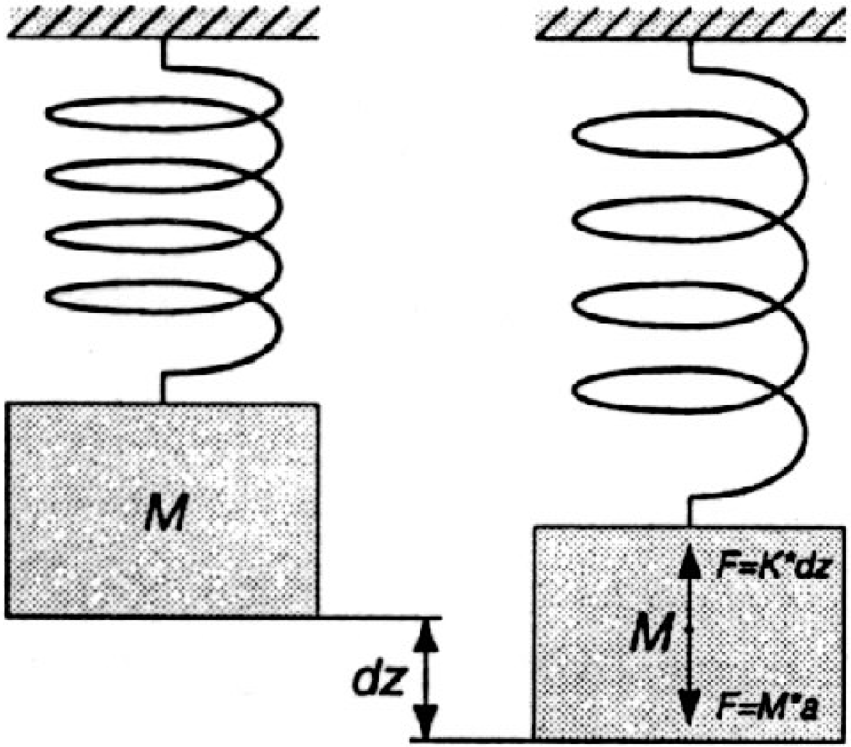
Introduction to Accelerometer

Applications:

- crash detector in airbag
    - 50g with 100’s bandwidth.
    - reliability is of vital importance.

      => self-test mechanism is mandatory.
- active suspensions
- anti-lock braking systems
- traction control systems
- inertial navigation systems.
    - integrate twice to obtain the position.
    - resolution ~ μg to ensure the accuracy over a long period of time.
    - thermal behavior is extremely important.

Principle of the Accelerometer



- Newton second law:

$$F = dP/dt = M a = K dZ$$

where

P: impulse momentum
M: mass
a: acceleration
K: spring stiffness
dZ: displacement

Displacement dZ => Acceleration a

Bulk-Micromachined Accelerometer

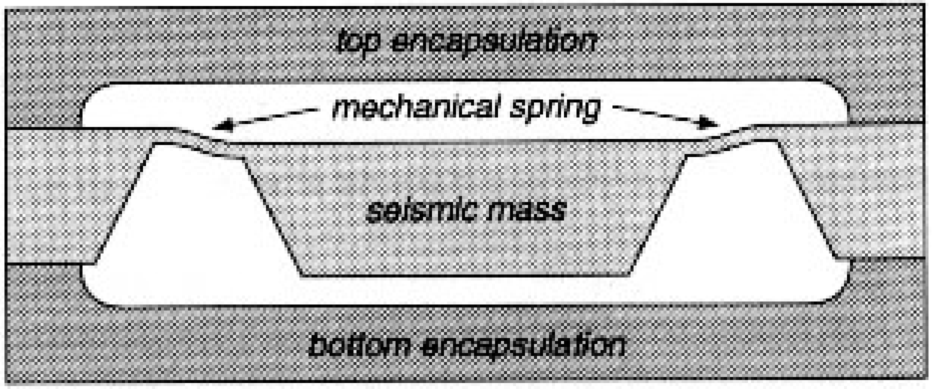


Fig. 1-2 *A bulk-micromachined silicon accelerometer.*

- The motion is perpendicular to the wafer plane, although also in-plane movements have been reported.
- High-Q system which can exceed 100000.
- To avoid an oscillatory behavior of the mass, the device is encapsulated.
- The gas or liquid between the mass and the encapsulation provides damping.

=> Squeeze-film damping mechanism

Surface-Micromachined Accelerometer

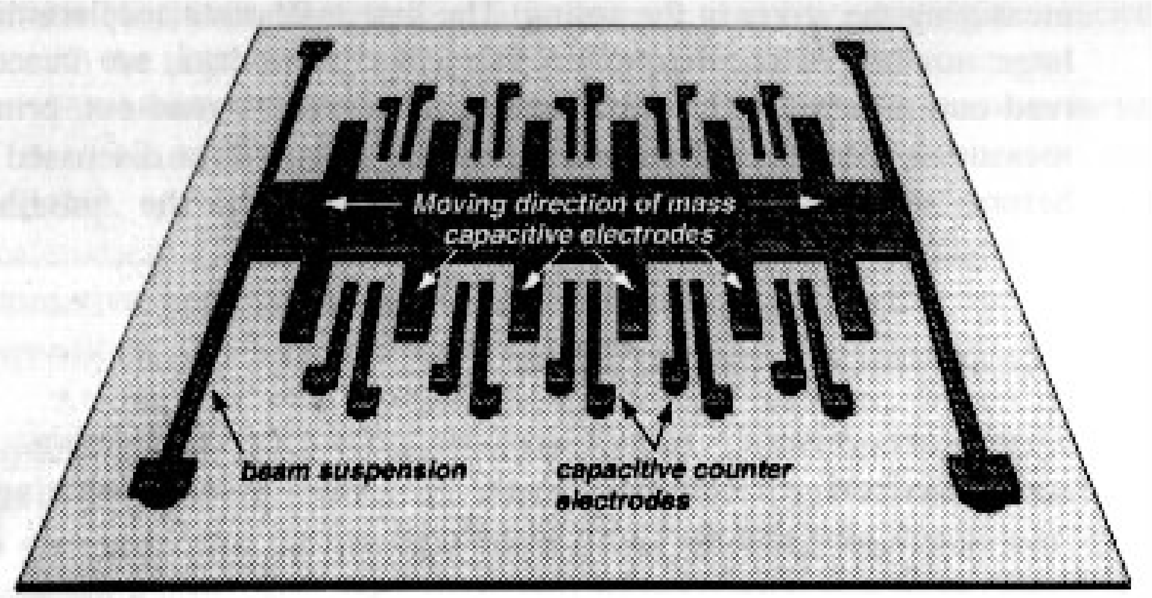


Fig. 1-3 *Surface micro-machined silicon accelerometer [1.17].*

- Formed by selective etching of sacrificial layers, which is typical 1 μm thick.

  => mass is small.

- The motion is usually in the wafer plane, although also the surface micromachined out-of-plane accelerometer have been reported.

- Sensor signal are rather small. => Need on-chip electronics

- Low cost in high volume fabrication.

LIGA Accelerometer

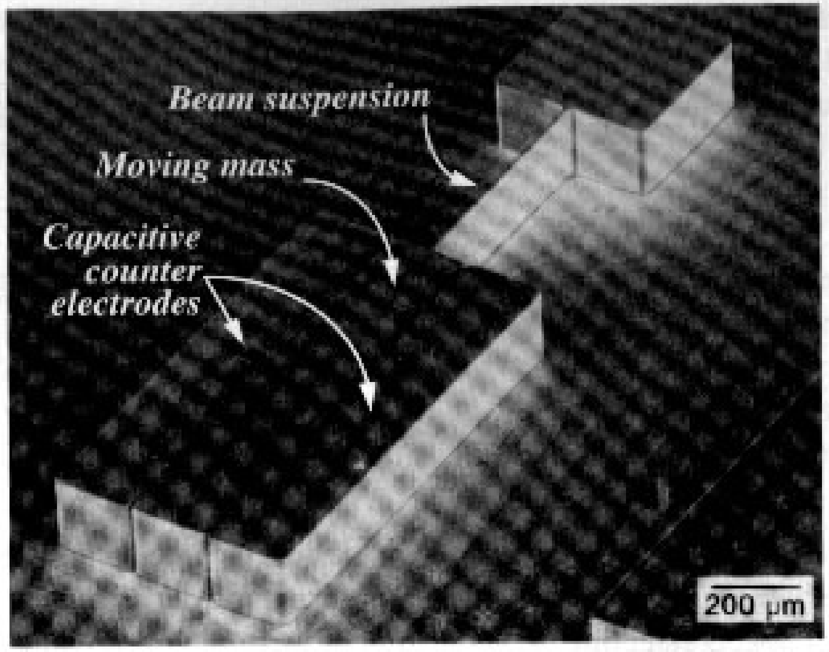


Fig. 1-4 *A capacitive accelerometer fabricated with the LIGA process [1.24].*

- Formed by LIGA, which can be very thick (up to 1 mm).

  => mass is large.

- The motion is usually in the wafer plane, although also the out-of-plane accelerometer have been reported.

Readout Principles

- Stress-based measurements:

- Most apply in **bulk-micromachined accelerometers** because the dimensions of the beam suspension in this case are relatively large, so that the stress sensitive elements (e.g. piezoresistors) are only under tensile or compressive stress, so that the resulting output signal is not averaged by stress components of opposite sign.

- In the case of the surface micromachined accelerometer, the displacement of the masses are usually in the wafer plane, which would require the stress sensing elements to be placed at the side of the beam suspension. The the dimensions of beam suspension are such that the stress goes from tensile to compressive in a very short distance, thereby canceling the effect on the output signal due to stress-averaging effects, when using implanted or diffused piezoresistors.

- However, polysilicon piezoresistors can be deposited on the top of the beam suspension to detect a vertical movement of the mass.

- Displacement-based measurements:

- Apply in bulk, surface and LIGA micromachined accelerometer.

Stress-Based Measurements

- Piezoresistance effect

- Piezojunction effect

By placing bipolar transistors in the beam suspension, a change in base-emitter voltage or collector current is observed when subjecting the device to an acceleration.

- Resonators

Piezoresistive Read-Out Principle

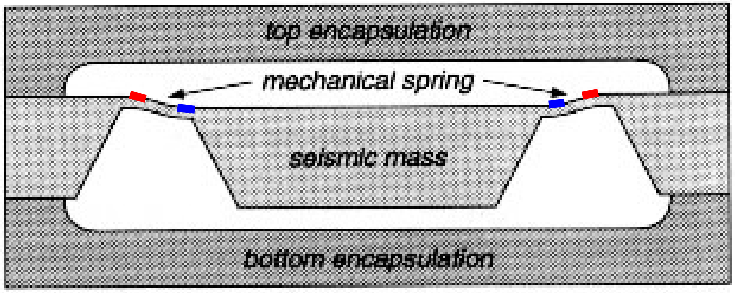


Fig. 1-2 *A bulk-micromachined silicon accelerometer.*

- The first solid-state accelerometers fabricated were piezo-resistive accelerometer.
- Piezo-resistors are placed in the beam suspension. When mass moves up or down due to acceleration, thereby resulting in stress-profile in the beam suspension, causing the value of piezoresistors to change.
- By connecting several piezo-resistors located in the beams in a Wheatstone configuration, in such a way that two piezoresistors experience tensile stress and two other resistors experience compressive stress, the acceleration can be determined.
- The lateral acceleration will also result in an output signal. => Cross-axis sensitivity can be reduced by using a convenient connection of piezo-resistors or by using a different geometry.

Small Deflection of Beams

$$\kappa = \frac{1}{\rho_c} = \frac{d\theta}{ds}, \qquad (2-$$

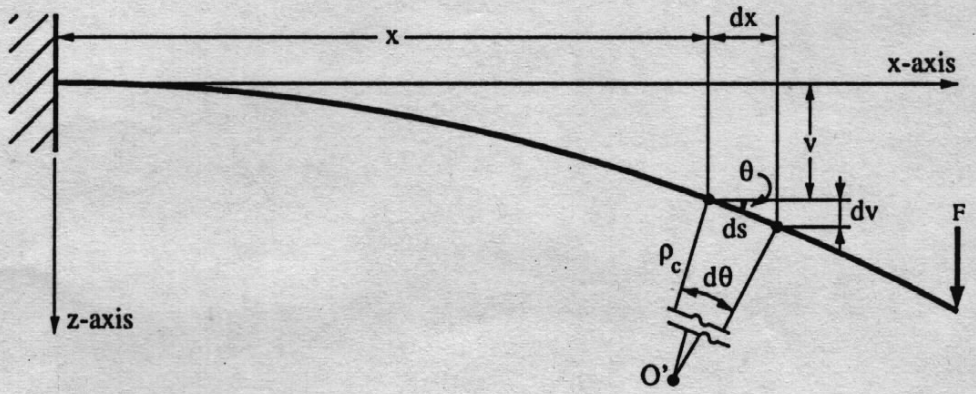


Fig. 2-3 *The deflection curve of a beam subjected to a transverse load.*

$\tan(\theta) = dv/dx \approx \theta$

$ds \approx dx$, $(dv/dx)^2 \ll 1$

$$\kappa = \frac{1}{\rho_c} \approx \frac{d\theta}{dx} \approx \frac{d^2 v}{dx^2}$$

Hook’s law:

$$\kappa = -\frac{M}{EI_y}$$

E is Young’s modulus

I_y is the second area momentum.

$$\kappa = \frac{d^2 v}{dx^2} = -\frac{M}{EI_y}$$

$$\xrightarrow{\text{Boundary conditions}} v(x)$$

Piezoresistivity

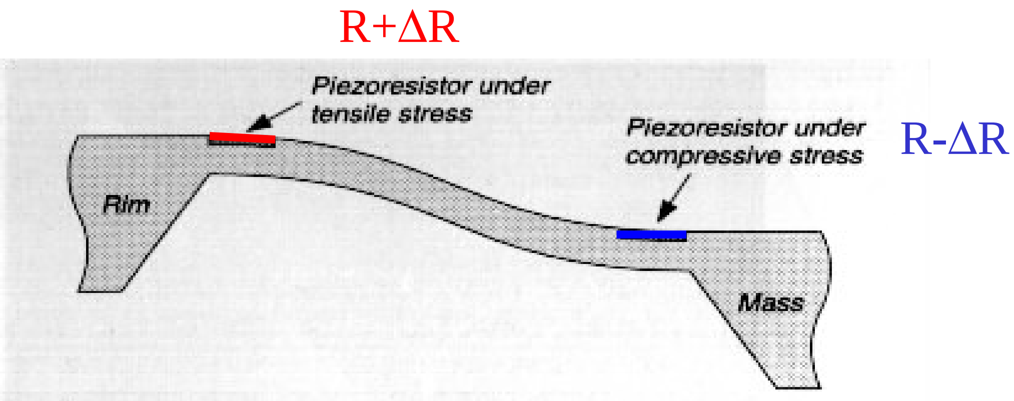
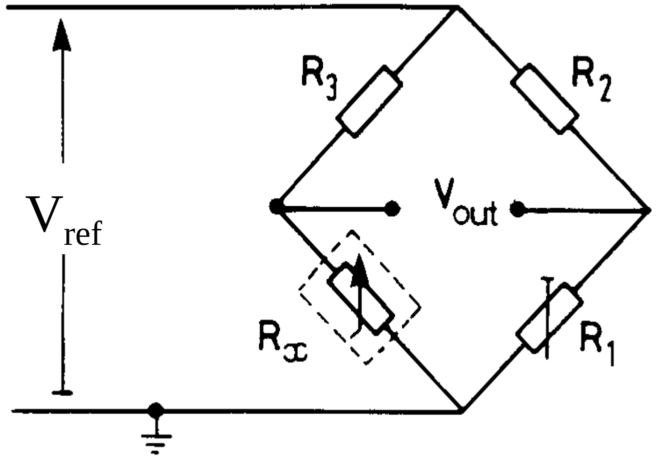


Fig. 1-5 *Location of the piezoresistors to obtain an output signal with moving mass position.*

$$\Delta R/R = \underbrace{G}_{\text{Gauge factor}}\ \underbrace{\varepsilon}_{\text{Strain}}$$

Wheatstone Bridge



$$V_{out} = V_{ref}\cdot\left(\frac{R_x}{R_3 + R_x} - \frac{R_1}{R_1 + R_2}\right)$$

At balance $V_{out} = 0$, so

$$\frac{R_x/R_3}{1 + R_x/R_3} = \frac{R_1/R_2}{1 + R_1/R_2}$$

$$\Rightarrow \quad \frac{R_x}{R_3} = \frac{R_1}{R_2}$$

$R_1 = R_3 = R - \Delta R$, $R_2 = R_x = R + \Delta R$

$V_{out} / V_{ref} = (\Delta R/R) = G\,\varepsilon$

Advantages of Piezoresistive Read-Out

Advantages:

- simplicity, no extra electronic circuitry is needed.
- The output voltage of the Wheatstone bridge is directly related to the acceleration.

Disadvantages:

- The piezoresistive effect also exhibits a relatively large temperature coefficient which requires additional temperature compensation circuitry.

Resonance Frequency Read-Out Principle

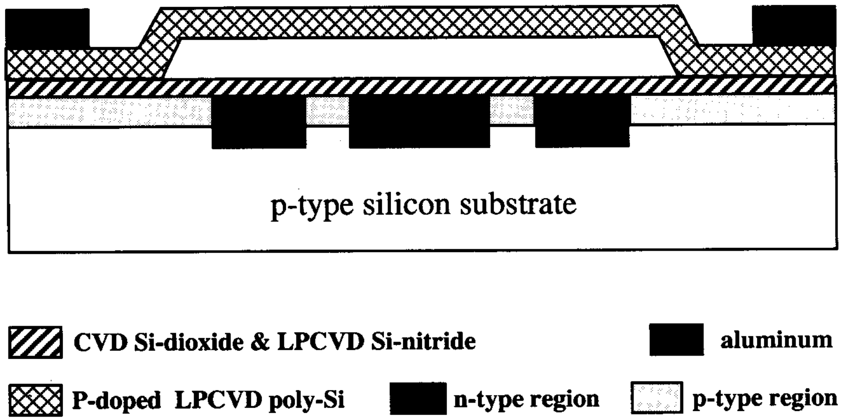


Fig. 4.1 Schematic cross section of the resonant polysilicon microbridge which is electrostatically (capacitively) excited and sensed.

- The resonance frequency of a micro bridge changes when submitted to tensile or compressive stress.

- By placing these resonance bridges in the beam suspension, the resonance frequency changes when subjecting the device to an acceleration.

- The beams are driven into resonance either electrothermally or electrostatically.

- The resonance frequency can be determined either piezoresistivity, capacitively or optically.

- The temperature effect is not important because it only affect the amplitude of the output signal, without affecting the resonance frequency. The only thermal effect is due to the mechanical properties of sensor , such as Young’s modulus and thermal induced stress in the package.

4.2 Short Theory on Vibrations of Beams

4.2.1 *Resonance Frequency*

The resonance frequencies of polysilicon microbridges can be approximated by applying the general equation of transverse free mechanical vibrations of prismatic beams [e.g. 178]:

$$\boxed{EI \frac{\partial^4 y}{\partial x^4} = -\rho h b \frac{\partial^2 y}{\partial t^2}} \tag{1}$$

where $\underline{I = bh^3/12}$ the moment of inertia of the rectangular beam cross section with respect to the neutral axis, ρ the mass density of the beam, E its modulus of elasticity, y denotes the transverse displacement of a beam segment located at x (the beam ends are $x = 0$ and $x = l$), h the thickness of the beam and b its width.

When the beam vibrates transversely in one of its natural modes, the deflection at any location varies harmonically with time, as follows:

$$y(x,t) = X(x)\{A \cos pt + B \sin pt\} \ . \tag{2}$$

Substitution of eq. (2) into eq. (1) results in:

$$\frac{d^4 X}{dx^4} - k^4 X = 0 \qquad \text{where: } k^4 = p^2 \frac{\rho h b}{EI} \tag{3}$$

The general form of the solution for eq. (3) becomes:

$$X = C_1 \sin kx + C_2 \cos kx + C_3 \sinh kx + C_4 \cosh kx \tag{4}$$

$$(X)_{x=0} = 0, \quad \left(\frac{\mathrm{d}X}{\mathrm{d}x}\right)_{x=0} = 0, \quad (X)_{x=l} = 0, \quad \left(\frac{\mathrm{d}X}{\mathrm{d}x}\right)_{x=l} = 0 \tag{5}$$

Substitution of (5) into (4) finally yields:

$$\boxed{\cos kl \cosh kl = 1} \tag{6}$$

A few of the lowest consecutive roots of eq. (6) are:

k_0l	k_1l	k_2l	k_3l
0	4.730	7.853	10.996

Using (3), the frequencies as a function of the k-values are:

$$f = \frac{1}{2\pi} p = \frac{1}{2\pi} k^2 \sqrt{\frac{EI}{\rho hb}} \, . \tag{7}$$

Thus, applying the above value for k_1, the first resonance frequency f_1 of a beam with both ends fixed can be written as:

$$f_1 = \frac{1}{2\pi} \frac{4.730^2}{l^2} \sqrt{\frac{Eh^2}{12\rho}} \tag{8}$$

As an example we can calculate the first frequencies f_1 of vibration of 1 µm thick polysilicon beams. Assuming the following material parameters for polysilicon: $\rho = 2300$ kg m^{-3} and $E = 170$ GPa [86,152, see also section 3.3.1], we obtain for 300 µm and 240 µm long beams resonance frequencies f_1 of 98 kHz and 153 kHz, respectively.

4.2.2 Effect of Axial Force on Frequency

If an oscillating (prismatic) beam is subjected to a tensile axial force F, the differential equation for transverse free vibration becomes [e.g. 178]:

$$\boxed{EI\,\frac{\partial^4 y}{\partial x^4} - F\,\frac{\partial^2 y}{\partial x^2} = -\rho h b\,\frac{\partial^2 y}{\partial t^2}} \qquad (9)$$

Solving eq. (9) for a beam with both ends fixed results in the following formula for the first resonance frequency f_{1F} (under tensile force) which can be expressed as a function of f_1 of (8):

$$f_{1F} = f_1 \sqrt{1 + \frac{l^2}{4.730^2}\,\frac{F}{EI}} \qquad (10)$$

By substituting $F = \sigma b h$ in (10) where σ denotes the tensile stress, we obtain:

$$\boxed{f_{1s} = f_1 \sqrt{1 + \frac{12}{4.730^2}\left(\frac{l^2}{h^2}\right)\frac{\sigma}{E}}} \qquad (11)$$

Note that the effect of the tensile stress on the resonance frequency increases with the square of the ratio of the length and the thickness of the beam.

Displacement-Based Measurements

- capacitive
- inductive
- optical
- thermal
- electron tunneling

Capacitive Read-Out Principle

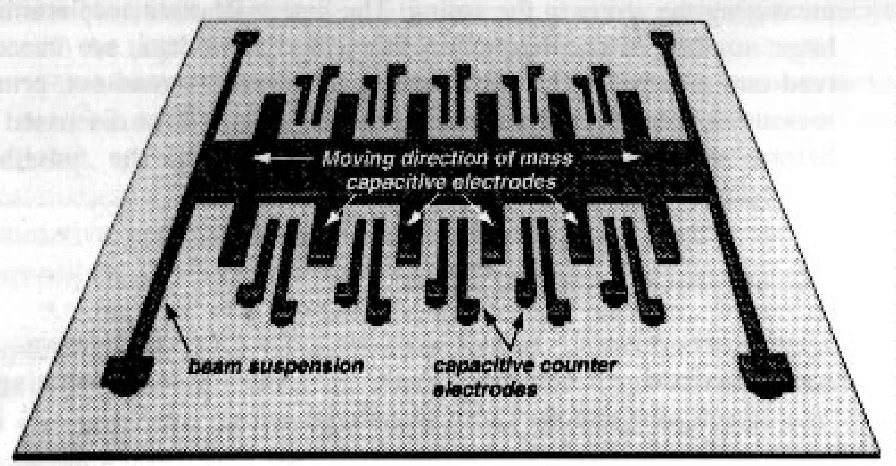
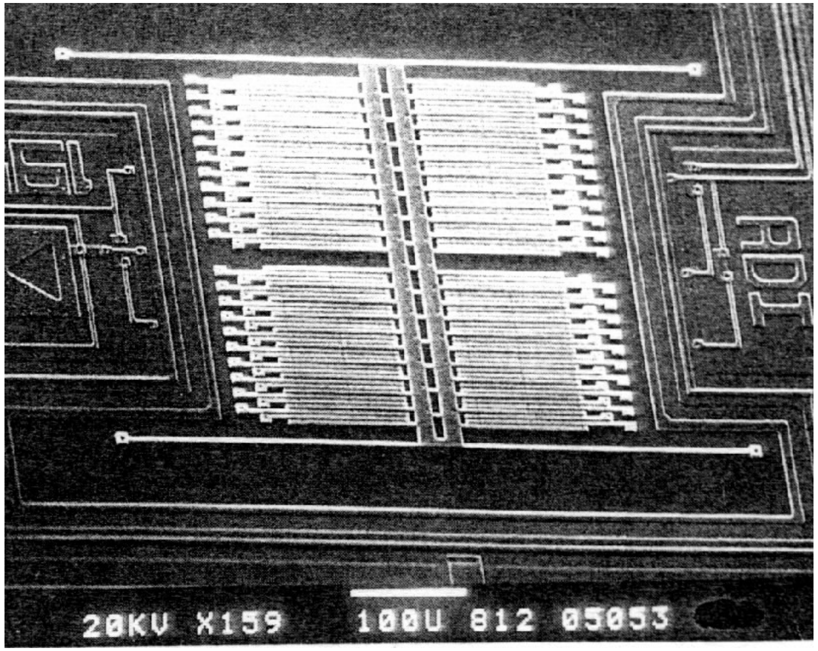
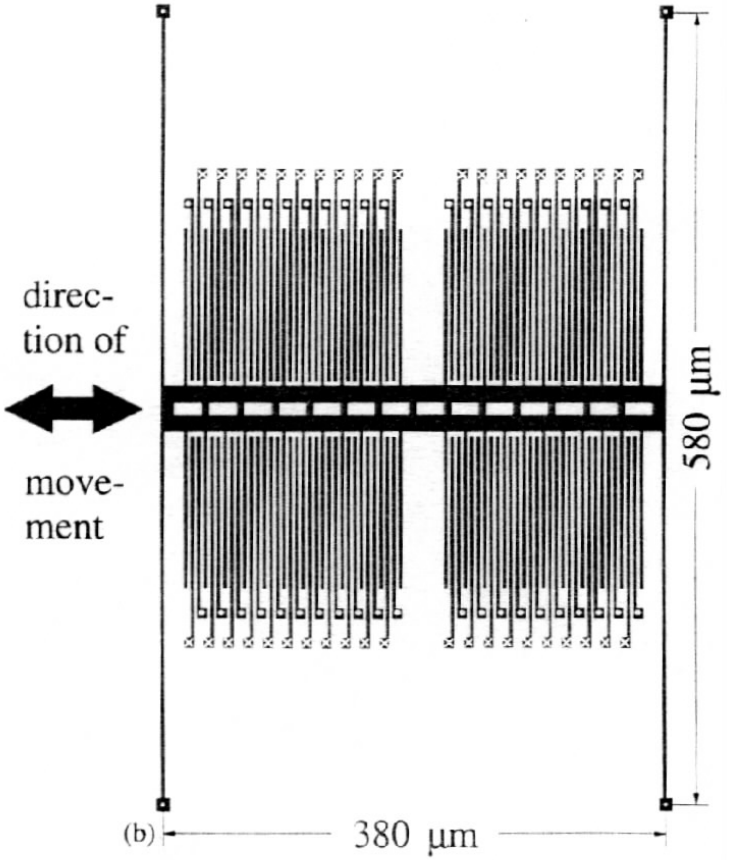


Fig. 1-3 *Surface micro-machined silicon accelerometer [1.17].*





Electromagnetic Read-Out Principle

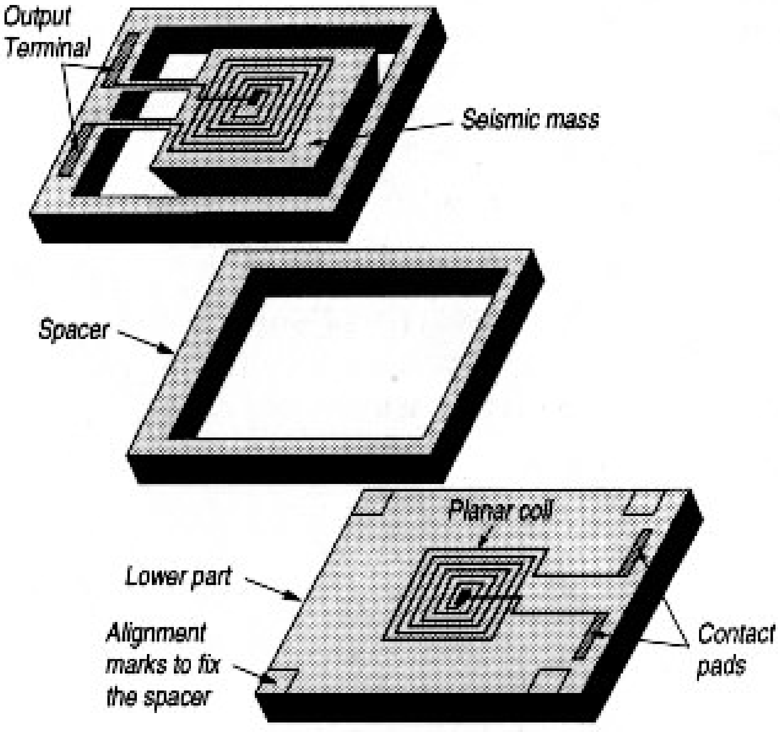


Fig. 1-6 *Accelerometer with electromagnetic read-out principle [1.52].*

- The sensor consists of two planar coils, one on the moving mass and one on the encapsulation.

- One of the coils is used to generate an alternating magnetic field.

- An induced voltage is generated in the other coil with an amplitude proportional to the distance between two coil. In this way, the mass displacement and hence the acceleration can be determined.

Thermal Read-Out Principle

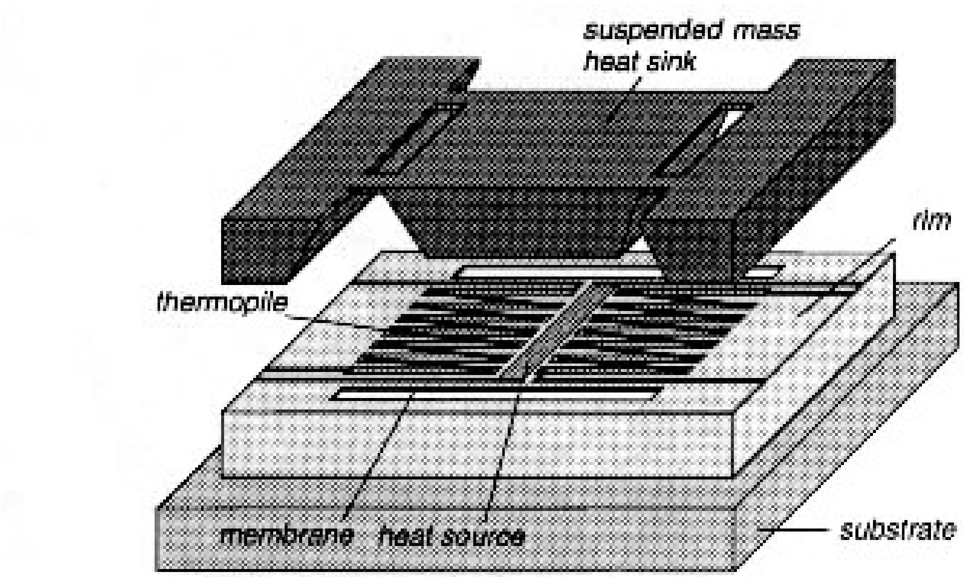


Fig. 1-7 *The thermal accelerometer with the mass acting as variable heat sink [1.77].*

In the thermal read-out principle the position of the mass affects the amount of heat flow due to the conduction through the gas between the mass and the encapsulation [1.75]-[1.77]. As a result of the variable heat flow, a temperature difference between the heated part and the heat sink arises, which depends on the position of the mass and thus on the acceleration.

Optical Read-Out Principle

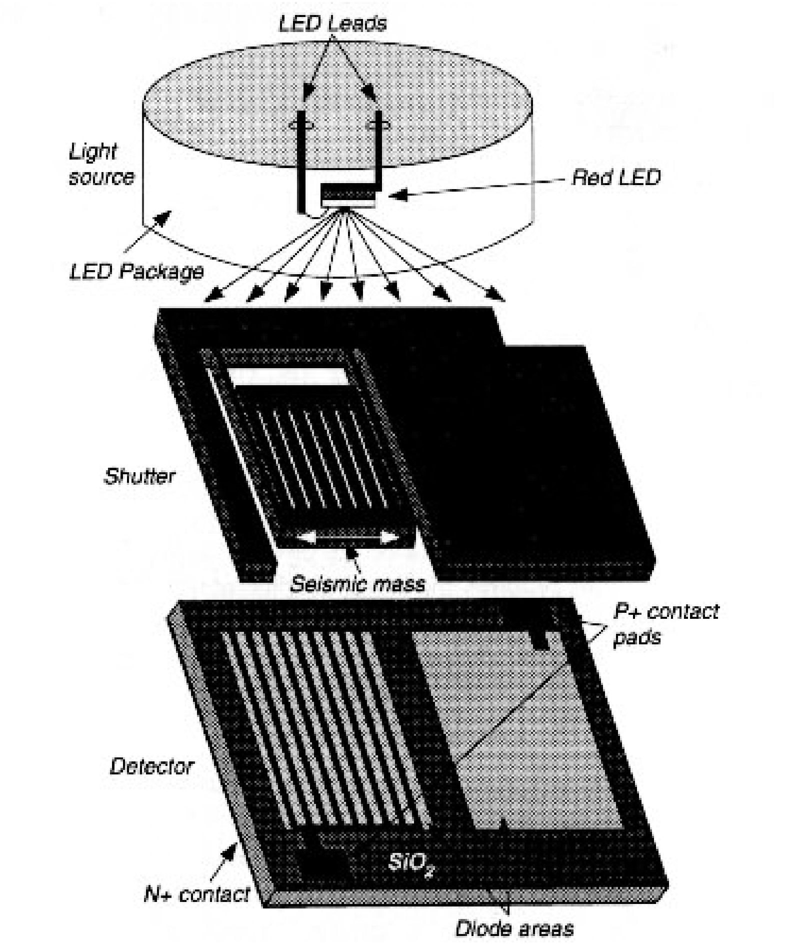
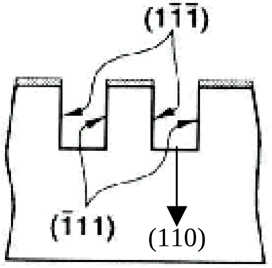


Fig. 1-8 *Accelerometer using an optical read-out mechanism, based on intensity changes [1.9].*

based on changes in intensity, by the moving mass,
which acts like a shutter
or by a change in reflected wavelength by using a Bragg grating
in a planar waveguide

The movement of the mass is in the wafer plane, which is realized by using (110)-cut wafers, in contrast to conventionally used (100)-cut wafers for the fabrication of electronic circuitry and out-of plane bulk-micromachined accelerometers. The side walls of the resulting structures are vertical, a feature, which in case of the intensity based accelerometer is used allow the propagation of light from the top to the bottom of the structure where photodiodes are located, as shown in Figure 1-8. A movement of the seismic mass, due to an acceleration, changes the light intensity on the photodiodes.



A-A' cross-section

Electron Tunneling Read-Out Principle

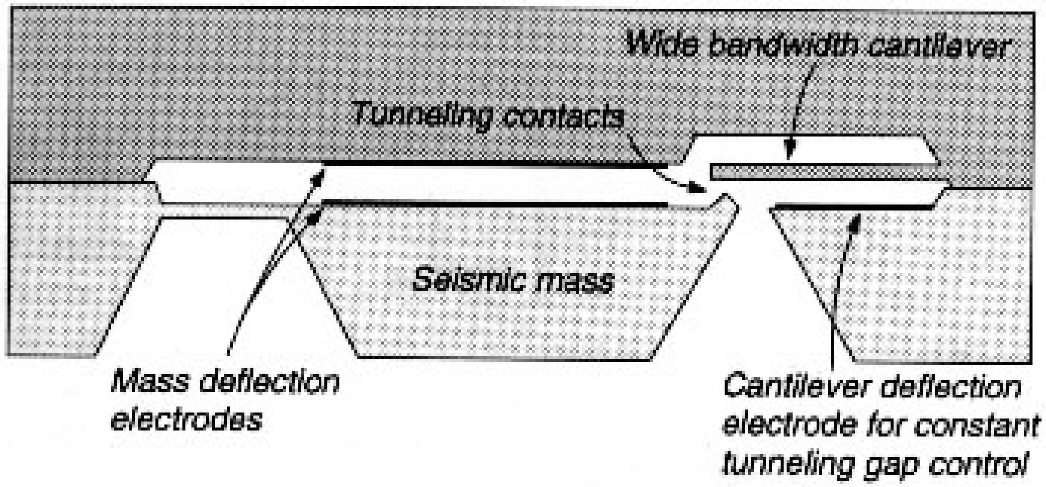
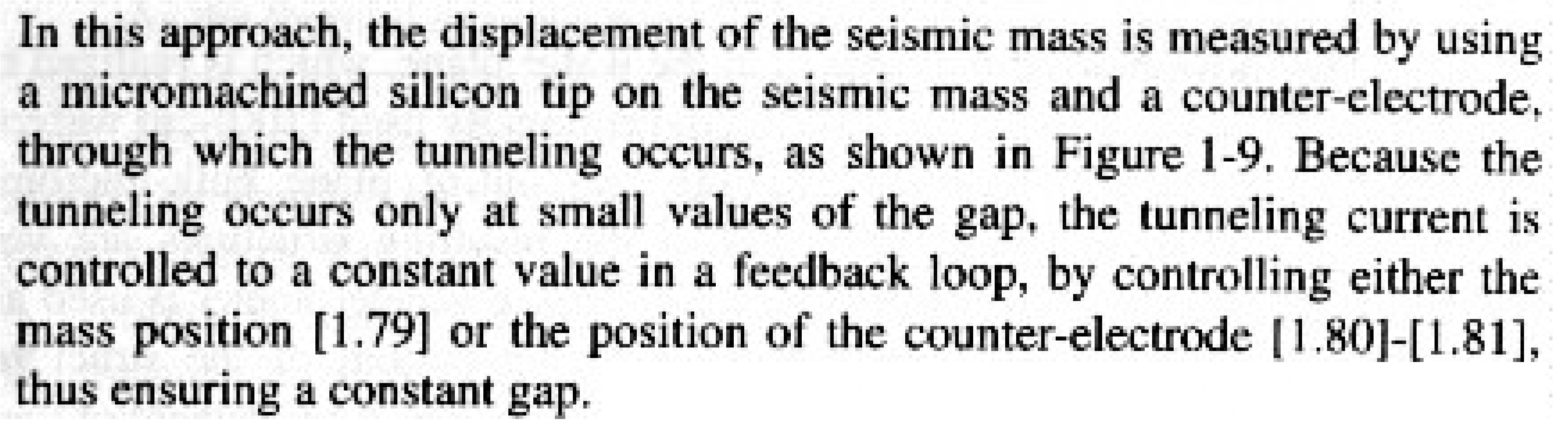


Fig. 1-9 *Accelerometer using an electron-tunneling read-out principle [1.80].*



In this approach, the displacement of the seismic mass is measured by using a micromachined silicon tip on the seismic mass and a counter-electrode, through which the tunneling occurs, as shown in Figure 1-9. Because the tunneling occurs only at small values of the gap, the tunneling current is controlled to a constant value in a feedback loop, by controlling either the mass position [1.79] or the position of the counter-electrode [1.80]-[1.81], thus ensuring a constant gap.

Self-Test Electronic Force Generation

• Electrostatic force generation:

- A voltage is applied across the electrodes on the moving seismic mass and the fixed encapsulation, causing an electrostatic force acting on the mass. Due to the attractive nature of the force, the mass deflects towards the tactic electrode. In this way proper operation of the accelerometer can be tested for diagnostics.

- **Disadvantage**: Large voltage required to obtain a reasonable force, which can be overcome by reducing the distance between the electrodes.

• Magnetic force generation

An attractive force acting on the seismic mass can be realized by magnetic forces acting on planar coil located on the mass. The magnitude of the force depends on the magnetic field, and thus on the current through the reference coil, located on the encapsulation.

• Thermal force generation

A relatively new self-test principle of accelerometers is based on the thermal expansion of a silicon beam when heated. One side of the beam is connected to the frame and the other side is connected to the mass. When a self-test voltage is applied across the resistive beam, it heated up relative to the rest of the chip, causing the heated beam to expand more than the chip and the mass be pushed downward, similar to an acceleration.