Paper

Development and evaluation of capacitance detection ASIC for three-axis common electrode type capacitive accelerometer

Member Yoshinori Matsumoto (Keio University)
Member Shoji Kawahito (Shizuoka University)
Member Makoto Ishida (Toyohashi University of Technology)

A capacitance detection CMOS ASIC has been developed for three-axis common electrode type capacitive accelerometers. The ASIC contains an analog output switched capacitor circuit and a digital output 2nd order delta-sigma modulator. The circuits were driven by three or six phase clocks for three-axis detection. The characteristics of the circuits were evaluated by a variable capacitor and a three-axis capacitive accelerometer. A novel compensation method was proposed to reduce the sensitivity dependence on Z-axis acceleration. The three-axis output voltages of the switched capacitor circuits were proportional to three-axis accelerations. The offset and sensitivity of the 2nd order delta-sigma modulator can be calibrated by outer voltages. The sensitivities of 1.5V/G and 20kHz/G were obtained respectively when the circuits were combined with a commercial available three-axis capacitive accelerometer.

Keywords: *three-axis accelerometer, detection circuit, switched capacitor, delta-sigma modulator, CMOS*

1. Introduction

High sensitive and low cost three-axis accelerometers in the range of 0-2G and the resolution of micro-order G have been required for the motion control systems such as airplane, robots and amusements. Recently, Many kinds of silicon micromachining accelerometers have been developed to satisfy the requirements[(1)-(11)]. However, it is difficult to detect micro-order G using a polysilicon surface micromachining technology because of its small mass of microgram[(6)].

The bulk micromachining common electrode type accelerometers have higher sensitivity, but the sensor chip-size is tend to be large by (111) side-walls at sensor peripheral and the glass bonded mass structure, which raises process complexity and sensor cost[(2)-(4)]. These problems can be solved by adopting a high aspect mass structure using a dicing method or a deep R.I.E process[(8)-(11)]. The accelerometers were formed by glass-silicon structure, and it has a high aspect ratio mass structure of over 500μm thickness in small chip-size of a few mm. The mass forms a common electrode. The base capacitance was a few pF and the capacitance change was from 10fF/G to 500fF/G. A high performance capacitance detection ASIC is necessary in order to detect micro-order G using the accelerometers.

This paper shows the design and evaluation of the switched capacitor circuit and 2nd order delta-sigma modulator.

2. Design

2.1. Sensor Structure

Figure 1 shows a principle of the common electrode type three-axis capacitive accelerometers[(7)-(11)]. The accelerometer has a high aspect mass structure of over 500μm thickness on the glass-silicon structure. The mass is supported by straight or spiral single crystal silicon beams in the thickness of less than 10μm. The mass forms a common electrode. A Z-axis accelerometer is formed between the mass and a metal electrode on glass substrate. Clover-leaf silicon plates are attached to the mass to form X,Y-axis capacitors. X,Y accelerometers are formed between the clover-leaf plates and metal electrodes on the glass. The equivalent circuit of three-axis accelerometer is shown in Fig.2. The X,Y-axis accelerometers were composed of the differential capacitors, which is effective to reduce the noise or temperature dependence. Stray capacitors exist between each electrodes and GND potential.

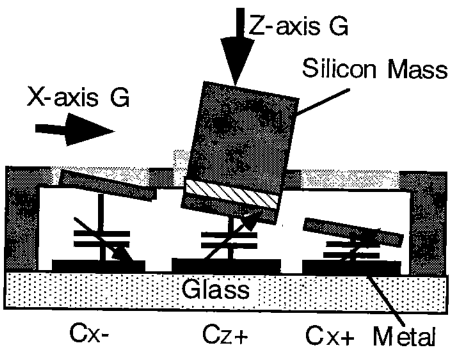


Fig.1. Principle of the three-axis common electrode type capacitive accelerometer.

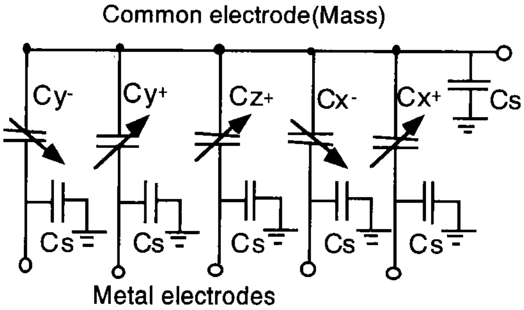


Fig.2. Equivalent circuit of the three-axis accelerometer.

The sensor capacitance is changed by the acceleration a as follows.

$$C_{+} = \frac{\varepsilon S}{d - Ka}, \quad C_{-} = \frac{\varepsilon S}{d + Ka} \tag{1}$$

where ε is the dielectric constant, S and d are the area and gap of the sensor capacitor and K is the spring constant.

The C-V converter and C-F converter were used for the detection of a common electrode type accelerometers[(2)-(4)]. These circuits connect the common electrode to GND potential, and measure the capacitance change with the charge and discharge periods. In that case, the stray capacitors C_s are equivalent to the sensor capacitors, thus the sensitivities are degraded by the stray capacitors. As other work, a full differential delta- sigma modulator was used for the three-axis detection[(6)]. In that case, the DC potentials of the electrodes were unstable, which causes the errors of electrostatic force.

The equivalent acceleration error caused by the electrostatic force is derived from the equation of as follows.

$$\rho hAG = \frac{\varepsilon V^2}{2d^2}A$$
$$G = \frac{\varepsilon V^2}{2\rho hd^2} \tag{2}$$

where ε is the dielectric constant, V is the voltage, ρ, A and h are the density, area and thickness of silicon mass, d is the gap of structure and substrate. The typical dimension of surface micromachining accelerometer is around h=5μm, d=2μm, the electrostatic force caused by a voltage of 1V is corresponding to 10G. The value is relatively large for the low G accelerometer. Therefore, a careful treatment between mass voltage and substrate voltage is necessary by using the shielding technique. In the case of the high aspect mass accelerometer, the typical dimension is h=500μm, d=2μm, the electrostatic force caused by a voltage of 1V is corresponding to 0.1G, which removes the complicated shielding technique.

2.2. Switched capacitor circuit

The switched capacitor circuit was designed for the common electrode type three-axis accelerometer. Figure 3 shows the circuit diagram of the switched capacitor circuit. Outer reference capacitor C_{ref} was used for Z-axis detection. The circuit is composed of three blocks and driven by 6 phase clocks. The output voltages $V_{x,y,z}$ of each blocks are given by the following equation.

$$V_{x,y,z} = \frac{C_{+}}{C_{+} + C_{-}} V_{dd} \tag{3}$$

where C_{+} indicates C_{x+}, C_{y+} and C_{z+} in Fig.3, and C_{-} indicates C_{x-}, C_{y-} and C_{ref} in Fig.3. V_{dd} is the power supply voltage.

Substituting the equation (1) into the equation (3), the X,Y-axis output voltages $V_{x,y}$ are proportional to the acceleration $a_{x,y}$ as given by the following equation.

$$V_{x,y} = \frac{1}{2}\left(1 + \frac{Ka_{x,y}}{d}\right) V_{dd} \tag{4}$$

A folded-cascode operational amplifier shown in Fig.4 was adopted for the switched capacitor circuit because it has wide frequency response and stability for capacitive loads. The unity gain frequency was simulated about 10MHz using 5μm CMOS process of Toyohasi University of Technology.

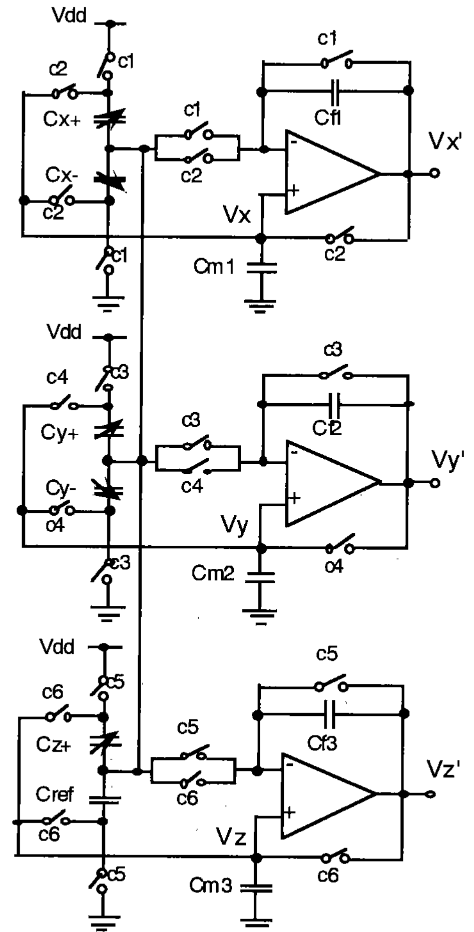


Fig.3. Circuit diagram of the switched capacitor circuit.

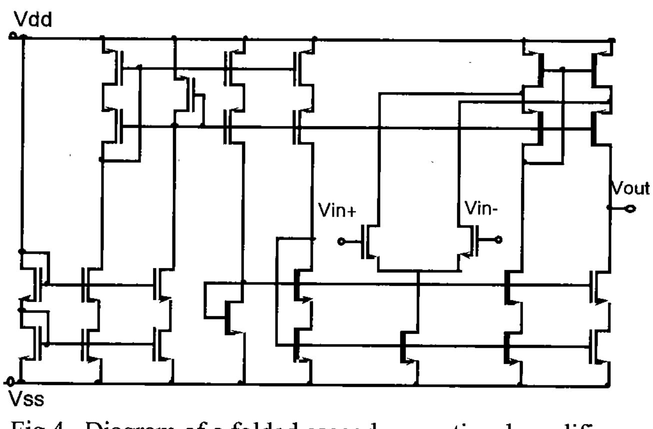


Fig.4. Diagram of a folded-cascode operational amplifier.

2.3. 2nd order delta-sigma modulator

2nd order delta-sigma modulators have been developed recently for capacitive sensors because of its wide dynamic range and high resolution[(6)(12)]. A full differential delta-sigma modulator was used for the three-axis detection by driving the common electrode[(6)]. However, the DC potentials of electrodes(inputs of full differential operational amplifier) were unstable which causes the errors of the electrostatic force.

A single-ended delta sigma modulator has been developed for the three-axis accelerometer. Figure 5 shows the circuit diagram of the delta-sigma modulator. The DC potential of common electrode is fixed to a voltage of V_s to reduce the errors of the electrostatic force.

The voltages of V_{off} and V_{ref} are used for the calibration of offset and sensitivity. The pulse density change ΔD of the bit-stream pulse ϕ_3 is given by the equation.

$$\Delta D \propto \frac{C_+ - C_-}{C} \frac{V_{dd}}{V_{ref} - V_s} + \frac{V_{off} - V_s}{V_{ref} - V_s} \qquad (5)$$

Three delta-sigma modulators are driven by 3 phase clocks for the three-axis accelerometeras illustrated in Fig.6.

The switched capacitor circuit and the delta-sigma modulator use the feedback principle, so that they have stability and low noise characteristics. The detection circuits and digital filter for the delta-sigma modulator were simulated by MicroSim Desgin Center and Cadence Analog Artist, and designed by Cadence Layout Editor. These circuits were fabricated by 5μm CMOS process of Toyohashi University of Technology. Figure 7 shows the photograph of circuits. The chip size is 5mm by 5mm.

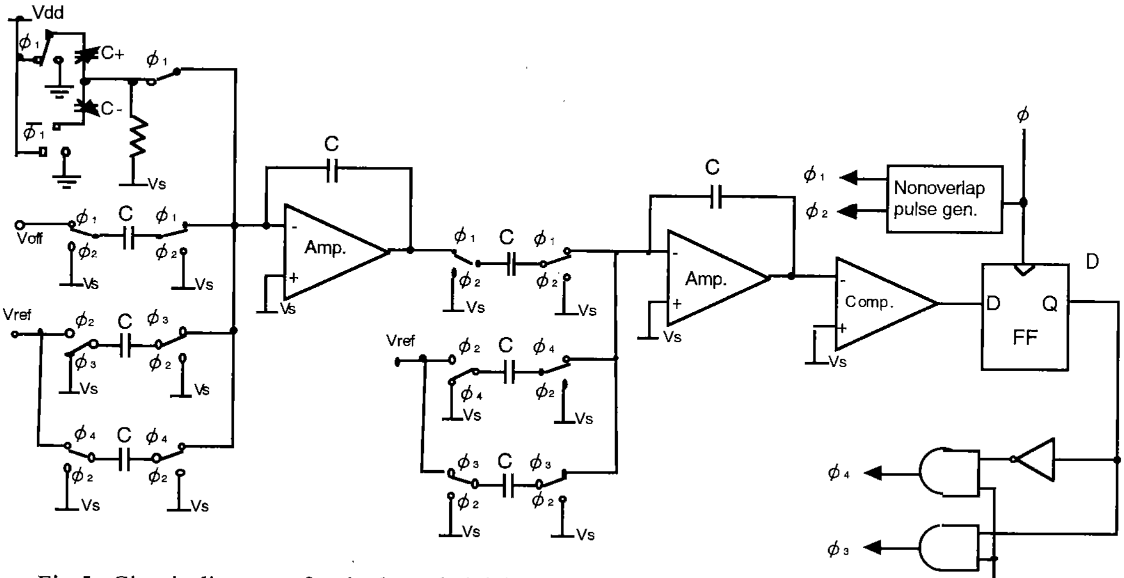


Fig.5. Circuit diagram of a single-ended delta-sigma modulator.

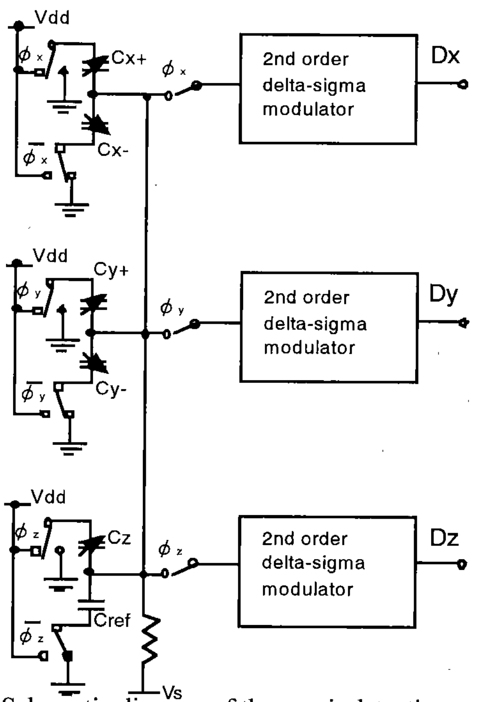


Fig.6. Schematic diagram of three-axis detection using three delta-sigma modulators.

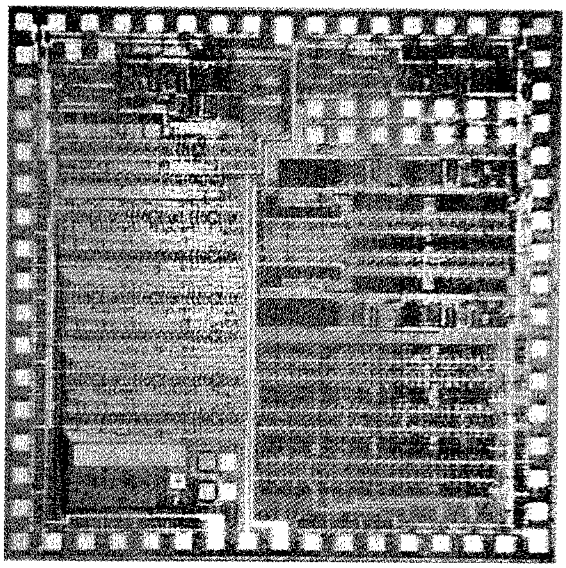


Fig.7. Photograph of capacitancedetection CMOS ASIC.

3. Characteristics

3.1. Switched capacitor circuit

The characteristics of the switched capacitor circuit were evaluated by a variable capacitor of 10pF. Figure 8 shows the capacitance to voltage characteristics. The output voltage is proportionally changed by the differential change of capacitance. On the other hand, The output voltage is not changed by the common change of capacitance. The feature is effective to reduce the noise or temperature dependence of the accelerometer.

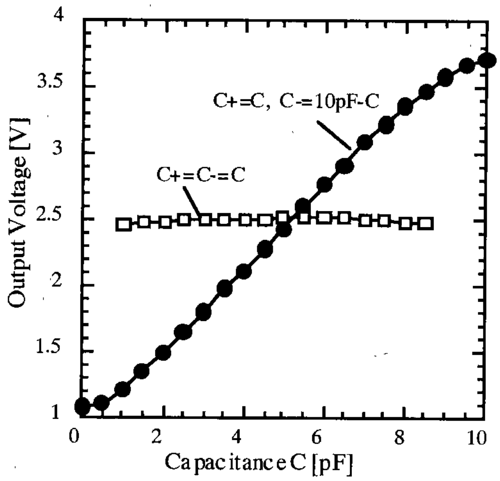


Fig.8. Capacitance to voltage characteristics of the switched capacitor circuit.

3.2. 2nd order delta-sigma modulator

The characteristics of the 2nd order delta-sigma modulator were evaluated by a variable capacitor of 10pF. Figure 9 and 10 show the capacitance to frequency characteristics. The frequency is changed by the capacitance, and the sensitivity and offset can be calibrated by voltages of V_{off} and V_{ref}.

4. Performance with the three-axis common mode type accelerometer

4.1. Switched capacitor circuit

Three ASICs were mounted in ceramic packages, and combined on circuit board for three-axis detection. The stray capacitors of a few pF exist in the ceramic packages and wires in the circuit board. The stray capacitors degrade the performance of the high aspect mass accelerometer because of the small base capacitance of a few pF. It is possible to reduce the stray capacitances dramatically by adopting the hybrid package in the future. But, in this work, the three-axis accelerometer fabricated by WAKHO Co. in ref. (2) was used for the evaluation of the circuits. The base capacitances for each-axis are 5 to 6pF, and the sensitivities are 60 to 80fF/G for X,Y-axis and 140 to 180fF/G for Z-axis. The output voltages of switched capacitor circuits were amplified at the gain of 100, then the outputs were filtered by 2nd order Butterworth low pass filter of which cut off frequency 100Hz.

Figure 11 and 12 show the three-axis output characteristics and waveform for X-axis acceleration. The sensitivities were about 1.5V/G for X,Y-axis acceleration and 0.5V/G for Z-axis acceleration respectively. The non-linearity for X,Y-axis acceleration was less than 0.1%/F.S, but non-linearity for Z-axis acceleration was 15%/F.S. The minimum detectable accelelation was measured about 1mG.

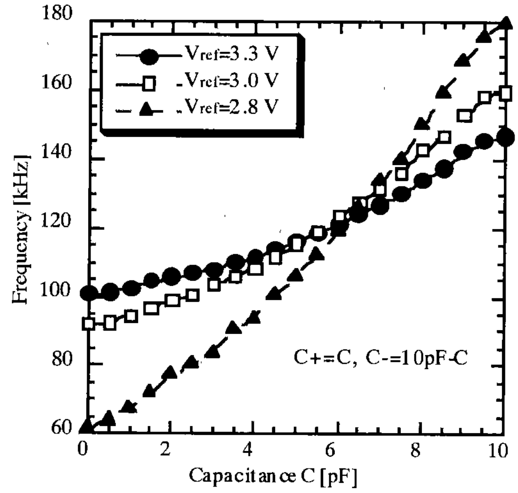


Fig.9. Capacitance to frequency characteristics of the 2nd order delta-sigma modulator in the different voltages of V_{ref}.

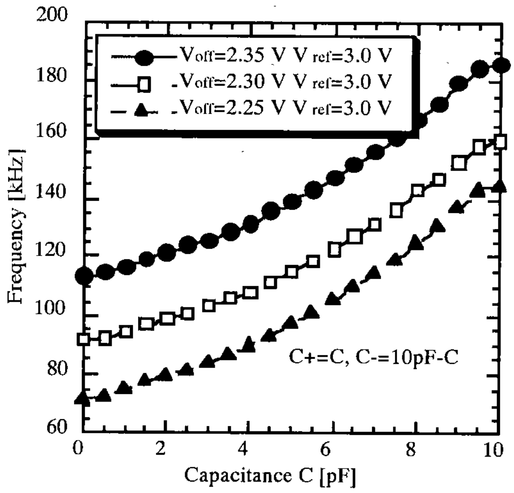


Fig.10. Capacitance to frequency characteristics of the 2nd order delta-sigma modulator in the different voltages of V_{off}.

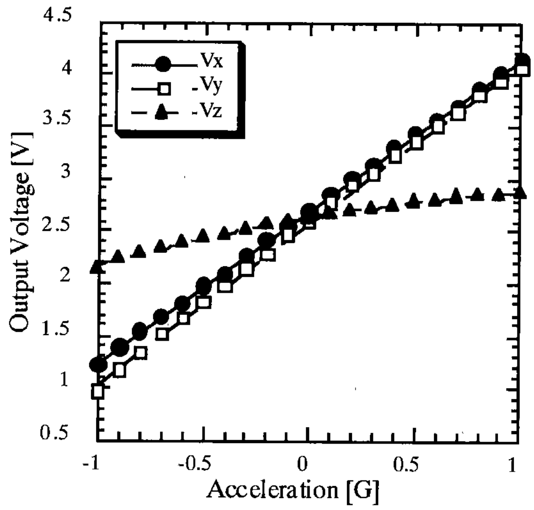


Fig.11. Three-axis output characteristic of accelerometer.

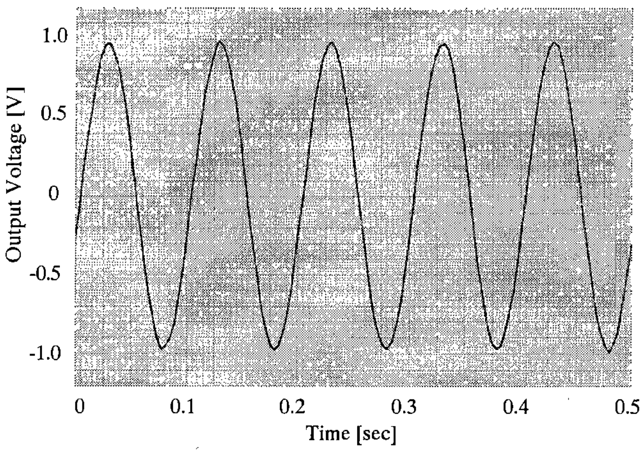


Fig.12. Waveform of X-axis output of accelerometer vibrating ±0.6G at 10Hz.

4.2 2nd order delta-sigma modulator

The X-axis output characteristics of 2nd order delta-sigma modulators were measured as shown in Fig.13. The pulse density change of bit-stream pulse ϕ_3 of delta-sigma modulator was measured by a frequency counter. The frequency change was changed by the acceleration, and the sensitivities of 20kHz/G was obtained when V_{ref}=2.7V. The non-linearity was about 8%/F.S. The minimum detectable acceleration was measured a few mG. The sensitivity and offset was calibrated by voltages of V_{off} and V_{ref}.

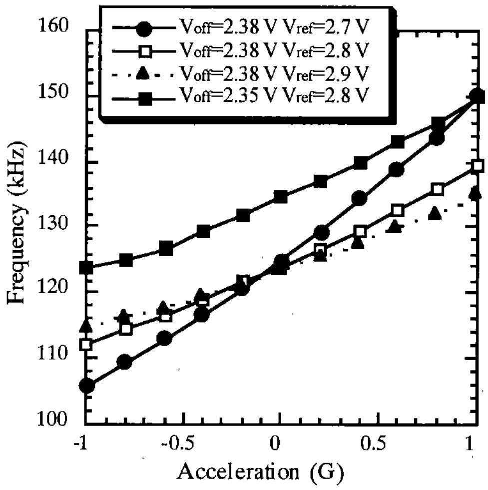


Fig.13. X-axis output characteristics of accelerometer in the different voltages of V_{off} and V_{ref}.

5. Reduction of sensitivity dependence on Z-axis acceleration

The X,Y-axis outputs of the switched capacitor circuit and the delta-sigma modulator have the sensitivity dependence on Z-axis acceleration a_z. The dependence of the X-axis output voltage V_x of the switched capacitor circuit is calculated as follows.

$$V_O = \frac{C_+}{C_+ + C_-} V_{dd} = \frac{1}{2}\left(1 + \frac{K_x a_x}{d - K_z a_z}\right) V_{dd} \qquad (6)$$

where K_x and K_z are the spring constants of X-axis and Z-axis accelerometers.

The dependence of the 2nd order delta-sigma modulators is calculated as follows in the condition of $(d-K_z a_z) << K_x a_x$.

$$D_x \propto C_{x+} - C_{x-} = \frac{\varepsilon S}{d - K_x a_x - K_z a_z} - \frac{\varepsilon S}{d + K_x a_x - K_z a_z} = \frac{\varepsilon S}{(d - K_z a_z)^2} 2 K_x a_x \qquad (7)$$

The dependence can be compensated using the signal from Z-axis accelerometer. But this method need a additional compensation circuit, furthermore Z-axis output have non-linearity and temperature dependence because a reference capacitor of C_{ref} is used for Z-axis detection circuit.

The Z-axis dependence can be compensated when another accelerometer is fixed against the three-axis accelerometer as illustrated in Fig.14. The each capacitors are connected as $C_{x+}=C_{x+u}+C_{x+d}$, $C_{x-}=C_{x-u}+C_{x-d}$, $C_{y+}=C_{y+u}+C_{y+d}$, $C_{y-}=C_{y-u}+C_{y-d}$, $C_{z+}=C_{zu}$, $C_{z-}=C_{zd}$. The capacitances do not have Z-axis dependence as calculated by the following equation.

$$C_{x+} = C_{x+u} + C_{x+d} = \frac{\varepsilon S}{d - K_x a_x - K_z a_z} + \frac{\varepsilon S}{d - K_x a_x + K_z a_z} \approx 2\frac{\varepsilon S}{d - K_x a_x} \qquad (8)$$

The Z-axis dependence using the compensation method was measured in Fig.15 and Fig.16. The non-linearity caused by the Z-axis acceleration was about 5%/F.S. without compensation. But the non-linearity became less than 0.5%/F.S. using compensation method. Furthermore, the Z-axis output voltage was proportionally changed by Z-axis acceleration as shown in Fig.17. The non-linearity for Z-axis acceleration became less than 0.5%/F.S.

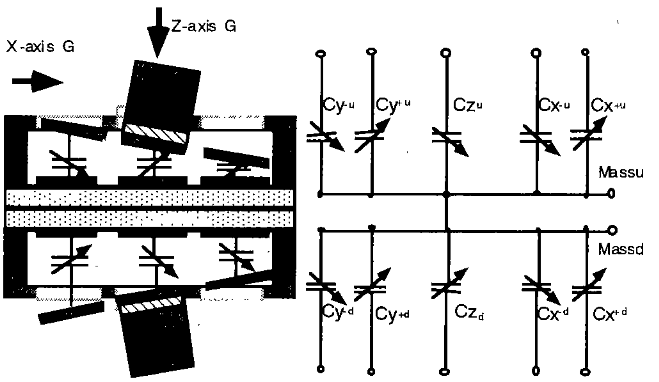


Fig.14. Compensation method using two accelerometers.

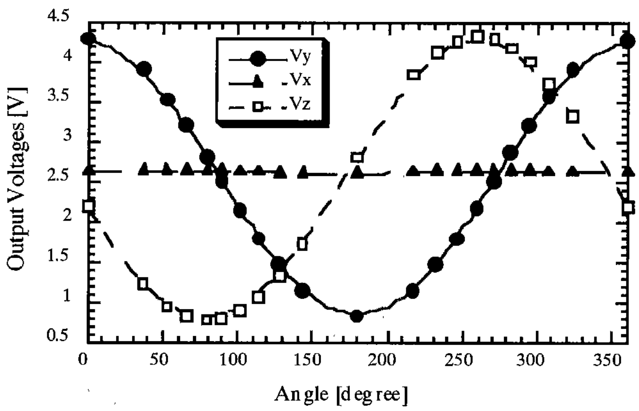
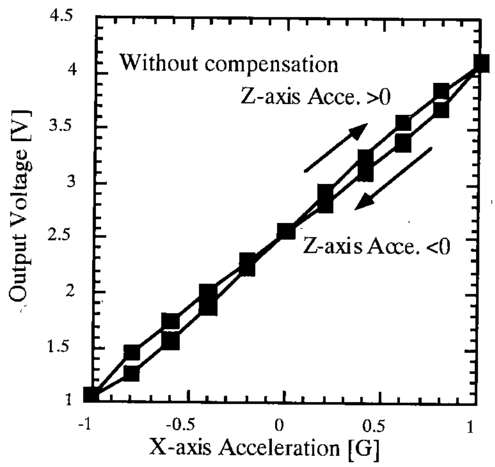
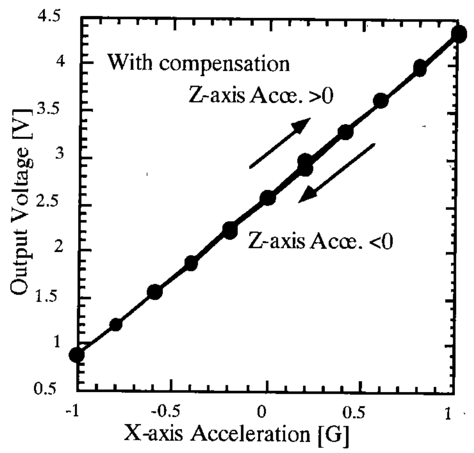


Fig.15. Output voltages of the switched capacitor circuit for Y,Z-axis ±1G acceleration using the compensation method.



(a) Without compensation method.



(b) With compensation method.

Fig.16. Z-axis dependence of X-axis output of the accelerometerusing the compensation method.

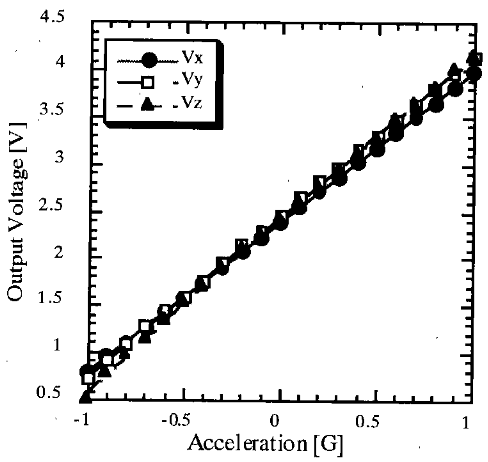


Fig.17. Three-axis outputs characteristics of the accelerometerusing the compensation method.

6.Conclusion

A capacitance detection CMOS ASIC has been developed, and the characteristics have been evaluated with three-axis capacitive accelerometer. And a novel compensation method for the Z-axis sensitivity dependence was proposed and confirmed in this paper. Three-axis output voltages of the switched capacitor circuit were proportional to three-axis accelerations. The sensitivity was 1.5V/G and the non-linearity for three-axis accelerations was less than 0.5%/F.S. The minimum detectable acceleration was about 1mG. The sensitivity non-linearity was less than 0.5%/F.S. by using the compensation method. The pulse density change of the 2nd order delta-sigma modulator was changed by the acceleration, and the offset and sensitivity of the modulator were calibrated by outer voltages. If the values are applied with D-A converter, and the digital signal is memorized with EEPROM, the offset and sensitivity can be digitally trimmed with outer digital signals. The performance of ASIC would be improved using a more precise CMOS process, and the hybrid package of the circuit and the high aspect mass accelerometer promise the low-cost and high performancethree-axis accelerometerin the future.

Acknowledgments

The research have been partly supported by MUPS project of Toyohashi University of techonology and TATEISI science and technology foundation.

(Manuscript received June 16, 2000, revised Oct. 24, 2000)

References

(1) R.T.Howe, B.E.Boser, A.P.Pisano, "Polysilicon integrated microsystems:technologies and applications", Sensors ans Actuators A56, 167-177 (1996).

(2) K.Okada, "Development of tri-axial accelerometers using piezoresistance,electrostatic capacitance and piezoelectric elements", Tech. Dig. of the 13th Sensor Symposium, 169-172 (1995).

(3) T.Mineta, S.kobayashi, Y.Watanabe, S.kanauchi, I.Nakagawa, E.Suganuma, M.Esashi, "Three-axis capcacitive accelerometer with uniform axial sensitivity", Proc. 1995 Int.Conf. Solid State Sensors and Actuators, 554-557 (1995).

(4) O.Torayoshiki, A.Takahashi, R.Tokue, "Capacitive type 3-axis accelerometer", Tech. Dig. of the 14th Sensor Symposium, 19-22 (1996).

(5) H.Takao, Y.Mastumoto, M.Ishida, "A monolithically integrated three axial accelerometer using stress sensitive CMOS differential amplifiers", Tech. Digest of 1997 international conference on solid-state sensors and actuators, 1173-1176 (1997).

(6) M.A.Lemkin,B.E.Boser,D.Auslander,J.H.Smith, "A 3-axis force balanced accelerometer using a single proof-mass", Proc. 1997 Int.Conf. Solid State Sensors and Actuators, 1185-1188 (1997).

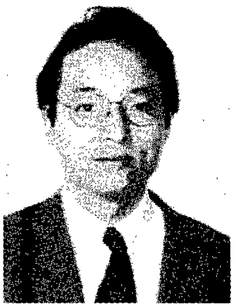
(7) Y. Matsumoto, M. Nishimura, M. Matsuura, M. Ishida, "Three-axis SOI capacitive accelerometer with PLL C-V converter" ,Sensors and Actuators A, Vol.75, 77-85 (1999).

(8) K. Yoshida, Y. Matsumoto, M. Ishida, K. Okada, "High-sensitive three axis SOI capacitive accelerometer using dicing method", Tech. Dig. of the 16th Sensor Symposium, 25-28 (1998).

(9) J-E. An, M-J. Son, K. Yoshida, Y. Matsumoto, M. Ishida, J-H. Lee, "Fabrication and characteristics of three axis capactive acceleromter using dicing method, Proc. of '99 conference on the korean sensors society, 275-278 (1999).

(10) Y. Yamaguchi, F. Katsumata, F. Nishida M. Nishimura, Y. Matsumoto, M.Ishida,"Small & high-sensitive three axis SOI capacitive accelerometer", Tech. Dig. of the 17th Sensor

Symposium, 221-224 (2000).
(11) M. Mizushima, M. Esashi," Capacitive 3-axis accelerometer using SOI wafer", Tech. Dig. of the 17th Sensor Symposium, 225-230 (2000).
(12) S. Kawahito, A. Koll, C.Hagleitner, H. Baltes, Y. Tadokoro, "Delta-sigma modulation sensor interface circuits with improved conversion gain for capacitive readout chemical sensors", Tech. Dig. of the 16th Sensor Symposium, 241-244 (1998).



Yoshinori Mastumoto (Member) received his B.E. and Ph.D. degree in electronic engineering from Tohoku University, Sendai, Japan in 1988 and 1993, respectively. From 1993 to 1999, he was a research associate at the department of Electric and Electronic Engineering of Toyohashi University of Technology. Since 1999, he has been an assistant professor of the Department of Applied Physics and Physico-Informatics, Keio University. His research interests include integrated capacitive sensors, integrated circuits and optical devices.

Shoji Kawahito (Member) received the B.E. and M.E. degrees in electrical and electronic engineering from Toyohashi University of Technology, Toyohashi, Japan, in 1983 and 1985, respectively, and the D.E. degree from Tohoku University, Sendai, Japan, in 1988. In 1988, he joined the Faculty of Engineering, Tohoku University. From 1989 to 1999, he was with Toyohashi University of Technology. He is currently a Professor with the Research Institute of Electoronics, Shizuoka University. From 1996 to 1997, he was a Visiting Professor at ETH Zurich. His research interests include high-sensitivity magnetic sensors, integrated smart sensors, integrated imaging devices, high-speed and high-sensitivity image sensors and mixed analog/digital LSI circuits.

Makoto Ishida (Member) received the Ph.D.degree in electronics engineering from Kyoto University, Kyoto, Japan, in1979. Since 1979 he has been at Toyohashi University of Technology, and he is a professor of electrical and electronic engineering. He is working on heteroepitaxial growth and processes of SOI material including epitaxial Al_2O_3 insulator and Si films, and their device applications for advanced semiconductor devices including sensors and IC in electron device research center in Toyohashi University of Technology.