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A novel sandwich capacitive accelerometer with a double-sided 16-beam-mass structure

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ABSTRACT

A novel sandwich capacitive accelerometer with a double-sided, 16-beam-mass structure is presented. In this design, the proof mass is supported by 16 tiny beams distributed uniformly on both sides, which aims to dramatically reduce the cross-axis response. Parameters of the beam-mass structure are analyzed and optimized by analytical modeling and the finite element analysis (FEA) method. The micro-accelerometer is fabricated by bulk micromachining technology, and the proof mass and tiny beams are released by KOH anisotropic wet etching from both sides of the silicon wafer, simultaneously. The resonance frequency and the quality factor of the accelerometer are 4.34 kHz and 311, respectively, which are measured in an open-loop system. The measurement results show that the accelerometer has a full-scale (FS) range of 30 g, a close-loop sensitivity of 80 mV/g, and a nonlinearity of 0.27% of FS. The cross-axis sensitivities are 0.353% (x/z axis) and 0.045% (y/z axis), respectively. The bias stability is 0.63 mg for an hour. The accelerometer can withstand high shock of over 10,000 g.

1. Introduction

The micro-electro-mechanical systems (MEMS) capacitive accelerometer is a well-known transduction mechanism that can convert a mechanical signal into an electrical signal. The capacitive accelerometers are used in automobiles, monitoring of high building vibration, inertial navigation systems, aerospace microgravity measurements, geological exploration and many other fields because of their advantages such as small size, integration ease, batch production, low noise, high sensitivity and low power consumption [1–9]. Therefore, the capacitive accelerometers have the ability to achieve high performance through optimum structure design and fabrication process improvement.

In MEMS, the beam-mass is used as the main sensitive structure to fabricate the capacitive accelerometer. Generally, there are two types of beam-mass structures: asymmetrically suspended proof mass and symmetrically suspended proof mass. The asymmetrically suspended proof mass always leads to high cross-axis sensitivity [10,11]. However, a symmetrically sensitive structure can reduce the cross-axis sensitivity dramatically. As reported, the symmetrically double-sided beam-mass structure can be realized mainly through three methods. First, the symmetrical beam-mass structures are realized through the silicon-silicon bonding technique as described in [11] and [12]. Relatively speaking, this technique has a complicated fabrication process in which the final proof mass is formed by bonding two-separated proof mass on each silicon wafer. Therefore, the performance of the accelerometer is affected by the deviation of the alignment during silicon-silicon bonding process. In addition, the complication in [11] is the four-layer (glass/Si/Si/glass) structure with double Si-glass bonding. Second, the symmetrical beam-mass structures are fabricated with a double-device-layer, silicon-on-insulate (D-SOI) wafer in [13] and [14]. The proof mass is formed by a single D-SOI wafer without bonding. However, the wire bonding is not very convenient as one of the middle electrodes is on the back. Most importantly, the thickness of the top silicon in a D-SOI wafer must be the same thickness as the spring beams, and the thickness of the spring beams cannot be adjusted during the fabrication process. Third, the symmetrical beam-mass structures are realized by only one conventional silicon wafer as reported in [15–17]. For beam formation during the device fabrication process, the method of self-stop etching in heavily boron-doped silicon is employed in [15], which has intrinsic, adverse mechanical and electrical properties. The thickness of the spring beams is determined by the depth of the heavily boron-doped silicon. The cross-section of the spring beams in [16] and [17] is "V"-shaped and is formed by KOH anisotropic wet etching. However, the "V" shape is not entirely uniform along the length of the beams.

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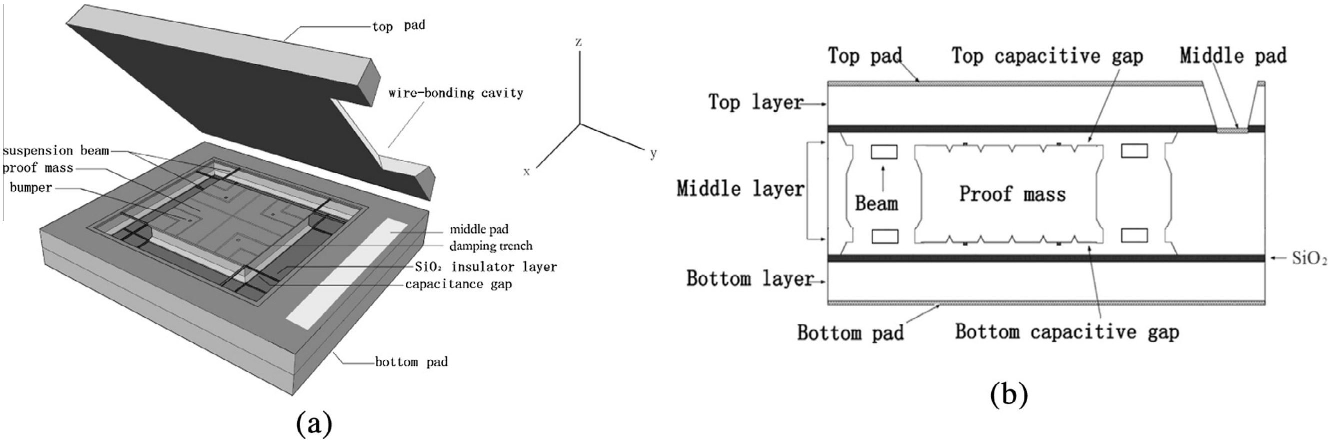

Fig. 1. Schematic structure of the accelerometer: (a) top view and (b) cross-sectional view.

Table 1
Physical dimensions of the accelerometer.

Properties	Name	Value
Length, width, thickness of mass	L_{mass}, W_{mass}, T_{mass}	3000 μm, 3000 μm, 420 μm
Weight of the mass	M_{mass}	8.8 mg (calculation value)
Length, width, height of beam	L_{beam}, W_{beam}, h_{beam}	400 μm, 20 μm, 20 μm
Initial capacitance gap	d_0	3 μm
Insulated SiO_2 thickness	t_{SiO_2}	2 μm

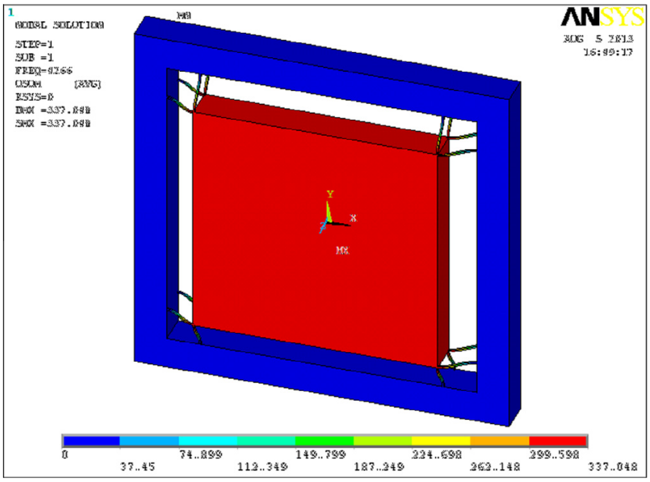

Fig. 2. First natural mode of the beam-mass structure.

To overcome the shortcomings mentioned above, a novel sandwich capacitive accelerometer with an entirely symmetrical 16-beam-mass structure is designed and realized. The 16-beam-mass structure exhibits symmetry around its proof mass. The design uses a full support configuration with 16 silicon spring beams connected to 8 corners of the proof mass, which aims to reduce the cross-axis sensitivity. Parameters of the beam-mass structure are designed and simulated. The highly symmetrical beam-mass structure is etched by KOH anisotropic wet etching of a (100) wafer, followed by a sandwich wafer level bonding and packaging. The fabrication process and measurement results are presented.

2. Structure design, analytical modeling and simulation

2.1. Structure design

To reduce the cross-axis sensitivity of the micro-accelerometer, a highly symmetrical sandwich capacitive accelerometer is designed. The highly symmetrical beam-mass structure has high structure stability and low cross-axis sensitivity. A schematic structure of the accelerometer with a 16-beam-mass structure is shown in Fig. 1. As shown in Fig. 1, the accelerometer consists of a top layer electrode, bottom layer electrode, and middle layer electrode for the beam-mass structure. The proof mass is sensitive to the *z*-axis acceleration signal. Both surfaces of the proof mass are used as the middle movable electrodes, and the top layer and bottom layer electrodes are used as the fixed electrodes. The thermal

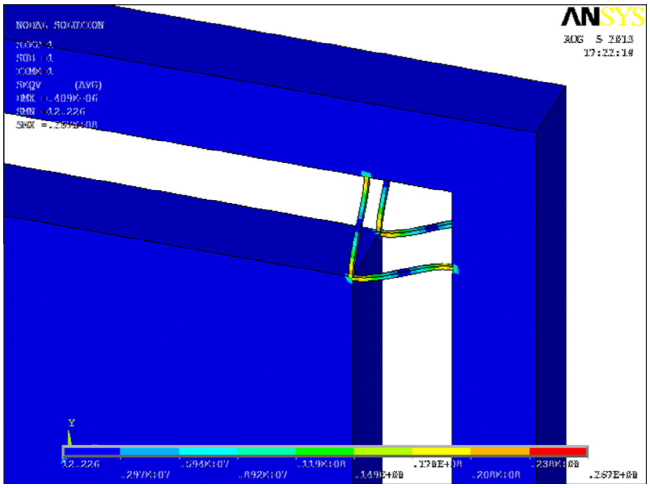

Fig. 3. Maximum displacement and von Mises stress.

Table 2
The results of the analytical modeling and simulation.

Properties	Analytical modeling	Simulation
First mode resonance frequency	4.422 kHz	4.266 kHz
Mechanical sensitivity	1.269E–2 μm/g	1.36E–2 μm/g
Capacitance sensitivity	0.209 pf/g	0.224 pf/g
Von Mises stress	–	26.70 MPa