Sensors and Actuators A 243 (2016) 43–51

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A double differential torsional accelerometer with improved temperature robustness

Dingbang Xiao[a,b,*], Dewei Xia[a,b], Qingsong Li[a,b], Zhanqiang Hou[a,b], Gao Liu[a,b], Xinghua Wang[a,b], Zhihua Chen[a,b], Xuezhong Wu[a,b]

[a] College of Mechatronics Engineering and Automation, National University of Defense Technology, Changsha, China
[b] Laboratory of Science and Technology on Integrated Logistics Support, National University of Defense Technology, Changsha, China

ARTICLE INFO

Article history:
Received 8 June 2015
Received in revised form 8 March 2016
Accepted 9 March 2016
Available online 15 March 2016

Keywords:
Torsional
Accelerometer
Double differential
Temperature robustness

ABSTRACT

This paper reports the design, realization and characterization of a novel double differential torsional MEMS accelerometer with improved temperature robustness. Based on the structure of conventional torsional accelerometers, normally composed of two unbalanced proof masses and an identical torsional beam, this work explores a torsional accelerometer with two structural optimizations aiming to improve the temperature robustness: a double differential configuration and an on-chip integrated reference capacitor configuration. The double differential configuration realizes the temperature self-calibration by making the two pairs of unbalanced masses have the same sensitivity to temperature but opposite sensitivity to acceleration. And the on-chip integrated reference capacitor realizes the temperature self-calibration by transferring the temperature dependent reference capacitor from ASIC or PCB into the MEMS structure. Totally ten accelerometer prototypes are fabricated with the pre-buried mask wet-etching method and tested. Comparison tests show that, for most of the accelerometers, by taking the double differential configuration and the on-chip integrated reference capacitor configuration, the temperature sensitivity of the scale factor, the bias stability and the output drift of in the full temperature range are greatly improved. The testing results experimentally demonstrate the effectivity of the optimization for improving temperature robustness.

1. Introduction

The MEMS market is year after year growing faster than the average semiconductor industry and accelerometers is widely used in most of the MEMS products [1]. Many kinds of MEMS accelerometers are reported recently, such as capacitive accelerometers [2–4], resonant accelerometers [5–8], optical accelerometers [9] and so on. Compared with the capacitive accelerometers, resonant and optical accelerometers have the ability to achieve better performances, but the structures are more complex and the cost is higher. This paper mainly focuses on the research of the capacitive accelerometers. Among capacitive accelerometers, the torsional accelerometer is one of the most popular structures for its simple design and low cost. The typical torsional accelerometer consists of a torsional beam and two proof masses suspended on it [10–13]. When it is accelerated in the out-plane direction, the two masses lose their balance and the beam gets a torsional deformation, resulting to differential output capacitance. While torsional accelerometers have proved themselves as successful devices, significant challenges remain in increasing their long term and temperature robustness, because the characteristics of the torsional beam have large temperature dependence. To get high end accelerometers which can be used in precise measurement and complex surrounding, temperature robustness and stability of accelerometers should be improved. A fabrication process was presented to solve the structure curling problems [14] and environment-resistant packaging technology was developed to improve the temperature robustness of MEMS sensors [15], but the methods are complicated and expensive. The fully differential z-axis accelerometer with torsional structures and planar comb fingers was reported to improve the temperature robustness [16], but the design had no ability to decline the error caused by the torsional deformation of the beam which was resulted from thermal stress.

Inspired from the high performance butterfly gyroscope [17,18] and the differential vibrating beam accelerometer [19], this paper presents an optimized torsional accelerometer with self-calibration against dynamic environment changes, mainly focuses

* Corresponding author at: National University of Defense Technology, Changsha, Hunan 410073, China.
E-mail address: dingbangxiao@nudt.edu.cn (D. Xiao).

http://dx.doi.org/10.1016/j.sna.2016.03.011
0924-4247/

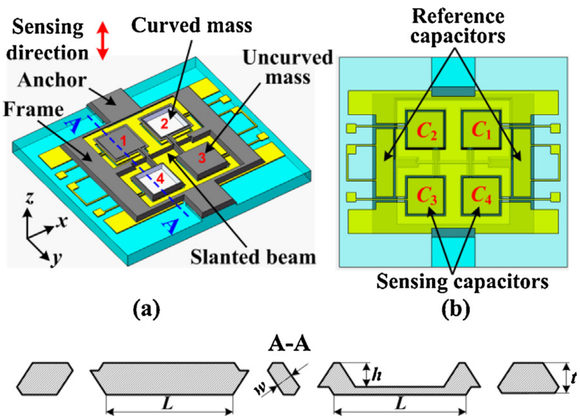

Fig. 1. Design model of the torsional accelerometer. (a) Front view of the micro structure and (b) back view of the micro structure. A–A shows the cross section of the silicon structure.

on two optimizations: a double differential configuration and an on-chip integrated reference capacitor configuration. The temperature self-calibration principles are analyzed in this paper and prototypes are fabricated. By taking comparison tests for the former structure and the optimized structure, it shows that the temperature sensitivity of the scale factor, the bias stability and the output drift in the full temperature range are improved greatly by taking the optimizations, experimentally demonstrating the effectivity of the optimizations for improving temperature robustness.

2. Design of the novel torsional accelerometer

2.1. Structure design and working principle

Design model of the novel torsional accelerometer can be illustrated schematically in Fig. 1. It consists of a glass substrate and a silicon structure bonded to it. The silicon structure comprises four proof masses, a slanted beam and a stress release frame. The slanted beam is formed by silicon wet-etching from reverse directions on its two different sides. And the stress release beam on the frame is designed to be asymmetry to ensure the same area of the two anchors. It can be seen that all the masses are suspended on the identical slanted beam and in the four masses, mass 2 and mass 4 are etched with a defined depth to realize the unbalanced mass. A pair of curved mass and uncurved mass (e.g. masses 1 and 4) composes a differential structure of the torsional accelerometer. As the two curved masses locate on the different sides of the beam, the two differential structures will rotate reversely when out-plane acceleration is applied. For example, when the device is accelerated in the positive z direction, masses 1 and 3 will go downwards while masses 2 and 4 go upwards, as shown in Fig. 2(a). Under each mass, an electrode is made on the substrate to form a capacitor. Because the differential structures are suspended on the identical beam, the torsional angles will be the same based on the fundamental beam theory [20]. Thus, the input acceleration can thus be related to the double difference of the four output signals by

$$a \propto (Out_2 + Out_4) - (Out_1 + Out_3), \quad (1)$$

herein, Out_i, i = 1–4, is the capacitance between the mass i and the bottom electrode.

Geometrical parameters and theoretically predicted performances of the novel designed accelerometer are listed in Table 1. In which, the theoretically predicted performances are obtained by the finite elements method (FEM) simulation.

Table 1
Geometrical parameters and theoretically predicted performances of the sensing element.

Description	Symbol	Value
Wafer thickness	t	240 μm
Curved depth	h	220 μm
Cantilever width	w	40 μm
Effective area of each sensing capacitor	A_0	4.0 mm^2
Original gap of the capacity	d_0	8.0 μm
Theoretical original capacitance of sensing capacitor	C_0	4.425 pF
Effective area of each reference capacitor	A_f	4.2 mm^2
Theoretical capacitance of each reference capacitor	C_f	4.65 pF
Mechanical sensitivity along z axis	S_z	0.068 pF/g
Fundamental resonance	f_0	1814 Hz
Measuring range	R_a	±15 g

2.2. Temperature self-calibration with the double differential configuration

Material properties of the silicon beam are easily to be influenced by the temperature, meanwhile, the coefficients of thermal expansion of silicon and glass are different, resulting the temperature dependency of the device. In the previous designs, consisting of only one pair of differential masses, the output errors caused by temperature drift cannot be declined [10–13,16]. However, the accelerometer proposed in this paper realizes the temperature self-calibration by the design of double differential configuration, greatly improving the temperature robustness.

In the fabrication process of MEMS sensors, there are lots of errors which will influence the performance of the sensors, in which the most important error is the structure asymmetry. To solve the problem, a special suspending frame is designed in accelerometer as shown in Fig. 1. The frame includes two parts: the wide beams with high stiffness and the narrow beams with low stiffness, which ensure smaller deformation and stress are located on the wide beams. The frame will have deformations along z direction, around x axis and around y axis resulting from the structure asymmetry and temperature changing, which will induce the output drift in the single differential configuration accelerometers. However, in the new designed double differential configuration accelerometer, all these errors can be reduced. When the frame has a deformation along z direction, all the capacitances will be smaller or bigger simultaneously with the same degree but the double differential output calculated by Eq. (1) will keeps invariant. Also, when the frame has a deformation around x axis, the capacitances 1 and 2 will have the same change while the capacitances 3 and 4 will have the inverse change, which also makes the double differential output be invariant. At last, when the frame has a deformation around y axis, the capacitances 2 and 3 will have the same change while the capacitances 1 and 4 will have the inverse change, which also makes the double differential output be invariant. So, theoretically, the double differential structure can realize the cancellation of any error induced by the fabrication and environment changing.

The simulation results are shown in Fig. 2. When the temperature is applied, the suspending frame has a deformation both along z direction and around x axis, resulting the change of each capacitor. However, from the comparison of the three figures in Fig. 2, it can be seen that the two masses on the identical side of the beam have the same sensitivity to temperature but opposite sensitivity to external acceleration. Thus, by taking the double differential calculation in Eq. (1), errors caused by the temperature drift can be declined, enabling drift free measurement of external acceleration.

To evaluate the proposed self-calibration concept, the thermal simulation for the novel accelerometer is taken from +60 °C to −40 °C without external acceleration. The output capacitances of each mass and the double differential results are shown in Fig. 3. It can be seen that capacitor 1 and 2 have 2.6 fF (38 mg) drift and