



微致動器一

Microactuators-1

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微致動元件及其應用

- Mechanical microdevices having components such as
 - ▶ Pumps
 - ▶ Valves
 - ▶ Robot grippers
 - ▶ Linear and rotational positioning elements
 - ▶ Simple cantilever actuators
 - ▶ Complex artificial muscle systems

- Micropumps and valves treating liquids and gasses:
 - ▶ In medicine for the dosing of medication or for chemical.
 - ▶ In biotechnological analysis to transport and measure liquid.
 - ▶ Technical devices such as ink jet printers.

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微致動元件及其應用

- Microactuators using the cantilever principle:
 - ▶ In optics as electronically tunable mirrors
 - ▶ In fluid dynamics as valves
 - ▶ In microrobotics as grippers.
- Micromotors:
 - ▶ Moved by electrostatic, electromagnetic or piezoelectric forces.
 - ▶ Performance parameters do not yet reach the application requirements.
- Artificial muscle:
 - ▶ Flexibility, versatility, and high strength.
 - ▶ Made up of a series of microactuators



Scheme of an Integrated Actuator

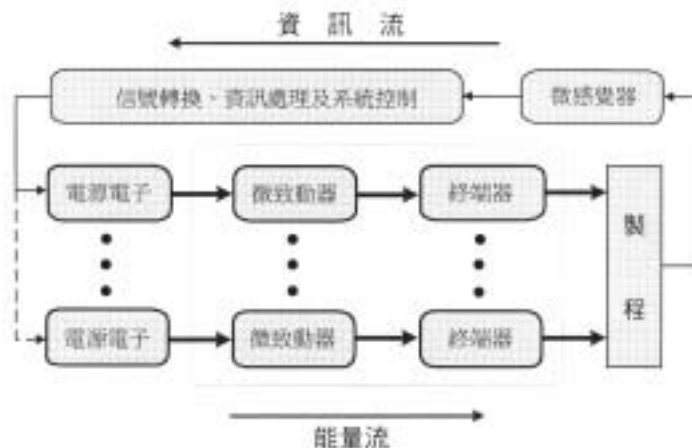


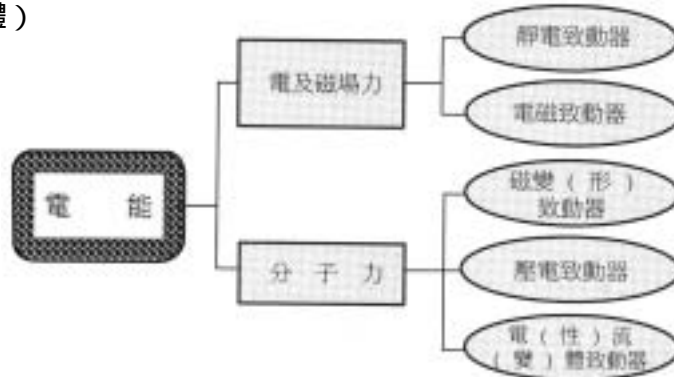
圖 5.1 整合微致動器入於微系統。根據 [Kall 94]。





Force-Producing Principles in MST - 1

- Electrostatic (靜電), Piezoelectric (壓電), Electromagnetic (電磁), Magnetostrictive (磁致伸縮), Electrostrictive (電致伸縮), and Electrorheological (電流體)



Force-Producing Principles in MST - 1

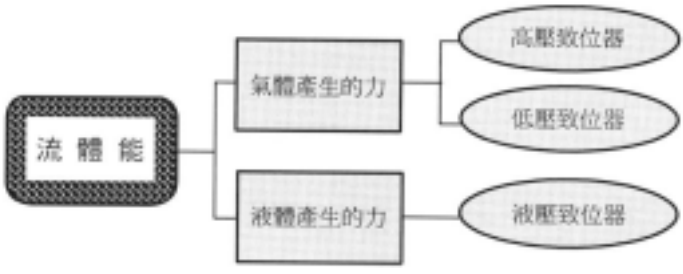
- “Smart” materials:
 - ▶ Piezoelectric (壓電) : The electric field causes expansion in ceramics
 - ▶ Magnetostrictive (磁致伸縮) : a magnetic field causes an expansion or contraction of the alloy.
 - ▶ Shape Memory Alloys (SMA形狀記憶合金) : return to their original shape when heated (thermal shape memory) due to martensitic transformation.
 - ▶ Electrorheological (電流體) : Change their viscosity under the influence of an electric field and switch from a liquid to a plastic state.
 - applications include clutches, valves or vibration absorbers.



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Force-Producing Principles in MST - 2

- Hydraulic (液壓) and Pneumatic (氣壓)



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    graph LR
      A[流體能] --> B[氣體產生的力]
      A --> C[液體產生的力]
      B --> D(高壓致位器)
      B --> E(低壓致位器)
      C --> F(液壓致位器)
    
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Force-Producing Principles in MST - 3

- Thermomechanical (熱機械)
- Shape Memory Alloys (SMA形狀記憶合金)



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    graph LR
      A[熱能] --> B[熱膨脹力]
      A --> C[形狀記憶效應]
      B --> D(雙金屬致動器)
      B --> E(熱致動器)
      C --> F(形狀記憶致動器)
    
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Force-Producing Principles in MST - 4

- Chemical energy (化學能)
 - ▶ 流體 (氣或液體) 因化學反應而產生氣體或體積膨脹 (Polymer Gel) 而作為驅動力



圖 5.2 致動器之分類。根據[Scheß 93]。



Electrostatic Microactuators 靜電微致動器



Motion Principle of Electrostatic Actuators

- Applying a voltage across two capacitor plates which are separated by an insulator.

$$F = \frac{\epsilon S V^2}{2d^2}$$

- Applying voltage (usually between 40 V and 200 V) introduces a deflection in the range of a few micrometers.

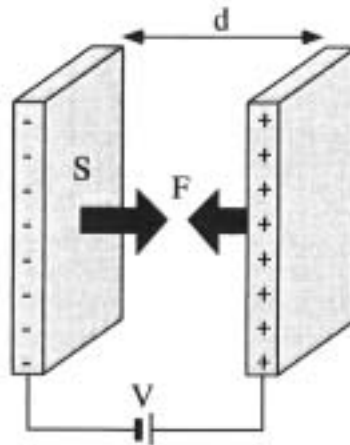


圖 5.3 靜電力之產生



Properties of Electrostatic Actuators

- 靜電力為表面力，與面積大小與距離有關而與電極板厚無關，故適合微製造件與輕材料如鋁。
- 磁力為物體力，其大小與面積板厚皆相關，磁致動器材料以鐵與鈷(cobalt)合金製成。
- 缺點
 - ▶ High applied voltage: To produce an actuator pressure of 1 kg/cm² for a gap of 1 μm, the required voltage is about 150V.
 - ▶ Need very smooth surfaces to avoid electrostatic collapse due to small surface defects.
 - ▶ Require a suitable insulating layer.
 - ▶ Attract dust.



Motion Using Electrostatic Principle

- A spring back mechanism to supply the pull back force.
- Small torque and short lifetime.

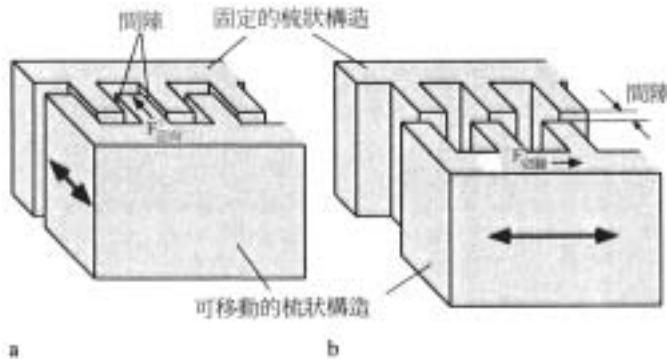


圖 5.4 由靜電力可獲得之兩種運動。根據 [Mohr 9]。



Electrostatic Microshutter

- 可撓曲的電極閘門，由鋁、金、或滲雜的複晶矽構成
- 扭轉樑與矽基材間以氧化矽隔離

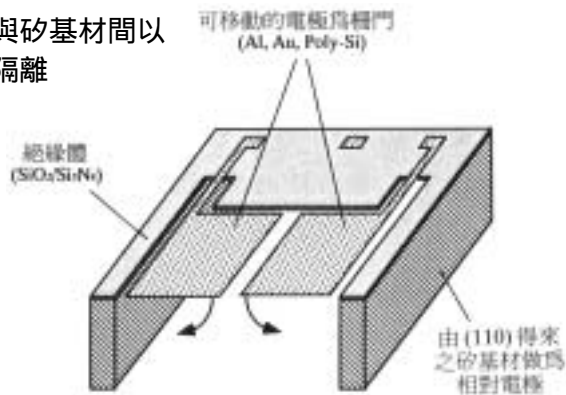
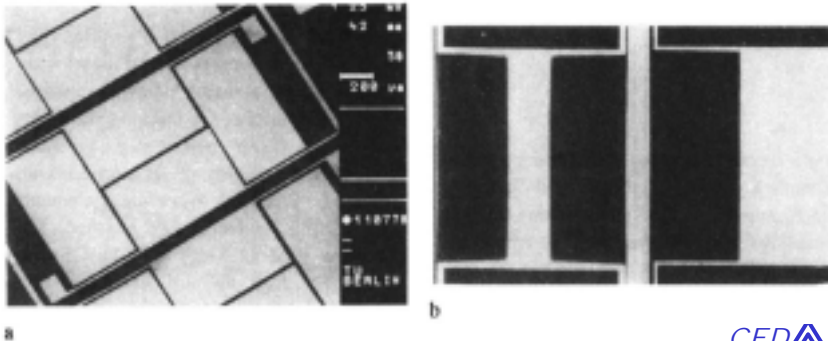


圖 5.5 靜電微閘門。根據 [Lin 93]。

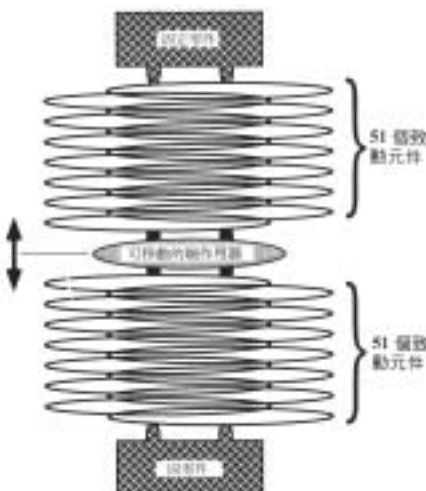


鋁製微閘門

- Movable electrodes 0.8 mm x 0.5 mm, a 450 μm long beam, 10 μm width and 1 μm thickness.
- 圖a 閘門為關閉位置，圖b 左雙開30°，圖右為單開90°。

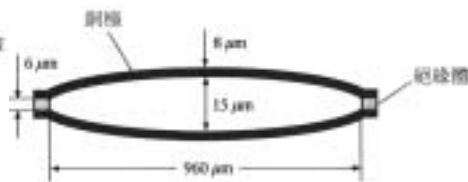



Microactuator Pile



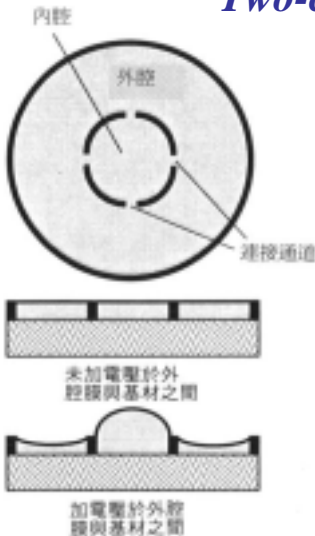
- Produced through photolithography, sputter technique and anisotropic wet etching.

- 160V時最大位移為28μm，產生的力超過6μN






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Two-chamber Actuator

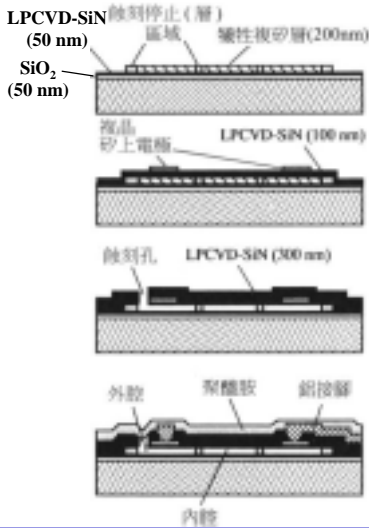


- Consists of two concentric air-tight chambers
- Voltage applied between the substrate and the membrane of the outer chamber.
- The inner-chamber of which had a radius of 100-250 μm and outer-chamber a radius 200-750 μm .
- Operated by 50 V, attaining motions from 1 to 4 μm .



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Fabrication of Two-chamber Actuator



- Produced with surface micro-machining techniques.
 - ▶ Si \ SiO₂ \ LPCVD-SiN
 - ▶ Pattern polysilicon
 - ▶ Doping etching stopping pattern on polysilicon
 - ▶ LPCVD SiN
 - ▶ Pattern the upper electrodes
 - ▶ LPCVD SiN
 - ▶ Remove sacrificial polysilicon layer
 - ▶ Pattern Aluminum circuit
 - ▶ Coating Polyimide


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Electrostatic Micropump

- 上兩片為靜電驅動單元，下兩片為幫浦腔，因此液體不會受電場影響，適合作為植入的投劑系統

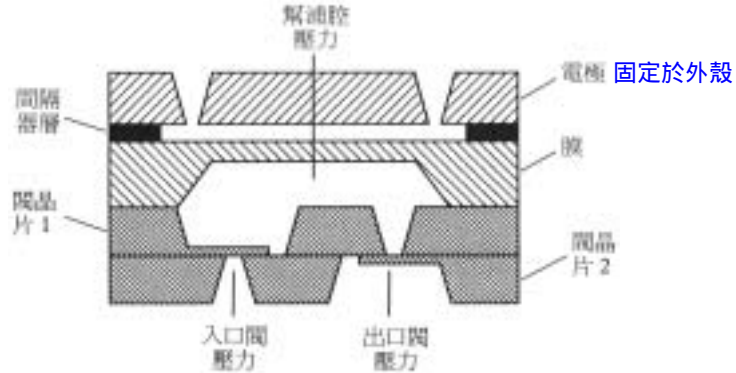


圖 5.9 代表微幫浦之示意圖。根據 [Rich 92]。



Electrostatic Foil Actuator

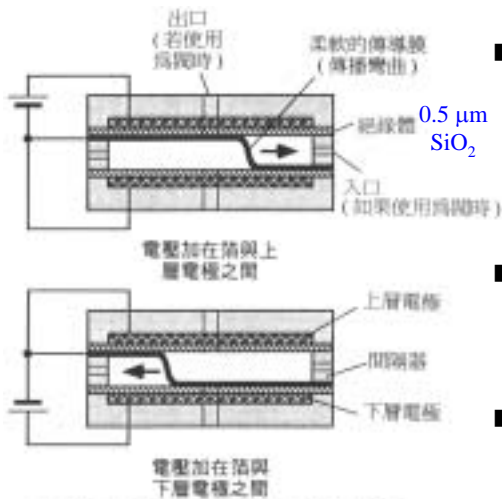


圖 5.10 箔形的致動器示意圖。根據 [Sato 92]。

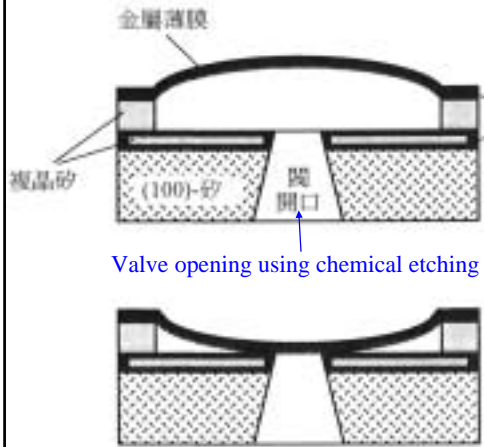
- Using a traveling foil bend made of steel or an Fe-Ni (鐵鎳) alloy (5 μm thick and 12 μm wide)

- 可作為氣流閥門，上下為出口，左右兩側為入口

- 在150V驅動電壓，箔的移動速度為 4 m/s



Electrostatic Microvalve



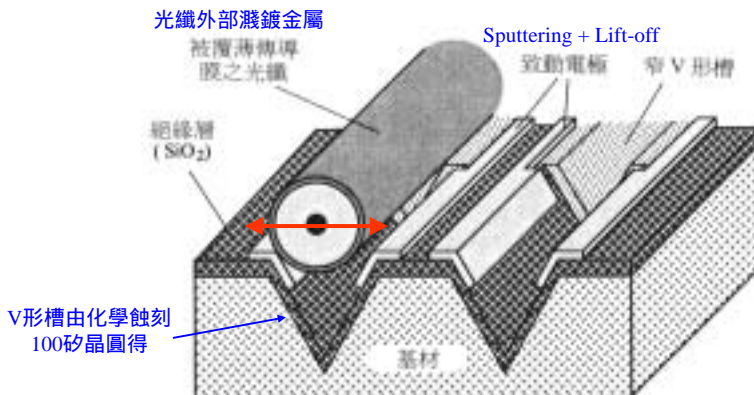
- Internal stresses of SiO₂ membrane during fabrication lead to the deformation of the layer.
- SiO₂ membrane coated with a thin chrome layer is used as a moveable electrode.
- A voltage is applied across the polysilicon electrodes to pull down the membrane and shut the valve.

圖 5.11 靜電微閥之工作原理。根據 [Haji 94]。



Electrostatic Micropositioner

- Used in the alignment of the optical fibers in the coupling.



V形槽由化學蝕刻
100矽晶圓得

圖 5.12 靜電微位置器。根據 [Kiko 93]。



Electrostatic Micromirror

- The aluminum mirror has a reflectivity of 83% and very short response times; its dimensions are $30 \times 30 \mu\text{m}^2$, and it is suspended on two $10 \mu\text{m}$ long and $0.6 \mu\text{m}$ wide torsion beams .

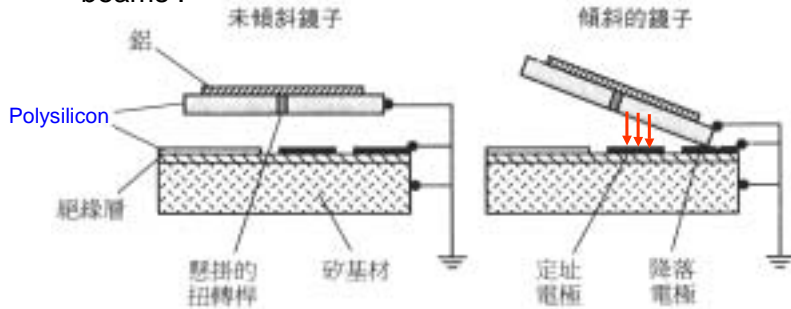


圖 5.13 靜電微鏡 = 根據 [Jarck 93] =



Electrostatic Micromirror

- Can be applied in a stable, high-resolution projection of computer and video images

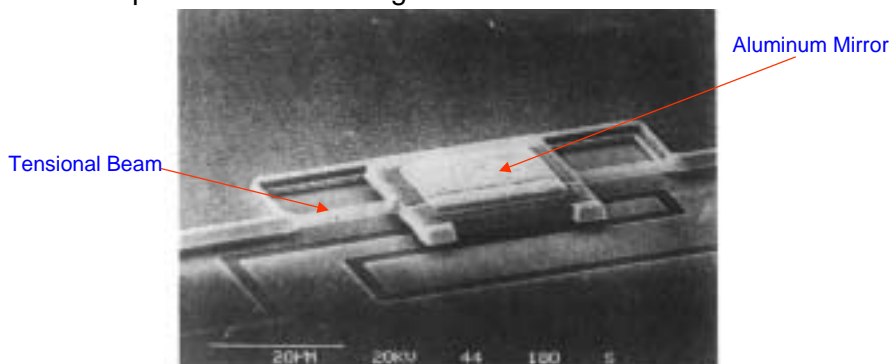
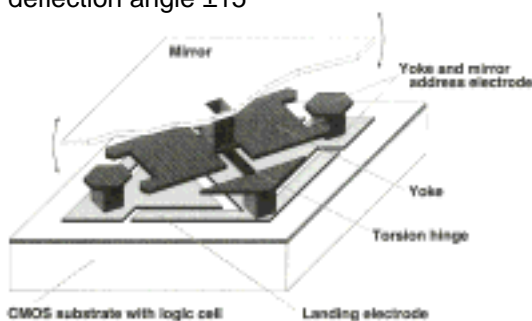


圖 5.14 鏡子原型的 SEM 像 = 感謝 the University of Neuchâtel (Institute of Microtechnology)



Application of Light Valves

- Digital Micromirror Device (DMD) [3]
 - ▶ Arrays of light switches composed of 1280X1024 torsional mirrors used in professional projection system (Texas Instruments).
 - ▶ Max. deflection angle $\pm 15^\circ$



Two Dimensional Positioner

- Linear comb-like microactuators

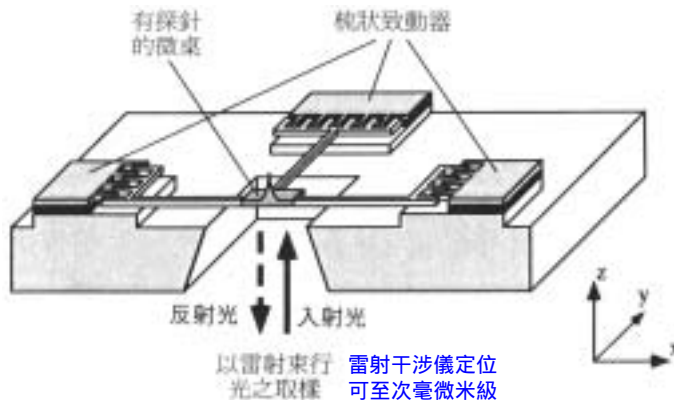
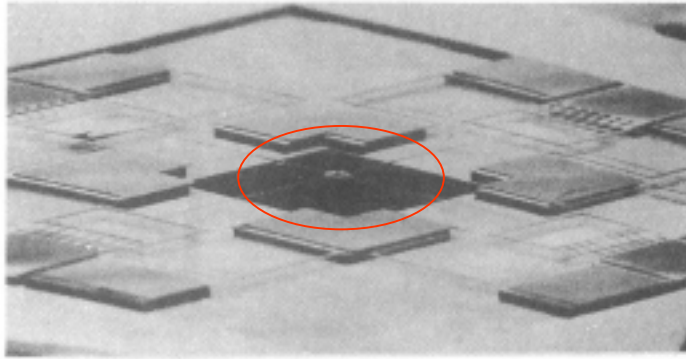


圖 5.16 AFM 定位系統草圖 = 根據 [SAML 93]



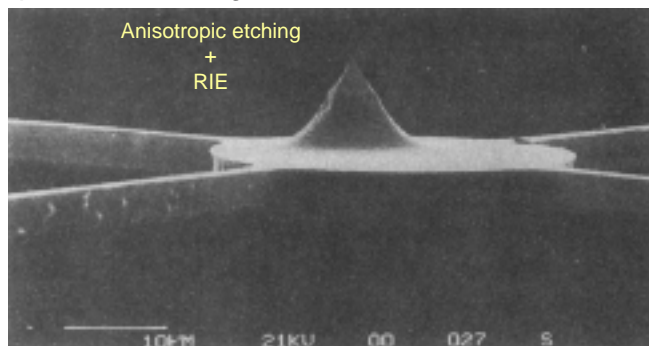
Two Dimensional Positioner

- Used in the production of semiconductors, optoelectronic elements, magnetic high-density memory units and especially for atomic force microscopy (nanopositioning).



Two Dimensional Positioner

- A microprobe mounted on the microtable ($8 \times 8 \mu\text{m}$), and each beam is $270 \mu\text{m}$ long, $0.6 \mu\text{m}$ wide and $2 \mu\text{m}$ high.
- The probe is $8 \mu\text{m}$ high and a maximum radius of 40 nm .



Oscillator Drive Motor

- The motor's rotor is driven by a friction rod.
- Short life.

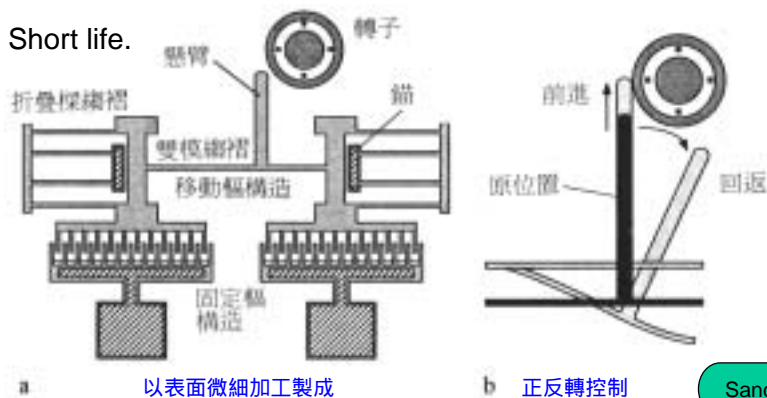


圖 5.18 振動微馬達之示意圖。(a) 上視圖；(b) 兩驅動模式。

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Linear Step Motor

- Utilizes the principle of variable capacitance, and made from LIGA

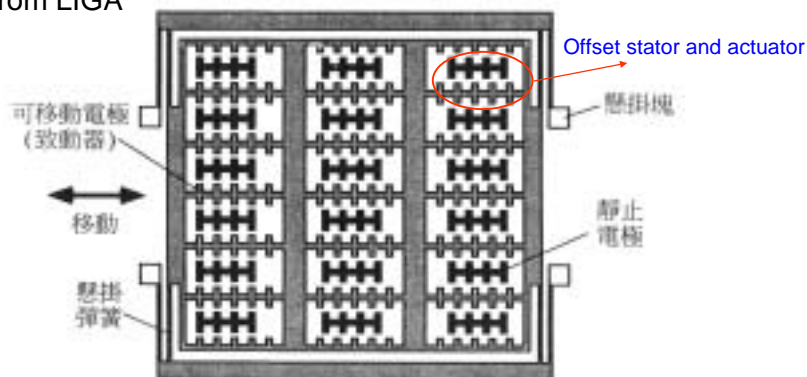
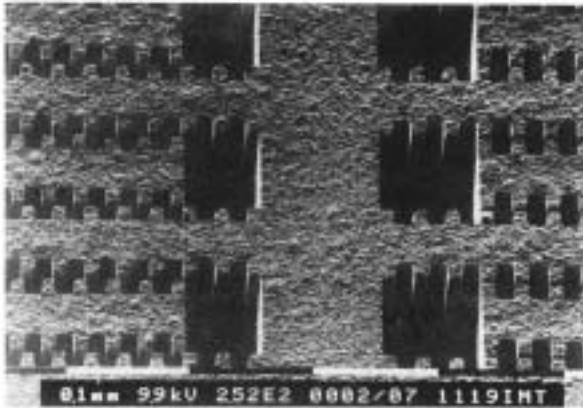


圖 5.19 靜電線性步進微馬達示意圖。根據 [Kaib 94]。

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Linear Step Motor



- 因靜電驅動力與電極高度呈正比，因此適合LIGA高深寬比的製程
- Al_2O_3 substrate.
- 原型高 $70\ \mu m$ ，電極間距 $4\ \mu m$
- Max. displacement $100\ \mu m$, max force $50\ mN$ (at $200V$)

圖 5.20 線性步進馬達原型。感謝 the Karlsruhe Research Center, IMT。



Electrostatic Rotational Motors

- An electrostatic Wobble motor (a comb-like rotor and a stator with six poles) was developed and built with LIGA processes.

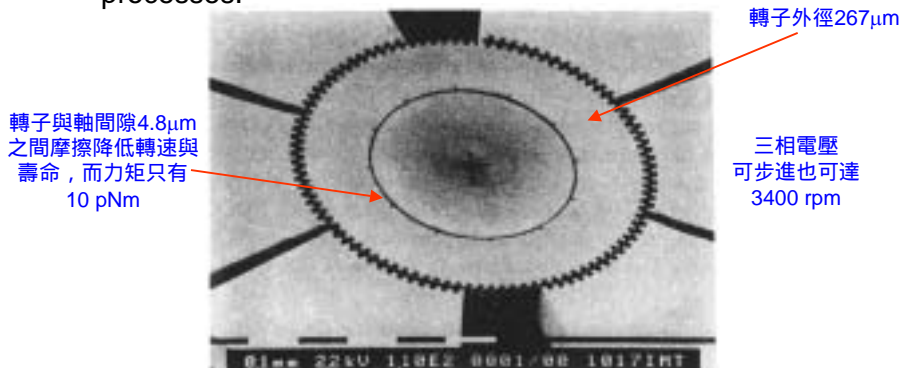


圖 5.21 靜電旋轉馬達原型。感謝 the Karlsruhe Research Center, IMT。





Electrostatic Three-Phase Micromotor

- A 3- phase micromotor with a stator/rotor pole ratio of 3:1.
- Made from polysilicon by the surface micromachining

轉子直徑120 μm ,厚
1.5 μm , 與靜子間隙
為4 μm

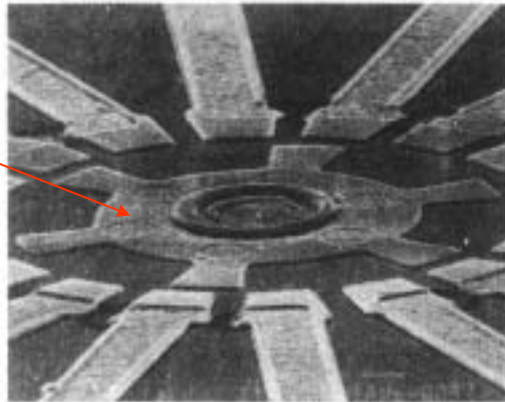


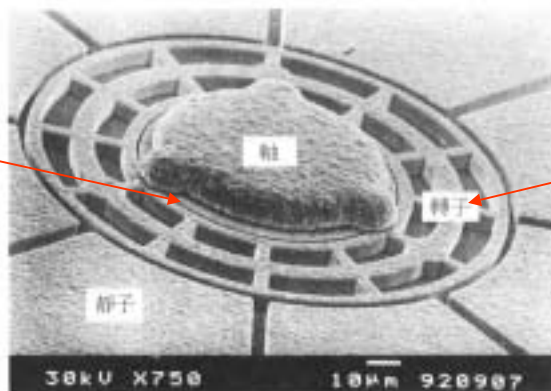
圖 5.22 靜電複晶系微馬達。感謝 the LAAS/CNRS, Toulouse。



Electrostatic Needle-Bearing Micromotor

- A needle structure as a mechanical bearing between the substrate and rotor.


軸與轉子間距為
2 μm , 因此會有
晃旋(wobbling)的
現象



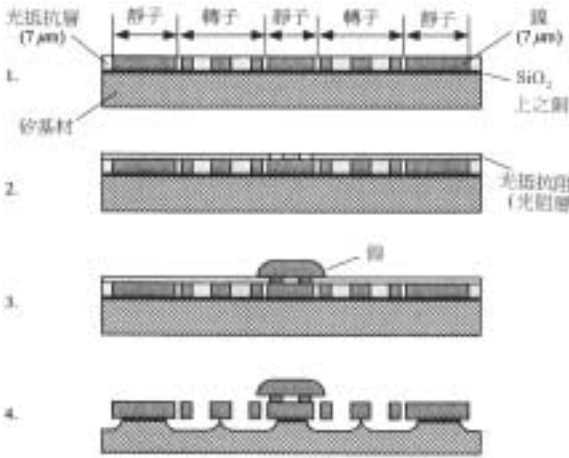
轉子外徑 140 μm

圖 5.23 具針狀承載(軸承)之靜電微馬達。感謝 IBM, Research, Tokyo Research Laboratory and the University of




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靜電旋轉馬達的製程




1. 光阻抗層 (7µm) 矽基材 矽 (7µm) SiO₂ 上之銅


2. 光阻抗阻層 (1µm)

3. 矽


4.

- 基材沈積氧化矽及銅
- 微影7µm光阻後電鍍鎳
- 微影1µm光阻後電鍍鎳形成軸蓋
- 移除部分光阻、銅及絕緣層
- 電漿蝕刻基材以釋放轉子


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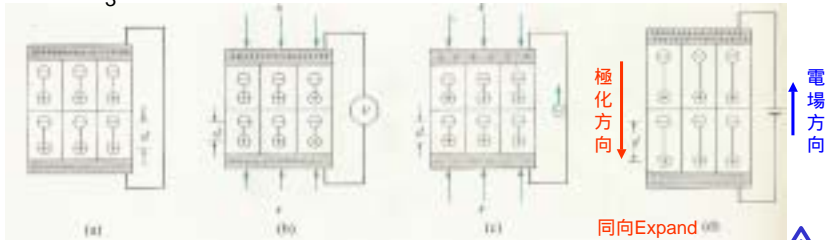
Piezoelectric Microactuators 壓電微致動器


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Piezoelectric Material

- 壓電(Piezoelectric)現象是一種存在某些材料的機電轉換
 - (a)無外加電場：正電與負電荷的中心不重合
 - (b)正壓電效應：外加壓力產生電位差
 - (d)負壓電效應：外加電場使壓電材料產生變形
- 主要的壓電材料：Quartz(SiO_2 crystal), PZT, PVDF, ZnO, BaTiO_3



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Motion Principle and Its Properties

- 首先由居里兄弟於1880年發現。
- 電壓與變形量的關係固定，故不需迴授系統。
- 約50%的電能可直接轉換成機械能。
- 機械耐久性高、對灰塵不敏感
- 但位移量小($\sim \text{nm/V}$)，一般壓電元件可膨脹0.1-0.2%，故適用於位移小但精密的場所
- 力量大、反應時間短

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多層壓電陶瓷的結構

- 帶鑄(tape casting) : Electrodes are printed onto the raw ceramic, and then the layers are stacked together and burned into a multi-layered structure.
- 壓電位移可累加、致動力較大

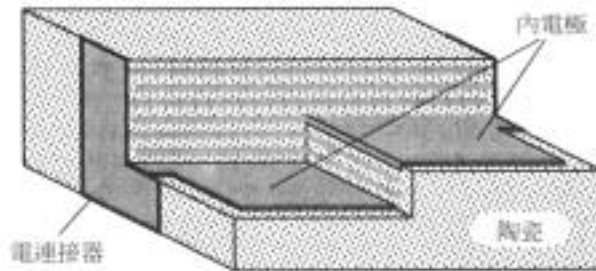


圖 5.25 多層壓電陶瓷之構造。根據 [Gibb 94]。



懸樑式壓電陶瓷的作動原理

- Bimorphic (雙態) Element: 陶瓷層固定在支撐板材的兩側。
- 當極化方向與電場方向**反向**時，壓電陶瓷在樑的**橫斷** (transverse)方向會**收縮**，因此在**長度**(longitudinal)方向會**膨脹** (上層)。若極化方向與電場方向**同向**時，壓電陶瓷在長度方向會**收縮** (下層)。懸樑式結構機電能互換低但位移量大

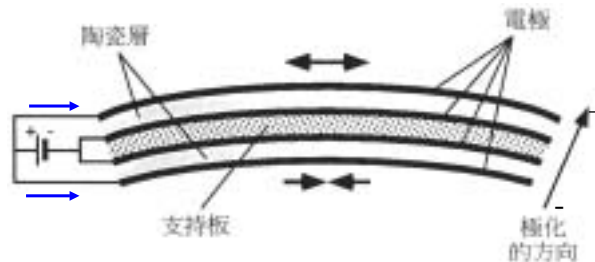
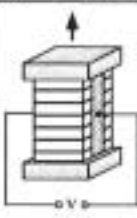
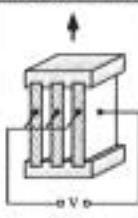
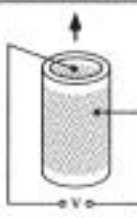
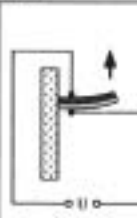


圖 5.26 雙態陶瓷構造。根據 [Moil 92]。



表 5.1 壓電致動器設計及它們的特性值。根據 [Jend 94]。

標 準 狀				
	堆疊	條	小管	懸臂
典 型 移	20–200 μm	$\leq 50 \mu\text{m}$	$\leq 50 \mu\text{m}$	$\leq 1000 \mu\text{m}$
典 型 力	$\leq 30000\text{N}$	$\leq 1000 \text{N}$	$\leq 1000 \text{N}$	$\leq 5 \text{N}$
典 型 供 應 電 壓	60–1000 V	60–500 V	120–1000 V	60–400 V

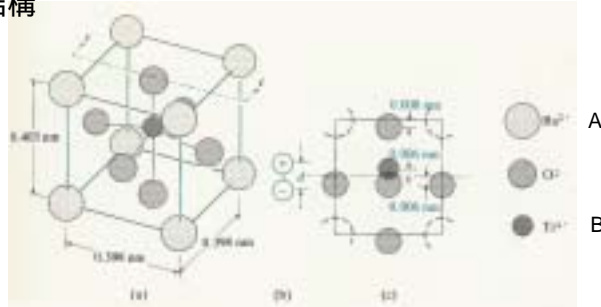
壓電特性

- 壓電材料需具有高壓電常數 (piezoelectric coefficient)、高阻抗、低內部電壓、高機械穩定性。
- 天然的壓電材料（結晶式）如石英(quartz)、電氣石(turmaline)，其電性不敷應用需求。
- 複晶陶瓷(Polycrystalline ceramics):
 - ▶ Excellent properties.
 - ▶ Lead-Zirconate-Titanate (PZT) is the best, but it is hard to work with.
 - ▶ ZnO is suitable material for integrated piezoelectric microactuator systems.



鐵電(Ferroelectric)材料的晶格結構

- 鈣鈦礦結構是鐵電材料中最常見的一種，化學式為 ABO_3
- Electric Dipole: 正、負電荷的中心不重合，具有自發極性
- $BaTiO_3$ 、PZT (鈦酸鉛和鋇酸鉛)、 $LiNbO_3$ 等化合物為鈣鈦礦結構



鐵電材料的晶格結構

- The Curie temperature defines the useful temperature range of a piezoceramic material.

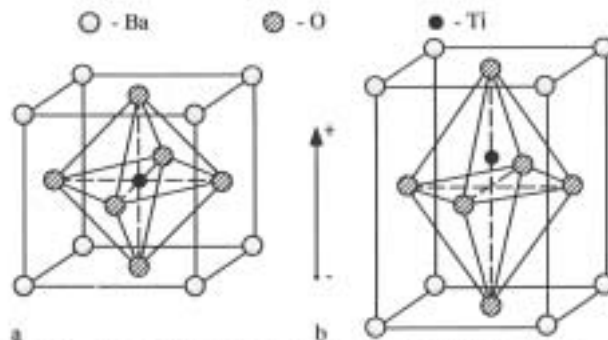


圖 5.27 典型的壓電基本晶胞 $BaTiO_3$ 。(a) 在居里溫度之上，是立方晶格。(b) 在居里溫度之下，是四方晶格。根據 [Jend 93]

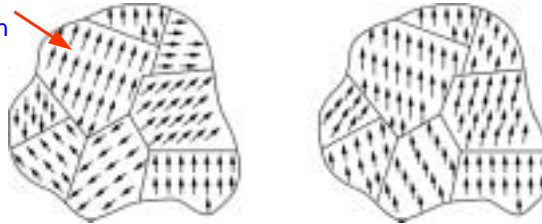




Poling of Ferroelectric Ceramic

- 當超過去極化壓力(depolarization pressure)與矯頑電場(coercive field strength)時，鐵電陶瓷將會失去極化而失效
- 未加電場前各domain分別有同一方向的極性，但靜極化值很小。在外加一大電場極化後，極性被扭轉產生一靜極化值

Weiss' domain



Electrostrictive Material

- 電變(electrostrictive)材料也具有壓電特性，但其晶格結構為對稱。
- 一般只具有正壓電效應或者是逆壓電效應中的一種。
- 相較於鐵電材料，電變材料的磁滯效應大，且特性易受溫度變化。



壓電致動器的應用

■ Advantages:

- ▶ Can easily be integrated into Microsystems.
- ▶ Using relatively simple control algorithms.
- ▶ By controlling the composition of the base material, the directions of expansion/contraction and physical properties of the actuator can be defined.
- ▶ Have a short response time.

■ Applications-micropositioning

- ▶ Adjust mirrors in a CCD camera or in an electron microscope.
- ▶ Align fiber optic cables, position fixtures in a precision milling machine.
- ▶ Drive micromechanical ultrasonic-motors.



壓電致動器的應用

■ Applications-medicine

- ▶ Manufacture micropumps and valves for the exact dosing of substances in biology and medicine.
- ▶ Serve as shock wave generators to crush kidney stones.
- ▶ Serve as micro-tools to perform minimal-invasive surgery.

■ Applications-automobile industry

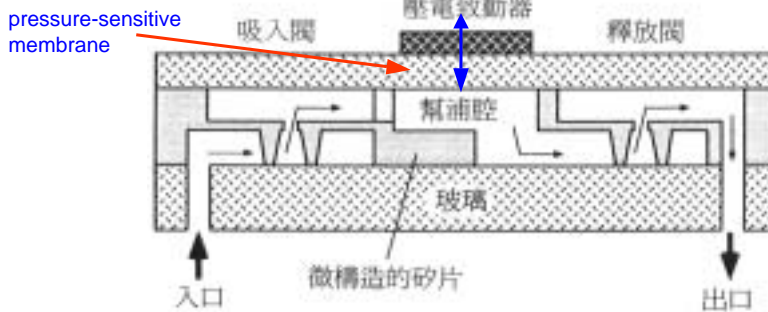
- ▶ Used for active vibration control, noise suppression and for motors to operate windows and sun roofs.
- ▶ Automotive valves for fast response, e.g. for electronically controlled inlet valves and injection nozzles.
- ▶ Used for active wheel damping.





Micromembrane pump

- Macro-prototype: Diameter 75 mm and thickness of 2 mm. Discharge pressure is 0.2 bar (max. 0.4 bar) and the pump has an operating voltage of 300V at a flow rate of 0.6 ml/min
- Only very clean liquids can be used



Microvalve

- A 130 μm thick actuator membrane with a diameter of 10 mm. The piezodisc acting as actuator is 300 μm thick. When a voltage of 50 V is applied, a gap of 4 μm can be reached.

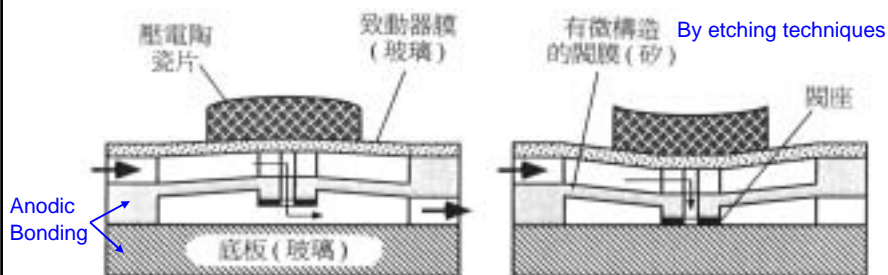


圖 5.29 微閥的功能原理及設計。根據 [Josw 92]。



Chopstick Gripper

- Two piezo-driven chopstick-like fingers, each having 6 degrees of freedom.

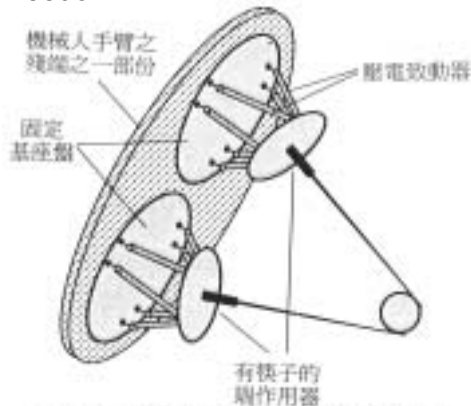


圖 5.30 壓電筷子手之設計。根據 [Arai 93]。



Chopstick Finger

- Driven by a parallel link mechanism made up of 6 prismatic piezo connecting elements.

50 mm長針，尖端
球徑30 μ m，亦可以
玻璃細管取代，尖
端半徑1 μ m，移動
距離8 μ m。

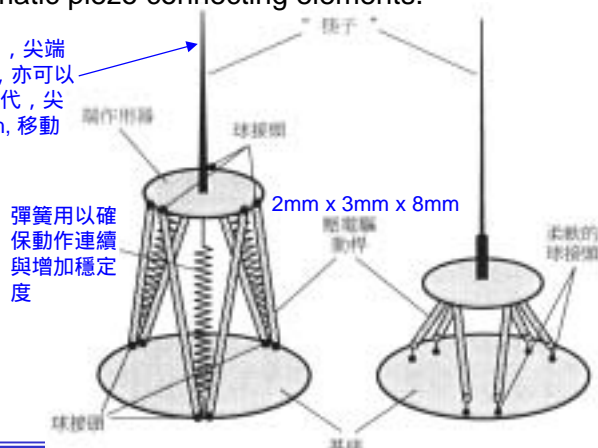
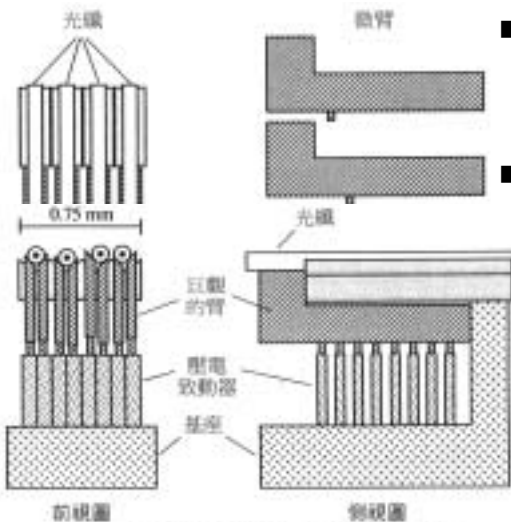


圖 5.31 筷子手指之兩個原型。根據 [Arai 93]。





Aligning Device for Optical Fiber



- Each positioning unit consists of two piezoelements.

- Resolution = 0.1 μm

圖 5.32 玻璃纖維對準裝置。根據 [Aosh 92]。



Aligning Device for Optical Fiber

- Each waveguide can be moved with a micrometer precision in two directions (about 20 μm x 20 μm)

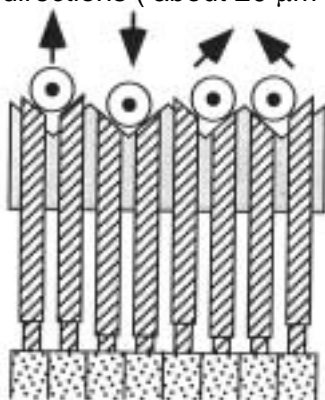


圖 5.33 藉壓電元件之纖維對準。根據 [Aosh 92]。

Cycloid Micromotor

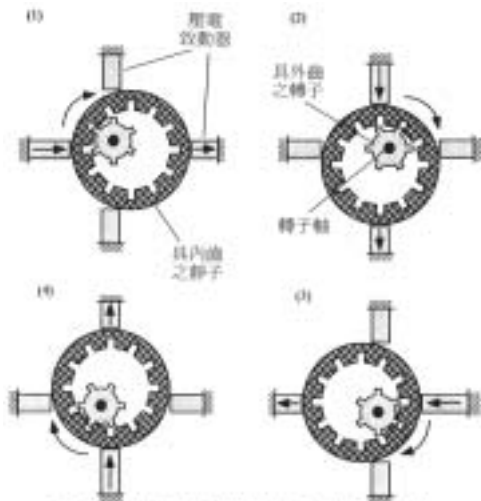
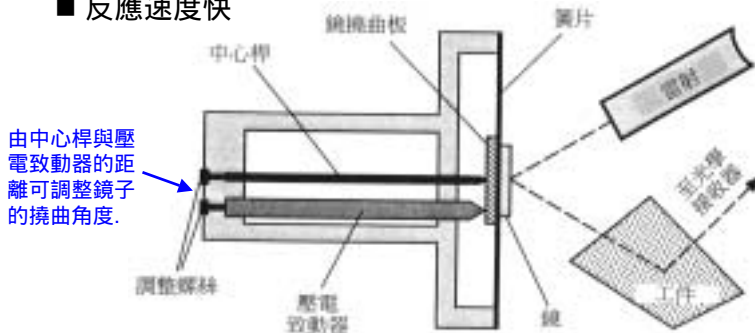


圖 5.34 壓電驅動馬達之基本原理。根據 [Hoya 91]。

- Ultrasonic motors are usually operated with a frequency of about 20-50 kHz.
- Advantage: high torque at low rotational speed.
- Disadvantage: short lifetime due to friction.

Laser Scanner

- The obtained displacement of the piezo-elements was 60 μm , with a deflection angle of 8 mrad.
- 反應速度快



由中心桿與壓電致動器的距離可調整鏡子的撓曲角度。

圖 5.35 雷射掃描器之示意設計。根據 [Brand 92]。



Reference

1. Microsystem Technology and Microrobotics, Fatikow and Rembold, Springer, (1997) – Chap. 5
2. 微機電系統技術與應用，國科會精儀中心，全華，民92- 第八章
3. Microsystem Technology, W, Menz, etc. Wiley (2001) – Chap.6
4. Fundamentals of Physics, Halliday et al., Wiley, John & Sons, (2000)

