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Fabrication and Characteristics of a Three-Axis Accelerometer with Double L-Shaped Beams

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Abstract: A three-axis accelerometer with a double L-shaped beams structure was designed and fabricated in this paper, consisting of a supporting body, four double L-shaped beams and intermediate double beams connected to two mass blocks. When applying acceleration to the accelerometer chip, according to the output voltage changes of three Wheatstone bridges constituted by twelve piezoresistors on the roots of the beams, the corresponding acceleration along three axes can be measured based on the elastic force theory and piezoresistive effect. To improve the characteristics of the three-axis accelerometer, we simulated how the width of the intermediate double beams affected the characteristics. Through optimizing the structure size, six chips with different widths of intermediate double beams were fabricated on silicon-on-insulator (SOI) wafers using micro-electromechanical systems (MEMS) technology and were packaged on printed circuit boards (PCB) by using an electrostatic bonding process and inner lead bonding technology. At room temperature and $V_{DD} = 5.0 \text{ V}$, the resulting accelerometer with an optimized size ($w = 500 \text{ }\mu\text{m}$) realized sensitivities of 0.302 mV/g, 0.235 mV/g and 0.347 mV/g along three axes, with a low cross-axis sensitivity. This result provides a new strategy to further improve the characteristics of the three-axis accelerometer.

Keywords: three-axis accelerometer; double L-shaped beam; MEMS technology; cross-axis sensitivity

1. Introduction

In recent years, with the rapid development of semiconductor technology, accelerometers have been widely used in many different fields, mainly including vibration detection [1], consumer electronics [2], medical treatment [3,4], vibration detection of wind turbines [5], navigation [6,7], automobile safety [8], and so on. Currently, although accelerometers have met the needs of real life, they are still facing the challenge of a wide measurement range, high accuracy, etc. Thus, high performance accelerometers have stimulated a particular attention from researchers, providing an opportunity to improve the characteristics of the accelerometer, making it possible to overcome the above mentioned limitation. For example, Sankar et al. proposed a quad beam silicon piezoresistive z-axis accelerometer with a very low cross-axis sensitivity of 0.316 μ V/V·g for an in-plane acceleration in 2013 [9]. After that, Han et al. presented a piezoresistive accelerometer with a low cross-axis sensitivity based on masked-maskless wet etching, realizing sensitivities of 0.069 V/V·g, 0.034 V/V·g and 4.15 V/V·g along the *x*-axis, *y*-axis and *z*-axis, and cross-axis sensitivities of 1.67% and 0.82% along the *x*-axis and *y*-axis, respectively [10]. Recently, Takahashi et al. reported an angular acceleration sensor composed of liquid ring channels and piezoresistive cantilevers as the sensing element, achieving an angular acceleration resolution of 0.01 rad/s² in the range of 0.1–100 Hz on a target axis about 100 times higher than that of the other axes, a high sensitivity and a low cross-interference [11]. Nowadays, the accelerometer can be divided into several types, mainly including piezoresistive, capacitive [12], piezoelectric [13], etc. The piezoresistive accelerometer, when compared with the ones having other structures, exhibits many

excellent properties, such as a fast response, easy signal processing and miniaturization, etc. However, the piezoresistive accelerometers are also facing challenges with respect to improving measurement consistency and reducing cross-interference, which have limited their further development.

To overcome the above obstacles, a piezoresistive three-axis accelerometer with double L-shaped beams was designed and fabricated on a silicon-on-insulator (SOI) wafer using MEMS technology in this study. Using the double L-shaped beams concentrated the stress distribution under the actions of a_x and a_y . Through a simulation to investigate how the width of the intermediate double beams affects the characteristics of an accelerometer, the structure size of the intermediate double beams was optimized. The test results indicate that it is possible to achieve the measurement of acceleration along three axes and reduce the cross-axis sensitivity using the resulting accelerometer. The study on the effects of intermediate double beams' structure sizes on the sensitivity of the proposed accelerometer provides a possibility to further improve the performance of three-axis accelerometers.

2. Basic Structure and Working Principle

2.1. Basic Structure

The three-axis accelerometer is composed of an elastic element and a sensitive element, where the elastic element consists of four double L-shaped beams, intermediate double beams and two mass blocks, and the sensitive element has twelve piezoresistors. The basic structure of the three-axis accelerometer with double L-shaped beams is shown in Figure 1, including a top view, bottom views, as well as a cross-section view along AA'. As shown in Figure 1a,b, the two mass blocks (m_1 and m_2) are first connected by the intermediate double beams (l_{z1} and l_{z2}) and are then connected to the support body by four double L-shaped beams (l_{x1} , l_{x2} , l_{x3} , l_{x4} , l_{y1} , l_{y2} , l_{y3} and l_{y4} ,) on a SOI wafer. Figure 1c gives the cross-section view along AA' for the three-axis accelerometer, in which the thicknesses of the intermediate double beams are the same as those of the four double L-shaped beams.



Figure 1. The basic structure of the three-axis accelerometer with double L-shaped beams: (**a**) top view; (**b**) bottom view; and (**c**) cross-section view along AA'.

As seen in Figure 1, the twelve piezoresistors (R_{x1} , R_{x2} , R_{x3} , R_{x4} , R_{y1} , R_{y2} , R_{y3} , R_{y4} , R_{z1} , R_{z2} , R_{z3} and R_{z4}) were designed on the roots of four double L-shaped beams and intermediate double beams, where the four piezoresistors (R_{x1} , R_{x2} , R_{x3} and R_{x4}) along the $<0\overline{1}1>$ orientation are fabricated on the four L-shaped single beams (l_{x1} , l_{x2} , l_{x3} and l_{x4}) to form a Wheatstone bridge (W_1). Meanwhile, the four piezoresistors (R_{y1} , R_{y2} , R_{y3} and R_{y4}) along the $<0\overline{1}1>$ orientation are fabricated on the four L-shaped

single beams $(l_{y1}, l_{y2}, l_{y3} \text{ and } l_{y4})$ to constitute a Wheatstone bridge (W_2) , and the other piezoresistors $(R_{z1}, R_{z2}, R_{z3} \text{ and } R_{z4})$ along the <011> and <011> orientations are respectively fabricated on the intermediate double beams $(l_{z1} \text{ and } l_{z2})$ to form a Wheatstone bridge (W_3) . In order to study the effect of the width (w) of the intermediate double beams $(l_{z1} \text{ and } l_{z2})$ on the characteristics of the proposed accelerometer, six chip sizes combined with the simulation in Section 3 of this study are shown in Table 1.

Table 1. The parameters of the six chips with different *w* values.

Туре	AS-1	AS-2	AS-3	AS-4	AS-5	AS-6
<i>w</i> (μm)	250	300	350	400	450	500

2.2. Sensitivity Analysis

Figure 2 shows the equivalent circuit of the proposed three-axis accelerometer under the actions of a_x , a_y and a_z . When the supply voltage is V_{DD} and no acceleration is applied to the chip, the output voltages of three Wheatstone bridges consisting of twelve piezoresistors are zero due to the fact that the resistances of the twelve piezoresistors are the same under ideal conditions. When exerting acceleration a_x along the x-axis to the chip, the four double L-shaped beams will produce deformations. According to the piezoresistive effect of the semiconductor material, the four piezoresistors of R_{x1} , R_{x2} , R_{x3} and R_{x4} on the roots of l_{x1} , l_{x2} , l_{x3} and l_{x4} are changed, i.e., the reducing of R_{x1} and R_{x3} attributed to the inducted compressive stress acted on the roots of l_{x1} and l_{x3} , while in contrast the increases of R_{x2} and R_{x4} caused by the tensile stress acted on the roots of l_{x2} and l_{x4} . The absolute variations of four piezoresistors are equal in ideal conditions, named as ΔR_x . Due to the fact that the output voltages V_{x1} and V_{x2} of W_1 are relative to the acceleration along the x-axis, it is possible to realize the measurement of a_x . When applying the acceleration a_y along the y-axis to the chip, the four double L-shaped beams will show deformations, and R_{y1} , R_{y2} , R_{y3} and R_{y4} located on the roots of l_{y1} , l_{y2} , l_{y3} and l_{y4} are changed, resulting in the reduction of R_{y1} and R_{y3} due to the induced compressive stress action on the roots of l_{y1} and l_{y3} , as well as in the increase of R_{x2} and R_{x4} caused by the tensile stress acting on the roots of l_{y2} and l_{y4} . The same absolute variations of four piezoresistors in ideal conditions are regarded as ΔR_{y} . The change of the output voltages V_{y1} and V_{y2} of W_2 under the action of a_y makes it possible to achieve the measurement of a_y . In addition, when exerting the acceleration a_z along the z-axis to the chip, the intermediate double beams l_{z1} and l_{z2} will produce a deformation along the *z*-axis, and R_{z1} , R_{z2} , R_{z3} and R_{z4} on the roots of l_{z1} and l_{z2} are changed, indicating that R_{z1} and R_{z3} are influenced by compressive stress, leading to the decreases of R_{z1} and R_{z3} and the increases of R_{z2} and R_{z4} . Similarly, the same absolute variations of four piezoresistors in ideal conditions are regarded as ΔR_z . The changes of the output voltages V_{z1} and V_{z2} of W₃ under the action of a_z contribute to the measurement of a_z .



Figure 2. The equivalent circuit of the three-axis accelerometer under the action of a_x , a_y and a_z .

When applying acceleration to the chip, the deformations of the proposed accelerometer beams would cause the variations of piezoresistors, where ΔR_x , ΔR_y , ΔR_z are the changes of piezoresistors under the actions of a_x , a_y and a_z , respectively.

In an ideal case, $R_{x1} = R_{x2} = R_{x3} = R_{x4} = R_{x0}$, $R_{y1} = R_{y2} = R_{y3} = R_{y4} = R_{y0}$, $R_{z1} = R_{z2} = R_{z3} = R_{z4} = R_{z0}$. In view of the equivalent circuit and piezoresistive effect, the relationship between the output voltages and the relative changes of piezoresistors can be expressed as follows [14]:

$$V_{\text{outx}} = V_{x1} - V_{x2} = \frac{\Delta R_x}{R_{x0}} \cdot V_{\text{DD}}$$

$$V_{\text{outy}} = V_{y1} - V_{y2} = \frac{\Delta R_y}{R_{y0}} \cdot V_{\text{DD}}$$

$$V_{\text{outz}} = V_{z1} - V_{z2} = \frac{\Delta R_z}{R_{z0}} \cdot V_{\text{DD}}$$
(1)

where R_{x0} , R_{y0} and R_{z0} are the piezoresistors under no acceleration, V_{outx} , V_{outy} and V_{outz} are the output voltages of W₁, W₂, and W₃, with the value of zero under the same condition.

In view of Equation (1), the output voltages of the Wheatstone bridges are directly proportional to the relative changes of the piezoresistors at a constant supply voltage. Thus, it is possible to measure the external acceleration based on the output voltage, where ΔR relative to stress is given in Equation (2) [15]:

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \tag{2}$$

where π_l and π_t are the longitudinal and transverse piezoresistance coefficients, and σ_l and σ_t are the longitudinal and transverse stress of the piezoresistors, respectively.

Due to the fact that the proposed accelerometer was designed on the SOI wafer with a device layer of n-type silicon with a <100> orientation, through combining Equation (1) with Equation (2), the relationship between the output voltages and the stress can be expressed as Equation (3):

$$V_{\text{outx}} = \frac{V_{\text{DD}}}{2} \cdot \pi_{44}(\sigma_{lx} - \sigma_{tx})$$

$$V_{\text{outy}} = \frac{V_{\text{DD}}}{2} \cdot \pi_{44}(\sigma_{ly} - \sigma_{ty})$$

$$V_{\text{outz}} = \frac{V_{\text{DD}}}{2} \cdot \pi_{44}(\sigma_{lz} - \sigma_{tz})$$
(3)

where σ_{lx} and σ_{tx} are the longitudinal and transverse stress of R_{x1} , R_{x2} , R_{x3} and R_{x4} , σ_{ly} and σ_{ty} are the longitudinal and transverse stress of R_{y1} , R_{y2} , R_{y3} and R_{y4} , σ_{lz} and σ_{tz} are the longitudinal and transverse stress of R_{z1} , R_{z2} , R_{z3} and R_{z4} , π_{44} is piezoresistive coefficient.

According to the sensitivity definition and sensitive principle of the three-axis accelerometer, the output voltages of the Wheatstone bridges along three axes can be expressed as Equation (4):

$$\begin{bmatrix} V_{\text{outx}} \\ V_{\text{outy}} \\ V_{\text{outz}} \end{bmatrix} = \begin{bmatrix} S_{xx}S_{xy}S_{xz} \\ S_{yx}S_{yy}S_{yz} \\ S_{zx}S_{zy}S_{zz} \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}$$
(4)

where S_{xx} , S_{yy} and S_{zz} are the sensitivities along the *x*-axis, *y*-axis and *z*-axis, respectively. S_{xy} and S_{xz} are the cross-axis sensitivities along the *x*-axis under a_y and a_z , respectively. S_{yx} and S_{yz} are the cross-axis sensitivities along the *y*-axis under a_x and a_z , respectively. S_{zx} and S_{zy} are the cross-axis sensitivities along the *z*-axis under a_x and a_z , respectively. S_{zx} and S_{zy} are the cross-axis sensitivities along the *z*-axis under a_x and a_y , respectively.

In an ideal case, the elastic deformations of the four double L-shaped beams under the action of a_z are identical, resulting in the same absolute variations of piezoresistors on the four double L-shaped beams, without the changes of the output voltages of W_1 and W_2 as well as the changes of the cross-axis sensitivities (S_{xz} and S_{yz}) of the sensor. Similarly, all the cross-axis sensitivities of S_{yx} , S_{zx} , S_{zy} and S_{xy} are zero and can be ignored. Thus, Equation (4) can be simplified as Equation (5):

$$\begin{bmatrix} V_{\text{outx}} \\ V_{\text{outy}} \\ V_{\text{outz}} \end{bmatrix} = \begin{bmatrix} S_{xx} & 0 & 0 \\ 0 & S_{yy} & 0 \\ 0 & 0 & S_{zz} \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}$$
(5)

Based on the above theoretical analysis, it is possible to realize the measurement of acceleration along the *x*-axis, *y*-axis and *z*-axis by the accelerometer. Meanwhile, the cross-axis sensitivity can be ignored by structural optimization under the ideal process conditions and the ideal environmental testing conditions, etc.

3. Simulation and Fabrication Technology

3.1. Simulation of Three-axis Accelerometer

To study how w affects the stress distribution, the finite element simulation software-Ansys 15.0 was used to simulate the characteristics of the proposed sensor, as shown in Figure 3. Figure 3a,b shows the top and bottom views of the sensor model with four double L-shaped beams, intermediate double beams and two mass blocks.



Figure 3. The structure model of the three-axis accelerometer: (a) top view; (b) bottom view.

On the basis of the model, the relationship between the average stress at the piezoresistor positions on the beams and w under the actions of a_x , a_y and a_z was investigated. By respectively exerting an external acceleration of 15 g along the *x*-axis, *y*-axis and *z*-axis to the sensor model, six sensors (see Table 1) with different w values were simulated. Then, the average stress at the corresponding piezoresistor positions was given, as shown in Figure 4. It can be seen that the average stress at the piezoresistor positions along teh *z*-axis decreases with the increase of w. With respect to that, the ones along the *x*-axis and *y*-axis do not change much, as shown in Figure 4. However, when increasing w up to 500 µm, the average stress differences along the three axes are very small, and the measurement consistency is good. According to the derived equation in Section 2, it can be found that S_{xx} , S_{yy} and S_{zz} increase with the increase of the average stress, resulting in the decrease of the sensitivity along the *z*-axis with an increasing w. Finally, a better consistence of sensitivity is achieved when w is 500 µm.



Figure 4. The relationship curves between the average stress at the piezoresistor positions along three axes and the width (*w*) of the intermediate double beams.

3.2. The Fabrication Process of Three-axis Accelerometer

As shown in Figure 5, the chip was fabricated on a SOI wafer with a n-type <100> orientation device layer and resistivity of 0.1 Ω ·cm by using MEMS technology, in which the insets of mask1-mask7 used for photolithography and bonding glass are given together. The synthesis procedure is illustrated as follows:



Figure 5. The main fabrication process of the proposed sensor (insets of mask1-mask7 used for photolithography and bonding glass): (a) cleaning the wafer; (b) forming p+ and p- regions; (c) performing contact holes to fabricate the electrodes and interconnects; (d) forming pad; (e) ICP etching the top and bottom surfaces of the chip to release the beam structure; and (f) bonding a glass plate with the bottom surface of chip.

(a) Cleaning a SOI wafer using a standard cleaning method, then growing a SiO₂ layer with a thickness of 50 nm by thermal oxidation method as an ion implantation buffer; (b) first, using photolithography to form an ion implantation window, performing the p+ region by utilizing ion implantation, and secondly using photolithography to etch the windows of piezoresistors, performing the p- region as piezoresistors repeating the above method. After that, placing the chip in a vacuum environment of 1000 °C for 20~30 min to activate impurity ions so as to form an impurity distribution and effectively eliminate the damage caused by the ion implantation. Etching an SiO₂ layer of 50 nm using wet etching technology, and thereafter growing the SiO₂ layer as an insulating layer by using plasma enhanced chemical vapor deposition (PECVD); (c) third, photolithography to etch the top surface and performing contact holes between the piezoresistors and the Al electrodes, fabricating metal Al on the top surface by a vacuum evaporation method, and fourth, photolithography to form the electrodes and interconnects, and then metalizing at 420 °C for 30 min to achieve ohmic contact; (d) growing a SiO₂ layer by using PECVD as a passive layer to protect the Al electrode, and

fifth, photolithography to form a pad; (e) etching the bottom surface of the chip by inductive couple plasma (ICP) technology [16] to form two mass blocks, thereafter etching the top surface of the chip by the identical technology to release four double L-shaped beams and intermediate double beams; (f) bonding a glass plate with a groove with the bottom surface of the chip by using electrostatic bonding technology to provide enough moving space for the two mass blocks.

To observe the morphology of the chip, a high-precision measuring microscope (Japan, Olympus, STM7) was used. Due to the large size (4000 μ m×4000 μ m) of the chip, the morphology stitching mode was used to complete the whole photograph. Figure 6a,b shows the top and bottom photographs of the fabricated chip, respectively. As shown in Figure 6a, the potential labeling of pad points on the chip corresponds to that in the equivalent circuit in Figure 2. Meanwhile, using the Dow Corning fluorosilicone solvent-resistant sealant attached the chip to the package-printed circuit board (PCB) [17]. After fully curing the sealant, bonding the leads between the chip and PCB using an integrated chip bonding machine (American, KNS, 4526) realized the connection between the solder joints on the chip and the corresponding solder joints on the PCB, as shown in Figure 6c [14].



Figure 6. The photograph of the proposed chip: (a) top view; (b) bottom view; and (c) packaged chip.

4. Results and Discussion

To study the characteristics of the three-axis accelerometer, a testing system was built, consisting of a standard vibration table (China, Dongling, ESS-050) with an excitation frequency range of 0~10,000 Hz and acceleration of 0~30 g with an accuracy of 0.1 g, a high performance digital multimeter (America, Agilent, 34410A), and a programmable linear direct-current power (China, Rigol, DP832A) to supply a voltage of 0~30 V. The test was carried out at room temperature and a humidity of 40% RH.

4.1. Frequency Response Characteristics

To investigate the frequency response characteristics of the six types of sensors, a frequency response characteristic test was carried out under conditions of the supply voltage of 5.0 V and an external acceleration of 3 g with a frequency range from 100 Hz to 10,000 Hz. Through taking the chip with $w = 500 \mu m$ as an example, the characteristic curves of the resonance frequency along the *x*-axis, *y*-axis and *z*-axis are respectively shown in Figure 7a–c. As shown in Figure 7a, the test result shows that the output voltages of the sensor do not markedly change with an increase of the excitation frequency. When increasing the frequency of the excitation signal up to 8898 Hz along the *x*-axis, the output voltage of the sensor along the *x*-axis reaches a maximum. Then, the output voltage of the sensor begins to gradually decrease as the vibration frequency continually increases, thus achieving the resonance frequencies along the *y*-axis and *z*-axis are 8395 Hz and 3270 Hz, as shown in Figure 7b,c. After that, a wide frequency sweep was performed on the proposed sensor, i.e., with a vibration frequency range from 100 Hz to 10,000 Hz at constant acceleration. The resonance frequencies of the

six types of chips (named as AS-1~AS-6, corresponding to different w values of 250–500 µm) were obtained by observing the output voltage changes, as shown in Table 2. According to Table 2, due to the fact that the two identical mass blocks in the basic structure of the accelerometer were connected by the intermediate double beams, a collective movement can be caused to form the deformations of the double L-shaped beams, benefitting the measurement of a_x or a_y . However, the widths of the intermediate double beams (w) have little influence on the movement along the x-axis or y-axis, without monotonous changes of the resonance frequency along the x-axis and y-axis with w.



Figure 7. The characteristic curves of resonance frequency when *w* is 500 μ m: (**a**) along the *x*-axis; (**b**) along the *y*-axis; and (**c**) along the *z*-axis.

Table 2. The resonance frequencies of the proposed sensor with different intermediate double beam widths.

Туре	<i>w</i> (μm)	Resonance Frequency along <i>x</i> -axis (Hz)	Resonance Frequency along <i>y</i> -axis (Hz)	Resonance Frequency along z-axis (Hz)	
AS-1	250	9106	8956	3211	
AS-2	300	9374	7963	3221	
AS-3	350	7787	8957	3314	
AS-4	400	8692	8694	3250	
AS-5	450	7996	8348	3109	
AS-6	500	8898	8395	3270	

4.2. Sensitivity and Cross Interference Characteristics

To research the sensitivity characteristics of the six types of sensors, the sensitivity test was repeated three times under the conditions of a supply voltage of 5.0 V and acceleration along the sensitive axis from 0 g to 15 g with a step of 3 g. Figure 8 gives the relationship curves between the output voltages and the external acceleration along the three axes, where V_{outx} (see the black line), V_{outy} (see the red line) and V_{outz} (see the blue line) are the output voltages for the resulting sensors. As shown in Figure 8a, it can be seen that the output voltages V_{outx} and V_{outy} of the AS-1 sensor linearly increase with an increase of a_x and a_y , respectively. With respect to that, the output voltage V_{outz} of the sensor nonlinearly increases with an increase of a_z . In addition, when $a_x = a_y = a_z$, V_{outz} are markedly bigger than V_{outx} and V_{outy} , where V_{outy} is close to V_{outx} . This indicates that the resulting AS-1 sensor can realize the acceleration measurement along the three axes, but with a low linearity and higher sensitivity along the z-axis when compared with the other axes. As shown in Figure 8b-e, the sensors of AS-2, AS-3, AS-4 and AS-5, when compared with AS-1, have similar sensitivities and linearity along the three axes. In particular, the corresponding output voltages of the AS-6 sensor linearly increase, not only with the increasing of the external accelerations a_x and a_y , but also with the increasing of a_z , as shown in Figure 8f. In addition, when $a_x = a_y = a_z$, V_{outx} , V_{outy} and V_{outz} are close, all having a relationship curve with an approximate linearity. On the basis of this, the characteristics of the AS-6 sensor are in accord with the previous simulating results.





Figure 8. The relationship curves between the output voltages of the proposed sensor and the external acceleration of the six types of sensors with different *w* values: (a) $w = 250 \text{ }\mu\text{m}$; (b) $w = 300 \text{ }\mu\text{m}$; (c) $w = 350 \text{ }\mu\text{m}$; (d) $w = 400 \text{ }\mu\text{m}$; (e) $w = 450 \text{ }\mu\text{m}$; and (f) $w = 500 \text{ }\mu\text{m}$.

In addition, according to the sensitivity definition and testing data, the sensitivities of the proposed sensor with different w values are shown in Table 3. It indicates that the *sensitivities* of three-axis accelerometers decrease along the *z*-axis with the increasing widths of the intermediate double beams. When w is 500 µm, the proposed sensor achieves a better consistence of sensitivities along the three axes, with sensitivities of 0.302 mV/g, 0.235 mV/g and 0.347 mV/g, respectively.

Туре	<i>w</i> (μm)	<i>S_{xx}</i> (mV/g)	S _{yy} (mV/g)	<i>S_{zz}</i> (mV/g)	Linearity (<i>x-</i> axis)	Linearity (y-axis)	Linearity (z-axis)
AS-1	250	0.211	0.324	0.646	3.3%	2.7%	9.1%
AS-2	300	0.135	0.163	0.633	7.6%	5.4%	6.8%
AS-3	350	0.158	0.117	0.515	7.1%	5.5%	7.2%
AS-4	400	0.369	0.271	0.504	3.0%	3.2%	8.3%
AS-5	450	0.239	0.142	0.470	5.3%	3.5%	10.0%
AS-6	500	0.302	0.235	0.347	4.1%	3.4%	3.4%

Table 3. The sensitivities of the proposed sensor with different widths of intermediate double beams.

To further study the cross-interference characteristics of the sensitivity of the AS-6 sensor, the output voltages along the three axes at constant accelerations of a_x , a_y and a_z were investigated at the same time, respectively. Figure 9 shows the relationship curves between the output voltages and the corresponding acceleration. As shown in Figure 9a, V_{outx} along the sensitive axis linearly increases with the increasing a_x , but with slight changes in V_{outy} and V_{outz} under the same acceleration, respectively. This indicates that the V_{outy} and V_{outz} of the cross-interference caused by a_x are low. Similarly, the output voltage V_{outy} (or V_{outz}) linearly increases with the increasing a_y (or a_z), with slight changes in the other output voltages under the action of a_y (or a_z), indicating that the V_{outx} and V_{outz} (or V_{outx} and V_{outy}) of the cross-interference caused by a_y (or a_z) are small as well, as shown in Figure 9b,c. The test result indicates that it is possible to achieve a high output voltage along the sensitive axis and a low cross-interference along the non-sensitive axes using the AS-6 sensor.



Figure 9. The cross-interference characteristic curves of the AS-6 sensor under three-axis acceleration along: (**a**) *x*-axis; (**b**) *y*-axis; (**c**) *z*-axis.

In addition, the characteristic parameters of the AS-6 sensor are shown in Table 4. It can be seen that, when w is 500 µm, maximum and minimum cross-axis sensitivities can be achieved by the proposed sensor, i.e., 0.019 mV/g and 0.001 mV/g, respectively. According to the above data analysis, it is possible to improve the consistency of sensor sensitivity and reduce the cross-interference by using the proposed scheme.

Characteristic Parameters	Resonant Frequency (Hz)	Bandwidth (Hz)	Sensitivity of the Sensor along the <i>x</i> -axis, <i>y</i> -axis and <i>z</i> -axis under Resonant Frequency (mV/g)		
Acceleration Sensor			a_x	a_y	a_z
Sensor along <i>x</i> axis	8898	100-8000	0.302	0.011	0.004
Sensor along y axis	8395	100-7500	0.019	0.235	0.014
Sensor along z axis	3270	100-3000	0.001	0.004	0.347

Table 4. The characteristic parameters of the AS-6 sensor.

5. Conclusions

In summary, a three-axis accelerometer with double L-shaped beams was designed and fabricated using micro-electromechanical systems (MEMS) technology in this study. When applying acceleration to the proposed sensor chip, the corresponding acceleration along the three axes could be measured according to the output voltage changes of three Wheatstone bridges based on the elastic force theory and piezoresistive effect. To investigate the characteristics of the accelerometer, the effects of the width of intermediate double beams on the characteristics were simulated to optimize the structure size. Based on that, six types of sensors with different sizes were fabricated on silicon-on-insulator (SOI) wafers using MEMS technology and were packaged on printed circuit boards (PCB) using an electrostatic bonding process and inner lead bonding technology. The test results indicate that, at room temperature and $V_{DD} = 5.0$ V, better sensitivities along the three axes can be achieved by the resulting sensor with an optimized size, i.e., 0.302 mV/g, 0.235 mV/g and 0.347 mV/g, respectively. This study provides an effective fabrication method to further improve the sensitivity characteristics of three-axis accelerometers.

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