15
Accelerometer

A good example of the use of capacitive sensors for silicon implementation is Analog Devices' surface-machined accelerometer.

Integrated circuit designers use precision lithography and micromachining to produce micron-dimension sensors in silicon. Several different silicon accelerometers have been built with bulk micromachining and piezoresistive sensors beginning in the 1970s, but the large size and the large number of process steps of the bulk technique as well as the temperature sensitivity of the piezoresistive sensors have slowed commercial acceptance. More recently, capacitive position sensing and electrostatic force-balance feedback have been used in a surface-machined device which uses more conventional integrated circuit processes. Surface micromachining allows a more highly integrated design with much smaller chip dimensions.

Analog Devices' ADXL50 is the first commercially available surface-micromachined accelerometer with integrated signal processing. It measures acceleration in a bandwidth from DC to 1 kHz with 0.2% linearity, and it outputs a scaled DC voltage. It is fabricated on a 9 mm^2 chip. It also is a force-balance device which uses electrostatic force to null the acceleration force on the "proof" (seismic) mass, with advantages in bandwidth, self test, and linearity.

15.1 ACCELEROMETER DESIGN

15.1.1 Surface micromachining vs. bulk micromachining

[Riedel, 1993, pp. 3–7, used with permission]

> Micromachining is a processing technique used to manufacture tiny mechanical structures from silicon. A silicon wafer of the type used to make semiconductors can be etched to produce small beams, masses, gears, and other structures measuring only a few thousandths of an inch.

Micromachining comes in two varieties: surface and bulk. Prior to the ADXL50, all the available micromachined devices used bulk micromachining. It was discovered in the 1950s that acid solutions attack different planes of crystalline silicon at different rates, depending on the crystal orientation. By exposing an area of silicon with a specific crystalline structure to acid, cavities with precisely angled walls are created.

Bulk micromachined accelerometers have existed for several years. Typically they consist of a membrane or diaphragm of silicon, roughly 10 μm thick, that is vertically formed in the wafer by chemical etching. In the center of the membrane is a large mass of silicon. On the top surface of the device, near the edge of the membrane, thin-film piezoresistors sensitive to strain and deformation are deposited. Most of the membrane is removed, leaving tethers with these resistors suspending the central mass. Vertical acceleration causes the test mass to move, deforming the diaphragm and changing the resistance of the piezoresistors. Bulk micromachined devices are large by IC standards—about 20× the size of the surface-machined ADXL50. Large size, coupled with the fact that the process for manufacturing bulk micromachines is inconsistent with semiconductor-circuit fabrication techniques, requires that signal conditioning be off-chip. Bulk piezoresistive accelerometers are very sensitive to temperature effects and difficult to test fully.

Surface micromachining, a more sophisticated technique than bulk micromachining, creates much smaller, more intricate, and precisely patterned structures. It adapts manufacturing techniques perfected for making ICs to produce mechanical structures close to the surface of the silicon substrate. Chemical machining is accomplished by deposition, then etching multiple thin films and layers of silicon and silicon-oxide to form complex mechanical structures. The feature dimensions of surface micromachined devices are typically 1 to 2 μm, similar to the feature dimensions of conventional electronic circuits. Most importantly, surface micromachining lends itself to the inclusion of conventional electronic circuitry on the same die. Thus, the surface-micromachined ADXL50 includes signal conditioning, resulting in a fully scaled, referenced and temperature-compensated volt-level output. Surface micromachining leverages the cost economies of standard IC wafer processing techniques, producing a highly integrated product at low cost.

15.1.2 Force balance

Early accelerometers measured the displacement of the proof mass. Problems with this approach are the presence of a resonant peak, the difficulty of achieving good dynamic range, and the need to carefully calibrate the force vs. displacement relationship. Force balancing allows the proof mass to deflect only microscopically, detects and amplifies this displacement, and feeds back a force to restore the rest position. With a high gain amplifier, the mass is nearly stationary and the linearity is determined by the linearity and precision of the voltage-to-force transducer rather than the suspension characteristics.

15.1.3 Capacitive feedback in silicon accelerometers

Although piezoresistive sensing of the displacement of the proof mass was used for early devices, a recent survey [Yun, 1991, p. 204A-4] showed that the excessive temperature sensitivity of piezoresistivity was incompatible with the preferred force balance technique. Capacitive sensing has replaced piezoresistive sensing in six new designs cited by Yun [1991]. Sze [1994, pp. 192–193] lists these advantages of capacitive sensors over piezoelectric or piezoresistive types:

- Wide temperature range
- Low temperature coefficient
- High sensitivity
- Response to DC
- No zero shift due to shock

Bulk-machined capacitively sensed accelerometers can have excellent specifications, as shown by a device built by CSEM with 1 μg resolution and cross-axis sensitivity of 0.4%, and Triton/IC Sensors' 0.1 μg, 120 dB dynamic range unit with cross-axis sensitivity of 0.001%. But fabricating the Triton design requires 27 separate lithography steps on five wafer surfaces of three bonded wafers.

15.2 ADXL50

Analog Devices' ADXL50 uses an exceptionally small (1 mm^2) capacitive sensor element. The full-scale range is ±50 g, compatible with automotive airbag deployment requirements, and the accuracy is 5% over temperature and power supply extremes. It uses a 5 V supply, and includes a calibrated high level output and a self testing feature, at a high volume price approaching $5.00. A more sensitive version, the ADXL05, spans the range of ±5 g with 0.005 g resolution and a typical nonlinearity of 0.3% full scale.

Two different photolithographic exposure processes are used to maximize process throughput: the capacitor fingers are exposed with fine line optics and the standard 4 μm BiCMOS signal processing circuits are exposed with the more relaxed optics of 1× lithography. The fine line exposure for the capacitive plates allows a very small gap width, which results in higher signal strength as the signal is inversely proportional to gap. The parallel connection of 42 similar 2 μm thick electrodes further increases the signal. The silicon-micromachined electrode design is a differential 0–180° type with square wave drive voltages (Figure 15.1).

The H-shaped proof mass and sensor electrode measures 500 μm × 625 μm. It is supported on the corners by slender tethers, measuring 2 μm square and 200 μm long, which anchor the central elements to the substrate and provide the electrical connection. The tethers are formed from crystalline silicon, a very stable and reliable spring element, and the geometry allows the central element to move only in the x-axis when displaced by acceleration. The strength of the tethers is sufficient to allow the device to withstand 2000 g of physical shock. Projecting from the central bar are 42 moving plates, of which four are illustrated. Each moving plate is adjacent to one fixed plate driven by 0° and one

driven by 180° as shown, so that the capacitance to one plate will increase with displacement as $Cx_0/(x_0+\Delta x)$ and the capacitance to the other plate will decrease as $Cx_0/(x_0 - \Delta x)$, with x_0 the undisturbed position and Δx the displacement.

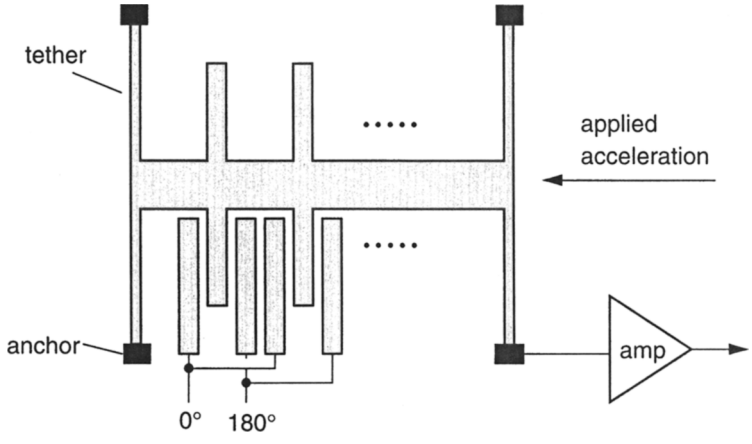

Figure 15.1 ADXL50 sensor electrodes

Sensor characteristics

The ADXL50 block diagram is shown in Figure 15.2. The sensor has approximately these characteristics:

Gap x_0 ..... 2 μm

Electrode width W ..... 2 μm

Electrode total length L ..... 100 μm × 50 × 2 = 10 mm total

Moving plate mass..... 0.1×10^{-6} g

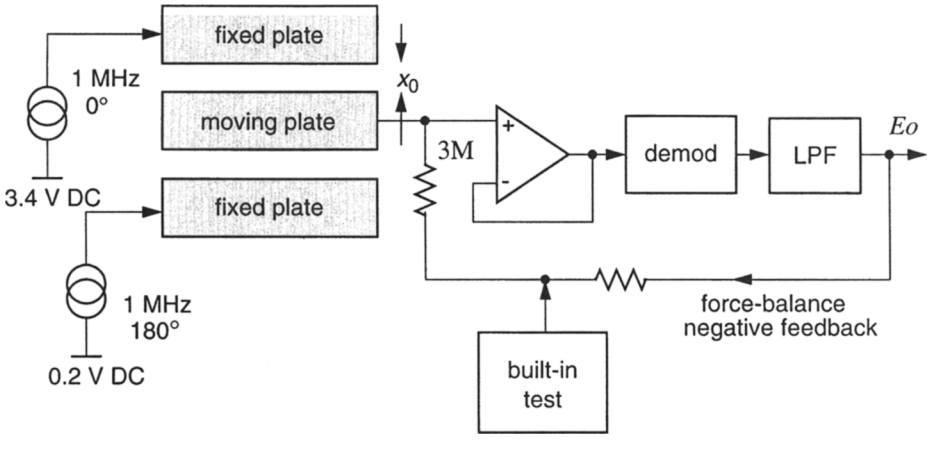

Figure 15.2 ADXL50 block diagram

The total sensor electrode capacitance, neglecting fringe fields, is $8.854 \cdot 10^{-12} \times A/d$ or about 0.1 pF. This small value would require extremely low amplifier input capacitance for accurate open-loop sensing, but with closed-loop operation the error contribution due to variations in gain is negligible if the amplifier gain is high. The open-loop change in capacitance with a 50 g acceleration is 0.01 pF, and the system can resolve a change of 20 aF, $20 \cdot 10^{-18}$ F, corresponding to a beam displacement of $20 \cdot 10^{-6}$ μm.

The amplifier is conventional, and the demodulator is a standard synchronous demodulator implemented in bipolar technology. The lowpass corner frequency has a single-pole response shape controlled by an external capacitor. The output signal is 1.8 V DC for zero acceleration, and spans ±1 V for ±50 g input.

Electrostatic restoring force

The acceleration force of a 0.1×10^{-9} kg proof mass at 50 g is 49×10^{-9} N. With a bias level of 1.8 V, midway between the two fixed plate DC levels, the electrostatic force is balanced. As the proof mass is deflected by acceleration, *Eo* provides a restoring voltage. The electrostatic restoring force *F* is developed by biasing the fixed plates with different DC levels and changing the DC level on the moving electrode through the 3 MΩ load resistor. From the electrostatic force equation, eq. 2.3 in Chapter 2, with $Vr = 1.6$ the maximum available electrostatic force is

$$F = \frac{4.427 \cdot 10^{-12} \cdot \varepsilon_r A V^2}{x_0^{\,2}} = 68 \cdot 10^{-9} \quad \text{N} \qquad 15.1$$

and is more than enough to balance the acceleration force. The nonlinearity with gap size x_0 is unimportant, as the gap does not change appreciably in operation.

Self test

When a logic signal is applied to the self test input, a voltage pulse is injected through the 3 MΩ load resistor to deflect the proof mass. If the system is working correctly, a proportional output voltage is produced.