National Kaohsiung First University of Sci. & Tech.

微感測器—機械感測器

Microsensors – Mechanical Microsensors

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Sensors的分類

- Smart Sensors: integrating sensor and signal processing units

表 6.1 感覺器分類，根據 [Gard 94]。

信號形式	被測元
熱	溫度、熱量、熱流、熵、熱容等等。
輻射	伽瑪射線、X 光、紫外光、可見及紅外光、微波、無線電波等等。
機械	位移、速度、加速度、力量、壓力、質量流、音波長度及振幅等等。
磁的	磁場、通量、磁矩、磁性、磁透率等等。
化學的	濕度、pH 值及離子、氣體濃度、毒性及有焰材料、蒸氣濃度及氣味、污染物等等。
生物的	糖、蛋白質、荷爾蒙（激素）、抗原等等。

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Major Applications - 1

- Medical Applications
  - 連續量測血液中的物理化學參數如溫度、壓力、流量、pH值
  - 呼吸系統中的氧、二氧化碳或麻醉劑
  - 體內量測 (*In situ* measurement)
    - 感測器需與生物共容，且長時間穩定，不需外加電源
- Environmental Protection
  - 偵測物質（氣體、液體的固形量）濃度，如一氧化碳、氧化氮、重金屬
  - 大氣中的二氧化碳濃度
  - 需常暴露於污水與垃圾中，感測器晶片可於現場同時進行資料的處理，減少訊號傳輸的必要性
- Food Processing: 化學與生物感測器以偵測污染與不純物

Major Applications - 2

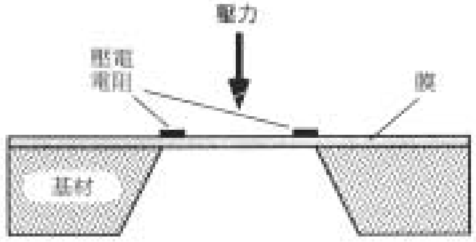
- Automobile Applications
  - Distance, acceleration, pressure, vibration, temperature and chemical sensors
  - 增加安全性與降低燃油消耗與污染
- Microrobotics
  - Often equipped with distance, acceleration, force, torque, tactile, pressure and temperature sensors.
- Materials: semiconductor materials, metals, plastics, ceramics, glasses, enzymes and antibodies (biosensors)
- Fabrication: Silicon technology, LIGA

Pressure Sensors

- First developed and used by industry
- Silicon-based pressure sensor: low cost, high sensitivity, and low hysteresis
- Typical pressure sensor
  - Deflection Membrane structure is proportional to pressure
  - Piezoresistive pressure sensor
  - Capacitive pressure sensor
  - Resonance pressure sensor
  - Interferometer pressure sensor

Piezoresistive Pressure Sensor

- Bulk micromachining of a (100) silicon substrate
  - Etch stop to produce membrane
  - Piezoresistors integrated in the membrane
  - Wheatstone bridge measure the change of resistance



$$\frac{\Delta R}{R} = \sigma_l \pi_l + \sigma_t \pi_t$$

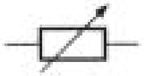
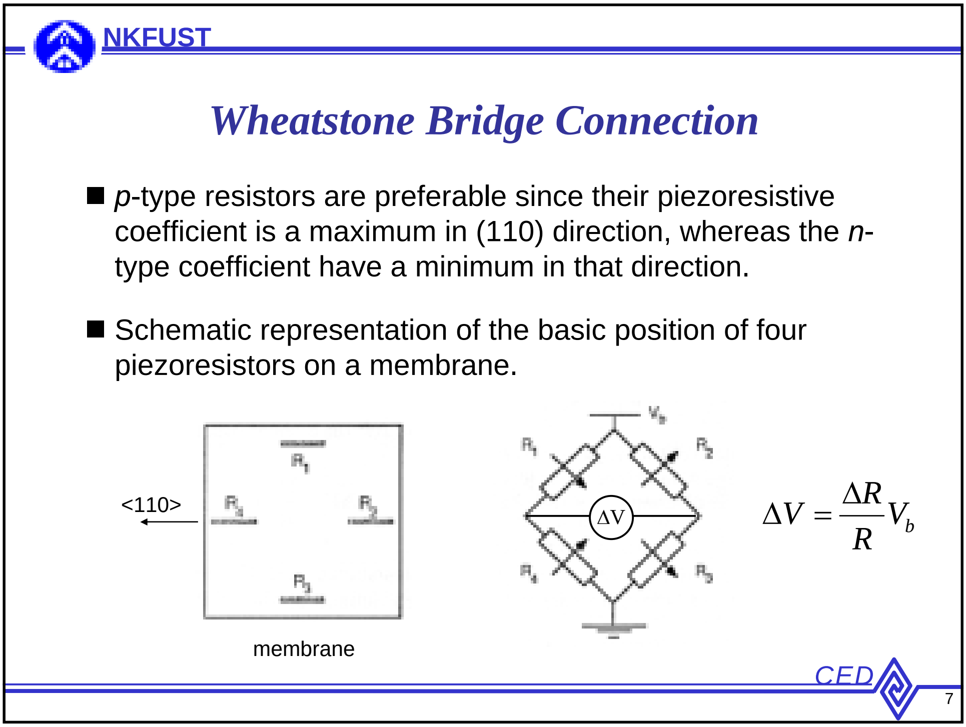


圖 6.4　壓電阻抗壓力感測器原理，根據 [Heub 91]。



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Wheatstone Bridge Connection

- *p*-type resistors are preferable since their piezoresistive coefficient is a maximum in (110) direction, whereas the *n*-type coefficient have a minimum in that direction.
- Schematic representation of the basic position of four piezoresistors on a membrane.

$$\Delta V = \frac{\Delta R}{R} V_b$$

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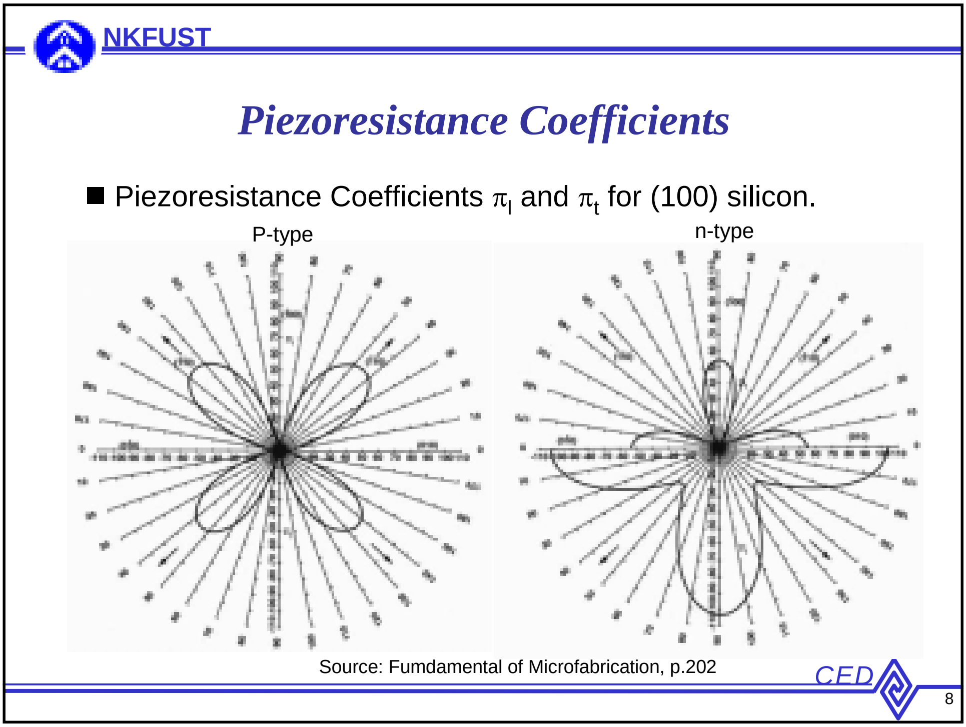

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Piezoresistance Coefficients

- Piezoresistance Coefficients π_l and π_t for (100) silicon.

Source: Fumdamental of Microfabrication, p.202

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Schematic Illustration of Pressure Microsensor

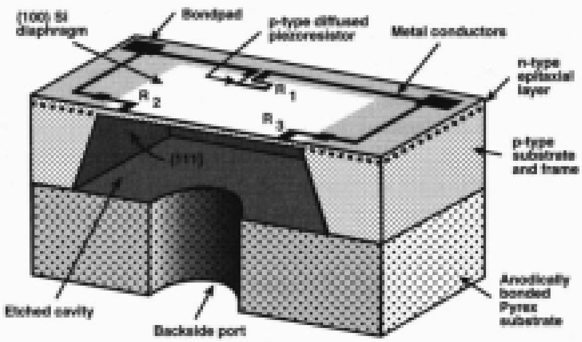


Figure 4.24 Schematic illustration of a pressure sensor with p-type diffused resistor in an n-type epitaxial layer. (Based on N. Maluf, *An Introduction to Microelectromechanical Systems Engineering*, Artech House, Boston, 2000.[30])

Source: Fumdamental of Microfabrication, p.203

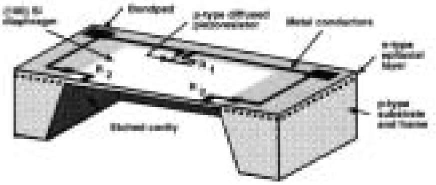
Membrane Stresses

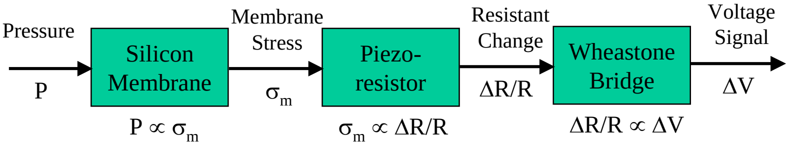
- Assumptions:
  - Deflections are very small compared to the membrane thickness.
  - No deformation in the middle plane.
  - Normal stresses in the direction transverse to the plate can be neglected.
- Surface stress in the middle of the sides of the membrane:
  - *p*: pressure
  - *a*: membrane side length
  - *h*: membrane thickness

$$(\sigma_x)_{\max} = 0.31 p \frac{a^2}{h^2}$$

壓阻式微壓力計的感測轉換機制

- 藉由感測器結構與電路設計將壓力轉換成電壓訊號
  - 矽薄膜：將壓力轉換為薄膜應力
  - 壓阻材料(P+ doping silicon)：將薄膜應力轉換為電阻改變率
  - 惠斯敦電橋：將電阻改變率轉換為電壓偏移量





Capacitive Pressure Sensor

- Displaced mass changes the capacitance between two attached metal plates.
- KOH anisotropic etching silicon substrate sandwiched between two Pyrex glasses through anodic bonding.

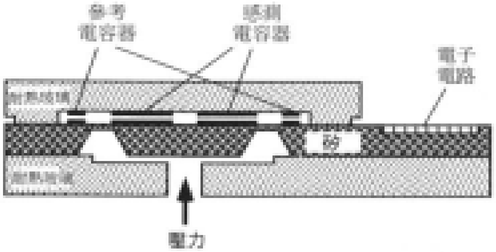
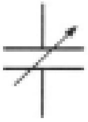


圖 6.5 由矽所製之電容性壓力感測器。根據 [Mehl 92]。

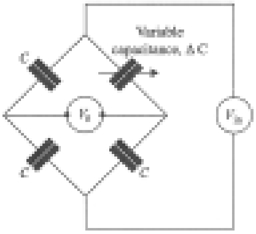


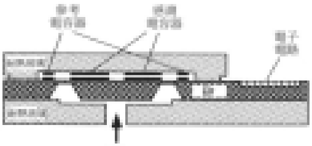
$$C = \varepsilon \frac{A}{d}$$

$$\frac{\Delta C}{\Delta d} = -\varepsilon \frac{A}{d^2}$$

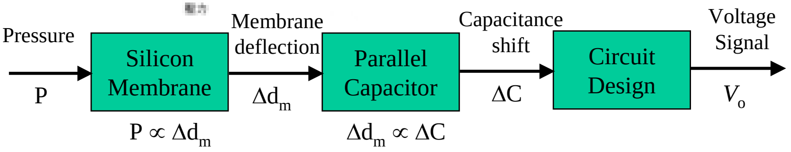
電容式微壓力計的感測轉換機制

- 藉由感測器結構與電路設計將壓力轉換成電壓訊號
  - 矽薄膜：將壓力轉換為薄膜位移量
  - 平行電容結構：將薄膜位移量轉換為電容改變量





$$V_0 = \frac{\Delta C}{2(2C + \Delta C)} V_{in}$$



Pressure

P

Silicon Membrane

$P \propto \Delta d_m$

Membrane deflection

Δd_m

Parallel Capacitor

$\Delta d_m \propto \Delta C$

Capacitance shift

ΔC

Circuit Design

Voltage Signal

V_o

Microoptical Systems

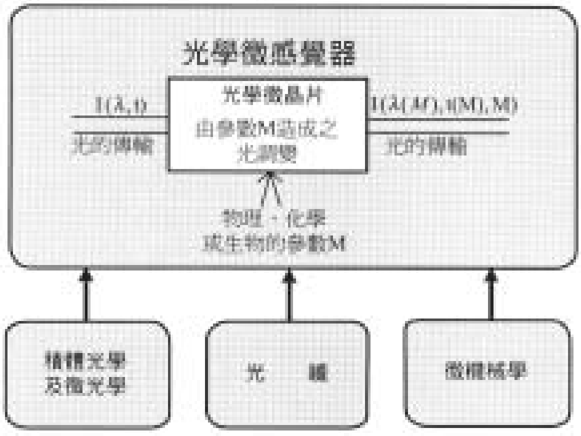


圖 6.1 光學微感覺器之架構，根據 [Lore 93]。

- Optical Parameters
  - Amplitude
  - Phase shift
  - Spectral distribution
  - Frequency
  - Time

光晶片的波導

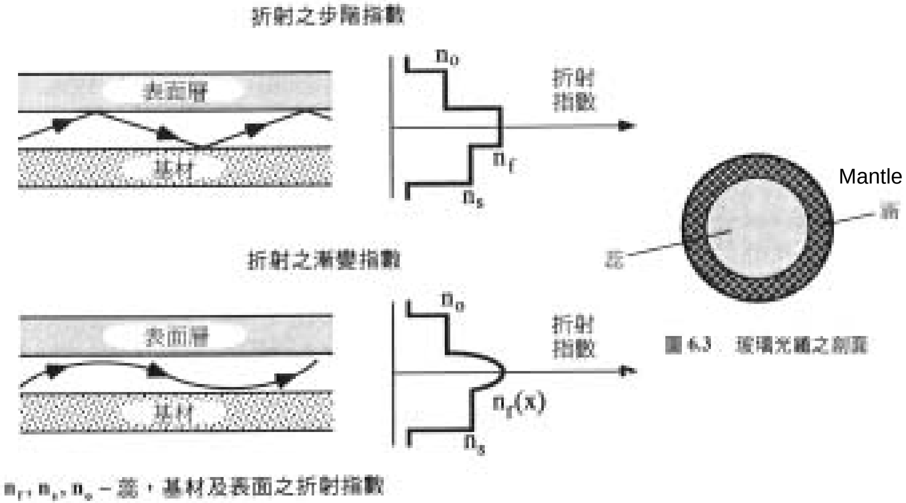


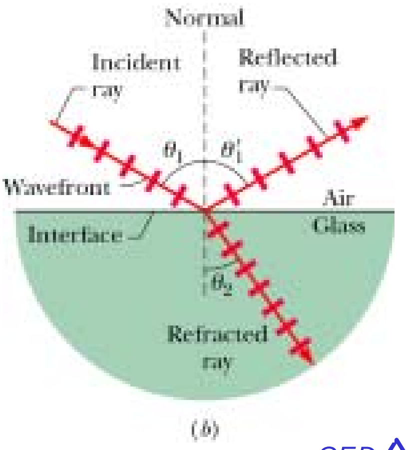
圖 6.3 玻璃光纖之剖面

n_f, n_s, n_o – 蕊，基材及表面之折射指數

Reflection and Refraction

- Law of reflection
  - $\theta'_1 = \theta_1$
- Law of refraction
  - $n_1 \sin\theta_1 = n_2 \sin\theta_2$
- Refraction rate
  - *c*: 光在空氣中的速度
  - v_m: 光在介質中的速度

$$n_m = \frac{c}{v_m}$$

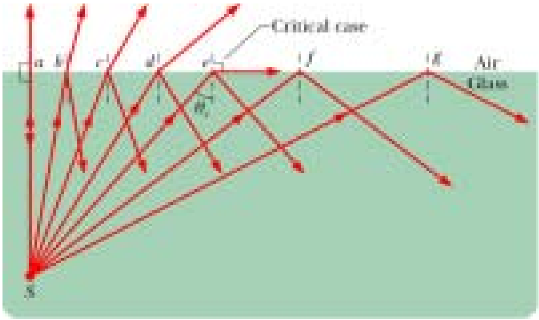


Total Reflection

- Total Internal reflection
  - $n_1 \sin\theta_c = n_2 \sin 90°$
  - Critical angle

$$\theta_c = \sin^{-1}\frac{n_2}{n_1}$$

- Typical materials
  - $SiO_2/SiON/SiO_2$
  - $n(SiO_2)=1.46$
  - $n(SiON)=1.52$



Mach-Zehnder Interferometer

- Waveguide deforms and changes the properties of the light beam
- Use phase shift to measure pressure
- Integrate SiON waveguides, sensitive silicon membranes, potodiodes, and CMOS amplifier.
- Sensitivity 14 μV/mbar

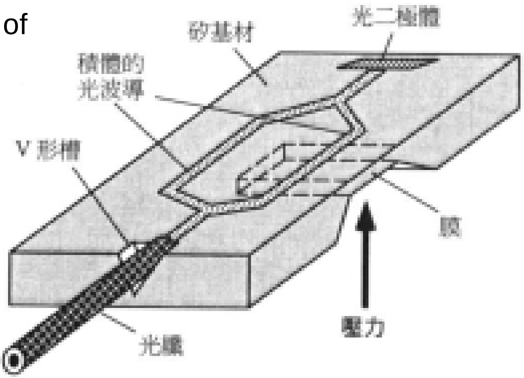


圖 6.8　馬赫切德干涉儀。根據 [Fisch 91]。

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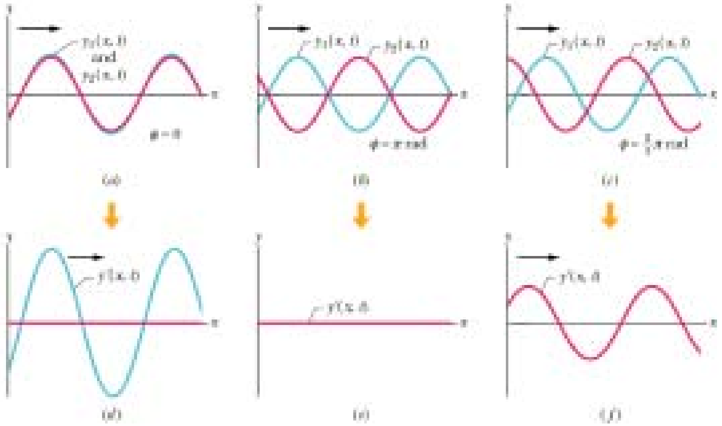
Interference of Waves

- (a) Fully constructive interference, (b) Fully destructive interference, and (c) intermediate interference



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Interferometer

- Superposition of two identical waves with a phase shift.
  - $y'(x,t) = y_1(x,t) + y_2(x,t)$
    $= y_m \sin(kx-\omega t) + y_m \sin(kx-\omega t+\phi)$

$$\overbrace{y'(x,t)}^{\text{Displacement}} = \underbrace{\left[2y_m \cos \tfrac{1}{2}\phi\right]}_{\text{Amplitude}} \underbrace{\sin\left(kx - \omega t + \tfrac{1}{2}\phi\right)}_{\text{Oscillating term}}$$

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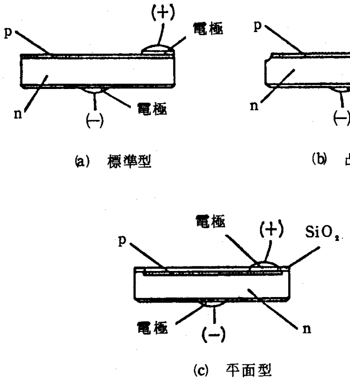
Photodiodes

- pn接合的半導體內有光射入時，激發正子與電子對，正子往p層電子往n層移動，產生的電流 I_λ 與入射光的能量呈正比



(a) 標準型 (b) 凸型

(c) 平面型

圖 1 矽受光元件的構造

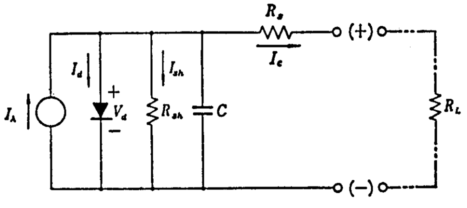


圖 2 矽受光元件的等效電路

Wave Guide of Pressure Sensors

- Consist of the light guiding layer (SiON) and a lower index of refraction (SiO_2) to allow the passage of light
  - A 2 to 3 μm thick silicon dioxide layer (index of refraction = 1.46) was applied to a (100) silicon wafer.
  - Deposit a 0.5 μm thick light guiding layer made of SiON (index of refraction = 1.52).
  - A 0.6 μm thick silicon dioxide layer was added and structured using a dry etching process.

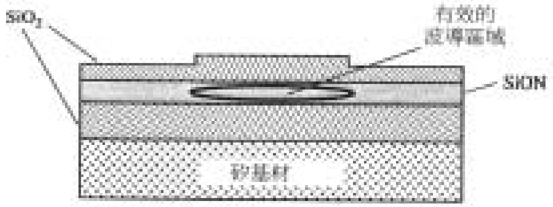
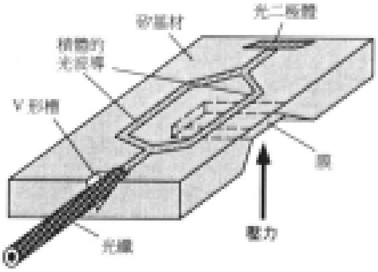
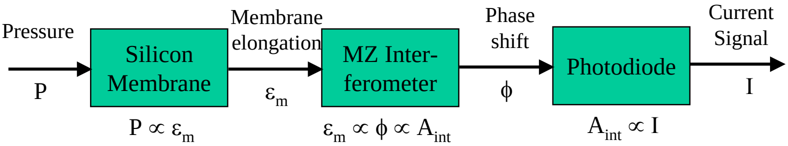


圖 6.9 壓力感測器之波導，根據 [Hill 94]。

光干涉儀式微壓力計的感測轉換機制

- 藉由感測器結構與光路設計將壓力轉換成電流訊號
  - 矽薄膜：將壓力轉換為薄膜變形量
  - 干涉儀：將薄膜變形轉換為光路的相位差，因而改變干涉的光強度
  - 光二極體：將光強度轉換為感應電流




Pressure

P

Silicon Membrane

Membrane elongation

ε_m

MZ Inter-ferometer

Phase shift

ϕ

Photodiode

Current Signal

I

$P \propto \varepsilon_m$

$\varepsilon_m \propto \phi \propto A_{int}$

$A_{int} \propto I$

Comparisons of Pressure Sensors

- Compared to piezoresistive signal transformers, capacitive pressure sensors have no hysteresis, a better long-term stability and a higher sensitivity.
- Capacitive pressure sensors have higher production costs, and the circuit design is more difficult.
- Interferometer pressure sensors have a much higher sensitivity.

Capacitive Force Sensor

- A movable elastic structure transforms a force into a displacement.
- A transformation unit consisting of the electrodes transforms the displacement into a measurable change of capacitance.
- Better linearity and less cross-sensitivity.
- Made by anisotropically etching (110) silicon

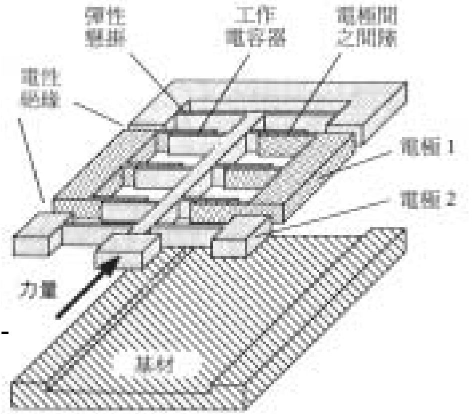


圖 6.6 矽製之電容式力感覺器，根據 [Desp 93]。

20 nm resolution, 0.01 ~ 10 N

Force Sensing Resistor

- Resistance is inversely proportional to the pressure
- Polymer foil with planar electrodes covered by semiconductor polymer
- Applied force reduces the resistance due to current flows across the shunting polymer foil
- Dynamic range affected by electrode pitch and sensitivity affected by foil thickness
- Major disadvantage: hysteresis

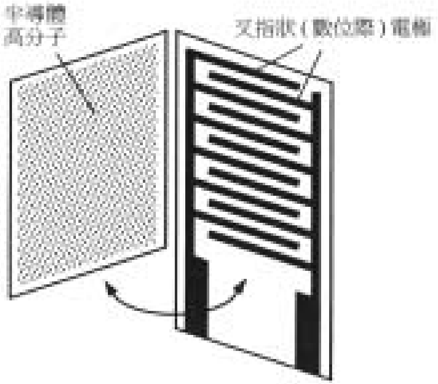
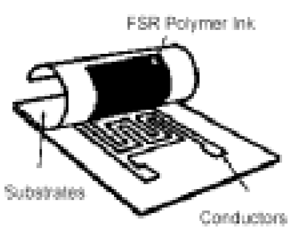


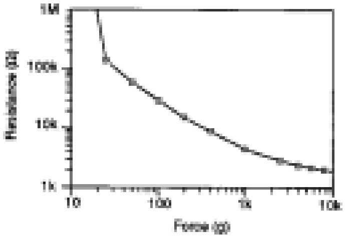
圖 6.10 力量偵測電阻，根據 [Witte 92]。

5%deviation, 10g ~ 10Kg

Force Sensing Resistor功能及用途

- 高分子膜加上平面電極，再加上一半導體高分子膜
- 當此裝置受一力時，電阻值會降低，即壓力與電阻成反比。
- 量測電阻值範圍1 MOhm(百萬歐姆)~2 KOhm，力量感測約 10g~10kg





http://www.steadlands.com

Position and Speed Microsensors

- Essential for automobiles, robots and medical instruments.
- Determine the exact position of an endeffector of a microrobotics.
- Contact-free optical and magnetic methods are the most significant ones:
    - Magnetic sensor for angular displacement
    - Inclination sensor
    - Ultrasound distance sensors
    - Capacitive rotational speed sensor
    - Fiber optical swing angle sensor

Magnetic Sensor for Angular Displacement

- Use Hall effect to detect angular displacement

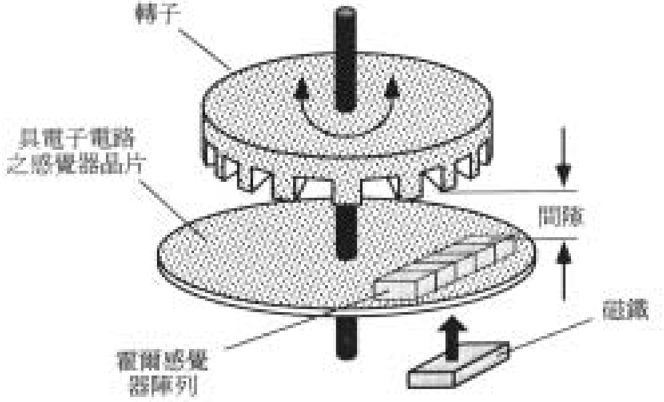
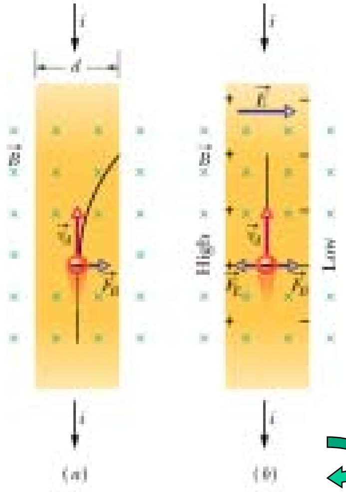


圖 6.12 角度量測微感覺器。根據 [Ueno 91]。

Hall Effect



- Magnetic Force (Lorenz Force)
  - $\vec{v}$:the velocity of charge *q*
  - $\vec{B}$: magnetic field

  $\vec{F}_B = q\vec{v} \times \vec{B}$

- Hall Effect
  - The separation of positive and negative charges produces an electric field $\vec{E}$
  - The force due to $\vec{E}$ and the force due to $\vec{B}$ are in balance.
  - Hall potential difference *V*

  $V=Ed$

Block Diagram for Magnetic Sensor

- Each Hall sensor covers one tooth and one notch of the rotor
- Multiplexer scans all *n* Hall sensor creating a step function to represent the magnetic distribution
- Rotation causes phase shift
- Accuracy of 0.028°

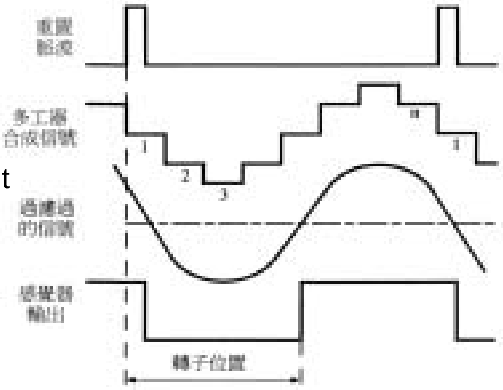


圖 6.13 量測程序之方塊圖，根據 [Ueno 91]。

Inclination Sensor

- Consists of an LED and a semi-spherical glass cup mounted on a photodiode matrix array

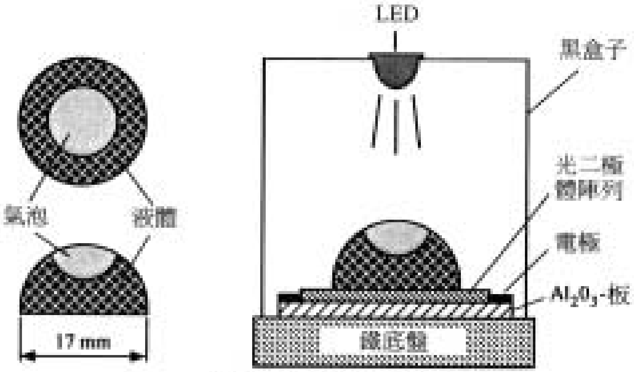


圖 6.14 傾斜感覺器，根據 [Kato 91]。

Principle of Inclination Sensor

- Speed should keep constant
- Accurate for small angle (10°)

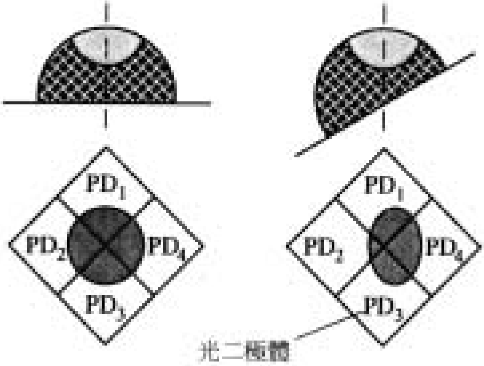


圖 6.15　感覺器的量測原理。根據 [Kato 91]。

Ultrasound Distance Sensors

- Use the pulse-echo principle.
- Ultrasound transducer made from piezoceramics emits a pulse sequence.
- “Blind spot" appears when the detector is too close to an object .
- Two identical independent ultrasound membranes, one transmitter and one receiver, integrated on a silicon substrate.
- Membrane is brought to resonance with integrated heating resistors.
- Acoustic pressure response is detected by piezoresistors, integrated in the form of a Wheatstone bridge.

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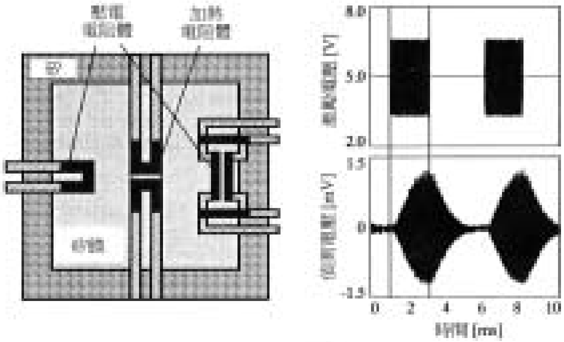
Ultrasound Distance Sensors

- Schematic design of a single sensor membrane and the measurement principle



Sensitivity 3 µV/mPa, at a bridge voltage of 5V.

圖 6.16 超音波距離感應感覺器，(a) 感覺器之設計，(b) 感覺器之量測原理，根據 [M²S²93]。

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Capacitive Rotational Speed Sensor

- Compact and inexpensive angular speed sensors in navigation and landing gear controllers

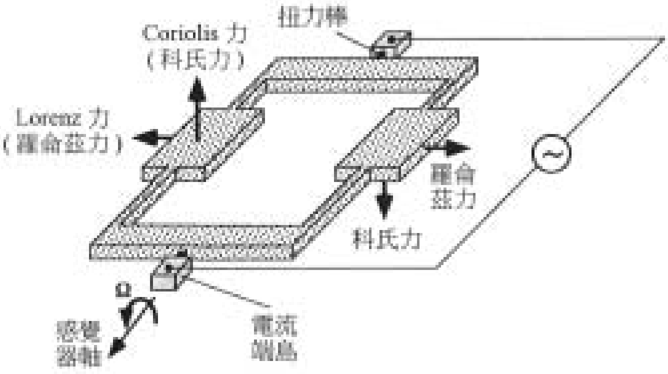

圖 6.17 旋轉速度微感覺器之工作原理，根據 [Hash 94]。

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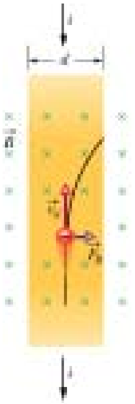
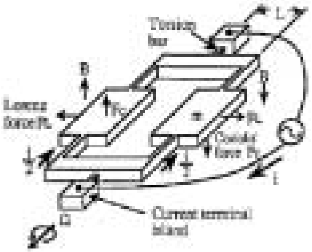
Lorenz Force (羅侖茲力)

- Lorenz Force (羅侖茲力)：運動中帶電粒子的磁力
  - 當帶電粒子 $\boldsymbol{q}$ 以一速度 $\boldsymbol{v}$ 垂直進入磁場 $\boldsymbol{B}$ 中，它會承受一偏向力 $\boldsymbol{F_B}$，稱為羅侖茲力。

$$\vec{F}_B = q\vec{v} \times \vec{B}$$

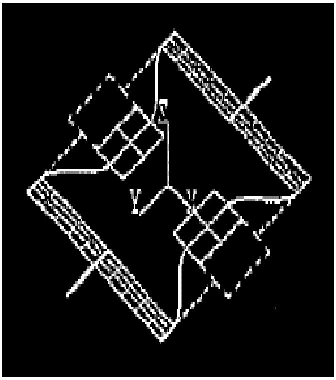
  - 當輸入電流為交流電，質塊因Lorenz Force而震盪

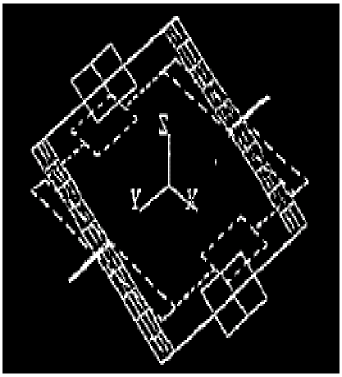




Capacitive Rotational Speed Sensor

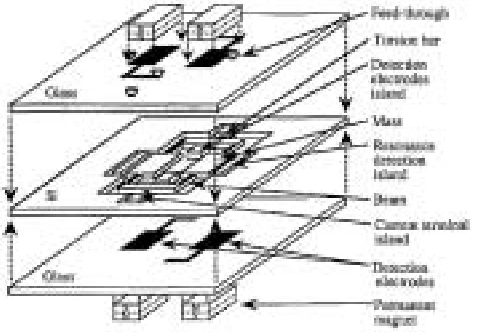
- 感測器運動模擬





電容式角速度感測器結構

- Made of (110) silicon



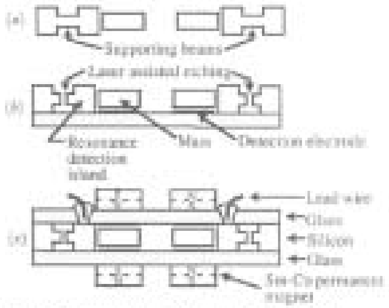


Figure 4. Fabrication process. (a) Wet etching after YAG laser drilling. (b) First anodic bonding and laser assisted etching. (c) Second anodic bonding and magnet gluing.

[Hashimoto, in Micro System Technologies, 94]

Fiber Optical Swing Angle Sensor

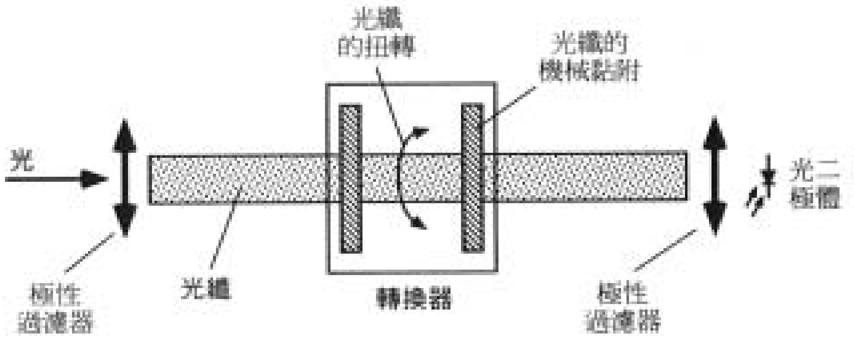
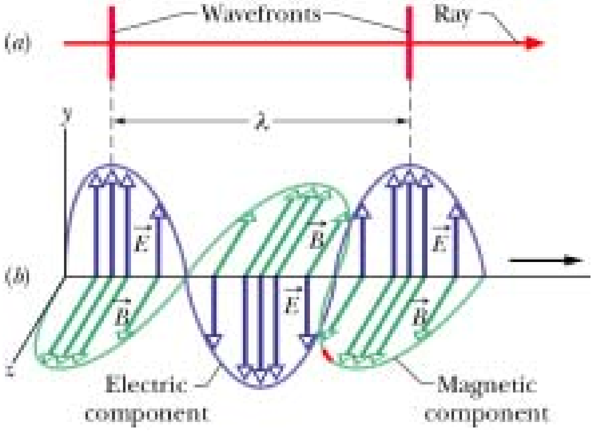


圖 6.18 光纖擺角度感覺器，根據 [Ecke 93]。

Electromagnetic Wave

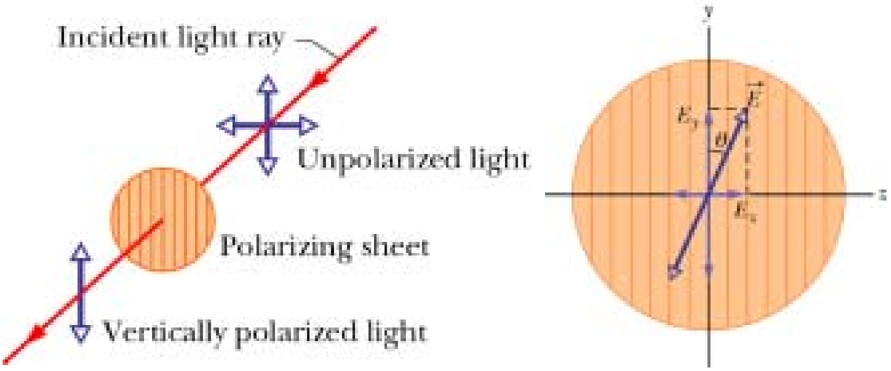
- An electromagnetic wave represented with a ray and two wavefronts.



Polarization Filter

- Unpolarized light becomes polarized when it is sent through a polarization filter.

$$E_y = E \bullet \cos\theta$$

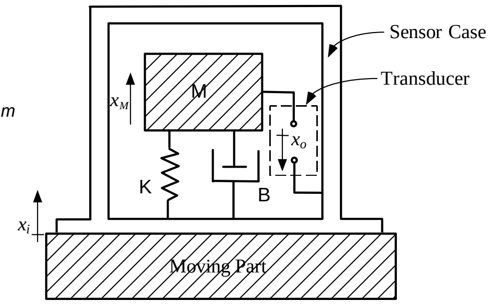


Fiber Optical Swing Angle Sensor

- Light is lead into a glass fiber via a polarization filter.
- A torque applied to the mechanical measuring section causes a torsion in the glass fiber and changes the direction of the polarization of the light.
- Change of the light intensity is detected by the second polarization filter and is then evaluated by a photodiode.

Typical Model of Accelerometer

- STRUCTURE OF ACCELEROMETER
  - Mass-Spring-Damper substructure
  - Displacement transducer
  - Amplification circuit
- SYSTEM MODEL
  - Mechanical subsystem G_m
  - Electric subsystem G_e

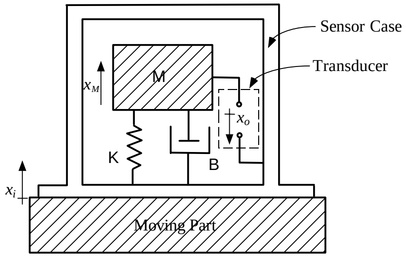


Mechanical Subsystem

- MASS-SPRING-DAMPER SUBSTRUCTURE

$$M\ddot{x}_i = M\ddot{x}_o + B\dot{x}_o + Kx_o$$

- NEWTON'S SECOND LAW



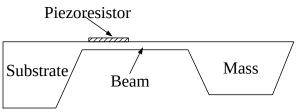
$$\frac{x_o}{\ddot{x}_i}(D) = S_m \cdot \frac{\omega_n^2}{D^2 + 2\zeta\omega_n D + \omega_n^2}$$

- MECHANICAL TRANSFER FUNCTION

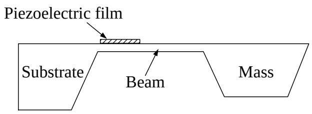
where $w_n = \sqrt{\frac{K}{M}}$ $\quad \zeta = \frac{B}{2\sqrt{KM}}$ $\quad S_m \equiv \frac{M}{K}$

Cantilever Principles

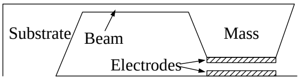
- DISPLACEMENT TRANSDUCER OF ACCELEROMETER
  - Piezoresistive
  - Capacitive
  - Piezoelectric



(a) Piezoresistive Mode



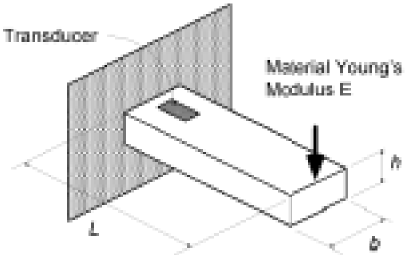
(c) Piezoelectric Mode



(b) Capacitice Mode

Cantilever Beam Spring

- 懸臂樑在自由端受負載之最大變形
  - $y_{max} = PL^3/(3EI)$
  - 虎克定律
    - $P = Ky$
    - $P = (3EI/L^3) \cdot y_{max}$
    - 懸臂樑的彈簧常數 $K = (3EI) / L^3 = (Ebh^3) / (4L^3)$



Capacitive Microaccelerometer

- 質塊位移造成電容的改變
  - ε : Permittivity, A: area, d: distance, V: voltage, Q: charge
  - ε_0: Permittivity in vacuum, ε_r: Dielectric constant

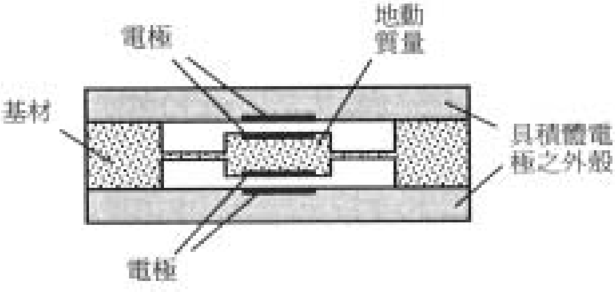


圖 6.19 加速度的電容性量測

$$C = \varepsilon \frac{A}{d}$$

$$C = \frac{Q}{V} \qquad \varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

$$\frac{\Delta C}{\Delta d} = -\varepsilon \frac{A}{d^2}$$

Piezoresistive Micro-accelerometers

- 在應變最大處鍍上壓阻（Piezoresistive）材料
- 加速度造成質塊位移而在懸樑上產生應變

$$\frac{\Delta R}{R}=\sigma_l\pi_l+\sigma_t\pi_t$$

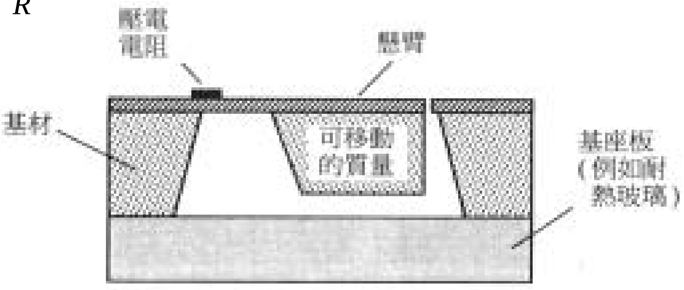
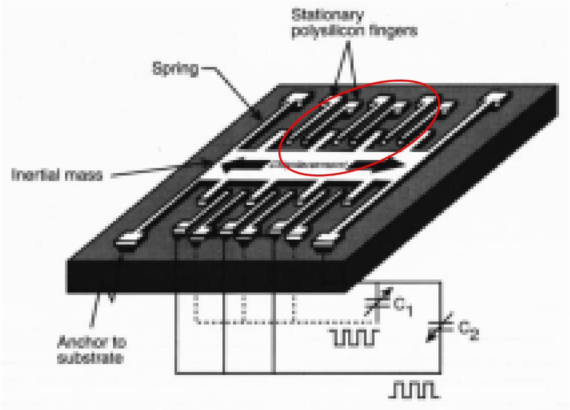


圖 6.20　壓電電阻加速度感覺器。

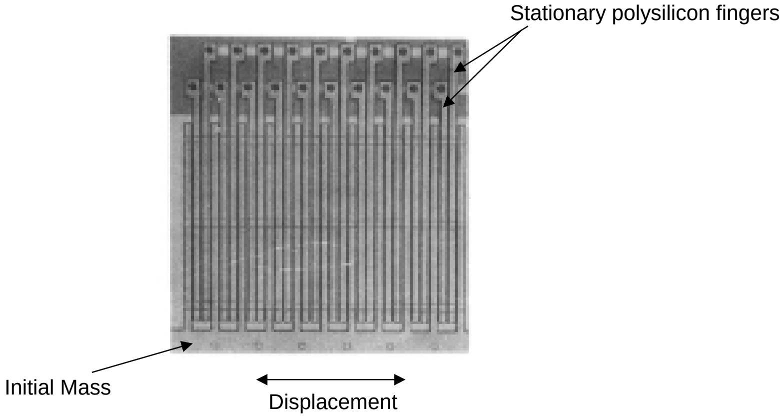
Integrated Capacitive Accelerometer

- Consists of independently fixed plates and a movable comb-like microstructure.



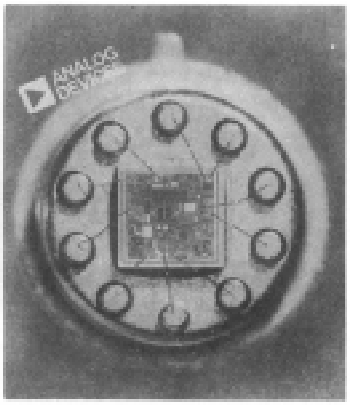
Integrated Capacitive Accelerometer

- Made from polysilicon by surface micromachining.



Integrated Capacitive Accelerometer

- First commercialized MST device. Used in airbag system.
- Sensor diameter about 9 mm.
- Signal pre-amplification, temperature compensation and system self-test purposes were integrated
- Accelerations up to ±50 g can be measured with a sensitivity of 10 mV/g.



Capacitive Cantilever Microsensor

- Consist of a cantilever beam over an opposite electrode and a contact strip.
- Threshold voltage applied to offset the forces caused by the acceleration.

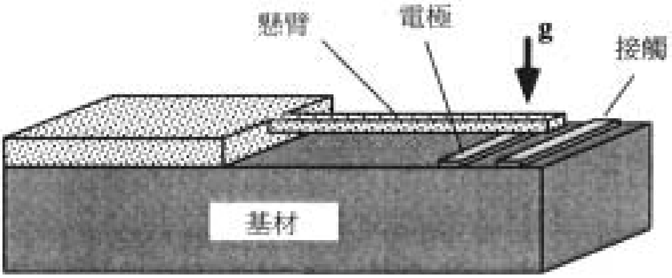


圖 6.22 加速度量測器之設計。根據 [Fick 93]。

Capacitive Cantilever Microsensor

- A sawtooth voltage is applied in defined steps across the cantilever and the electrode.
- Electrostatic force acting on the cantilever increases with the applied voltage until contact occurs.
- For a cantilever length of 120-500 μm, the microsensor sensitivity is in a range of 0.6-100 mV/g.

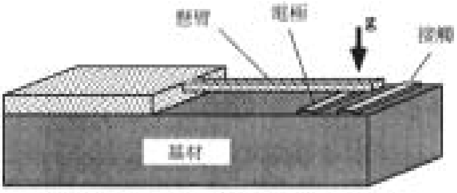


圖 6.22 加速度量測器之設計。根據 [Fick 93]。

Capacitive Cantilever Microsensor

- Made of polysilicon by the dry etching process.
- Microstructure height (polysilicon) = 2.2 μm.
- The gap attained between the cantilever and the contact strip is 1.5 μm.

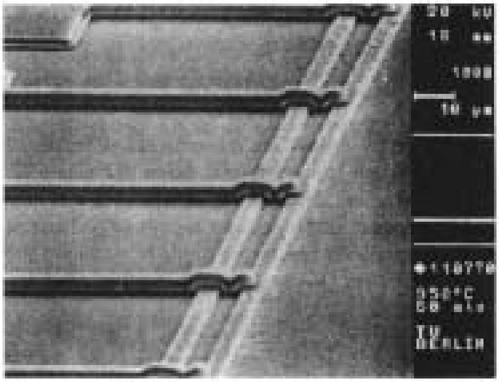


圖 6.23 感覺器之微構造。感謝 the Technical University of Berlin (Department of Electrical Engineering, Microsensor and Microactuator Technology)。

Piezoresistive Microsensor with Oil Damping

- Oil dampen the resonance of the suspended mass.
- The cantilever is 480 X 200 X 12 (μm); the seismic mass weighs 2 (mg).
- Measurement range
  - 20 ~ 50 g.

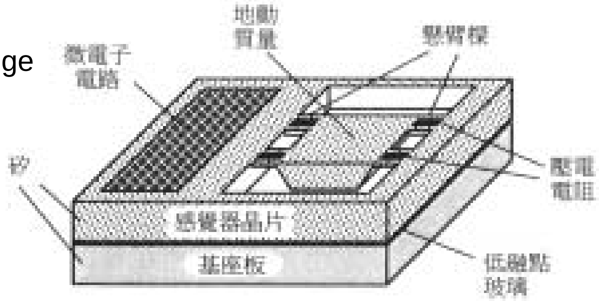
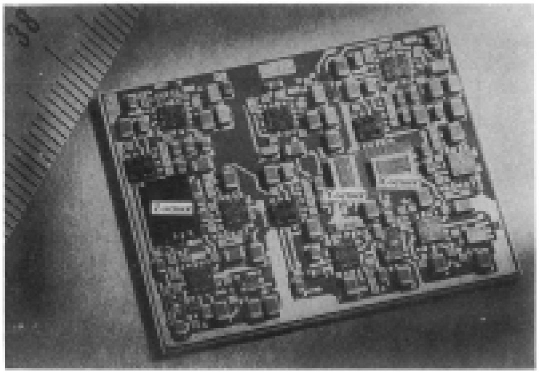


圖 6.24 微感覺器之設計。根據 [Muro 92]。

Multi-sensor Acceleration Measurement System

- 以SLIGA製作微機械電容感測器，整合三軸加速度計與放大電路、溫度補償於一晶片中



2 x 25 x 35 mm

Range: ±3 g

Sensitivity 2.5 V/g

圖 6.35 三維度加速度量測系統。感謝 the Karlsruhe Research Center, IMT。