Single- and Triaxis Piezoelectric-Bimorph Accelerometers

Qiang Zou, Member, IEEE, Wei Tan, Eun Sok Kim, Senior Member, IEEE, and Gerald E. Loeb, Member, IEEE

Abstract—This paper describes the novel single- and triaxis piezoelectric-bimorph accelerometers that are built on parylene beams with ZnO films. The unamplified sensitivity and the minimum detectable signal of the fabricated single-axis accelerometer are measured to be 7.0 mV/g and 0.01 g, respectively, over a frequency range from 60 Hz to subhertz. The linearity of the sensitivity as a function of acceleration is measured to be 0.9% in the full scale. A highly symmetric quad-beam bimorph structure with a single proof mass is used for triaxis acceleration sensing and is demonstrated to produce high sensitivity, low cross-axis sensitivity, and good linearity, all in a compact size. The unamplified sensitivities of the X-, Y-, and Z-axis electrodes (of the triaxis accelerometer) in response to the accelerations in X-, Y-, and Z-axes are 0.93, 1.13, and 0.88 mV/g, respectively. The worst-case minimum detectable signal of the triaxis accelerometer is measured to be 0.04 g over a bandwidth ranging from subhertz to 100 Hz. The cross-axis sensitivity among the X-, Y-, and Z-axis electrode is less than 15% in the triaxis accelerometer. The theoretical analyses of the charge sensitivities and resonant frequencies along with the effects of residual stress on the charge sensitivities are presented for both the single- and triaxis accelerometers. [1686]

Index Terms—Parylene beam, piezoelectric accelerometer, piezoelectric bimorph, triaxis piezoelectric accelerometer.

I. INTRODUCTION

M ICROMACHINED accelerometers are highly desirable for inertial navigation, stability, and rollover control of automobile and for biomedical instrumentation because of their small size, particularly if combined with low cost, high performance, and low power consumption. Various micromachined accelerometers have already been developed based on capacitive, piezoresistive, resonant, tunneling, thermal, and piezoelectric sensing methods [1]–[6]. Among the micromachined silicon accelerometers, the piezoresistive and capacitive approaches have been most popular due to easiness of fabrication and high sensitivity, respectively. However, piezoresistive sensing consumes inherently high power, whereas capacitive sensing requires rather elaborate electronics that is often power hungry. Moreover, piezoresistors tend to drift in time due to heating by the bias current. In addition, capacitive sensors require narrow air gap over a relatively large area, which overdamps, and sometimes squeeze-film damps, and limits the usable frequency bandwidth.

A piezoelectric accelerometer, on the other hand, has the advantages of extremely low power consumption, simple detection circuit, high sensitivity, and inherent temperature stability. Thus, we have developed piezoelectric accelerometers to be integrated into an implantable neuromuscular stimulator called the BION [7] that is cylindrical with 20-mm length and 2-mm diameter (shown in Fig. 1). The accelerometers are used to sense human body movement and provide BION with the acceleration of the body or its inclination with respect to the gravitational field. Consequently, the accelerometers have to be very compact, extremely low power consuming, highly sensitive, and insensitive to cross-axis accelerations. The specifications of the MEMS accelerometer for BION application are shown in Table I.

The micromachined piezoelectric accelerometers have typically relied on bulk micromachining [8]–[11] and surface micromachining techniques [12], [13] to produce a spring-mass structure. Some finite-element-method simulations on triaxis piezoelectric-unimorph accelerometers that are built on very thin silicon beams have been reported [14], [15]. However, very few theoretical analyses and experimental results on triaxis piezoelectric accelerometers have been reported.

All of the previously reported micromachined piezoelectric accelerometers use single crystal silicon, polysilicon, or Si$_x$N$_y$ as a supporting beam. Nevertheless, the high stiffness and residual stress of these materials limit the accelerometers’ performance. Usage of parylene as a support diaphragm for piezoelectric acoustic transducers was reported in [16]–[18] and had shown to improve the sensitivities due to parylene’s very low Young’s modulus (~3.2 GPa) and nonbrittle characteristics. When parylene film is used as a support beam for piezoelectric accelerometers, it is difficult to place the neutral plane outside the piezoelectric layer with a unimorph structure because of the extremely low stiffness of parylene. Thus, we use a bimorph structure with two ZnO piezoelectric films of opposite C-axis orientations to make the neutral plane location outside of the ZnO films and to maximize the sensitivities of the accelerometers. In this paper, the mechanical structure design, theoretical analysis, fabrication, and measurement results of the single- and triaxis piezoelectric-bimorph accelerometers are presented.
Fig. 1. Schematic view of BION with MEMS accelerometer.

<table>
<thead>
<tr>
<th>Chip size</th>
<th>$&lt; 3 \times 1.2 \times 0.6 \text{ mm}^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>$&lt; 0.5 \text{mW}$</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>DC to 20Hz</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$-1g - 1g$</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.01g</td>
</tr>
</tbody>
</table>

### II. SENSOR STRUCTURES

#### A. Single-Axis Piezoelectric-Bimorph Accelerometer

The single-axis piezoelectric-bimorph accelerometer with a beam-mass structure is schematically shown in Fig. 2. The beam consists of parylene/Al/Si$_2$N$_3$/ZnO/Si$_2$N$_3$/Al/Si$_2$N$_3$/ZnO/Si$_2$N$_3$/Al/parylene multiple layers. The neutral plane is just at the middle of the symmetric bimorph beam. Parylene is used because of the following reasons: 1) It has a very small Young's modulus (~3.2 GPa) and adds negligible stiffness to the sensing structure, and 2) it is a nonbrittle plastic material with a very large linear elastic range (its yield strain being ~3%). Moreover, parylene is moisture-blocking, chemically inert, electrically insulating, and biocompatible.

In order to make the neutral plane location outside of the piezoelectric films, a bimorph structure with two oppositely oriented 0.3-μm ZnO piezoelectric films is used. Each of the ZnO films is encapsulated with two 0.1-μm-thick plasma-enhanced chemical-vapor-deposited (PECVD) Si$_2$N$_3$ insulating layer to improve the accelerometer’s low-frequency response so that the accelerometer has a quasi-DC response [19]. A 0.4-μm-thick Al is used for the top, middle, and bottom electrodes. The middle Al electrode (buried between two piezoelectric films) is electrically floating. The piezoelectric-bimorph beam is mechanically supported by two thick parylene layers (1.0-5.0 μm thick) on the top and bottom of the bimorph.

When Z-axis acceleration is applied to the structure, the proof mass is displaced such that the bimorph beam goes through bending, producing tensile and compressive stresses above and below the neutral plane. Because of the opposite C-axis orientations of the ZnO films on the top and bottom of the neutral plane, the opposite distribution of the stress above and below the neutral plane will produce a voltage (between the top and bottom electrodes) that is the sum of the voltages developed between the top and middle electrodes and between the middle and bottom electrodes. The thickness and material properties of the layers used in the piezoelectric bimorph are summarized in Table II.

#### B. Triaxis Piezoelectric-Bimorph Accelerometer

Fig. 3 shows the schematic of the triaxis accelerometer. Fig. 3 shows the schematic of the triaxis accelerometer with a single seismic mass suspended by four symmetric parylene/Al/Si$_2$N$_3$/ZnO/Si$_2$N$_3$/Al/Si$_2$N$_3$/ZnO/Si$_2$N$_3$/Al bimorph beams. The electrodes on the top side of the four beams are segmented into $Z_1$, $Z_2$, $Z_3$, $Z_4$ (for Z-axis sensing), $X_1$, $X_2$ (for X-axis sensing), and $Y_1$ and $Y_2$ (for Y-axis sensing) (Fig. 3). The operating principle of the triaxis accelerometer is shown in Fig. 4. When the seismic mass is accelerated vertically (along the Z-axis), it produces tensile stress in the top half of the bimorph in $X_1$, $X_2$, $Y_1$, and $Y_2$ and compressive stress in $Z_1-Z_4$. Furthermore, there exists a finite voltage ($V_z$) between the parallel-connected $Z_1-Z_4$ and the electrode on the other face of the diaphragm because the top and bottom halves of the bimorph have opposite stress distribution. However, the voltage ($V_z$) between $X_1$ and $X_2$ (and also $V_y$ between $Y_1$ and $Y_2$) is almost zero because the net stress between the two electrodes is zero. When the seismic mass is accelerated laterally (e.g., in X-direction), it rotates around Y-axis and produces tensile stress in $X_1$ and $Z_2$ and compressive stress in $Z_1$ and $X_2$. It also produces shear stress in $Y_1$, $Y_2$, $Z_2$, and $Z_4$, which can be neglected. Thus, acceleration along X-direction
Fig. 2. Schematic view of the single-axis piezoelectric-bimorph accelerometer.  

**TABLE II**

**Thickness and Material Properties of the Layers Used in the Single-Axis Piezoelectric-Bimorph Accelerometer**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (µm)</th>
<th>Materials properties (Young's modulus, Poisson's ratio, Density)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>0.4</td>
<td>E=69 GPa, 0.33, 3700 kg/m²</td>
</tr>
<tr>
<td>Parylene</td>
<td>1.0 - 5.0</td>
<td>E=5.2 GPa, 0.4, 1289 kg/m²</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.3</td>
<td>C₁₁=210 GPa, C₁₂=120 GPa, C₁₃=105 GPa, C₃₃=210 GPa, C₄₄=45 GPa, 5700 kg/m³</td>
</tr>
<tr>
<td>Si₃N₄</td>
<td>0.1</td>
<td>E=272 GPa, 0.25, 3100 kg/m³</td>
</tr>
</tbody>
</table>

produces a finite differential signal $V_x$ but almost zero $V_y$ and $V_z$ because of zero net stress between $Y_1$ and $Y_2$ and of $Z_1$ and $Z_2$ canceling each other, respectively. The same principles apply to the case in which the seismic mass is accelerated laterally in $Y$-direction.

**III. THEORETICAL ANALYSIS ON MECHANICAL DESIGN**

In order to predict the sensor performance and optimize the mechanical design, we formulate and analyze the charge sensitivity and mechanical resonant frequency for the single- and triaxis piezoelectric-bimorph accelerometers. For a piezoelectric ZnO film on a cantilever beam with the cantilever's length in $X$-direction, the electrical-field displacement $D$ in $Z$-direction (i.e., the thickness direction) is related to the $Z$-directed electrical field ($E_{field}$) and $X$-directed normal stress ($\sigma$), which is generated by the cantilever bending as follows:

$$D = \epsilon E_{field} + d_{31} \sigma$$  \hspace{1cm} (1)$$

where $\epsilon$ and $d_{31} (= 2.3 \times 10^{-12} \text{ C/N for ZnO [13]})$ are the permittivity and piezoelectric coefficient of the piezoelectric film, respectively.

For piezoelectric sensing, we usually do not apply any external electric field, and (1) can be simplified to

$$D = d_{31} \sigma.$$  \hspace{1cm} (2)$$

The normal stress in $X$-direction (produced in a piezoelectric film of a bimorph cantilever by a pure bending) can be obtained by the following [20]:

$$\sigma = \frac{E_p}{R} \cdot \frac{1}{z_p} = E_p \cdot \frac{M}{\sum_i E_i (I_i + A_i Z_i^2)} \cdot z_p$$  \hspace{1cm} (3)$$

where $E_p$ is the Young’s modulus of the piezoelectric film, $1/R$ is the bending curvature of the bimorph cantilever beam by pure bending moment $M$, $z_p$ is the distance between the center of the piezoelectric film and bending neutral plane, $E_i$ is the Young’s modulus of each layer in the bimorph beam, $I_i$ is the area moment of inertia for each layer in the bimorph beam, $A_i$ is the cross-section area of each layer in the bimorph beam, and $Z_i$ is the distance between the center of each layer and neutral plane of the bimorph beam. Thus, the charge produced on the electrode is

$$Q = \int D \cdot w \cdot dl$$

$$= \int d_{31} \cdot E_p \cdot \frac{M}{\sum_i E_i (I_i + A_i Z_i^2)} \cdot z_p \cdot w \cdot dl$$  \hspace{1cm} (4)$$

where $w$ and $dl$ are the sensing electrode width and elemental length, respectively.

**A. Single-Axis Piezoelectric-Bimorph Accelerometer**

When the sensor is subject to acceleration (of magnitude acc) in $Z$-direction, the inertial force of the proof mass induces a deflection of the bimorph beam suspension according to the
Fig. 4. Operating principle of the triaxis piezoelectric-bimorph accelerometer: (a) When vertical acceleration is applied (Z-axis) and (b) when lateral acceleration is applied (X- or Y-axis).

Fig. 5. Free-body diagram of the single-axis piezoelectric-bimorph accelerometer when Z-axis acceleration is applied.

Free-body diagram of the suspension beam shown in Fig. 5. Substituting the bending moment in the beam (of length $l$, at location $x$) into (4) and integrating along the suspension beam, we obtain the following equation for the charge sensitivity $S_q$ (i.e., the charge per unit acceleration) of the single-axis piezoelectric-bimorph accelerometer

$$S_q = \frac{d_{31} \cdot E_p \cdot z_p \cdot m \cdot \frac{1}{2} \cdot (L_m + l) \cdot l}{\sum_i E_i \left( \frac{1}{12} \cdot h_i^3 + h_i \cdot Z_i^2 \right)}$$

(5)

where $h_i$ and $l$ are the thickness of the $i$th layer in the bimorph beam and the length of the suspension beam, respectively, whereas $m$ and $L_m$ are the mass and the length of the silicon proof mass, respectively. In obtaining (5), we use $I_i = w \cdot h_i^2/12$ and $A_i = w \cdot h_i$, and we see that the beam width has no effect on the charge sensitivity, as expected, since the stress equation is for a beam bending.

B. Triaxis Piezoelectric-Bimorph Accelerometer

As the triaxis accelerometer has the symmetric quad-beam structure, the X- and Y-axis sensors have the same response when X- and Y-axis accelerations are applied. In this section, we analyze the Z- and X-Y-axis responses of the accelerometer.

1) Z-Axis Sensitivity Analysis: Fig. 6 shows a free-body diagram of the triaxis accelerometer when Z-axis acceleration is applied. The proof mass in the middle moves vertically, whereas the four suspension beams deflect with the same displacement. Solving the governing differential equation according to the boundary conditions ($y|_{x=0} = 0$, $(dy/dx)|_{x=0} = 0$, $(dy/dx)|_{x=l} = 0$), we obtain the vertical displacement $y$ and bending moment $M$ in the suspension beam at a location $x$ as follows:

$$y(x) = \frac{1}{\sum_i E_i \left( I_i + A_i Z_i^2 \right)} \times \left( \frac{1}{24} \cdot m \cdot \text{acc} \cdot x^3 - \frac{1}{16} \cdot m \cdot \text{acc} \cdot l \cdot x^2 \right)$$

(6)

$$M(x) = \frac{1}{4} \cdot m \cdot \text{acc} \cdot \left( x - \frac{1}{2} l \right)$$

(7)

where acc and $l$ are the acceleration applied to the proof mass and the suspension-beam length, respectively. From (7), we see that the bending moment changes its sign just at the half of the
Based on the previous boundary conditions, we can obtain the vertical displacement $y$ and bending moment $M$ in the $X$-axis suspension beam at a location $x$ as follows:

$$y(x) = \frac{1}{\sum_i E_i \cdot (I_i + A_i \cdot Z_i^2)} \cdot \frac{\frac{3}{2} \cdot (l + L_m)}{k^2 \cdot l} \cdot \frac{m \cdot \text{acc} \cdot \frac{H_m}{2}}{\left[ \frac{2}{1 + v} + 3 \cdot (1 + \frac{L_m}{l})^2 \right]} \cdot \left[ 1 - \frac{1}{2} \cdot k \cdot l \cdot e^{k \cdot x} - \frac{1}{2} \cdot k \cdot l \cdot e^{-k \cdot x} - 2 \cdot \frac{2}{i \cdot x + 1} \right]$$

(10)

$$M(x) = \frac{\frac{3}{2} \cdot (l + L_m)}{k \cdot l^2} \cdot \frac{m \cdot \text{acc} \cdot \frac{H_m}{2}}{\left[ \frac{2}{1 + v} + 3 \cdot (1 + \frac{L_m}{l})^2 \right]} \cdot \left[ \left( 1 - \frac{1}{2} \cdot k \cdot l \right) \cdot e^{k \cdot x} - \left( 1 - \frac{1}{2} \cdot k \cdot l \right) \cdot e^{-k \cdot x} \right]$$

(11)

where $k = \sqrt{F_1 / \sum_i E_i \cdot (I_i + A_i \cdot Z_i^2)} = \sqrt{(1/2) \cdot m \cdot \text{acc} / \sum_i E_i \cdot (I_i + A_i \cdot Z_i^2)}$, with $F_1$ being the lateral force applied to the suspension beam by the fixed boundary, whereas $H_m$ and $v$ are the thickness of the silicon proof mass and the Poisson's ratio of silicon, respectively.

From (11), we see that the bending moment changes its sign at the half of the beam length, and consequently, the stress changes its sign at the half of the beam length. Substituting (11) into (4) and integrating along the length of the $X$-axis sensing electrode (shown in Fig. 7) produce the $X$-axis charge sensitivity of the triaxis accelerometer as follows:

$$S_q = \frac{d_{31} \cdot E_p \cdot z_p \cdot \frac{1}{32} \cdot m \cdot l^2}{\sum_i E_i \cdot (\frac{1}{12} \cdot h_i^3 + h_i \cdot Z_i^2)} \cdot \frac{m \cdot H_m}{8 \cdot \left[ \frac{2}{1 + v} + 3 \cdot (1 + \frac{L_m}{l})^2 \right]}$$

(12)

From (12), we see that the charge sensitivity does not depend on the width of the suspension beams as long as the rotation $\theta$ is small.

C. Resonant-Frequency Analysis

Assuming the proof mass as a rigid body that keeps its dimensions without deformability [21], we obtain the following equation for the lowest resonant frequency of the single-axis accelerometer by using the Rayleigh–Ritz method:

$$f = \frac{1}{2\pi} \cdot \sqrt{\frac{\sum_i E_i \cdot (I_i + A_i \cdot Z_i^2)}{\rho \cdot L_m \cdot W_m \cdot H_m \cdot l^3}} \cdot \sqrt{\frac{6\alpha^2 + 12\alpha + 8}{2\alpha^4 + 7\alpha^3 + 10.5\alpha^2 + 8\alpha + \frac{8}{3}}}$$

(13)

where $\alpha = L_m / l$ is the ratio between the proof-mass and the suspension-beam lengths. Similarly, we obtain the following
equation for the lowest resonant frequency of the triaxis accelerometer:

$$f = \frac{1}{2\pi} \sqrt{\frac{48 \cdot \sum_i E_i (I_i + A_i Z_i^2)}{\rho \cdot L_m \cdot W_m \cdot H_m \cdot \theta}}$$

where $\rho$, $L_m$, $W_m$, and $H_m$ are the density, length, width, and thickness of the proof mass, respectively.

**D. Effect of the In-Plane Residual Stress**

The previous analysis ignores in-plane stress in the suspending beam, and this section analyzes the effect of in-plane residual stress on the sensitivity of the single- and triaxis accelerometers.

1) Single-Axis Piezoelectric-Bimorph Accelerometer Under In-Plane Residual Stress: Assuming that the residual stress results in a tensile axial force $P$, we analyze the effect of the axial force $P$ on the sensitivity of the single-axis accelerometer, using Fig. 9(a) that shows a free-body diagram of the single-axis piezoelectric accelerometer, including the in-plane residual stress.

With pure torque $M_0$, Z-axis force $F_0$, and in-plane residual stress $P$ applied to the suspending beam at the same time [Fig. 9(a)], we solve the governing differential equation, according to the boundary conditions, to obtain the bending moment in the beam as follows:

$$M(x) = -\frac{M_0 - F_0}{e^{kz} + e^{-kz}} \cdot e^{kz} - \frac{M_0 + F_0}{e^{kz} + e^{-kz}} \cdot e^{-kx}$$

where $k = \sqrt{P/\bar{E}I}$. Using (15) in (4) and integrating over the sensing electrode from $x = 0$ to $x = l$, the charge sensitivity on one sensing electrode of the single-axis accelerometers is

$$S_q = \frac{d_{31} \cdot E_p \cdot z_0 \cdot m}{\sum_i E_i \left(\frac{1}{12} \cdot h_i^3 + 2 \cdot 1 \cdot Z_i^2\right)} \cdot \left[\frac{1}{k^2} \cdot \left(\frac{1}{\cosh(k \cdot l)} - 1\right) - \frac{1}{k} \cdot \tanh(k \cdot l)\right].$$

The calculated result shows that in-plane axial force has little effect on the charge sensitivity in the case of the single-axis accelerometer because of the cantilever-like structure.

2) Z-Axis Sensitivity in the Triaxis Piezoelectric-Bimorph Accelerometer Under In-Plane Residual Stress: Using Fig. 9(b) (that shows a free-body diagram of the triaxis piezoelectric accelerometer, including an axial force $P$ due to in-plane residual stress), we obtain the following equation for the bending moment in the triaxis accelerometer that is built on bridge-like beams:

$$M(x) = \frac{F_0}{e^{kz} - e^{-kz}} \cdot e^{kz} + \frac{F_0}{e^{kz} - e^{-kz}} \cdot e^{-kx}$$

where $k = \sqrt{P/\bar{E}I}$.

Using (17) in (4) and integrating over the Z-axis sensing electrode in the triaxis accelerometer from $x = l/2$ to $x = l$ (Fig. 7), we obtain the Z-axis charge sensitivity on one sensing electrode of the triaxis piezoelectric accelerometer as follows:

$$S_q = \frac{d_{31} \cdot E_p \cdot z_0 \cdot m}{\sum_i E_i \left(\frac{1}{12} \cdot h_i^3 + 2 \cdot 1 \cdot Z_i^2\right)} \cdot \left[\frac{1}{4 \cdot k^2} \cdot \left(1 - 2 \cdot \frac{\sinh(\frac{k \cdot l}{2})}{\sinh(k \cdot l)}\right)\right].$$
Fig. 10. Z-axis charge sensitivity of the triaxial piezoelectric-bimorph accelerometer as a function of an in-plane axial force (due to residual stress) in the suspending beams.

TABLE III
DESIGNED STRUCTURE PARAMETERS AND EXPECTED CHARACTERISTICS FOR A TRIAXIS PIEZOELECTRIC-BIMORPH ACCELEROMETER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam length (µm)</td>
<td>340</td>
</tr>
<tr>
<td>Beam width (µm)</td>
<td>300</td>
</tr>
<tr>
<td>Al thickness (µm)</td>
<td>0.4</td>
</tr>
<tr>
<td>Al electrode length (µm)</td>
<td>130</td>
</tr>
<tr>
<td>Al electrode width (µm)</td>
<td>250</td>
</tr>
<tr>
<td>ZnO thickness (µm)</td>
<td>0.3</td>
</tr>
<tr>
<td>PECVD SiNx thickness (µm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Parylene thickness (µm)</td>
<td>2.1</td>
</tr>
<tr>
<td>Proof mass length (µm)</td>
<td>1700</td>
</tr>
<tr>
<td>Proof mass width (µm)</td>
<td>1700</td>
</tr>
<tr>
<td>Proof mass thickness (µm)</td>
<td>400</td>
</tr>
<tr>
<td>Expected Z-axis charge sensitivity (C/m²s²)</td>
<td>1.14×10⁻¹⁴</td>
</tr>
<tr>
<td>Expected X-axis charge sensitivity (C/m²s²)</td>
<td>3.93×10⁻¹⁵</td>
</tr>
</tbody>
</table>

Fig. 10 shows the calculation result of the Z-axis charge sensitivity (for a typical case of the triaxial piezoelectric-bimorph accelerometer with its structure parameters shown in Table III and the thickness of the parylene beam being equal to 2.1 µm) as a function of in-plane axial force (due to residual stress) in the multilayer beam of the triaxial accelerometer. The charge sensitivity decreases from 1.14×10⁻¹⁴ to 1.09×10⁻¹⁵ C/m²s² (more than ten times) by mere 0.01-N in-plane axial force, and we see that the triaxial accelerometer is heavily influenced by residual stress, as expected, since the suspending beams are like bridges with their two edges clamped.

3) X-Y-Axis Sensitivity in the Triaxial Piezoelectric-Bimorph Accelerometer Under In-Plane Residual Stress: Using Fig. 9(c) (that shows the side view of the free-body diagram of the triaxial accelerometer when X-axis acceleration and in-plane residual tension stress are present at the same time), we solve the governing differential equation for the deflection of the suspending beam, according to the boundary conditions, to obtain the bending moment M in the suspending beam at location x:

\[
M(x) = \frac{3}{2} \cdot \frac{(l + L_m)}{k \cdot l^2} \cdot \frac{m \cdot \text{acc} \cdot \frac{H_m}{2}}{\left(\frac{2}{1+\nu} + 3 \cdot \left(1 + \frac{L_m}{l^2}\right)^2\right)} + \frac{P \cdot L_m}{2 \cdot \sum_i E_i \cdot (l_i + A_i \cdot Z_i^2)} - \left(1 - \frac{1}{2} \cdot k \cdot l \right) \cdot e^{kx} - \left(1 + \frac{1}{2} \cdot k \cdot l \right) \cdot e^{-kx}
\]

where \( k = \sqrt{(F_1 + P) / \sum_i E_i \cdot (l_i + A_i \cdot Z_i^2)} = \sqrt{(1/2) \cdot m \cdot \text{acc} \cdot P / \sum_i E_i \cdot (l_i + A_i \cdot Z_i^2)} \), whereas \( F_1 \) is the lateral force applied on the suspension beam by the fixed boundary, and \( P \) is the axial force due to in-plane residual stress.

Using (19) in (4) and integrating along the length of the X-axis sensing electrode (Fig. 7), we obtain the X-axis charge sensitivity of the triaxial accelerometer under in-plane tension force \( P \) as follows:

\[
S_x = \frac{d_{31} \cdot E_p \cdot z_p}{\sum_i E_i \left(\frac{1}{12} \cdot h_i^2 + h_i \cdot Z_i^2\right)} \cdot \frac{(l + 3 \cdot L_m)}{8} \cdot \frac{m \cdot \frac{H_m}{2}}{\left(\frac{2}{1+\nu} + 3 \cdot \left(1 + \frac{L_m}{l^2}\right)^2\right)} + \frac{P \cdot L_m}{2 \cdot \sum_i E_i \cdot (l_i + A_i \cdot Z_i^2)}
\]

(20)

From (20), we can see that the X-axis charge sensitivity in the triaxial accelerometer decreases when the residual stress force \( P \) increases. Fig. 11 shows the calculation result of the X-axis charge sensitivity (for a typical case of the triaxial piezoelectric-bimorph accelerometer with its structure parameters shown in Table III and the thickness of the parylene beam being equal to 2.1 µm) as a function of in-plane axial force (due to residual stress) in the multilayer beam of the
Fig. 12. Fabrication process of the single-axis piezoelectric-bimorph accelerometer. (a) Bulk-micromachined Si. (b) Deposit and pattern 0.4-μm Al, 0.1-μm PECVD Si₃N₄, 0.3-μm ZnO, 0.1-μm PECVD Si₃N₄, 0.4-μm Al, and 3.7-μm parylene on the wafer front side. (c) Etch Si₃N₄ from the wafer backside. (d) Deposit 0.1-μm PECVD Si₃N₄, 0.3-μm ZnO, 0.1-μm PECVD Si₃N₄, 0.4-μm Al, and 3.7-μm parylene on the wafer backside. (e) We use wax to fix the wafer to a dummy wafer and dice the wafer to form a beam-mass structure.

Fig. 13. Fabrication process of the triaxis piezoelectric-bimorph accelerometer. (a) Bulk-micromachined Si. (b) Deposit and pattern 0.4-μm Al, 0.1-μm PECVD Si₃N₄, 0.3-μm ZnO, 0.1-μm PECVD Si₃N₄, 0.4-μm Al, and 2.1-μm parylene on the wafer front side. (c) Etch Si₃N₄ from the wafer backside. (d) Deposit 0.1-μm PECVD Si₃N₄, 0.3-μm ZnO, 0.1-μm PECVD Si₃N₄, and 0.4-μm Al on the wafer backside.

triaxis accelerometer. The charge sensitivity decreases from $3.93 \times 10^{-15}$ to $1.36 \times 10^{-15}$ C/m/s² (by 2.9 times) due to 0.01-N in-plane axial force.

IV. FABRICATION

The main fabrication steps for the single- and triaxis piezoelectric-bimorph accelerometers are similar to each other. The fabrication processes for the single- and triaxis accelerometers are briefly shown in Figs. 12 and 13, respectively, and are described in the succeeding sections.

A. Single-Axis Piezoelectric-Bimorph Accelerometer

Following the steps shown in Fig. 12, we first form a 0.8-μm-thick Si₃N₄ diaphragm on a silicon wafer by KOH etching, which is followed by deposition and patterning of 0.4-μm-thick Al, 0.1-μm-thick PECVD Si₃N₄, 0.3-μm-thick ZnO, 0.1-μm-thick PECVD Si₃N₄, 0.4-μm-thick Al, and 3.7-μm-thick parylene film on the front side of the wafer. The ZnO is electrically insulated through two 0.1-μm-thick PECVD Si₃N₄ films for static response of the accelerometer. After etching away the Si₃N₄ diaphragm from the wafer backside,
we deposit 0.1-μm-thick PECVD Si₃N₄ insulating layer, 0.3-μm-thick ZnO, 0.1-μm-thick PECVD Si₃N₄, 0.4-μm-thick Al, and 3.7-μm-thick parylene supporting layer on the wafer backside for the bottom half of the bimorph. The bimorph beams are formed by etching away most of the diaphragm through reactive-ion etching (RIE). Finally, the silicon wafer is glued to a dummy wafer with wax and is diced to form the beam-mass structure with vertical sidewalls.

B. Triaxis Piezoelectric-Bimorph Accelerometer

Following the fabrication steps shown in Fig. 13, we first form a 0.8-μm-thick Si₃N₄ diaphragm, producing a proof-mass silicon island (by KOH etching with a proper convex corner compensation) in the middle of the Si₃N₄ diaphragm. Then, 0.4-μm-thick Al, 0.1-μm-thick PECVD Si₃N₄, 0.3-μm-thick ZnO, 0.1-μm-thick PECVD Si₃N₄, 0.4-μm-thick Al, and 2.1-μm-thick parylene film are deposited and patterned on the front side of the wafer. After etching away the Si₃N₄ diaphragm from the wafer backside, we deposit 0.1-μm-thick PECVD Si₃N₄ insulating layer, 0.3-μm-thick ZnO, 0.1-μm-thick PECVD Si₃N₄, and 0.4-μm-thick Al on the wafer backside for the bottom half of the bimorph. Then, we form the bimorph beams by etching away a portion of the diaphragm through RIE, which is followed by dicing of the wafer into individual chips.

Fig. 14 shows the front-side view of a fabricated single-axis piezoelectric-bimorph accelerometer, whereas Fig. 15 shows the front-side and backside views of a completed triaxis piezoelectric-bimorph accelerometer.

V. EXPERIMENTAL SETUP

Fig. 16 shows a schematic of the experimental setup for measuring the sensitivity and resonant frequency of a piezoelectric accelerometer. A fabricated accelerometer chip and a voltage amplifier on a printed circuit board are housed in a metal box to shield out electromagnetic interference. A vibration exciter is used to provide acceleration force to the accelerometer chip. A commercial accelerometer ADXL202 from Analog Devices, Inc. is used to calibrate the vibration system. We use a voltage amplifier rather than a charge amplifier since a voltage amplifier gives a higher signal-to-noise ratio in case of relatively small charge developed. The piezoelectric-bimorph accelerometer and its amplifying circuitry are modeled by the equivalent circuit shown in Fig. 17. A diode D is used to provide a very high resistance so that a tiny leakage path will be present to drain off stray charges that might accumulate on the exposed electrode. The voltage at the input of the voltage amplifier is

$$V_m = \frac{Q}{C_p + C_e + C_p \cdot \frac{1}{C_a}}$$  \hspace{1cm} (21)

where $Q$ is the total charge produced on the sensing electrode, $C_p$ is the composite capacitance across the ZnO layer and the electrically insulating PECVD Si₃N₄ layer covering the ZnO [22], and $C_a$ is the parasitic capacitance (measured to be 11.56 pF) due to the amplifier, the diode, and the conductor line connecting the accelerometer to the amplifier. Fig. 18 shows the typical outputs of the bimorph piezoelectric accelerometer and ADXL202 when sinusoidal signal is applied to the vibration exciter.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

A. Single-Axis Piezoelectric-Bimorph Accelerometer

A few different designs of the single-axis piezoelectric-bimorph accelerometer with different suspension-beam widths and electrode areas have been fabricated and tested. The structure parameters of one such design and its expected characteristics are listed in Table IV. The frequency response of the fabricated piezoelectric accelerometer for a 1-g constant acceleration (Fig. 19) is measured to have a flat response from subhertz to 60 Hz, with a resonant frequency around 98 Hz. Fig. 20 shows the low-frequency response of the fabricated accelerometer. The achievable low-frequency response (down to quasi-dc) depends on the effective impedance of the detection circuit in Fig. 17. With the current detection circuitry, the achievable minimum detectable frequency is 0.1 Hz. The measured unamplified sensitivity of the bimorph piezoelectric accelerometer is around 7.0 mV/g in the flat frequency range, and the minimum detectable signal level is around 0.01 g, with most of the noise coming from the detecting-circuit noise. The accelerometer output is measured as a function of acceleration amplitude and is shown to have a linearity of 0.9% up to 3 g (Fig. 21).

Table V summarizes the calculation and measurement results for the single-axis piezoelectric-bimorph accelerometer, with the structure parameters listed in Table IV. The measured resonant frequency is a little lower than the calculated value, possibly due to the actual Young's moduli of the multilayer suspending beam being smaller than the ones used in the calculation. The measured voltage sensitivity (7.0 mV/g) is a little lower than the calculated value (8.3 mV/g), partly due to $d_{31}$ of the ZnO film being less in the real device than the one used in the calculation. The residual stress in the suspending beam is expected to affect the sensitivity only slightly since the beam is essentially a cantilever.

B. Triaxis Piezoelectric-Bimorph Accelerometer

Fig. 22 shows the triaxis accelerometer outputs on the X-, Y-, and Z-axis electrodes as a function of acceleration amplitude.
Fig. 15. Photos of a completed triaxial piezoelectric-bimorph accelerometer. (a) Front side. (b) Backside.

Fig. 16. Testing setup for the piezoelectric accelerometers.

Fig. 17. Equivalent circuit of the single-axis piezoelectric-bimorph accelerometer along with the loading from the detection circuit.

when the acceleration is applied along X-, Y-, and Z-axes, respectively. The unamplified sensitivities of the X-, Y-, and Z-axis electrodes in response to accelerations in X-, Y-, and Z-axes are measured to be 0.93, 1.13, and 0.88 mV/g, respectively.

Figs. 23 and 24 show the accelerometer outputs on the X-, Y-, and Z-axis electrodes when the acceleration is applied only along the X- or Y-axis. The figures show that the cross-axial sensitivity among the X-, Y-, and Z-axis electrodes is less than 15%. The measurement results of the cross-axial sensitivity include not only the output from the accelerometer chip itself but also the noise picked up by the circuit. The noise spectrum of the output signal is measured with a spectrum analyzer, and the minimum detectable signal is estimated to be 0.04 g over a 100-Hz bandwidth (Fig. 25).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam length (μm)</td>
<td>140</td>
</tr>
<tr>
<td>Beam width (μm)</td>
<td>1000</td>
</tr>
<tr>
<td>Al thickness (μm)</td>
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<tr>
<td>Al electrode length (μm)</td>
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</tr>
<tr>
<td>Al electrode width (μm)</td>
<td>1000</td>
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<tr>
<td>ZnO thickness (μm)</td>
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</tr>
<tr>
<td>PECVD SiNx thickness (μm)</td>
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</tr>
<tr>
<td>Parylene thickness (μm)</td>
<td>3.7</td>
</tr>
<tr>
<td>Proof mass length (μm)</td>
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</tr>
<tr>
<td>Proof mass width (μm)</td>
<td>1200</td>
</tr>
<tr>
<td>Proof mass thickness (μm)</td>
<td>330</td>
</tr>
<tr>
<td>Expected resonant frequency (Hz)</td>
<td>131</td>
</tr>
<tr>
<td>Expected charge sensitivity (C/m² s⁻¹)</td>
<td>2.36 x 10⁻¹⁴</td>
</tr>
</tbody>
</table>
Table VI summarizes the simulated and measured results for the triaxis piezoelectric-bimorph accelerometer, with its structure parameters listed in Table III. The measured Z-axis voltage sensitivity is about 12 times lower than the sensitivity calculated without considering the residual stress effect (though the measured X-axis voltage sensitivity is close to the calculated value), demonstrating the significant effect of the residual stress on the Z-axis sensitivity of the triaxis piezoelectric-bimorph accelerometer. The residual stress affects the Z-axis sensitivity much more significantly than the X-Y-axis sensitivity, as can be seen from the prior theoretical analysis.

VII. SUMMARY

Novel single- and triaxis piezoelectric-bimorph accelerometers have been designed, fabricated, and tested for low-frequency applications such as human-body-movement sensing. A piezoelectric-bimorph structure of parylene/Al/Si$_2$N$_x$/ZnO/Si$_2$N$_x$/Al/Si$_2$N$_x$/ZnO/Si$_2$N$_x$/Al/parylene is fabricated by depositing a ZnO film on both sides of the wafer and is mechanically supported mainly by parylene. With the neutral plane fixed just at the middle of the beam thickness and the two piezoelectric layers above and below the neutral plane, the sensitivity is maximized. The sensitivity is improved also because of the low stiffness of a parylene layer supporting
### Table VI
Simulated and Measured Characteristics of the Triaxial Piezoelectric-Bimorph Accelerometer

<table>
<thead>
<tr>
<th>Axis</th>
<th>Calculated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-axis</td>
<td>38.5</td>
<td></td>
</tr>
<tr>
<td>Y-axis</td>
<td>1.59</td>
<td>0.93</td>
</tr>
<tr>
<td>Z-axis</td>
<td>38.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.59</td>
<td>1.13</td>
</tr>
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<td></td>
<td>111.7</td>
<td></td>
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<tr>
<td></td>
<td>10.89</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Fig. 23. Measured unamplified outputs on the X-, Y-, and Z-axis electrodes (of the triaxial accelerometer) for 20-Hz accelerations applied along X-axis as a function of acceleration amplitude.

Fig. 24. Measured unamplified outputs on the X-, Y-, and Z-axis electrodes (of the triaxial accelerometer) for 20-Hz accelerations applied along Y-axis as a function of acceleration amplitude.

Fig. 25. Output (Z-axis) of the triaxial accelerometer measured by a spectrum analyzer for a 70-Hz 1-g acceleration applied in Z-axis.

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REFERENCES


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