Development of a 3-DOF Micro Accelerometer with Wireless Readout

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Keywords : accelerometer, wireless readout, MEMS, piezoresistor

This paper describes the design, simulation and fabrication of a 3-DOF (degree of freedom) micro accelerometer with wireless readout system. The working principle of this accelerometer is based on piezoresistive effect in single crystal silicon. The sensor can independently detect three components of acceleration in three orthogonal directions, i.e. X, Y and Z axes. The sensor was simulated and developed using FEM (finite element model) and fabricated by MEMS (micro electromechanical systems) technology from SOI (silicon on insulator) wafer. Fig.1 and Fig.2 illustrate the model of the accelerometer and its microphotograph after being fabricated and packaged, respectively.

This accelerometer has been characterized. With 10μm beam thickness and 3V bias voltage, the sensitivity to the acceleration in X, Y, Z axis are 30μV/g, 30μV/g, 23μV/g (g=9.81m/s²) and the bandwidth at -3dB is 700Hz. Due to its small size and reliable characteristics, this sensor had been integrated with wireless readout system in order to form a smart micro accelerometer.

The system consists of two main parts, i.e. the sensing-transmitter and the receiver parts (Fig.3). The sensing-transmitter includes offset reduction, amplifier with gain of 1000, a low pass filter, a microcontroller, power amplifiers and antenna matching blocks. The microcontroller used in this study is nRF24E1 of Nordic Semiconductor. At the microcontroller, the signal is converted to digital, encoded and modulated with carrier frequency of 2.4GHz. This RF (radio frequency) signal is matched with an antenna and, finally, transmitted out. In this study, the antenna is spiral antenna (Fig.4), it was designed to transmit the 2.4GHz ISM (Industrial, Scientific and Medical) radio band signal over a distance of 20m. At the receiver part, RF signal is collected, amplified, demodulated and decoded into the actual output voltage component. These sensors can be applied to biomedical applications for remotely health monitoring or motion sensing for image artifact compensation in live. The work is expected to be applied in a wireless accelerometer network in the near future.
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This paper describes the design, simulation and fabrication of a 3-DOF (degree of freedom) micro accelerometer with wireless readout system. The fabricated accelerometer has dimensions of 1000µm×1000µm×500µm (Length×Width×Thickness) and can detect three components of linear acceleration simultaneously. The sensitivities to X-axis, Y-axis and Z-axis are 30µV/g, 30µV/g and 23µV/g, respectively. A three input-channels wireless transceiver system has been developed and integrated with the sensing element to form a sensor node. The antenna has been designed to transmit the signal from sensor node to a server at a communication frequency of 2.4GHz over a distance of 20m. Three output signals, i.e. X-axis, Y-axis and Z-axis, from the accelerometer are transmitted to the server by time division multiplexing protocol. This allows our wireless sensor system to detect three components of acceleration independently.

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1. Introduction

MEMS silicon sensors have shown their advantages in the aspects of small size, high performance, high yields, low cost, and compatibility with IC technology. So they become more and more popular in such fields as navigation, automobiles, patient monitoring, consumer, etc., especially inertial sensors such as accelerometer, which are very important for industry and consumer applications[1][2]. The demands to improve the accelerometer like reducing the dimension or integrating with wireless network are increasing. In this paper, we introduce a prototype of an accelerometer with wireless readout system, i.e. the combination of small piezoresistive 3-DOF accelerometer with a wireless transceiver. With its advantages, this prototype can be improved to apply in human vital signal monitoring system.

This prototype includes 2 main parts, the sensing-transmitting

![Fig. 1. Overview of the accelerometer with wireless readout system](image-url)
part and the receiving part. At the sensing-transmitting part, the information from the environment can be collected, preprocessed and fed to transmitting module, where it is sent to the receiver part. The overview of the system is illustrated on Fig.1. By this system, the acceleration information can be obtained remotely.

2. Development of the Acceleration Sensing Element

2.1 Design of Sensing Element  The sensing element in this work is a 3-DOF micro accelerometer made of Si, with a seismic mass suspended at the ends of the four surrounding beams, which themselves are fixed to the “rigid” frame at the middles. The model of this sensor is illustrated in Fig.2. The die size is 1000µm×1000µm×500µm. The principle of this accelerometer is based on piezoresistive effect in single crystal silicon\(^{(3)}\). This sensor had been designed and simulated by finite element method (FEM) using ANSYS. After optimizing the specifications\(^{(4)}\) (such as sensitivity, nonlinearity, frequency mode etc.), the dimensions of the beam are decided to be 425µm×40µm×10µm. Based on the stress distribution analysis on the beam, the positions of Si piezoresistors are decided. The piezoresistors are formed by diffusing boron ions at the suitable places on the surface of the Si sensing beams in order to obtain high sensitivity with lowest crosstalk from one axis to the others. The distribution of the stress along the beam is shown in Fig.3 and the arrangement of the piezoresistors on the beam is in Fig.2-(b).

When an external acceleration is applied to the sensor, the seismic block is displaced due to the inertial force. This movement of the seismic mass makes the beams deformed; as a result, the electrical resistance of Si piezoresistors is changed. The change of resistance will be converted to an output voltage change by a Wheatstone bridge. The sensitivities to each components of acceleration \(A_x, A_y, A_z\) can be respectively expressed as

\[
S_x = \frac{V_{out}}{A_x} = \frac{1}{A_x R} \frac{\Delta R}{R} \frac{V_{in}}{A_x} = \frac{1}{A_x} (\sigma_{x} + \sigma_{y}) V_{in} \quad \text{(1)}
\]

\[
S_y = \frac{V_{out}}{A_y} = \frac{1}{A_y R} \frac{\Delta R}{R} \frac{V_{in}}{A_y} = \frac{1}{A_y} (\sigma_{x} + \sigma_{y}) V_{in} \quad \text{(2)}
\]

\[
S_z = \frac{V_{out}}{A_z} = \frac{1}{A_z R} \frac{\Delta R}{R} \frac{V_{in}}{A_z} = \frac{1}{A_z} (\sigma_{x} + \sigma_{y}) V_{in} \quad \text{(3)}
\]

where \(\sigma_x, \sigma_y\) are the longitudinal and transverse stress at the piezoresistor \(R\) due to the application of acceleration \(A\); \(\pi_0, \pi_\pi\) are the longitudinal and transverse piezoresistive coefficient of the piezoresistor; \(\pi_0 = 35 \times 10^{-3} \text{MPa}^{-1}\), \(\pi_\pi = -31 \times 10^{-3} \text{MPa}^{-1}\) at the impurity concentration of \(5 \times 10^{19} \text{atoms/cm}^3\). In this case, the shear piezoresistive coefficient, \(\pi_\pi = -0.5 \times 10^{-3} \text{MPa}^{-1}\) is not calculated due to their small contribution compared with longitudinal and the transversal components. Furthermore, from stress analysis results, the shear stress components are much smaller than the longitudinal stress. \(V_{in} = 3\text{V}\) is the input voltage. From the stress results simulated above, the sensitivities are calculated to be \(S_x = S_y = 48.7 \mu \text{V/g} ; S_z = 32.4 \mu \text{V/g}\).

2.2 Fabrication of Sensing Element  The sensors were fabricated using micromachining process with simple 5-mask process which is shown schematically in Fig.4.
The sensing chip was fabricated by micromachining process shown briefly in the following:

**Step 1:** The starting material was 4-inch n-type (100) SOI (silicon on insulator) wafer with the thickness of device layer of 10µm, and of handle substrate is 500µm, the resistivity is 0.5 Ohm-cm

**Step 2:** A 0.3µm-thick insulation layer SiO2 was formed by thermal oxidation process.

**Step 3:** Piezoresistors were patterned so that their principal axes align with the crystal directions <110> and <110>. Boron ions were diffused to form p-type piezoresistors by using spin-on diffusion source (Polyboron Film - PBF). Pre-deposition process was performed in N2 at 1000°C for 60 min. Then, a drive-in process was done in O2 at 1100°C for 30 min to move the boron ions deeper into the substrate and to reduce the surface impurity concentration. In order to reduce the temperature sensitivity of piezoresistors, the surface impurity concentration was controlled at about 5×10^19 atoms/cm^3.

**Step 4:** Front-beam pattern was defined by photolithography by using a double-side mask aligner and wet etching in buffered hydrofluoric acid (BHF) solution.

**Step 5:** The gap between the bottom of the mass and the substrate is formed using ICP (inductive coupled plasma) etching.

**Step 6:** Contact holes were opened by wet etching in BHF solution.

**Step 7:** 0.5µm-thick aluminum wires and bonding pads were formed by vacuum evaporation, photolithography, and etching processes. Next, a sintering process was performed in N2 for 30 min at 450°C to make Ohmic contact between electrodes and piezoresistors.

**Step 8:** The seismic mass was formed by deep reactive ion etching (D-RIE) from the backside. Finally, buried oxide was removed by RIE etching in gas CHF3.

The microphotographs of the sensor after fabricated and packaged are shown in Fig.5, and Fig.6.

Fig. 5. Microphotograph of the fabricated accelerometer  
Fig. 6. Microphotograph of the packaged accelerometer

The wireless readout circuit having three channels was designed to transfer the signals from the 3-DOF accelerometer to the receiver part. The circuit includes a pre-processing, an analog to digital converter (ADC), a controller, a transceiver and an antenna. Fig.7 shows the circuit of the sensing-transmitter part.

The preprocess part consist of offset reduction, amplifier and a low pass filter modules. Pre-processing part makes the signal suitable for the input of the ADC.

The microcontroller used in this work is nRF24E1 of Nordic Semiconductor, with the ADC, codec and modulator are integrated inside. Because the sampling frequency of the ADC is finite then the signal must be filtered before reaching to the input of the ADC. In this case, the filter is a passive filter constructed from R-C circuit. The cutoff frequency of this filter should be decided by the ADC’s sampling frequency. The conversion time for each sample is calculated by t_conventional = \(N/2^N \), \( t_{	ext{clk}} \) where \( N = 12 \) is the number of resolution bit, \( t_{	ext{clk}} \) is the clock cycle (=5.3µs), therefore \( t_{	ext{conventional}} = 48\mu s \), or the sampling frequency of the ADC is 20 kHz. Based on Nyquist-Shannon theorem we have the maximum frequency of the signal at the input of the ADC is 10 kHz. This bandwidth is divided into three corresponding to three axis of accelerometer (X, Y and Z axes), then the cut-off frequency of the filters is 3.3 kHz.

The signals after be converted to digital, encoded and modulated with carrier frequency of 2.4GHz, will be RF impedance matched with an antenna and, finally, transmitted out. The integrated transceiver in the microcontroller consists of a fully integrated frequency synthesizer, a power amplifier, a modulator and two receiver units. The antenna was designed to transmit the 2.4GHz ISM ((Industrial, Scientific and Medical)) band signal. Spiral antennal can be used in this study, because of its small size and comparability with printed circuit board assembly process. The miniature printed square spiral chip inductor/antenna and its equivalent circuit are shown in Fig.8-(a) and (b). The circuit is modeled as a series inductor \( L_s \) and resistor \( R_s \) in parallel with in capacitor \( C_s \). The \( L_s \) is computed using the current sheet expression given in Eq.4 and \( C_s \) and \( R_s \) are computed by using the expressions given in Eq.5 and 6 as follows(38)

\[
L_s = K_s \mu_n \frac{n^2 \mu_0}{1 + K_s \rho} 
\]

\[
R_s = \frac{1}{\sigma \omega_0 (1 - e^{-i \theta})} 
\]

\[
C_s = \frac{\epsilon_0 n^2}{(t_{	ext{M1-M2}})} 
\]

where \( \rho \) is the fill ratio = \( (d_{\text{out}} - d_{\text{in}})/(d_{\text{out}} + d_{\text{in}}) \); \( d_{\text{avg}} = (d_{\text{out}} - d_{\text{in}})/2 \).
$K_1$, $K_2$ are coefficients depending on the shape of the inductor/antenna, in this case $K_1 = 2.34$; $K_2 = 2.75$; $\mu_0 = 4\times10^{-7}$ H/m is the magnetic permeability of free space; $I$ is the inductor length = $4.n.d_{\text{avg}}$, $n$ is the number of turn; $t = 0.3\text{mm}$ is the turn thickness and $\sigma = 59.6\times10^{-6}$ Siemens per meter or $(\Omega\text{m})^{-1}$ is the conductivity of copper, skin depth given by $\delta = \frac{2}{\pi f(\sigma \mu_0)}$ (where $\omega = 2\pi f$) is working frequency = $2.4\text{GHz}$; $t\text{PCB}$ is the PCB thickness between the spiral and the under-pass, $t\text{PCB} = 1.6\text{mm}$; $\varepsilon = 4.5\varepsilon_0 = 4.5\times8.854\times10^{-12}\text{F/m}$ is the permittivity of PCB board.

With $n = 30$ turns, $d_{\text{in}} = 5\text{mm}$, $d_{\text{out}} = 28\text{mm}$, $w = 0.4\text{mm}$ we have the impedance of the inductor/antenna equal to 50$\Omega$, matched with impedance of the out put of the modulator.

To calculate the distance of communication between the transmitter and receiver we depend on the following Eq.7:

$$P_{\text{dBm}} = P_{\text{dBm}} + G_1 + G_2$$

$$= -20\log_{10}(\frac{f}[\text{MHz}]R[\text{km}]) - 32.4418$$

where $R$ is the distance (in km) between the transmit antenna and receive antenna, $f$ is the communication frequency, $P_{\text{in}}$ and $P_{\text{out}}$ are the power input to the transmitting antenna and the sensitivity of the receiving antenna, respectively $G_1$ and $G_2$ are the gain of transmitting and receiving antenna. Suppose that the antennas are isotropic then $G_1 = G_2 = 1$. We have $P_{\text{in}}$ in the range of 0dBm to $-20$dBm and $P_{\text{out}} = -90$dBm $\mu_0$ (at bit error rate BER = 1%). Therefore, $R$ is in the range of 0.314km to 0.0314km.

The experimental results show that with $P_{\text{in}} = -20$dBm, the wireless readout can work perfectly in the range of 20m.

The signals from the output of three axis of accelerometer are multiplexed using time division multiplexing technique. The number of bits for each sample of each channel is fixed (12 bits, the resolution of the ADC) then the signals from the output of three axis of accelerometer are sampled, converted to digital, coded and packaged in the order: X axis, Y axis and Z axis. At the receiver part, data can be unpackaged in the proper order.

4. Results and Discussion

The accelerometer had been calibrated using acceleration generator system as shown schematically in Fig.9. The reference accelerometer used in this case is the product of Mitutoyo Corporation (V301TB). The preliminary calibration of the accelerometer was performed in the range from 0g to 24g. Fig.10 and Fig.11 show the X- and Z-bridge output characteristics of the fabricated accelerometer (with $V_{in} = 3\text{V}$). Fig.12 shows the frequency response of the accelerometer. The bandwidth at $-3\text{dB}$ is about 700Hz. This result is small then the calculated value. It is because of the glue for fixing the chip to the PCB (printed circuit board) not strong enough to be considered as “stiff bonding” as was done in the simulation and the squeezed-film air damping effect occurred in the gap between the bottom of seismic mass and the PCB.

At room temperature, the sensitivity for Z-axis is $23\mu\text{V/g}$ with the non-linearity is 4% and the cross axis sensitivities less than 5.5%. The sensitivity, cross-axis sensitivity and the non-linearity for X axis are 30$\mu\text{V/g}$, 4.5% and 2% full scale; and with Y axis these values are 30$\mu\text{V}$, 4.2% and 3% full scale, respectively. The reason of cross-axis sensitivity of about 5% is assumed to be the misalignment occurred during fabrication of the chip, and misalignment between the accelerometer and the PCB circuit. The experimental sensitivities are lower than the calculated values. The reason is the impurity concentration of Boron at diffusion process not exactly $5\times10^{19}$ atoms/cm$^3$ following the different of piezoresistive coefficients.

The whole system consumes about 24 mW when it is in active status. A 3 Volt lithium battery is used to supply power for the system. The capacity of lithium battery is about 220mAh then the lifetime of the system is about 27.5 hours.

5. Conclusion

A prototype of accelerometer with wireless readout had been
developed and tested. These wireless sensors can measure three components of acceleration with the sensitivities to X, Y and Z-axis are 30 µV/g, 30µV/g and 23µV/g; cross-axis sensitivity less than 5.5% and the wireless communication operation was tested to be good in the range of 20m. These sensors can be applied to biomedical applications for remotely health monitoring or motion sensing for image artifact compensation in live. The work is expected to be applied in a wireless accelerometer network in the near future.

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