

A Monolithic Surface Micromachined Accelerometer with Digital Output

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Abstract—A surface micromachined accelerometer with on-chip electronics realized in a 3 μm BiCMOS technology is described. The sensing element consists of a thin film of polysilicon that is deposited after fabrication of the electronic circuitry. Acceleration is measured by capacitively sensing sub-angstrom displacements of a mechanical proof-mass weighing 0.5 μgrams . The sensor uses force-feedback and achieves a resolution of 1.6 $\text{mg}/\sqrt{\text{Hz}}$ ($1\text{ g} = 9.8\text{ m/s}^2$). The limitations arising from the small size and mass of the sensing element and means for improvement are discussed. The small active die area of less than 3 mm^2 including the sensor along with the possibility to combine several different sensors on a single chip make this approach particularly attractive for applications demanding very small form factors.

I. INTRODUCTION

INTEGRATED CIRCUITS play an important role in the process of gathering and processing “real world” information. In many cases, however, the actual sensing element is not part of the integrated circuit but fabricated in a different technology using substantially different tools and materials. As a result, the cost reductions and performance enhancements of IC solutions have not been fully realized.

Over the past decade, surface micromachining has become established as a technology for fabricating micromechanical structures from deposited thin films of polysilicon [1], aluminum [2], silicon nitride [3], [4], and other materials. Monolithic integration of surface microstructures with electronic circuitry is relatively straightforward and economically attractive with the microstructure typically occupying only a small fraction of the die area. By bringing the sense element onto the integrated circuit, surface micromachining leverages the experience and sophisticated processes of IC manufacturing and brings about all the customary advantages of integrated solutions: batch fabrication, high yield, small size, low power, and low cost. Elimination of a separate sense element miniaturizes the package and also results in improved reliability. For example, commercial surface micromachined accelerometers are rated for shocks in excess of 1000 g ($1\text{ g} = 9.8\text{ m/s}^2$) [5], [6], a level of robustness that is difficult to achieve with larger macroscale devices.

Several combined sensors and circuits technologies have been described in the literature [7], [8]. Applications include

inertial sensors for acceleration and angular rate, as well as nonsensing functions such as low-drift clocks and high- Q , low-power electro-mechanical filters [9]. In addition to traditional sensor markets such as the automotive industry where this technology is competing with established approaches [10], an even bigger impact can be expected from future applications that take full advantage of the small size and versatility of surface micromachining. Motion sensors for head-mounted displays, for example, depend on very low-power, weight, and size sensors to track head movement in several directions. All these requirements can be met with a surface machined solution by combining several different sensing elements and all interface electronics on a single chip measuring only a few millimeters on a side.

In this paper, a surface micromachined acceleration sensor with on-chip electronics is described. The circuit is fabricated using Analog Device’s BiMOS2e process, a 3 μm BiCMOS technology with an added layer of polysilicon used for building the mechanical sensing elements. Section II compares different choices for the sensing element and explores trade-offs between sensitivity and robustness of the devices. Potential performance limitations arising from the small size and extremely low mass, on the order of micro-grams, of typical polysilicon surface micromachined sensing elements are addressed as well.

The sense electronics used to detect subangstrom displacements of the sensing element due to acceleration inputs is described in Section III. The factors limiting the achievable resolution are evaluated and options for improvement analyzed. Feedback is explored in Section IV as a means to improve overall sensor performance. An experimental monolithic surface micromachined accelerometer and its measured performance are reported in Section V.

II. SENSING ELEMENT

For the technology used in this project [7], [11], mechanical elements consist of a 2 μm thick sheet of doped polysilicon suspended 1.6 μm above the substrate. The minimum width of beams is 2 μm , and the gap between adjacent features must be at least 1 μm . An additional mask specifies where structures are anchored to the substrate.

Despite the limitation to planar structures, a large variety of different sensors can be realized in this technology. Fig. 1 shows a conceptual diagram of two acceleration sensors with sensitivity to linear inputs perpendicular (z -axis) and parallel (x - or y -axis) to the chip surface. Both consist of a proof-mass anchored to the substrate with springs fabricated out of a single

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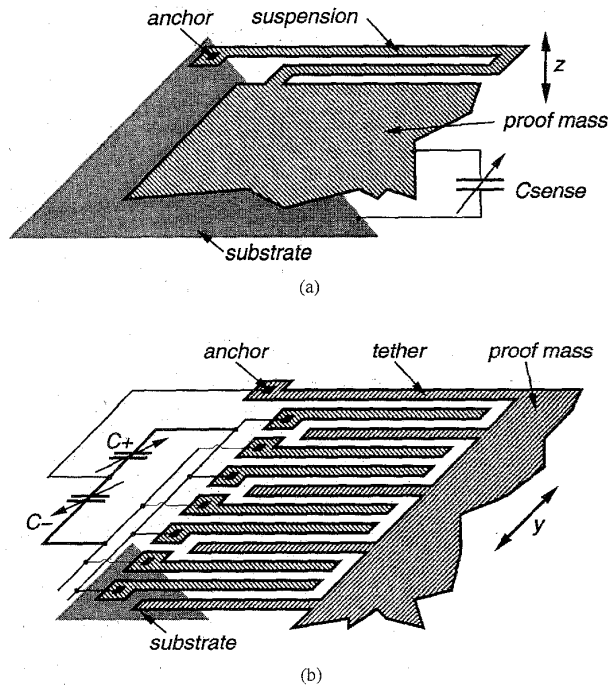


Fig. 1. Acceleration sensors with sensitivity to inputs (a) perpendicular and (b) parallel to the chip surface.

sheet of polysilicon. Acceleration of the sensor results in a displacement of the proof-mass with respect to the substrate that is sensed capacitively.

Both arrangements have their respective merits. The y -axis sensor uses a comb of stationary and movable electrodes for a fully differential readout. In the case of the z -axis sensor, the sense capacitor is formed by the substrate and the proof-mass itself. The inherent asymmetry of this interface leads to an offset and nonlinearity that must be compensated for in the electronic interface. Moreover, the sense voltage applied across the capacitor results in a pull-down force acting on the proof-mass that must be compensated by an equal pull-up force to prevent the sensor from collapsing onto the substrate.

The typically two to four times larger sense capacitance of z -axis structures in a given area is an advantage of this device. Even more importantly, the sensitivity to motion of the proof-mass and hence acceleration inputs is larger for devices that use a parallel plate capacitor for position sensing. This is because in the case of the sense combs used in x - or y -axis elements a substantial fraction of the sense capacitance is due to fringing fields and does not change appreciably due to small displacements. In the case of parallel plate capacitors, on the other hand, almost the entire parallel plate capacitor of the z -axis structure is sensitive to vertical motion of the proof mass. The increased sense capacitance and its higher sensitivity to displacement reduce the noise from the electronic position sense interface and result in a better resolution of the accelerometer provided that the problems arising from the asymmetry of the capacitive interface can be overcome.

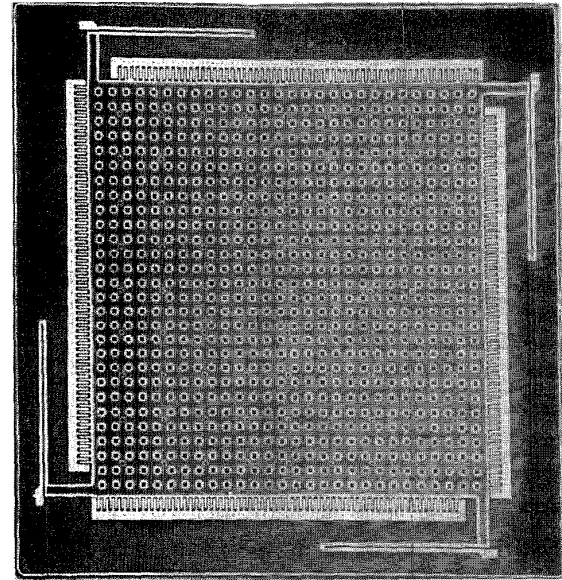


Fig. 2. Top-view of acceleration sensor.

A z -axis structure is used in this paper. In addition to the higher sense capacitance of this type of sensor, this choice is motivated by the need for a z -axis device in applications that demand acceleration measurement in several directions. Sensors with sensitivity parallel to the chip surface have already been demonstrated in surface micromachining technology [12]. The z -axis sensor is the missing piece needed for a fully monolithic 3-axis accelerometer. The symmetry of the device can be improved by adding an additional electrode above the movable proof-mass to generate equal pull-up and pull-down forces [13]. The fabrication of this additional plate, however, adds substantially to the process complexity and is not compatible with the fabrication technology used for this work. Instead, an alternative approach to overcome the problems arising from the asymmetry of the z -axis structure with an appropriate electronic interface is chosen and will be described in Section IV.

Fig. 2 shows a close-up view of the fabricated sensing element. It consists of a $400 \times 400 \mu\text{m}^2$ proof-mass suspended above the substrate with four folded beams. The distinctly visible holes ensure complete etching of the sacrificial oxide between the silicon surface and the proof-mass at the end of the fabrication process. Combs around the periphery of the proof-mass exert an electrostatic pull-up force on the proof mass, as will be described later.

The sensitivity of the accelerometer is optimized by maximizing the inertial mass m and minimizing the spring constant k_z of the suspension in the z -direction. In practice, this demands trade-offs with sensor reliability, susceptibility to off-axis acceleration signals, and yield. Polysilicon flatness imposes an upper limit on the dimensions of the mechanical structures and hence the achievable mass, which for this sensor is approximately $0.5 \mu\text{grams}$, a figure that is representative of polysilicon surface micromachined sensors.

Because of the low inertial mass, very soft springs are needed to achieve a detectable displacement of the sensor. The excellent control of dimensions that is characteristic of modern IC technologies is the key to overcoming this problem. The minimum feature width and spacings achievable in the fabrication technology used for this project are 2 and 1 μm , respectively, and in principle permit realization of springs with constants as low as 1 mN/m [14]. Such weak springs, however, are impractical because of sagging due to gravitation, susceptibility to self-resonance, and a tendency to stick to the substrate.

Sensitivity to off-axis acceleration is a further concern in the choice of a suitable suspension. Ideally, the suspension permits motion only in the z -direction, while rejecting all other inputs. The single-fold suspension chosen for this sensor (Fig. 2) exhibits excellent suppression of translation in the x - and y -directions. Its length is constrained by polysilicon warpage.

The spring constant of the sensor is found indirectly from the resonant frequencies using finite element simulation [15] and invoking the relation $2\pi f_r = \sqrt{k_z/m}$. The simulation results for the four lowest resonances are illustrated in Fig. 3. Each plot shows magnified views of the motion of the proof mass corresponding to the particular mode. The first resonance occurs for excitations in the z -direction as desired. The resonant frequency of $f_r = 7488$ Hz corresponds to a spring constant $k_z = 1.1$ N/m. A 10 mg acceleration results in only a 0.44 Å displacement and thus demands an extremely sensitive position measurement circuit. Assuming linear springs, a 360 g acceleration is needed for the sensor to touch the substrate.

The suspension rejects translations as expected but is susceptible to rotation about either diagonal of the proof-mass at 12.6 kHz. This result closely matches analytical calculations, which predict this resonance at $\sqrt{3}f_r$ [16]. The remaining modes correspond to much higher frequencies. Because of that, the displacement for a given force is much smaller, and its influence on sensor performance is negligible. The fourth resonance occurs at 64 kHz. At this frequency, the proof-mass acts no longer as a rigid body. Two opposite corners move upwards while the others move down. The finite element simulation package features a dynamic animation mode to help visualize the motion.

Aside from the reduced sensitivity, the low inertial mass of only 0.5 μgrams makes the structure susceptible to thermal noise, setting an ultimate limit on the achievable resolution of the accelerometer. Thermodynamics postulates that the thermal energy of a device equals $\frac{1}{2} k_B T$ for each mode. For example, the mean kinetic energy of the acceleration sensor in Fig. 1(a) in z -direction is $\frac{1}{2} m v_z^2 = \frac{1}{2} k_B T$. A reduction of the mass m consequently implies an equivalent increase of the average thermal velocity v_z^2 and results in a white input referred acceleration noise of [17], [18]

$$\sqrt{\frac{a_z^2}{\Delta f}} = \sqrt{\frac{8\pi k_B T f_r}{m Q_z}}$$

In this equation, f_r is the resonant frequency in the z -direction of the structure, and m and Q_z are the mass and the Q -factor of the spring-mass system. As expected, increasing the mass reduces the Brownian noise floor, but this approach is incompatible with the size constraints of micromachined

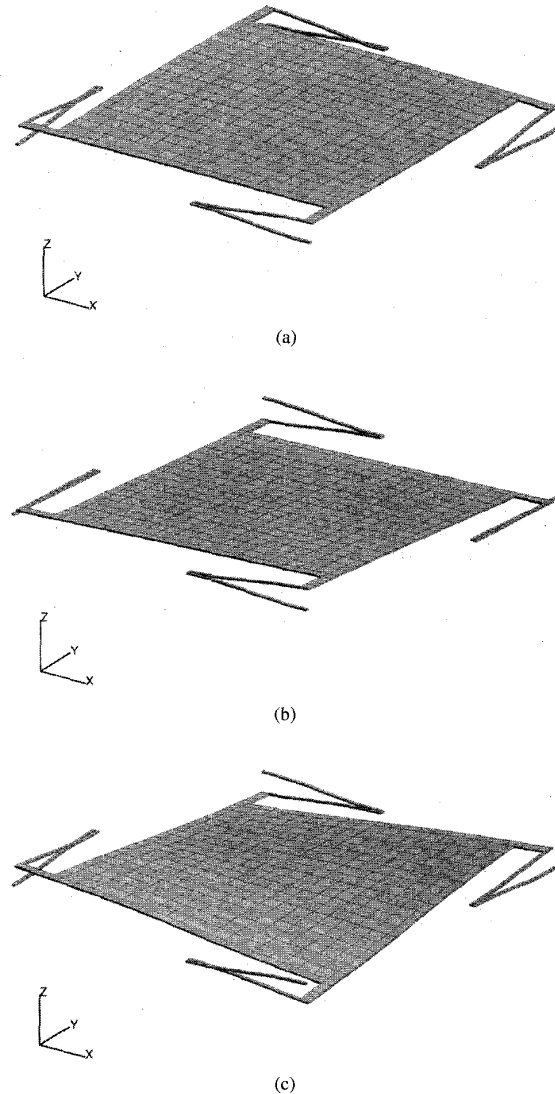


Fig. 3. Finite-element analysis of the resonant frequencies of the accelerometer. The plots show a greatly enlarged view of the motion corresponding to the (a) first mode at 7.5 kHz. (b) second mode (and symmetric third) at 12.6 kHz. (c) fourth mode at 64.4 kHz.

sensors. A more attractive approach consists of increasing Q_z . In this structure, the loss in the z -direction is dominated by squeeze film damping. At atmospheric pressure $Q_z \approx 1$, resulting in a thermal acceleration noise floor of approximately 120 $\mu\text{g}/\sqrt{\text{Hz}}$. Much higher Q -factors and correspondingly lower noise are achieved at reduced pressures. Q -factors as high as 80 000 have been experimentally confirmed for polysilicon structures [19] corresponding to a decrease of the noise floor by over two orders of magnitude.

III. POSITION SENSE ELECTRONICS

Acceleration is measured by detecting the change of capacitance between the proof-mass and the substrate. Fig. 4 shows a model of the capacitive interface of the sensor. An n^+ emitter diffusion implant in the p^- substrate under the

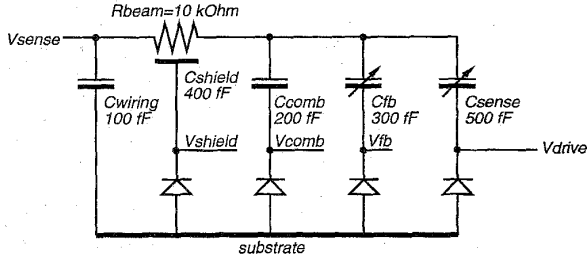


Fig. 4. Electrical sensor interface. Bottom plates of capacitors are indicated with a heavy line, and the capacitance between the suspension and the shield is shown as a distributed element.

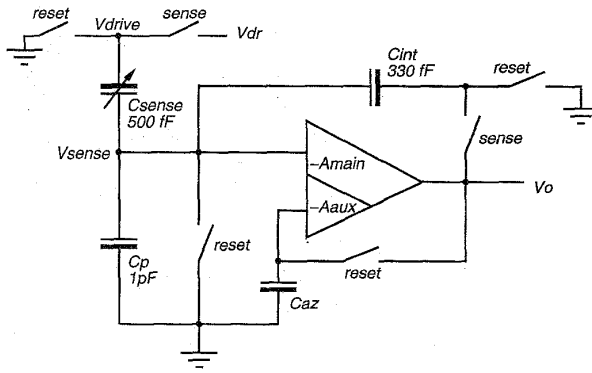


Fig. 5. Capacitance sense circuit.

proof-mass serves as the bottom plate of the sense capacitor. The nominal value of the sense capacitor is 500 fF, and its sensitivity to vertical displacements $dC/dz \approx 310 \text{ fF}/\mu\text{m}$ based on the $1.6 \mu\text{m}$ nominal gap. A 10 mg acceleration signal resulting in a $0.44 \text{ \AA}$ displacement produces a capacitance change of only 14 aF, which must be detected in the presence of much larger parasitics.

The bottom plate parasitics in this design are dominated by a diffusion capacitance to the substrate of several pico-Farads. The top plate parasitic, on the other hand, comprises the capacitance associated with a levitation comb, an electrostatic actuator used for force-feedback, wiring capacitance, and electrostatic shields, and is approximately 1 pF. Shielding is required, for example, under the suspension to prevent electrostatic actuation due to stray fields.

The capacitance sense circuitry is shown in Fig. 5. The top plate parasitics are lumped into a single capacitor C_p . The large bottom plate is driven by a voltage source in this circuit and thus irrelevant to first order. The circuit operates in two phases by first charging C_{sense} to a known voltage and then transferring the charge onto a capacitor C_{int} with known value, resulting in voltage across C_{int} , which is proportional to the size of C_{sense} . The amplifier A_{main} establishes a low impedance at its input, effectively shorting the parasitic C_p . The value of C_{int} represents a trade-off between the output level, suggesting a small C_{int} , and the achievable sampling rate, which calls for a large integrating capacitance.

Correlated double sampling is used to attenuate the flicker noise from A_{main} by storing it on C_{az} during the reset phase

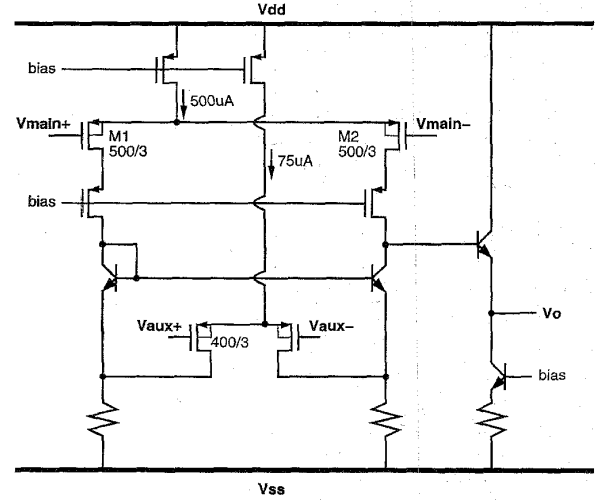


Fig. 6. Circuit diagram of the position sense amplifier.

with the help of an auxiliary amplifier with reduced gain A_{aux} [20]. In addition, the dc-potential at the sense node is also established during reset. Compared to other solutions, this approach obviates the need for and associated noise of a leakage resistor for setting this potential [12].

The transistor level circuit diagram of the amplifier is shown in Fig. 6. The differential inputs of the main and auxiliary amplifier are labeled V_{main} and V_{aux} , respectively. A telescopic configuration is used to minimize the noise. The input transistors of the auxiliary amplifier are tied to the degeneration resistors of the load to overcome the systematic offset between the input and output of telescopic amplifiers. For the main amplifier, C_{int} stores the necessary level shift between the input and output of the main amplifier.

The noise in this circuit is the sum of the broad band noise from the amplifier during the sense phase plus the noise sampled onto C_{sense} and C_{int} during reset. Because of the small capacitor values, the latter contribution is dominant in this implementation and results in an input-referred acceleration noise with one-sided spectral density

$$\sqrt{\frac{a_n^2}{\Delta f}} = \frac{(2\pi f_r)^2 z_0}{V_{dr}} \sqrt{\frac{2k_B T}{f_s C_{\text{sense}}} \left(1 + \frac{C_{\text{int}}}{C_{\text{sense}}}\right)}.$$

In this equation, f_s and z_0 are the sampling rate and the nominal gap of the sense capacitor, and in this design equal 500 kHz and $1.6 \mu\text{m}$, respectively. For $V_{dr} = 0.5 \text{ V}$, the noise floor is $167 \mu\text{g}/\sqrt{\text{Hz}}$. It can be improved either by reducing the first factor in the equation, corresponding to increasing the sensitivity of the sensing element, or by decreasing the electronic noise, amounting to increasing f_s or C_{sense} . The latter is achieved preferably by decreasing the gap z_0 rather than enlarging the area of the capacitor, since this approach consumes no additional real estate and yields a double benefit in the form of a larger value of both C_{sense} and dC_{sense}/dz . Increasing the sensitivity of the sensor by decreasing its resonant frequency potentially has even greater merit. Dropping f_r from 7.5 kHz down to 1 kHz, for example, would reduce

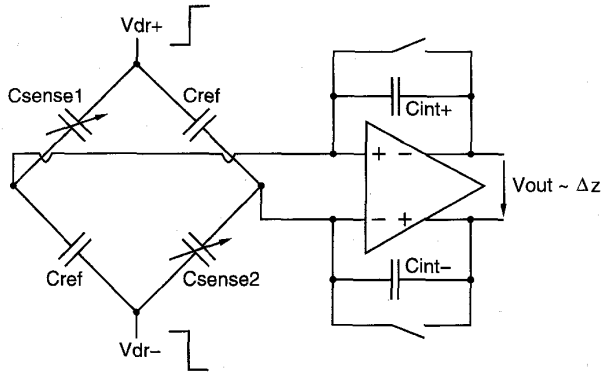


Fig. 7. Simplified diagram of a fully differential z-axis accelerometer. Two sense elements are used for capacitors C_{sense1} and C_{sense2} .

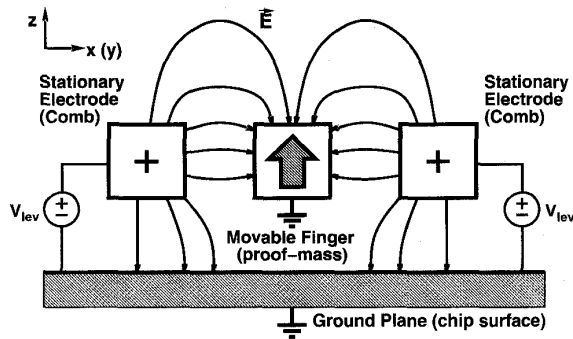


Fig. 8. Levitation comb principle.

the electronic noise floor to less than $3 \mu\text{g}/\sqrt{\text{Hz}}$, well below the Brownian motion noise floor at atmospheric pressure. The practical problems associated with low resonant frequencies have been discussed in Section II.

The sense voltage V_{dr} used to detect changes of C_{sense} also exerts an electrostatic pull-down force. The comb-fingers arranged around the proof-mass generate an opposing force to maintain the nominal position of the sensing element. Fig. 8 illustrates the electrical field distribution between a movable and two stationary comb fingers. The silicon surface acting as a ground plane results in an asymmetric field distribution with more field lines terminating at the top of the movable finger. The result is a net pull-up force, which for small displacements is approximately proportional to the square of the applied bias [21].

The asymmetry of the z-axis sensing element results in an offset, which in this design requires external calibration. A better solution employs two sensors with their sense capacitors configured as a full bridge for a fully differential readout (Fig. 7) [22]. The sense and reference capacitors must be precisely matched. This is achieved with a dummy proof-mass anchored to the substrate. Better noise immunity of the position sense circuit and reduced drift are further advantages of this approach. It has not been pursued in this implementation because of size limitations of the sensors imposed by the fabrication technology.

IV. FORCE-FEEDBACK LOOP

Feedback offers a number of critical advantages in the design of acceleration sensors. The most important ones are summarized here.

The sensitivity of an open-loop accelerometer is inversely proportional to the spring constant of the suspension which in turn is proportional to the cube of the length and thickness of the polysilicon spring. Small variations in the processing consequently cause large changes in sensitivity. By operating the sensing element in an electronic force-feedback loop, this strong dependence of the accelerometer on processing parameters can be reduced substantially since for sufficiently large loop gain the linearity and drift of a feedback system are determined by the feedback path only and thus independent to the first order of nonidealities of the sensing element. Moreover, open-loop designs call for a trade-off between sensitivity and measurement bandwidth; in a closed loop accelerometer, these characteristics can be chosen independently. Sensors with low damping to decrease the Brownian motion noise floor also depend on feedback to electrically dampen the motion at the resonant frequency.

The implementation of a feedback control loop requires an actuator to restore the proof-mass to its nominal position in the presence of an external force. Electrostatic actuation is particularly attractive for surface micromachined sensors since no additional fabrication steps are needed. While electrostatic forces are often too small to be useful in larger sensors, this is no problem here because of the small mass of polysilicon micromachined devices. Forces amounting to an acceleration of the proof-mass corresponding to several hundred g's can be produced within the bounds of standard supply voltages.

In this design, a separate feedback capacitor underneath the proof-mass is used to generate a pull-down force. The quadratic relationship between the applied voltage and the resulting force demands some means of linearization. The poor matching between the parallel plate capacitor pull-down structure and the levitation comb pull-up preclude cancellation of the nonlinearity with a differential arrangement, an approach that is often used with symmetric sensing elements [12]. Instead, the feedback signal is quantized to only two levels and only the voltage across the feedback capacitor is modulated.

Fig. 9 shows a block diagram of the force-feedback loop. Together with the electronic position sense circuit and 1-b comparator, it forms an oversampled ADC where the proof-mass provides second-order noise shaping for frequencies above its resonance [23], [24]. The digital 1-b output is processed by a decimation filter analogous to those used in purely electronic implementations of oversampled converters.

Without compensation, the second-order feedback-loop is unstable. Previous designs either limit the loop bandwidth electronically to less than the resonant frequency of the sensor [12] or employ an over-damped sensor [24]. The former solution is not acceptable since the limited bandwidth interferes with oversampling. The second solution results in an elevated Brownian noise floor. In this work, a lead compensator is used for stabilization. The filter is dimensioned to provide sufficient phase lead to push the quantization noise to as high frequencies

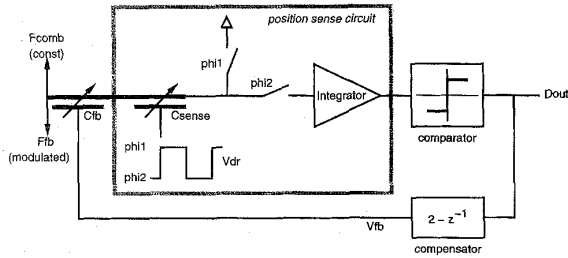


Fig. 9. Force-feedback accelerometer block diagram.

as possible. In a second-order modulator, this requirement is met when the total phase at $f_s/4$ is less than 180° [25], [18]. The compensator is implemented in the feedback path of the modulator and since its input is a 1-b signal consists of only a latch and a few gates.

Due to the high sampling rate required to suppress the sampling noise from the position measurement circuit, quantization noise is negligible in this implementation. However, the high resonant frequency of the proof-mass, which is acting here as the noise shaping filter, results in a dead-zone for small inputs. The width of the dead-zone corresponds to the minimum input required to cause the comparator output to change and is [26]

$$a_{\min} = a_{\max} \left(\frac{f_r}{f_s} \right)^2.$$

For an input range of the accelerometer of $a_{\max} = \pm 5$ g, the dead-zone width is ± 9 mg. This relatively high value is unacceptable in many applications but can be reduced either by increasing the sampling frequency or by decreasing the resonant frequency of the proof-mass.

V. MEASUREMENT RESULTS

Fig. 10 shows a die photograph of the z -axis accelerometer. The sensing element is placed in the center of the chip to minimize errors due to package-induced stress. The close proximity of the position sense integrator minimizes interconnect parasitics. The sensor and associated electronics consume less than half of the available die area of 9 mm^2 . This small size demonstrates the feasibility to integrate entire systems consisting of several different types of sensors on a single die.

For performance evaluation, the accelerometer is mounted on a shaker table and excited with a sinusoidal acceleration signal. The digital output is evaluated by a computer and for calibration compared to the output from a reference accelerometer. The measured output spectrum is shown in Fig. 11. The noise floor is at $1.6 \text{ mg}/\sqrt{\text{Hz}}$, corresponding to a resolution of 11.3 mg for a 50 Hz input bandwidth. The spectrum of the noise is independent of the magnitude of the input for signals up to ± 5 g.

This performance is comparable to that achieved by other monolithic accelerometers fabricated in the same [5], [6] or a similar surface micromachining technology. It is adequate for automotive applications such as active suspension as well as a number of other applications, such as tracking systems for head mounted displays.

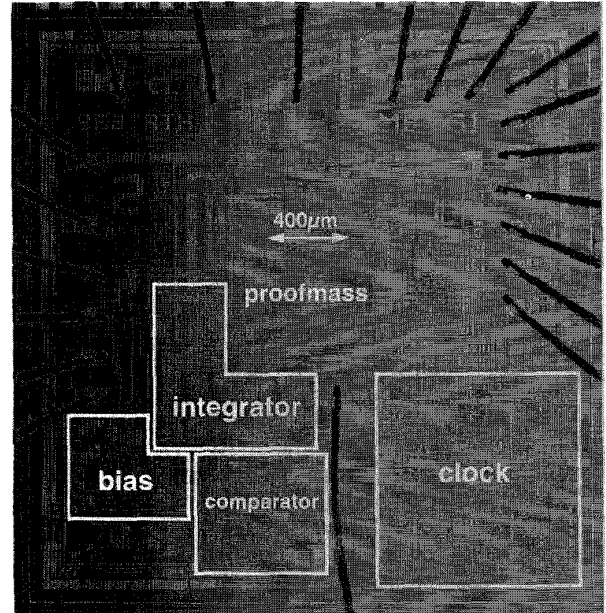


Fig. 10. Die photograph of the prototype accelerometer.

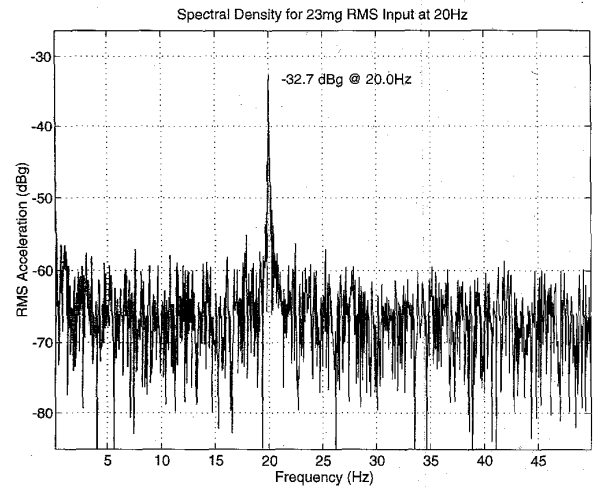


Fig. 11. Measured output spectrum for a 23 mg rms input at 20 Hz.

The noise is dominated by excess quantization noise folded into the baseband not predicted in the analysis presented above. It is caused by the delay in the electronic circuitry from the time the position of the proof-mass is measured to the time the feedback pulse is generated [18]. This delay introduces a phase delay causing the quantization noise to shift to lower frequencies [25]. The problem can be overcome with a different clocking scheme and some changes in the position measurement electronics. These changes are expected to decrease the noise floor down to a value that is close to the Brownian noise floor at atmospheric pressure, which for this device is approximately $120 \text{ } \mu\text{g}/\sqrt{\text{Hz}}$.

VI. CONCLUSIONS

Cofabrication of surface micromachined sensors and electronic circuits represents an attractive and versatile technology covering a large range of devices and applications. The small form factor and possibility of integrating several different sensors on a single die constitute particularly attractive features of this approach.

The miniature scale of surface micromachined sensors results in elevated Brownian motion and electronic noise, but the achievable performance is compatible with the needs of most applications of such devices. Resolution in the milli-g range has been demonstrated in a first generation *z*-axis device. This figure can be improved by at least an order of magnitude through circuit improvements. Micro-g resolution is possible with vacuum packaged devices and a faster electronic circuit technology.

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