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Research paper

Case studies of a planar piezoresistive vibration sensor: Measuring transient time history signal waves

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ABSTRACT

With the development of the economy, more and more social problems are exposed to us. There is a clear need for rational methods of monitoring the safety of civil structures over time. Similarly, home-security systems require several low-power sensor nodes in order to monitor the motion of windows or doors. On the other hand, by using a novel cavity-first micromachining process, a planar piezoresistive vibration sensor can be fabricated that has both a simple structure and fewer packaging difficulties. To determine whether such piezoresistive-based vibration sensors can satisfy previous demands, this paper presents a comprehensive evaluation of the given sensors. We measured random vibrations, transient time history waves, and earthquake vibrations using the developed vibration sensors. Before reporting the results of this evaluation, we offer an analysis of the sensor's functional features with regard to noise density. As the results show, the piezoresistive planar vibration sensor performs ideally and can be used to monitor residential security or the conditions of civil structures in real time. Moreover, we demonstrate how several advanced civilian and industrial applications are feasible with this sensor.

1. Introduction

With the development of microelectromechanical systems (MEMS) and techniques, many high-performance MEMS devices have been invented and implemented. For instance, temperature sensors are suitable in a wide range of applications [1,2]. Capacitance and hygrometric-based humidity sensors can be used to measure changes in humidity [3,4]. MEMS sensors are also widely used to measure pressure [5,6], motion, and vibration [7], among other physical phenomena.

In particular, vibration-detecting acceleration sensors have multiple applications in industry and science. For example, accelerometers are used to detect and monitor vibrations in rotating machinery [8]. In the military, highly sensitive accelerometers are components of inertial navigation systems for aircraft and missiles [9]. In the civilian domain, accelerometers are widely used in tablet computers and smartphones to ensure that images on screens are always displayed upright [10].

Principally, a vibration sensor (accelerometer) has a proof mass on one or several spring structures. When the vibration sensor experiences acceleration, the proof mass is displaced, and the displacement is then measured to give the acceleration value. Technically, capacitive- [11] and piezoelectric- [12] based vibration sensors are being used increasingly, because these sensors offer many advantages: small size, high responsivity, low power consumption, etc.

However, motion-detecting sensors are normally installed in complicated and variable environments. Moreover, in order to improve the testing accuracy, a group of long-term workable sensors should be set in one system and calibrated to each other. Thus, the operation and maintenance costs of a sensor system can be controlled. However, capacitive-based sensors require vacuum packaging in order to eliminate environmental influences. Moreover, piezoelectric material (effect unit of piezoelectric sensor) has several complicated and high-cost flow paths in preparation, seriously restricting its applications. In contrast to capacitive and piezoelectric techniques, piezoresistive-based sensors are not sensitive to environmental change. Indeed, the piezoresistive effect only results in a change in electrical resistance, offering a straightforward and robust approach to signal detection. As a result, only piezoresistive-based vibration sensors can satisfy the above demands: viz., long-term use, easy integration, and low cost.

Previous works [13,14] have focused on the practical need for environmental robustness (i.e., for sensors that are not sensitive to environmental change), along with low-power consumption and easy signal processing. In these works, a planar mode piezoresistive vibration sensor was successfully developed using the front-side-only micromachining technique with a low-cost process and fewer packaging difficulties. A Wheatstone bridge piezoresistive gauge was designed on the surface of the thin flexure to detect vibration-induced strain at

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the fixed end of the proof mass. Finite element analysis (FEA) by ANSYS® was carried out to configure the layout of these piezoresistors, in order to ensure responsivity comparable to that achieved by other capacitive sensors or by a complicated 3D ion-implantation process.

The design guidelines for the planar vibration sensor were demonstrated. The effective dimensions of the fabricated sensor, including the length and width of the flexure beam, have been characterized with respect to the proof-mass angle on the responsivity. The responsivity of fabricated planar sensors of 0.09–0.46 mV/V/g was measured at a low frequency of 20 Hz. The functional features of the fabricated planar vibration sensors, including the amplitude-frequency response and free vibration response, have also been evaluated comprehensively [13]. The vibration sensor demonstrated good responsivity performance: when the frequency and amplitude of a measured sine signal is >6 Hz and 0.05 g, respectively, the planar sensor can stably and precisely provide the output due to the vibration. Other functional features such as the linearity and sweep output of the vibration sensor have also been evaluated [14].

As shown in Fig. 1, there is a clear need for rational and economical methods of monitoring the safety of civil structures over time. Similarly, home-security systems require several low-power sensor nodes to monitor the motion of windows or doors. Moreover, the population is aging at an unprecedented rate, and seniors need personal health-monitoring systems. In order to address these needs, planar sensors can be adopted in all three types of monitoring systems. To determine whether piezoresistive-based vibration sensors can satisfy these demands, this paper presents a comprehensive evaluation of these sensors. As a much-needed complement to previous work, our paper discusses the applications of this planar sensor. In this paper, we describe a planar mode piezoresistive vibration sensor, which was successfully fabricated using the novel MEMS method (i.e., the cavity-first process). As a result, the given sensor has a simple structure and fewer packaging difficulties. Several significant case studies of random vibrations, TTH signal waves, and earthquake waves were evaluated comprehensively. The noise level directly affects the performance of MEMS devices. We measured the output noise spectral density of the fabricated sensor. In doing so, one of most important mechanical properties of the given planar sensor can be understood. By comparing the response results, the planar sensor exhibited performance that was comparable to that of a high-quality commercial device.

2. Device fabrication and evaluation

Fig. 2 shows a schematic view of the fabrication process using the cavity-first method. The fabrication of the device was completed with the cavity-first process using six photo masks. The cavity-first method is a kind of front-side-only micro-machined process with high efficiency and low cost.

First, as with conventional MEMS fabrications, the process begins with a silicon-on-insulator (SOI) wafer. Boron diffusion is carried out to fabricate the piezoresistors (Fig. 2(a)). Then, unlike traditional methods, in order to etch the box layer to generate a cavity, release holes of several micrometers in diameter are fabricated with deep reactive plasma etching (DRIE). The box layer is then dry-etched with vapor-phase hydrofluoric (HF) acid (see Fig. 2(b and c)). The SiO_2 passivation layer is generated with a second thermal oxidation, and a patterned amorphous fluoropolymer is used to fill and cover the release holes, as shown in Fig. 2(d). AlSi metal is then sputtered and etched by ion milling to generate the electrodes (see Fig. 2(e)). After the annealing process for ohmic-contact between the AlSi and the piezoresistor, as Fig. 2(f) shown, O_2 plasma is used to remove the photoresist and other residuals.

Fig. 3 shows a scanning electron microscopy (SEM) image of the structure of the planar vibration sensor. The sensor has three reference piezoresistors with no proof-mass structure and a piezoresistor with a large proof mass. The four piezoresistors are connected in a Wheatstone bridge circuit. The Wheatstone bridge circuit unit can be used to measure acceleration or vibration due to shaking. As shown in Fig. 3, the sensor's structure contains a sector proof mass with a radius of 1 mm. This proof mass is supported by a high-aspect ratio 20 × 8 μm flexure beam. Precision microstructures can be obtained successfully with this cavity-first process. This device layout results in a final device die of <2 × 2 mm, which greatly reduces its production cost in foundries. Assuming this sensor can be mass-produced in 8 in. or 12 in. foundries, the manufacturing cost of one chip will be very low. Further details can be found in [15,16].

The insert in Fig. 3 shows a close-up of the piezoresistor unit. As shown in the image, the release holes are completely filled with an amorphous fluoropolymer. Moreover, because the release holes are etched at <4 μm in diameter, the proof-mass loss can be minimized, providing the sensor with relatively high responsivity. A close look at the image shows that small residuals (four micro-pillars) are retained tenaciously on the bottom surface of the cavity. These micro-pillars are the byproducts of the cavity-first process. Nevertheless, the micro-pillars do not affect the sensing function, since they are at a reasonable distance from the flexure beam. Moreover, micro-pillars can be eliminated when optimally designing the release holes.

A diffusion furnace (MSKTF-100200ES, Motoyama Co., Ltd.) was used to fabricate the piezoresistive gauge on the n-type silicon substrate. To etch the amorphous fluoropolymer with a desired pattern—and ultimately to remove the photoresist and other residuals—a reactive ion etching (RIE-10NRS SAMCO Co., Ltd.) was used. An inductively coupled plasma (ICP) etch system (MUC-21, SPP Technologies Co., Ltd.) was used to etch the SOI wafer to release the sensor structure. A rapid thermal processing system (AS-One, AnnealSys Co., Ltd.) was used during the annealing process to ensure that the

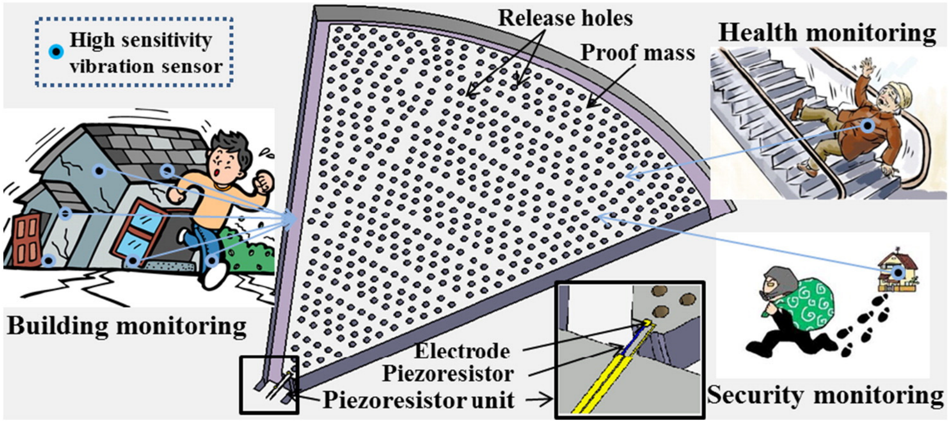

Fig. 1. Schematic view of our proposed planar vibration sensor with potential application fields.