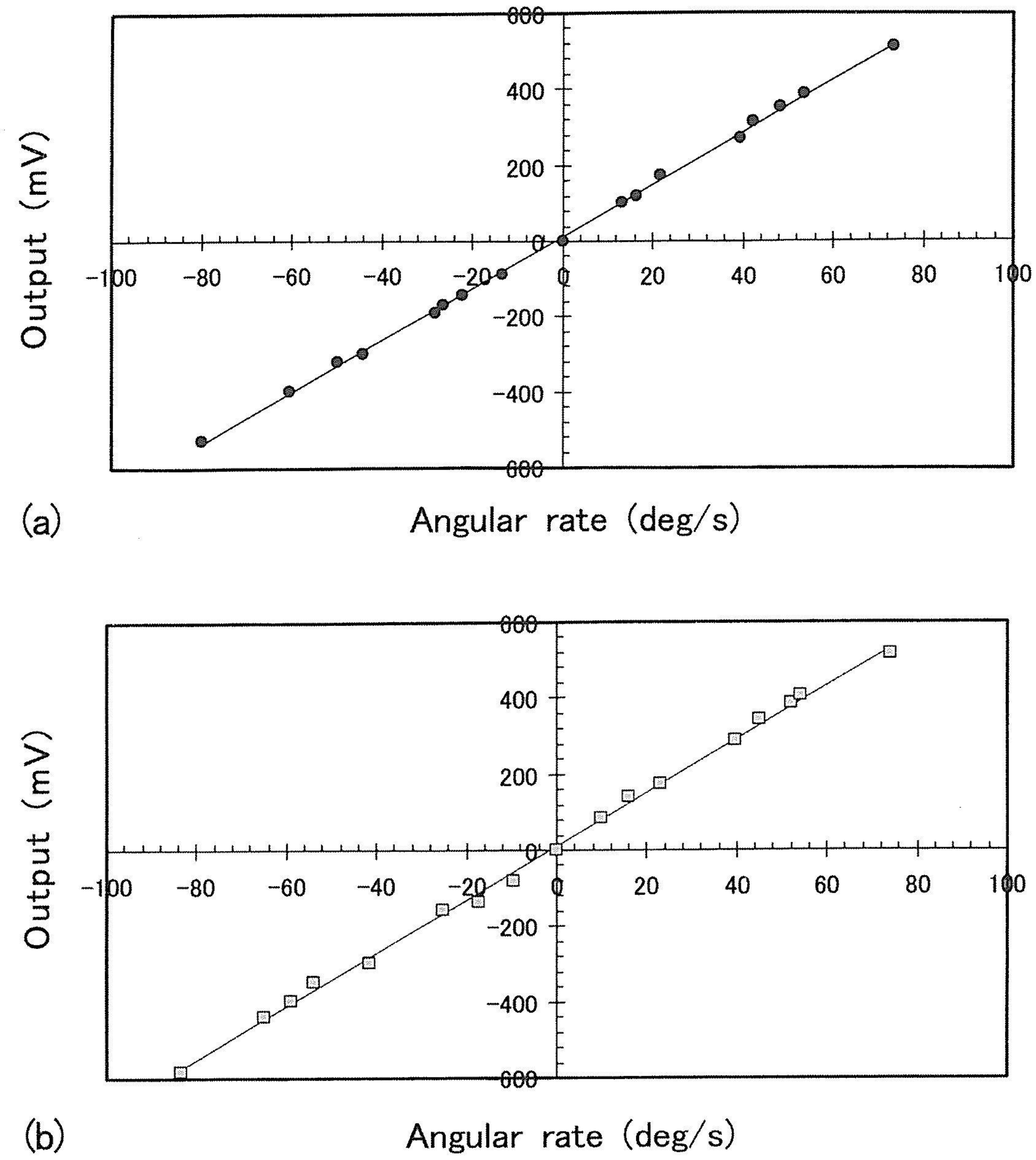


Fig. 9. Measured angular rate characteristics: (a) angular rate around X-axis (Ω_x); (b) angular rate around Y-axis (Ω_y).

5. Conclusions

We have developed a five-axis motion sensor with electrostatic drive and capacitive detection by using silicon bulk-micromachining technique. As vibrating the mass with resonant drive of 1875 Hz and non-resonant sense, three-axis accelerations and two-axis angular rates could be detected successfully. Measured sensitivities of Z- and X-(Y-) axis accelerations were approximately 20 and 6 fF/G, respectively, and the cross-axis sensitivity was less than 5%. The sensitivities of two-axis angular rates around X- and Y-axis are approximately 3 aF/(deg/s). The cross axis sensitivity of Ω_x against Ω_y was less than 3%, and that of Ω_z against $\Omega_x(\Omega_y)$ was not observed. The chip size of developed sensor is 8.4 mm × 8.0 mm × 1.4 mm.

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Biographies

Yoshiyuki Watanabe received the BS degree in physics from Niigata University, Japan, in 1991. He joined the Yamagata Research Institute of Technology in 1991 and, since then he has been engaged in research and development on micromachined devices. His research interests are mechanical sensors and microassembly.

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Nobumitsu Taniguchi received BS degree in mechanical engineering from Musashi Institute of Technology, Japan, in 1986. He joined the development section of A and D Corporation Ltd., in 1986. He joined the WACOH Corporation, Saitama, Japan, in 1997. He is a manager of research and development division, and he is responsible for mechanical and circuit design of the multi-axis sensors, multi-axis motion sensor, three-axis accelerometer, three-axis angular rate sensor and three-axis force sensor.

Kazuhiro Okada received BS and MS degree in electronic engineering from Sophia University, Japan, in 1975 and 1977, respectively. From 1979, he has been engaged in the research and development of micro-machined pressure, acceleration and angular rate sensor. He established WACOH Corporation in 1988, and succeeded in development of a first piezo-resistive three-axis acceleration sensor in 1992. He and his company hold more than 100 patents in Japan, US and Europe with regard to the above sensors, and is currently a president, and CEO.