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A low cross-axis sensitivity piezoresistive accelerometer fabricated by masked-maskless wet etching

Jianqiang Han*, Zhengqian Zhao, Wenju Niu, Rongyu Huang, Lizhen Dong

The College of Mechanical & Electrical Engineering, China Jiliang University, Hangzhou, 310018, China

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ABSTRACT

The paper focuses on the design, simulation, fabrication and experiment of a low cross-axis sensitivity piezoresistive accelerometer fabricated by masked-maskless wet etching in iodine-supersaturated KOH solution. The piezoresistive accelerometer consists of a proof mass, eight supporting beams and four sensing beams. The sensing beams are located at the top surface of silicon chips in order to pattern piezoresistive resistors and metal lines. A boron-diffused piezoresistive Wheatstone bridge is located at the frame-side end of a sensing beam to detect the strain. The gravity center of the proof mass lies within the neutral plane of supporting beams to minimize the rotation of the proof mass under in-plane acceleration. Compared with accelerometer of which the supporting beams located at the surface of chips, the rotating angle of the newly designed sensor under in-plane acceleration is reduced by 98.91%. Preliminary experimental results show that the cross-axis sensitivity under X and Y acceleration is 1.67% and 0.82%, respectively.

1. Introduction

Accelerometers are used in various fields such as automotive industry, aerospace engineering, military, medical and biological engineering, robotics and so on. There are different sensing mechanisms such as piezoresistive, capacitive, piezoelectric and resonant type to convert acceleration into electrical signals. Among these sensing mechanisms piezoresistive technique is widely used because of its simple structures and read out circuits, good DC response, high sensitivity, linearity and reliability, high inherent ruggedness, low cost [1–13].

Although various structures of piezoresistive accelerometers were proposed, most of these structures are asymmetrical along Z axis, i.e. the neutral plane of supporting beams kept well above the gravity centre of the proof mass due to bulk micromachining technique. These piezoresistive accelerometers have a disadvantage of high cross-axis sensitivity. Various structures have been proposed to reduce cross-axis sensitivity by arranging resistors at specific regions, such as two beams structure [14], cantilever-membrane structure [15], four beams structure [16], six-beam structure [17,18], eight-beam structure [19]. However, the complicated metal interconnections on the beams have detrimental effects on the performance and yield [18]. More importantly, the proof mass will rotate when in-plane acceleration is input.

KyuHyun Kim proposed a skew-symmetric cantilever accelerometer to reduce the transverse sensitivity, but a projection aligner must be used to focus and exposure the resistors and aluminum electrodes on the stepped wafer surface [20]. Selectively electroplating a copper [21] or gold layer [22] atop the proof mass can shift the center of the proof mass toward the beam plane and reduce transverse sensitivity. The method has a sound effect but the additional operations will lead to additional fabrication process, higher cost and even more possible interconnection failure in Wheatstone bridge [19].

The paper presents a novel piezoresistive accelerometer consisted of a proof mass, eight supporting beams and four sensing beams. The gravity centre of the proof mass lies within the neutral plane of supporting beams to minimize the rotation of the proof mass under in-plane acceleration.

2. The mechanism of piezoresistive accelerometers

2.1. The structure of piezoresistive accelerometers

The developed piezoresistive accelerometer is schematically shown in Fig. 1. A proof mass is supported by eight elastic supporting beams with isosceles triangle cross section and four thin sensing beams with isosceles trapezoid cross section. The included

* Corresponding author.
E-mail address: hjqsmx@sina.com (J. Han).

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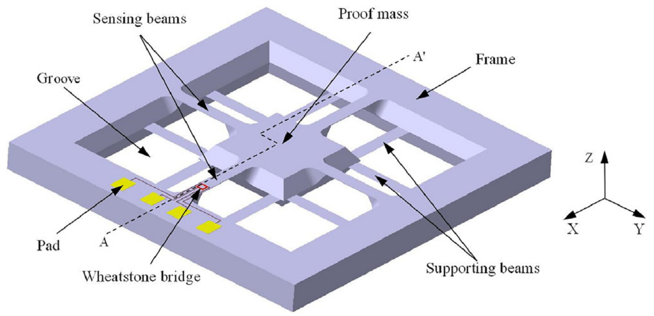

Fig. 1. The three-dimensional schematic of the piezoresistive accelerometer.

Table 1
The geometry of the piezoresistive accelerometer (unit: μm).

Sensing beams	Length(L_1)	592
	Width(b_1)	180
	Thickness(h_1)	h_{Si}=4, h_{SiO2}=0.6, h_{Si3N4}=0.3, $h_{a\text{-}Si}$=0.47
Supporting beams	Length(L_2)	880
	Width(b_2)	150
	Thickness(h_2)	25
Proof mass	Length	1000
	Width	1000
	Thickness(H)	389

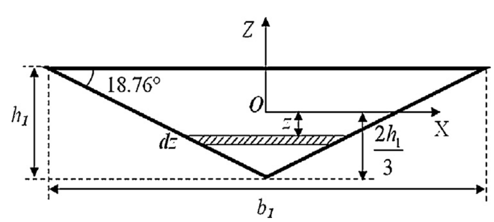

Fig. 2. The cross section of a supporting beam.

angle between the side flank and the top surface of supporting beams is 18.76°. The supporting beam has such shape because of the maskless wet etching and the process will be shown later. The sensing beam consists of four materials, which are successively a 0.47-μm-thick amorphous silicon film, several microns thick silicon layer, a 0.6-μm-thick silicon dioxide film and a 0.3-μm-thick silicon nitride film from bottom to top. The thin sensing beams are located at the top surface of the sensor chip in order to pattern piezoresistive resistors and metal lines. The geometry of the piezoresistive accelerometer is shown in Table1. A piezoresistive Wheatstone bridge made from polysilicon film on the silicon nitride film is arranged at the maximum stress region of sensing beams. The distance from the center of the Wheatstone bridge to the frame is 60 μm. The gravity center of the proof mass lies within the neutral plane of supporting beams to minimize the rotation of the proof mass under in-plane acceleration. Under a Z-axis acceleration, the proof mass, the free ends of supporting beams and sensing beams moves upward and downward. The deformation of sensing beams is detected by the piezoresistive Wheatstone bridges at the clamped.

2.2. Analytical calculation

The cross section of supporting beams is isosceles triangle (as shown in Fig. 2) formed during maskless wet etching L_1, b_1, h_1 are the length, width and thickness of the supporting beams, respectively. The included angle between the flank and the upper surface is 18.76°. The moment of inertia to X axis is

$$I_1 = \int_{-\frac{2}{3}h_1}^{\frac{1}{3}h_1} b_1(z)z^2dz = \int_{-\frac{2}{3}h_1}^{0} \frac{b_1}{h_1}\left(\frac{2}{3}h_1 - (-z)\right)z^2dz + \int_{0}^{\frac{1}{3}h_1} \frac{b_1}{h_1}\left(\frac{2}{3}h_1 + z\right)z^2dz = \frac{b_1h_1^3}{36} \quad (1)$$

Since sensing beams are much thinner than supporting beams, the stiffness of sensing beams on the displacement of the proof mass can be reasonably ignored. Therefore, the bending equation of supporting beams under Z-axis acceleration a can be expressed as [23]

$$w_1(x_1) = \frac{Ma/8}{6E_1I_1}x_1^2\left(\frac{3}{2}L_1 - x_1\right) \quad (2)$$

Here x_1 is the distance from a point on supporting beams to the frame. M is the mass of the proof mass. E_1 is the Young modulus of silicon supporting beams. Thus the displacement of the clamped ends close to the proof mass, that is, the displacement of the proof mass under Z-axis acceleration is

$$w_1(L_1) = \frac{L_1^3}{96E_1I_1}Ma \quad (3)$$

The elastic coefficient of the total supporting beam system in Z direction can be expressed as

$$K_z = \frac{Ma}{w_1(L_1)} = \frac{96E_1I_1}{L_1^3} \quad (4)$$

The upward and downward movement of the proof mass will bend sensing beams according to similar bending equation as supporting beams since both sensing beams and supporting beams are fully clamped to the frame at one end and clamped to the proof mass at the other end. Thus the bending equation of sensing beams can be expressed as

$$w_2(x_2) = \frac{F}{6E_2I_2}x_2^2\left(\frac{3}{2}L_2 - x_2\right) \quad (5)$$

Here F is the equivalent force acting on a sensing beam in Z direction when the proof mass moves upward and downward. x_2 is the distance from a point on the sensing beam to the clamped end. E_2 is the equivalent Young modulus of materials comprising sensing beam. The moment of inertia of sensing beams is

$$I_2 = \frac{b_2h_2^3}{12} \quad (6)$$

Here L_2, b_2, h_2 are the length, width and thickness of the sensing beams, respectively.

The deflection of sensing beams and supporting beams is exactly the same since they are fully clamped to the proof mass.

$$w_2(L_2) = w_1(L_1) \quad (7)$$

Substituting Eqs. (3) and (5) into Eq. (7), we obtain the following correlation

$$\frac{L_2^3F}{12E_2I_2} = \frac{Ma}{K_z} \quad (8)$$

Therefore, the equivalent force F acting on a sensing beam can be calculated as

$$F = \frac{12E_2I_2Ma}{K_zL_2^3} = \frac{E_2b_2h_2^3Ma}{K_zL_2^3} \quad (9)$$

The longitudinal strain at the top surface of the sensing beam can be calculated as

$$\varepsilon(x_2) = \frac{6F}{b_2h_2^2E_2}\left(\frac{1}{2}L_2 - x_2\right) = \frac{6h_2Ma}{K_zL_2^3}\left(\frac{1}{2}L_2 - x_2\right) \quad (10)$$