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# Vertical-plate-type microaccelerometer with high linearity and low cross-axis sensitivity

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ABSTRACT

This paper reports the development of a microaccelerometer with high performance in linearity and cross-axis sensitivity. The accelerometer consisted of a vertical, double-ended flexural beam, a proof mass integrated at the middle section of the beam, and four suspended piezoresistors fixed at the mass block and across the trenches to the anchor pads. The mass block had maximum displacements of the dynamic structure which would activate the sensors to deliver maximal output. The sensing chip was fabricated on a silicon-on-insulator wafer through MEMS processes. The accelerometer was placed on a rate table that provided stable centrifugal acceleration up to approximately 3000 × $G$ for testing. The output voltage of the accelerometer was digitized and radio-frequency transmitted for remote data acquisition. The correlations for the individual runs showed that the accelerometer had a sensitivity of 3.0015 $\mu V/V_{exc}/G$ with extraordinary performance. The linearity of the sensing output was only 0.11% of full scale output (FS, or 59 dB), as deduced from the average standard deviation of all test runs. The average of the maximum reading deviations from the corresponding correlated curves was approximately 0.26% FS. Moreover, the cross-axis sensitivity for the two orthogonal directions nearly vanished in the test range. With the high rigidity of the microstructure, the accelerometer exhibited an ultra high performance factor of $25.8 \times 10^6$ MHz$^2$. The accelerometer possessed exceptional sensitivity, linearity, and repeatability, and extremely low cross-axis interference and noise.

## 1. Introduction

In modern microelectromechanical systems (MEMSs), key interdisciplinary elements have been integrated, and these systems can be used to fabricate new devices that are capable of performing elaborate functions. These devices have a small volume and weight, and they are typically low cost because they are batch-processed. A variety of MEMS devices have been developed and marketed over the past few decades. Among the devices used in conventional applications in microsensing and actuating, the most popular include pressure transducers, *G* sensors, valves, nozzles, and fluidics. Microaccelerometers are widely applied in many fields, as personal appliances, health care aids, transportation carriers, and in aeronautics and the aerospace industry. Many institutions have progressively devoted effort to developing various accelerometer configurations and characteristics for specific purposes.

A typical accelerometer typically consists of an inertial structure and an electric detection assembly. The structure response characteristics and resonant frequency determine the applications and sensing range of an accelerometer. The conversion mechanism and detection component configuration determine the sensitivity and resolution of the sensing signal. The use of a signal conditioner and an amplifier can improve the quality of the output by suppressing noise and increasing the signal strength. Key factors, such as sensitivity, linearity, stability, reliability, dynamic range, and signal-to-noise ratio, should be considered when designing or identifying accelerometers for specific applications.

Several sensing mechanisms are used to convert the detected acceleration into an electric signal for processing [1,2]. The electrical resistivity of semiconductor materials is significantly changed when stress is applied to the atomic lattice [3]. Single-crystal-silicon-based piezoresistive devices offer the advantages of high sensitivity, low cost, and easy fabrication [4–14]. The piezoresistor is typically positioned with a specific orientation to detect the maximal current flow in the material lattices. A piezoelectric accelerometer employs piezoelectric material to detect strain resulting from an applied acceleration [15]. The high elastic modulus and high linearity of piezoelectric materials render piezoelectric

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transducers an attractive option for high stress in high-*G* impact environments. The piezoelectric sensors, however, show limitations in situations such as those involving static measurements or static force loads, and situations in which the sensor is fabricated from imperfect insulation materials. Capacitive accelerometry is a mature technology used to measure dynamic motion. The capacitive sensor has a high resolution and is sensitive to small changes in the field force. In addition to good performance in the low-frequency range, the sensor shows high stability, low temperature sensitivity, and low power consumption [16,17]. It often requires a fixed reference capacitor for ac signal conditioning and readout for the subsequent process. This will occupy additional space in the sensing chip.

Other types of dynamic motion detectors have been developed by employing various energy conversion methods in accelerometers. Dauderstädt et al. [18] detected acceleration by sensing temperature changes between the suspended mass of a heat sink and the heated base by using thermopiles in the low-frequency response. The amplitude of a cantilever beam that was caused to vibrate by applying shock was used to modulate the light intensity of a multimode fiber for direct digital output [19]. The extremely sensitive relation between the tunneling current and the distance of the two electrodes, respectively, embedded at the moving seismic mass and the stationary frame of the accelerometer, was employed to detect small acceleration [20]. Seshia et al. [21] conducted acceleration measurements in digital mode by monitoring the change in the resonant frequency of a sensing structure coupled to the proof mass in response to the applied stress. The large variety of accelerometers being developed is evidence of the products having pertinent applications in a broad spectrum of fields and in daily life.

Acceleration testing is essential to characterize an accelerometer. In laboratories, several experimental methods are employed for performance evaluation. For static testing, a convenient method is to use a dividing head inclined at various angles along with gravitation, and testing is conducted for a stationary acceleration within $\pm 1 \times G$ (9.81 m/s$^2$) [4,7,17,18,20,21]. Some dynamic tests also use gravity to convert the potential energy of a mass at a predetermined level into kinetic energy, and they involve hitting an anvil at the datum. The magnitude of acceleration can be controlled by varying the initial potential energy and the hardness of the surfaces for instantaneous collision [4,5,8]. These types of setups can produce accelerations ranging from $1 \times G$ to several tens of k*G*. Shakers can provide a wide range of frequency and amplitude for periodic acceleration test [7,13,14,19]. Dynamic apparatuses used for impact surveys are driven by external power to accelerate the mass to a high velocity before collision. In the split Hopkinson pressure bar method, the impact strength at the target sensor can be varied up to the order of $200 \times$ k*G* [8,11,22]. Objects fired from a gas gun can provide a higher magnitude of acceleration [23]. In dynamic test methods, the response of an accelerometer is often converted into the frequency spectrum. The response spectrum can be compared to the spectrum of a reference accelerometer to validate the characteristics of the tested accelerometer. Steady centrifugal acceleration, on the other hand, can be used to calibrate the sensitivity, linearity, and resolution of an accelerometer during the accelerometer development phase for performance evaluation [5,6,9,12,13]. The experiment with stable centrifugal acceleration also avoids damping effects of the packaging layers of the sensor chip [22]. However, the test rigs should transmit sensing signals from the rate table for remote data acquisition and analysis [5].

High sensitivity, high linearity, high resolution, high repeatability, and low hysteresis are basic requirements for a sensor to perform accurate and precise measurements. Many reported accelerometers can achieve an acceptable linearity in the order of 1% of full scale (FS) output [4,8,9,11–14,17,20]. Some instruments that are used for detecting dynamic behavior require additional characteristics, for example, the cross-axis sensitivity must vanish or be minimal. For embedded sensing components based on a strain converting mechanism, this requirement is not easy to fulfill because of the properties of the stressed material. The Poisson's ratio of 0.22 to 0.28 for a silicon substrate implies that an off-axis acceleration will produce significant strain in the sensing direction greater than 5% [4,13]. This cross-axis interference requires additional effort to resolve the actual dynamic quantity in the sensing axis if the applied force direction is not prescribed [10]. Some elaborative designs could reduce this off-axis sensitivity to the order of 1% [9,14]. Sankar and Das [12] reduced further the cross-axis sensitivity to 0.37%. A self-supported transducer can effectively reduce the off-axis interference because the sensor is activated in the axial direction by a force or a displacement. Kuells et al. [11] designed and fabricated a high-*G* accelerometer with suspended piezoresistors having a remarkably high figure of merit (sensitivity multiplied by frequency squared). This high value was achieved by fixing three edges of a vertical mass plate, resulting in extremely high resonant frequencies. They positioned four piezoresistors in the center region of the free longitudinal edge of the plate to sense the in-plane impact. The highly restricted flexural plate allows the accelerometer to withstand up to $200\text{k} \times G$ in a survivability test.

This paper describes the design, simulation, microfabrication, and testing of a vertical plate, in-plane motion accelerometer. Accurate measurements were conducted on a centrifuge in which the electric signal of the piezoresistive bridge circuit was transmitted by a radio frequency module to a PC for remote data storage and analysis. The sensor exhibited outstanding calibration results in both linearity and cross-axis sensitivity over a wide range of acceleration.

## 2. Design and simulation

The high-performance accelerometer designed in this study consisted of a mass-appended vertical plate and four suspended piezoresistors. It was easy to fabricate with typical MEMS facilities. Fig. 1 shows the symmetric configuration of the core structure, which was fabricated from a silicon-on-insulator (SOI) wafer. The wafer had a p-type device layer of 7 μm in thickness, separated by a 1 μm-thick insulation layer from a handle layer of 400 μm in thickness. The central proof mass was supported by two flexural beams that were fixed at the ends. The beams with a width of 100 μm and 600 μm in length had sufficient stiffness to reduce movement in the transverse directions. Four piezoresistors were located at the top central edges of the mass block along the prime impact direction, and they were anchored across the trenches. The piezoresistors measured 80 μm in length, 10 μm in width, and 7 μm in depth. The two adjacent piezoresistors on the same side of the mass block were 40 μm apart. The four detectors were connected by top metal thin films to form a Wheatstone bridge circuit for acceleration measurement.

Because the four piezoresistors were aligned parallel to the prime impact *Z*-direction, they mainly experienced axial forces. Even in the case the proof mass received an off-axis shock, its displacement primarily exerted longitudinal strain in the slender piezoresistors. Consequently, the fractional change in the resistance when subjected to a longitudinal stress can be approximated as [3]

$$\frac{\Delta R}{R} = \pi_l \sigma_l \qquad (1)$$

where $R$ is the resistance of piezoresistor, $\Delta R$ the change in resistance, $\pi_l$ the longitudinal piezoresistive coefficient, and $\sigma_l$ the experienced longitudinal stress. The stress is related to strain by