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A high-performance multi-beam microaccelerometer for vibration monitoring in intelligent manufacturing equipment

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ABSTRACT

A piezoresistive microaccelerometer with multi-beam structure is developed for vibration monitoring in intelligent manufacturing equipment. The proposed accelerometer provides a promising solution to the trade-off between the cost-effective development and demands on high-performance sensors. By incorporating tiny sensing beams, the multi-beam accelerometer obtains a higher resonant frequency and favorable measurement sensitivity compared with the quad-beam one. Theoretical analysis and finite element method (FEM) simulation demonstrate satisfactory results of an improved resonant frequency increased by a factor of 1.81 at the expense of slight sensitivity loss. Fabricated on an n-type single crystal silicon wafer, the sensor chips with multi-beam structure and quad-beam structure are wire-bonded to printed circuit boards (PCBs) and simply packaged for experiments. The static and dynamic characteristics of the two types of sensors are tested and compared. The temperature coefficient of offset output is also measured. The results show that the developed accelerometer has favorable features that allow its usage in the demanding application.

1. Introduction

Intelligent manufacturing equipment requires the usage of sensor technology and expert system to determine processing state, predict potential failure, enhance production efficiency and ensure plant safety. One of the key tasks for the intelligent equipment is to monitor its working status in terms of detecting spindle vibration, cutting force, working temperatures, etc. Among these parameters, vibration directly presents the working status and determines the product quality [1,2]. In machines, anomalous vibration usually appears in the form of velocity, displacement or acceleration and can be measured by velocity sensor, displacement probe and accelerometer [3,4], respectively. As for practical applications, accelerometers are the most appropriate vibration sensors for high-frequency surveillance because of their easy installation and good universality [5]. However, with the development of intelligent manufacturing equipment and wireless state monitoring technique, the common piezoelectric sensors used in practical cannot satisfy the new requirements for miniaturization and low cost despite their appropriate characteristics for high frequency vibration detection [5,6].

Since the first silicon based micromachined accelerometer developed in 1979 [7], MEMS accelerometers have achieved great success in many commercial applications, stimulated by the advantages offered by bulk and surface micromachining techniques, viz. low power consumption, miniaturization and low cost [8,9]. The diversity of transduction mechanism has allowed MEMS-based accelerometers to substitute those conventional ones in numerous applications. Among these sensors, the piezoresistive accelerometer is an important alternative in vibration monitoring, whose remarkable improvements have been achieved by many different sensing configurations, e.g. cantilever beam-mass structure, quad-beam structure and twin-mass structure [10–13]. Additionally, a couple of studies about characteristic improvements based on these structures have also been realized, such as incorporating stress concentration regions to cantilever beam-mass structure [14], electroplating metal layers on the top of proof mass in quad-beam structure [15]. The additional operations lead to higher cost, lower reliability and possible failure in fabrication though these proposals are efficacious. Meantime, some novel structural designs are also developed in piezoresistive accelerometers design. Huang et al. reported an in-plane accelerometer in which two axially stressed tiny beams were combined with a supporting cantilever [16]. This design greatly enhanced the sensitivity but its resonant frequency remained at a low level, and the similar structure can be found in [17]. A high-shock accelerometer with bonded hinge structure was demonstrated by Fan et al. Its measurable range was extended to 2×10^5 g with a resonant frequency up to 573 kHz,

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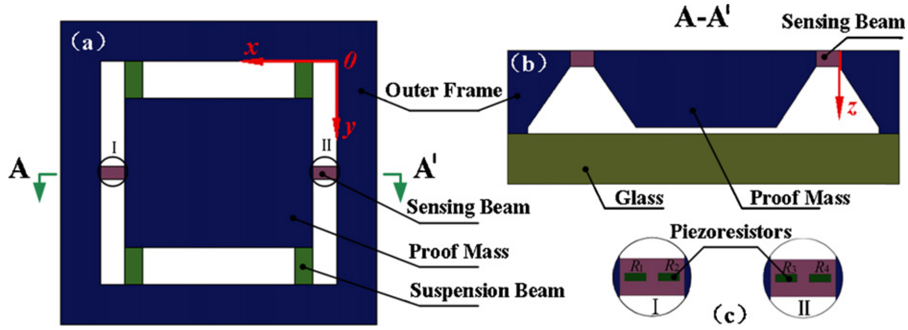

Fig. 1. Diagrammatic sketch of the multi-beam accelerometer: (a) the front view of the structure; (b) the cross-sectional view along A-A′; (c) piezoresistors in sensing beams.

but the sensitivity was only 0.516 μV/g/5 V [18]. Many approaches explored for high-performance accelerometers mainly concentrate on one aspect of the performance, but sacrifice the others. In theory, the acceleration-induced deformation is inversely proportional to the square of the resonant frequency [19]. When the frequency is increased, the sensitivity is inevitably decreased and vice versa. Vibration monitoring in high-speed spindle and fault diagnosis of early defect in bearings play a significant role in the condition monitoring of intelligent manufacturing equipment, especially the ones for aerospace [20,21]. Therefore, a microaccelerometer with resonant frequency above the interested range and high measurement sensitivity for weak acceleration acquisition is needed [22].

This paper aims at providing a cost-effective solution to the accelerometers requiring high resonant frequency and favorable sensitivity, which can be used in the vibration monitoring of intelligent manufacturing equipment. The requirements for the sensors are a resonant frequency of at least 10 kHz and a sensitivity of 0.5 mV/g/3 V. Considering the relatively large acceleration in the process of packaging or experiment installation, the measurement range is specified to 100 g. Focused on these performances, a MEMS-based piezoresistive accelerometer with multi-beam structure is developed. Theoretical and FEM model are established to analyze and verify the scheme. Bulk micromachining technique is used to fabricate the sensor chips and necessary characterization of the developed devices is presented. Finally, a short discussion is made about the experimental results and multi-beam structure design.

2. Modeling and design

The proposed multi-beam accelerometer is schematically shown in Fig. 1. The proof mass is suspended by two groups of beams: four normal suspension beams at the corner of the proof mass (quad beams) and two tiny beams along the centerline of proof mass (sensing beams). On each sensing beam, two identical diffused resistors are implanted along ⟨1 1 0⟩ crystal direction, and all resistors are interconnected, forming a full Wheatstone bridge. Under an acceleration a along z axis (the direction normal to sensor chip), the beams will be involved in a bending movement together with the vertical motion of proof mass. Since there is no rotation in the movement of proof mass, displacements of beam cantilever-ends are the same; the tiny sensing beams will obtain a larger stress compared with the suspension ones. Moreover, the additional tiny beams give the multi-beam structure a higher resonant frequency.

Dimensions (length × width × thickness) of sensing beams and suspension beams are $a_1 \times b_1 \times h_1$ and $a_2 \times b_2 \times h_2$, respectively. Let F_1 and F_2 be the total forces applied to sensing beams and

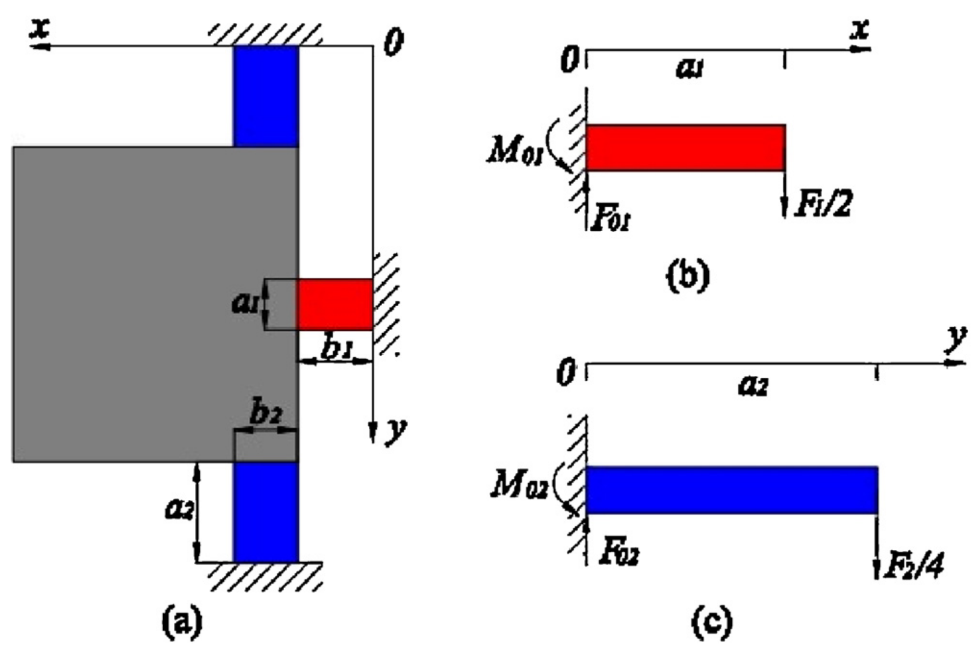

Fig. 2. Simplified model for the multi-beam structure: (a) dimensions of the beams; (b) model for the sensing beam; (c) model for the supporting beam.