Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp974-975

A Sub-1G Tri-axis MEMS Capacitive Sensor for Integrated CMOS-MEMS Accelerometers

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Abstract

This paper reports a novel sub-1G tri-axis microelectromechanical systems (MEMS) capacitive sensor by employing the high-density of gold for the proof mass. All the MEMS structures have been fabricated by post complementary metal-oxide semiconductor (CMOS) process such that the sensor can be implemented as integrated CMOS-MEMS accelerometers. We demonstrate the capacitance shift as a function of input acceleration in X-, Y- and Z- axis, and the experimentally obtained Brownian noise have been below 1 μG/Hz$^{1/2}$ (G = 9.8 m/s^2).

1. Introduction

In recent years, microelectromechanical systems (MEMS) accelerometers have been playing a major role in a variety of motion sensing. Yet as with the performance requirements of potential applications [1,2], further improvement for the accelerometer should be realized in terms of device size, sensing range and resolution, and integration with complementary metal-oxide semiconductor (CMOS) circuits. Given the above background, we have proposed an integrated CMOS-MEMS accelerometer as shown in Fig. 1; by utilizing the high density of gold, we have demonstrated the reduction of the Brownian noise on the small-sized proof mass [3], the wide sensing range of the arrayed accelerometer [4], multi-axis sensing of above 1G [5, 6], and the capability of sub-1G (G = 9.8 m/s^2) sensing on a single-axis capacitive sensor [7]. In this work, we have succeeded in designing and implementing a sub-1G tri-axis capacitive sensor by employing gold electroplating used as a post-CMOS process, and hence the MEMS structure can be integrated as CMOS-MEMS accelerometers.

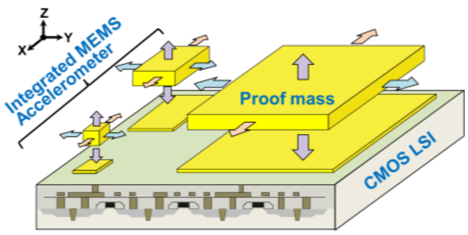

Fig. 1 Schematic image of an integrated CMOS-MEMS accelerometer for tri-axis sensing.

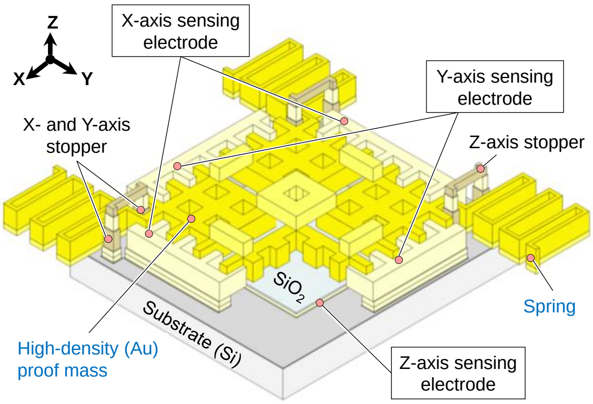

Fig. 2 Design concept of a sub-1G tri-axis MEMS capacitive sensor with a high-density proof mass.

2. Design Concept

Fig. 2 represents the design concept of sub-1G tri-axis MEMS capacitive sensor with a high-density proof mass. The gold electroplating [3] enables to integrate all the mechanical components with the optimized thickness for each

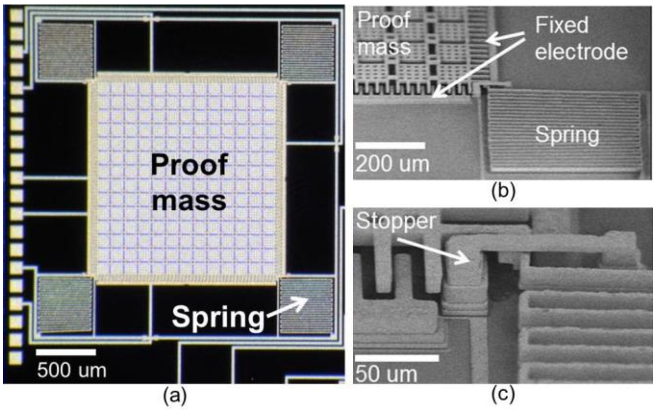

Fig. 3 Fabrication results. (a) chip view. (b) SEM image and (c) its close-up view.

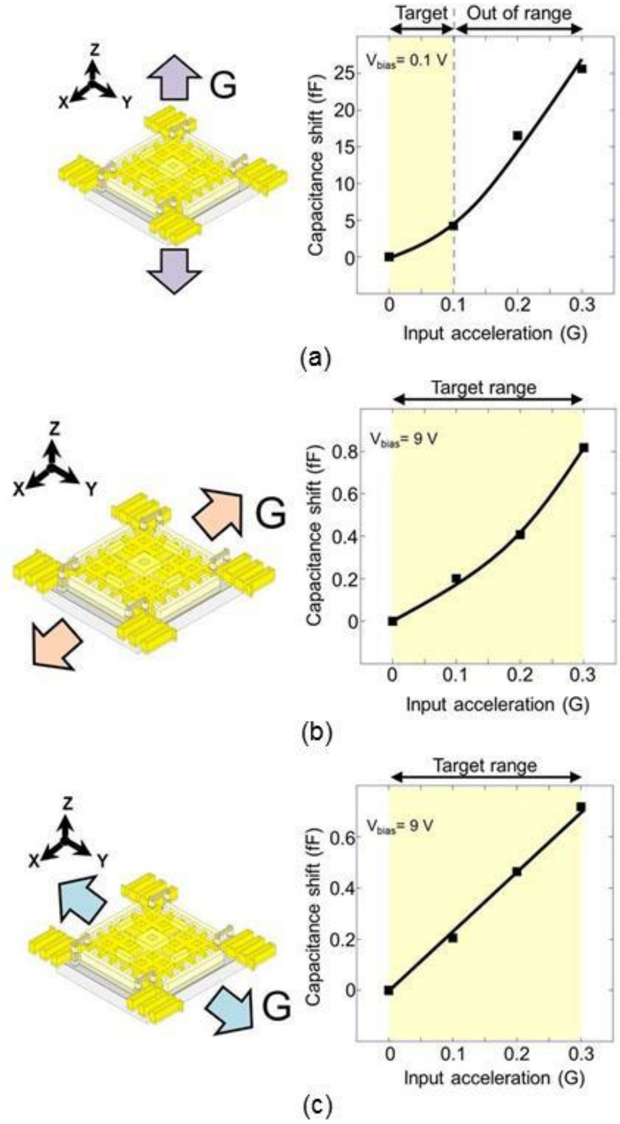

Fig. 4 Measured capacitance shift as a function of input acceleration in (a) Z-axis, (b) X-axis, and (c) Y-axis directions.

part by using multi-layered metal structures; the side electrodes for X- and Y-axis sensing allow the single piece of proof mass to function as a tri-axis inertial sensor. The folded mechanical springs benefit to obtain the optimal spring constants for tri-axis sensing of the sub-1G sensor. To enhance the capacitance shift, we adopt comp-type side electrodes. At each corner of the proof mass, we set stoppers to avoid self-destructions of the movable parts at higher acceleration. The proof mass is segmented into several sub-blocks and cross-linked by the additional metal layer to moderate the metal warpage.

3. Experimental Evaluations

Demonstration of Capacitance Shift

Fig. 3(a) shows the developed tri-axis MEMS capacitive sensor, and the scanning electron microscope (SEM) images of the sensor are shown in Fig. 3(b) and (c). To verify the capacitive sensing capability as an inertial sensor, we have experimentally measured the capacitance characteristics as a function of the input acceleration on each sensing axis as shown in Fig. 4. The vibration exciter (WaveMaker05, ASAHI SEISAKUSYO Ltd.) applied the input acceleration with the minimum resolution of 0.1-G and at the acceleration frequency of 19.9Hz. The capacitance values were measured on the semiconductor device analyzer (B1500A, Agilent Tech., Inc.) by applying the dc bias voltages. Within the designed sensing range, as shown in Table I, we confirmed that the developed sensor showed the capacitance shift in each axis.

Table I Device parameters and characteristics

	Sensing axis		
	Z	X	Y
Designed sensing range (G)	± 0.1	± 0.3	± 0.3
Designed Brownian noise (μG/Hz$^{1/2}$)	0.30	0.30	0.30
Measured proof mass (kg)	2.08×10^{-7}		
Estimated Brownian noise (μG/Hz$^{1/2}$)	0.28	0.28	0.28

Brownian Noise Characteristics

Table I summarizes the device parameters and characteristics, and the Brownian noise estimated by using the measured proof mass have a good agreement with the designed ones. According to our previous study [7], the developed tri-axis MEMS capacitive sensor provides the minimum detectable acceleration of below 1mG in each axis.

3. Conclusions

A novel sub-1G tri-axis MEMS capacitive sensor was realized with a single high-density proof mass. We have experimentally confirmed the capacitance shift within the target acceleration. The estimated Brownian noise has shown sub-1mG sensing potential of the developed sensor, indicating a promising result for broadening the sensing range of integrated CMOS-MEMS accelerometers.

Acknowledgements

The authors would like to thank Prof N. Ishihara, Associate Prof. H. Ito, Dr. T. Maruno, Dr. Y. Akatsu, M. Yano, K. Kudo, and M. Fujinuma for technical discussion. This work has been supported by the Grant-in-Aid for Scientific Research (B) (No. 23360149) of the Japan Society for the Promotion of Science (JSPS).

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