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Tilt Characteristics of a MEMS Accelerometer fabricated by Multi-layer Metal Technology

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Abstract

This paper describes the tilt characteristics of a MEMS accelerometer with an Au proof mass. We analytically and experimentally investigate the tilt noise and the capacitance of the accelerometer as a function of tilt degree. In conclusion, it is revealed that the MEMS accelerometer has a potential to detect sub-1m° tilt.

1. Introduction

MEMS (microelectromechanical systems) tilt sensors are widely used in various applications such as robot control, navigation system, and human-movement monitoring [1-2]. MEMS technology enables us to make small-sized tilt sensors with the performance of low-power consumption, low cost, and high reliability [3]. Tilt sensors utilize accelerometers to detect tilt degree, and thus the resolution of tilt sensors can be dominated by the accelerometer performance. Recently, we have developed a highly-sensitive MEMS accelerometer fabricated by multi-layer metal technology, as schematically shown in Fig. 1 [4]. In order to utilize this sensor as an inclinometer, we have investigated the tilt characteristics of a MEMS accelerometer fabricated by multi-layer metal technology.

In this paper, the tilt noise characteristics were analyzed by using a theoretical model, and the capacitance change as a function of tilt degree was experimentally obtained. With the measurement results, we evaluated the actual tilt noise and estimated the potential tilt resolution of the MEMS accelerometer.

2. Principle

Resolution

By using a MEMS accelerometer, we can measure the tilt degree as a reference to gravitational acceleration. In a practical case, the tilt measurement is disturbed by thermo-mechanical noise, Brownian noise (B_n), on the proof mass of the accelerometer. B_n is defined as [5]

$$B_n = \frac{\sqrt{4k_B T b}}{9.8m}[\mathrm{G}/\sqrt{\mathrm{Hz}}], \qquad (1)$$

where k_B, T, and b are the Boltzmann constant (1.38×10^{-23} J/K), the absolute temperature, and the viscous damping coefficient, respectively. Tilt noise θ_n is determined by [6]

$$\theta_n = \sin^{-1}(\frac{\sqrt{4k_B T b}}{9.8m})[°/\sqrt{\mathrm{Hz}}]. \qquad (2)$$

Figure 2 shows analytical modeling of θ_n on proof mass. The proof mass made of gold can significantly reduce θ_n, as density of gold is much higher than those of other materials. Accordingly, using gold for proof-mass material could contribute to make small-sized and high-resolution MEMS tilt sensor.

Detection of Tilt Degree

Fig. 3 (a) shows inertial force acted on a MEMS accelerometer placed on a tilt table. A model of a single-axis MEMS capacitive accelerometer is shown in Fig. 3 (b). Capacitance C_M of the MEMS accelerometer is defined as

$$C_M = \varepsilon \frac{S}{d - \frac{9.8mG\cos\theta}{k}}[\mathrm{F}], \qquad (3)$$

where ε, S, d, k are the dielectric constant, the proof-mass area, the initial gap between the proof mass and the fixed electrode, and the spring constant, respectively. When MEMS accelerometer is tilted by θ, sensed acceleration is decreased by G-$G\cos\theta$, and proof mass moves the opposite direction from fixed electrode. Consequently, tilt degree θ can be sensed by observing C_M. From eq. (3), high density of proof mass can increase the sensitivity. Thus, using gold could be an effective approach to achieve high sensitivity for tilt sensing.

3. Experimental Results

A MEMS accelerometer with an Au proof mass fabricated by multi-layer metal technology is shown in Fig. 4 (a). The proof-mass footprint was designed to be 2.0 mm × 2.0 mm. Each proof mass corner was suspended by micromechanical suspensions. The fabricated MEMS accelerometer was connected with CDC (capacitance-to-digital converter: AD7745, Analog Devices) to compose a tilt sensor module, as shown in Fig. 4 (b). The size of the sensor module was 13 mm × 19 mm in area. The frequency response of the MEMS accelerometer was measured by the LCR meter (HIOKI E.E. IM3533-01). Figure 5 shows the capacitance and phase change as a function of the frequency of the sensing signal. The mechanical resonant frequency f_{res} and the quality factor Q were measured to be 445 Hz and 3.29, respectively. With the results, the actual B_n was estimated to be 398 nG/√Hz.

Then, by using eq. (2), the tilt noise of the MEMS accelerometer was evaluated to be 22.8 µ°/√Hz, as summarized in Table I. The tilt noise level shows a potential for sub-1m° sensing.

Experimental setup for tilt measurement is schematically shown in Fig. 6. The tilt sensor module was set on a tilt table where tilt degree was controlled by jacks. Capacitance change was measured by CDC, and the microcontroller (Arduino Due, Arduino) received digital codes from the CDC and sent the codes to a PC (personal computer) to store the data.

To investigate the tilt characteristics of the MEMS accelerometer, capacitance change as a function of tilt degree was measured as shown in Fig. 7. Tilt degree in Fig. 7(a) was measured by a reference tilt sensor (BBMO-66, MonotaRO). Tilt degree in Fig. 7(b) was calculated by the length L and the height H of the setup. The fitting curve in Fig. 7(a) was derived by eq. (3) with estimated parasitic capacitance. We confirmed that the accelerometer could follow the theoretical model within the tilt range from 0° to 180° (Fig. 7(a)), and showed capacitance change below 1° tilt (Fig. 7(b)).

4. Conclusions

Tilt characteristics of the MEMS accelerometer with an Au proof mass were investigated. We analytically and experimentally evaluated the tilt noise and the capacitance change as a function of tilt degree. In conclusion, it is revealed that the MEMS accelerometer has a potential to detect sub-1m° tilt.

Acknowledgements

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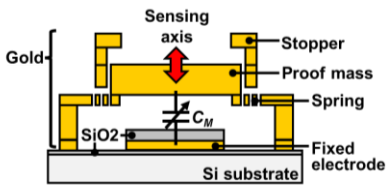

Fig. 1 Schematic of MEMS accelerometer fabricated by multi-layer metal technology.

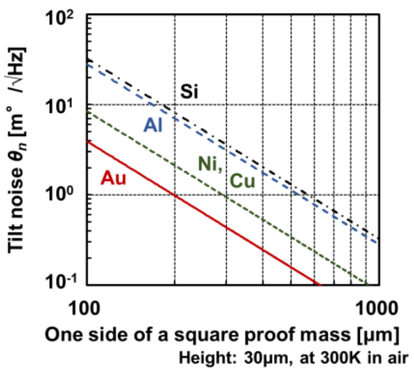

Fig. 2 Analytical modeling of tilt noise.

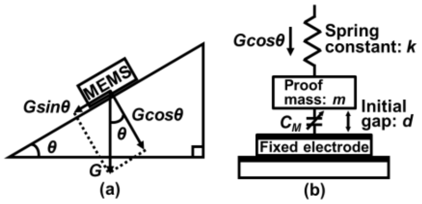

Fig. 3 Analytical models of (a) inertial force acted on a MEMS accelerometer placed on a tilt table, and (b) single-axis MEMS capacitive accelerometer.

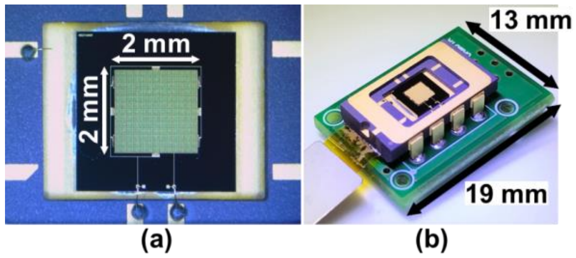

Fig. 4 Photos of (a) the MEMS accelerometer and (b) the sensor-module.

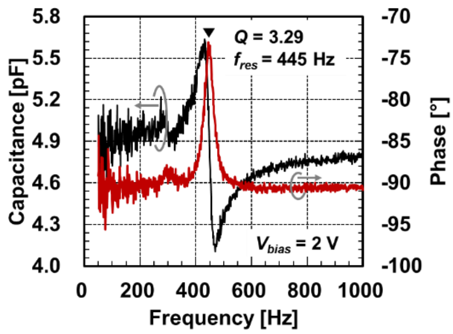

Fig. 5 Measured capacitance and phase as a function of frequency on the MEMS accelerometer.

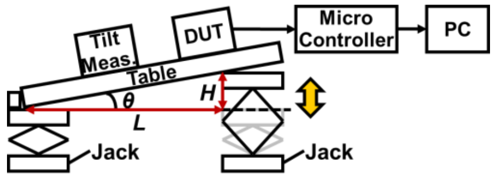

Fig. 6 Experimental setup for tilt measurement.

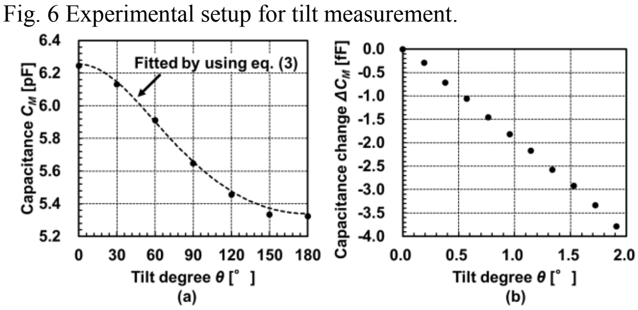

Fig. 7 Capacitance change as a function of tilt degree with ranges (a) from 0° to 180° and (b) from 0° to 2°.

Table I Design parameters of the MEMS accelerometer

	Measured	Design	Unit
m	9.27×10^{-7}	8.43×10^{-7}	kg
f_{res}	445	262	Hz
B_n	398	67.0	nG/√Hz
θ_n	22.8	3.84	µ°/√Hz