Sensors and Actuators

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Sensors

- Transfer the mechanical behavior (such as deformation, stress, and acceleration) to electrical signal

- Sensing techniques can be characterized as static and dynamic approaches

- Static method : stress/strain and deformation/displacement

  + **stress/strain detection -** piezoresistive strain gauges piezoelectric sensing

  + **deformation/displacement detection -** capacitance interferometer

- Dynamic method : resonant frequency

  + resonant frequency

Stress detection - piezoresistive strain gauge

- **Strain gauge** - a conductor or **semiconductor** that is **fabricated on** or bonded directly to the surface to be measured and that changes in dimension along with the surface

- The gauge resistance varies proportional with the change in gauge dimension by two factors,

  + deformation of the shape of the gauge

  + piezoresistivity effect

- **Piezoresistivity** - a material property where the bulk resistivity, ρ, is influenced by the mechanical stresses applied to the material

- The sensitivity is expressed by the **Gauge factor, GF (ε×GF = dR/R)**

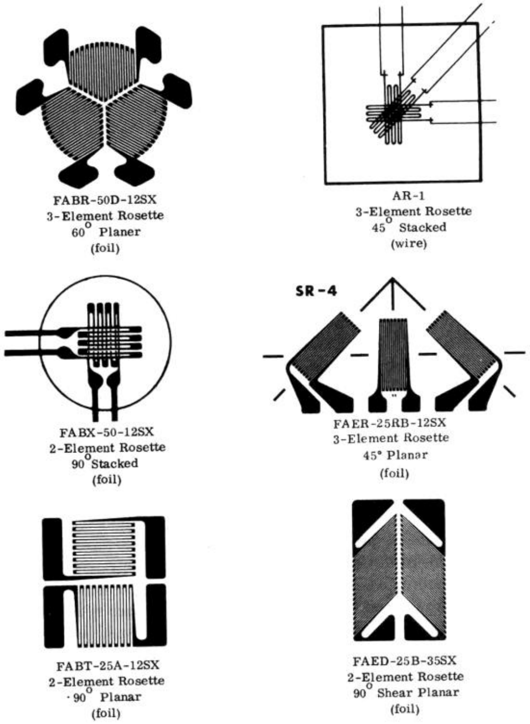
$$GF = (1+2\underset{\uparrow\ \text{Poisson's ratio}}{\mu}) + (d\rho/\rho)/\underset{\uparrow\ \text{residual strain}}{\varepsilon}$$

- The strain gauge can also be used to measure the vibration frequency of a structures

  + the stress status of a structure (at a certain face) can vary from tension to compression during vibration, for example, a cantilever beam

- Micromachined strain gauge has two advantages

+ Easy to define the pattern of the gauge



E.O. Doebelin, Measurement Systems, 1990

+ **High GF -** traditional conductor strain gauge the GF mainly determined by μ, however, the GF is dominated by (dρ/ρ) for a semiconductor strain gauge

Material	**GF**
metal	1 ~ 5
p-type silicon	up to 200
n-type silicon	down to -140

Stress detection - piezoelectric sensing

- **Piezoelectricity** - the phenomenon in which an electrical voltage develops due to an externally applied stress

- An opposite effect is also true - the piezoelectric material will deform under an input voltage, therefore it can also be **a material for actuator**

- **Silicon is not a piezoelectric material**, therefore an additional piezoelectric film has to be deposited onto the substrate when applying this technique

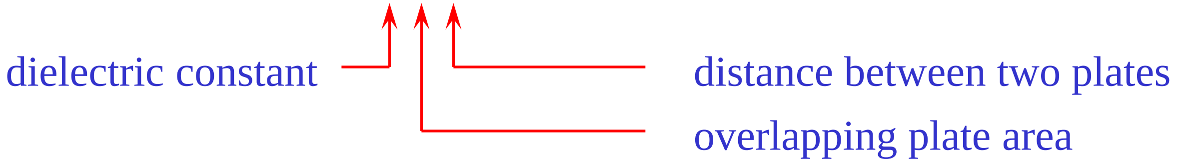
- **ZnO** is the most common piezoelectric material used in microfabrication

- Piezoelectric materials are very sensitive sensors since a very small displacements will cause large detectable voltages, the reverse argument shows that they are poor actuator materials

Deformation detection - capacitance

- The basic parallel plate capacitor equation is

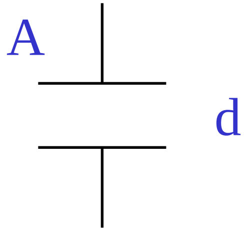
$$C = \varepsilon A/d$$



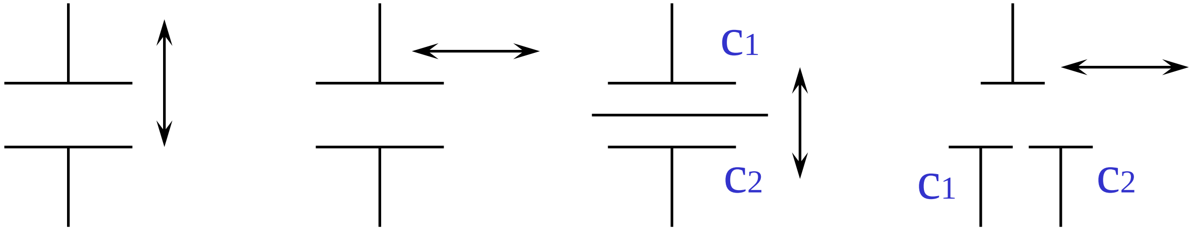
dielectric constant

distance between two plates

overlapping plate area



- There are several ways to sense the deformation by the changing of capacitance, for example



Why microsensors?

- The primary advantages of the microsensor is the reducing of its size

  + lower weight (greater portability)

  + lower manufacturing cost (less material)

  + sensitivity

  + power consumption

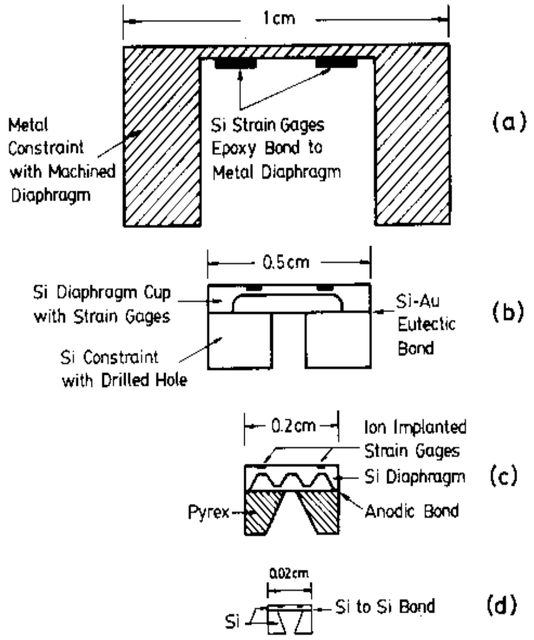


Fig. 5 Evolution of diaphragm pressure sensors. (After Ref. 11)

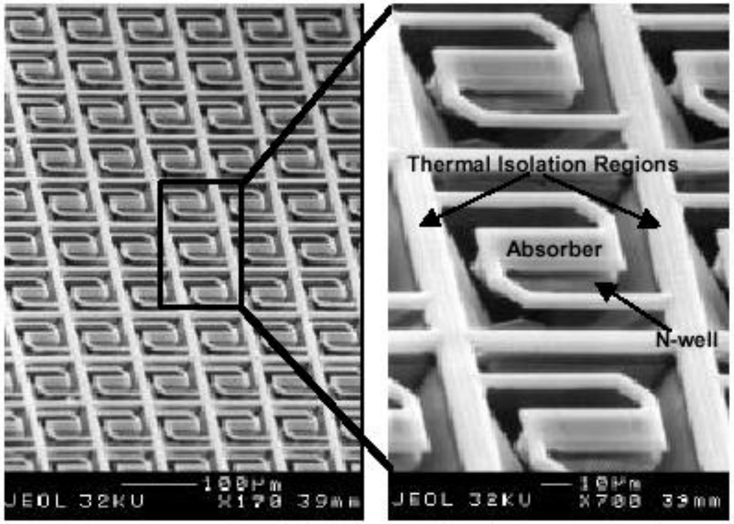
Semiconductor Sensors, edited by S.M. Sze, 1994.

- Micromachining processes - batch fabrication, and IC processes compatible

  + lower cost (batch processes)

  + integration of the electrical and mechanical parts (less material)

  + performance (distributed sensor)



Honeywell

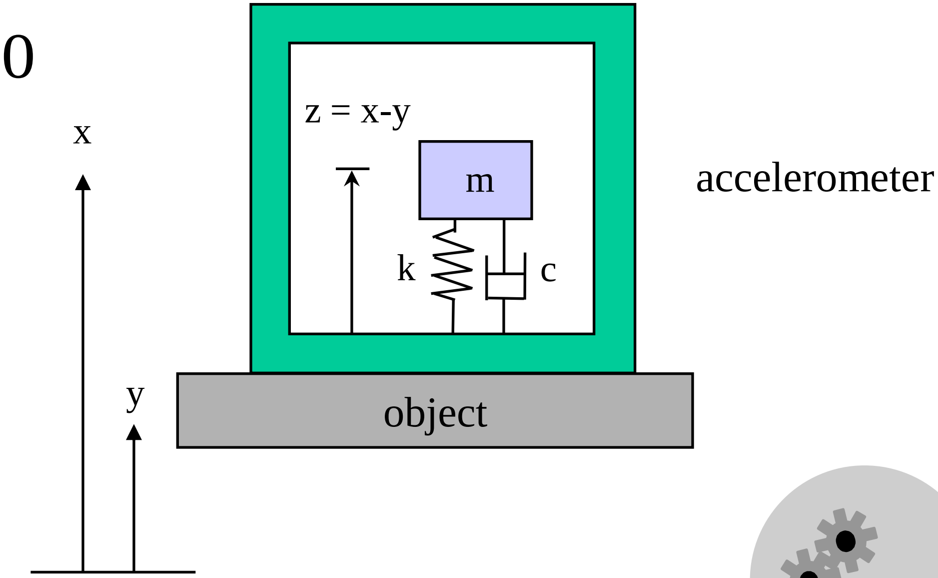
Accelerometer

Basic concept

- Accelerometer is applied in diverse areas, including deploying air bags, monitoring machinery, etc.
- The basic components of an accelerometer are a proof mass **m**, a spring **k**, and a damper **c**

$$m\ddot{x}+c(\dot{x}-\dot{y})+k(x-y)=0$$

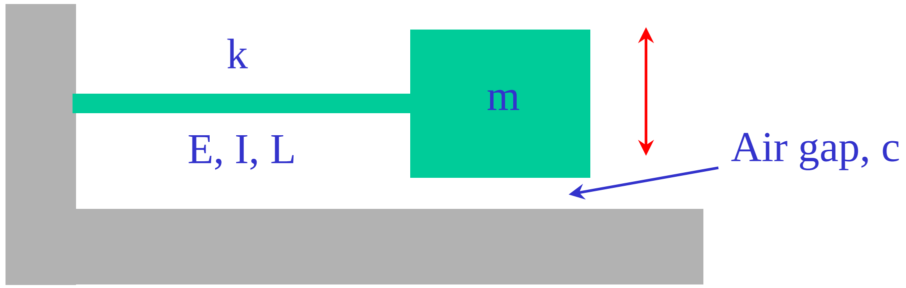
$$m\ddot{z}+c\dot{z}+kz=m\ddot{y}$$

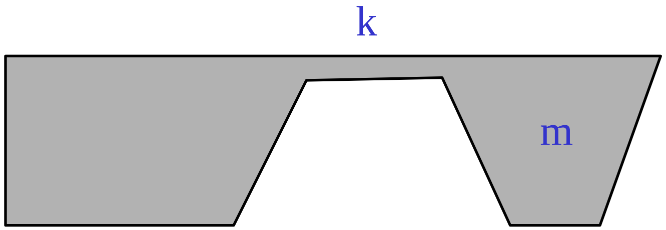


- The real structure associated with the physical model

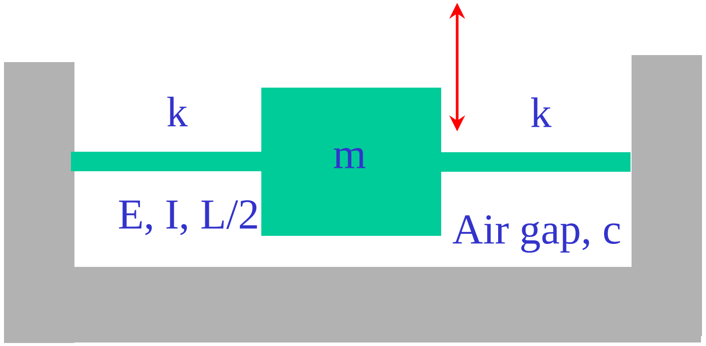
+ K : $3EI/L^3$, beam stiffness

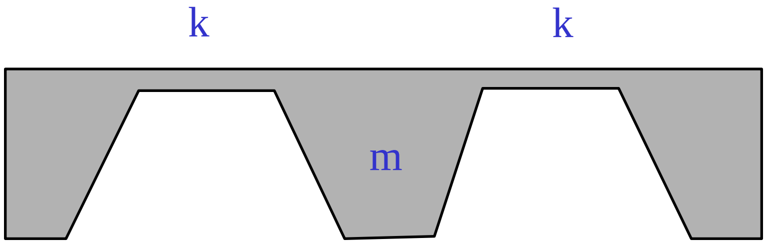
+ c: damping, comes from both
structure and air effect





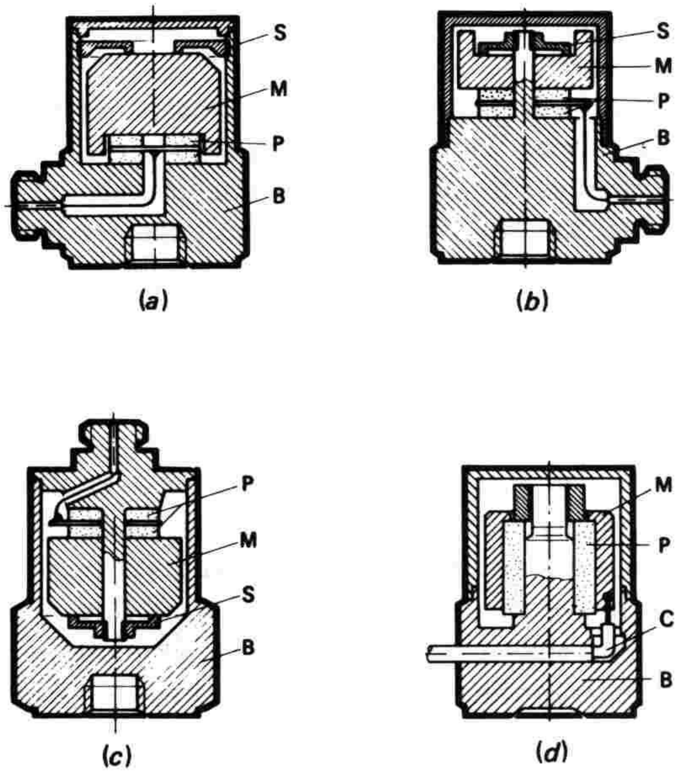
- + K : 48EI/L^3, beam stiffness
- + c: damping, comes from both structure and air effect



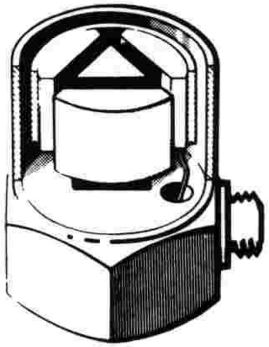


Conventional accelerometer

- **Piezoelectric accelerometer**



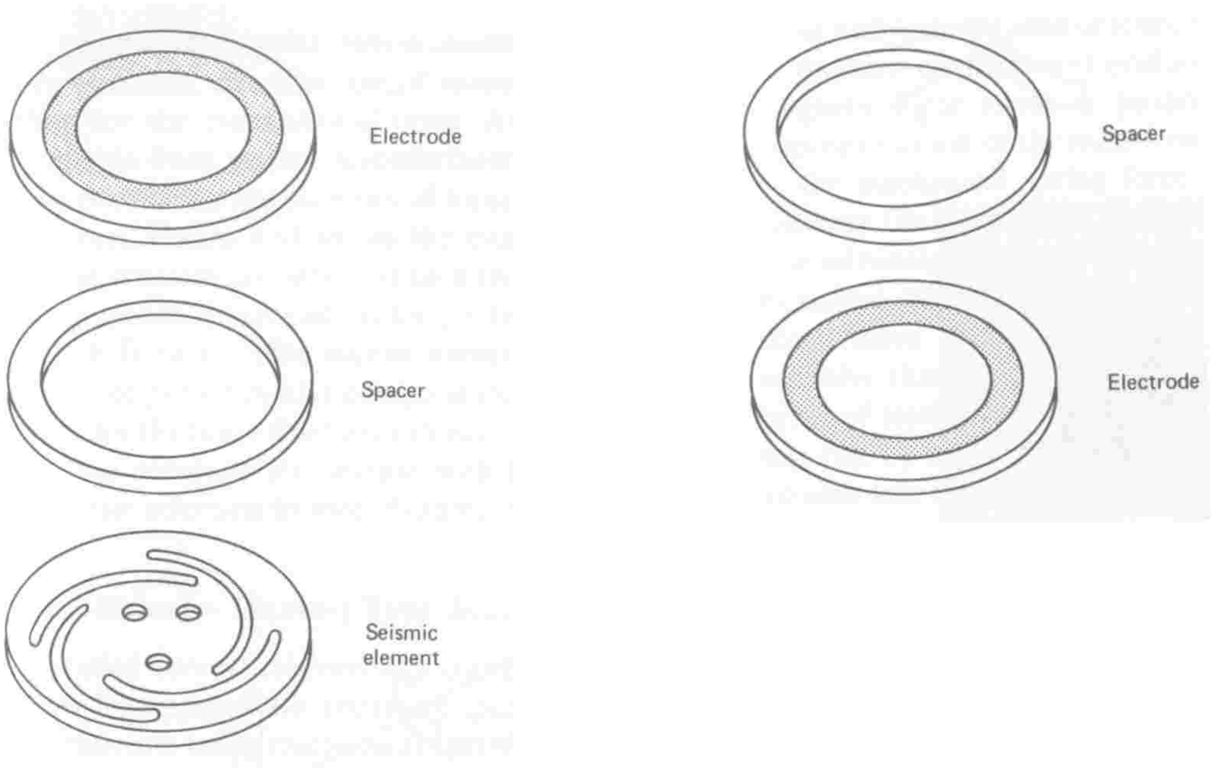
S: spring
M: mass
P: piezo
B: base



Measurement Systems 4th ed., E.O. Doebelin, 1990
Figure Courtesy: B & K Instruments, Marlboro, Mass., USA

Conventional accelerometer

- **Capacitive accelerometer**

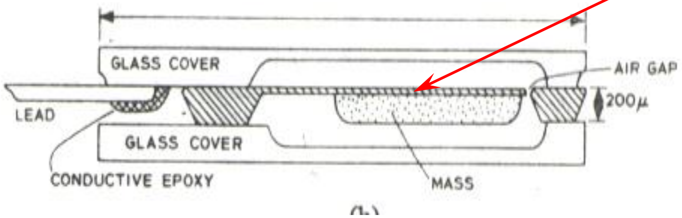


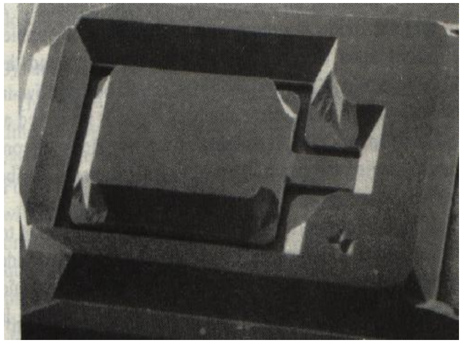
Measurement Systems 4th ed., E.O. Doebelin, 1990
Figure Courtesy: B & K Instruments, Marlboro, Mass., USA

Bulk micromachined accelerometer

- **Piezoresistive type**

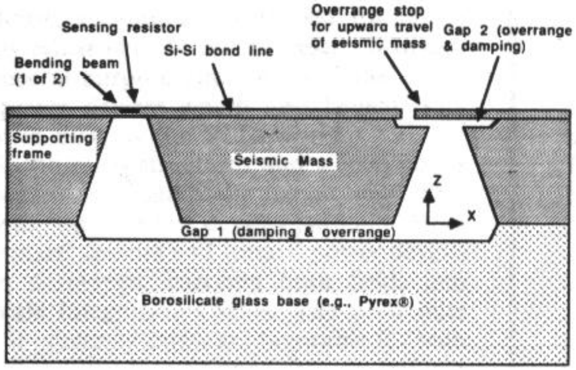
+ Early product

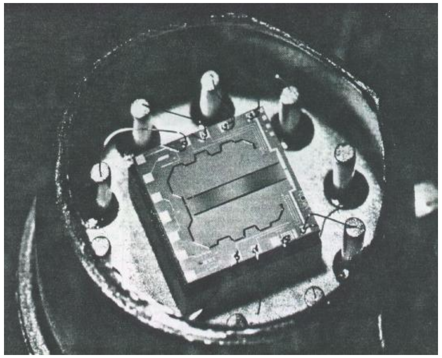




L.M. Roylance and J.B. Angell, IEEE Transaction on ED, 1979.

+ Modern product

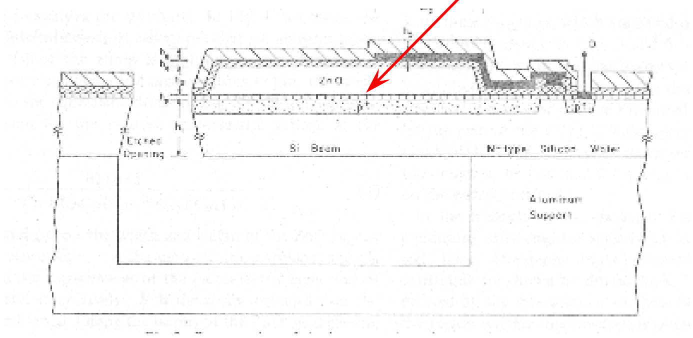




P.W. Barth, Sensors and Actuators, 1990

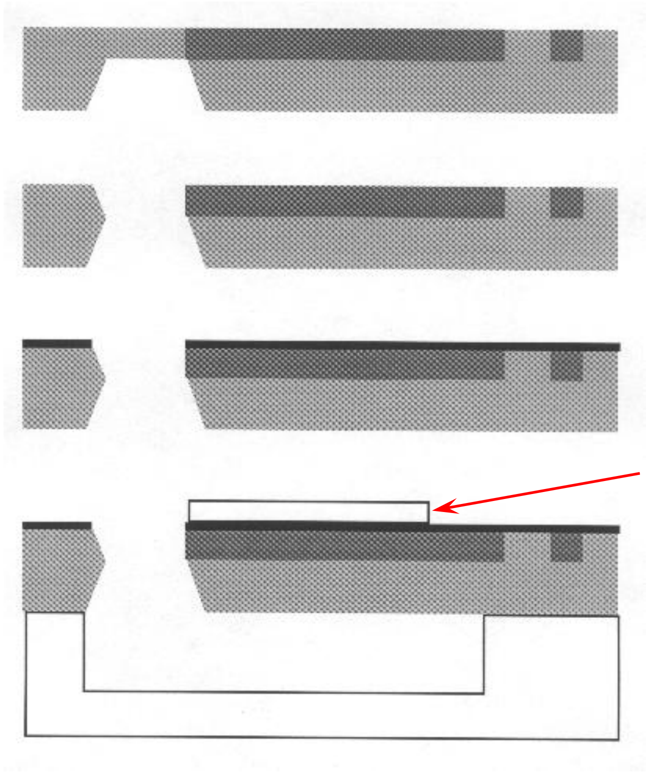
- **Piezoelectric type**

ZnO, piezoelectric material



P.-L. Chen, et al., IEEE on ED, 1982.

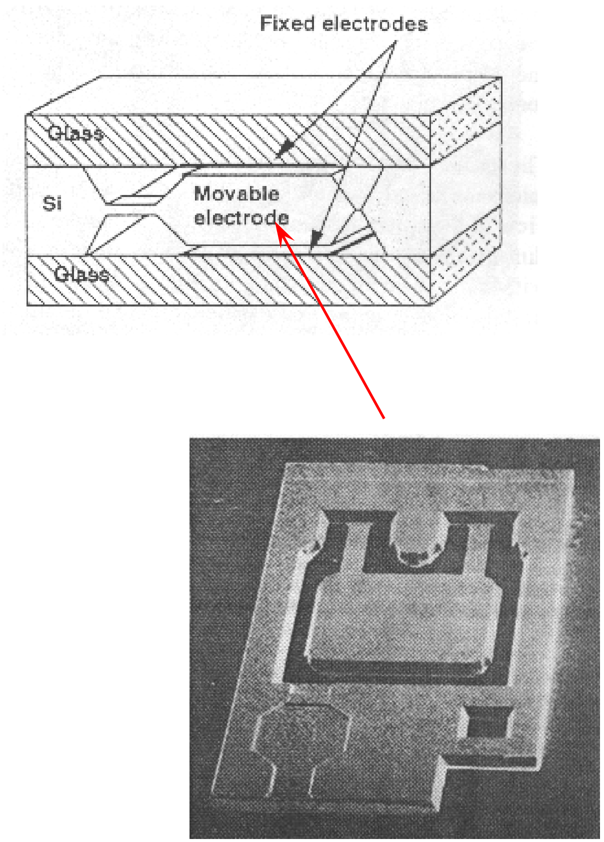
+ Part of the fabrication processes

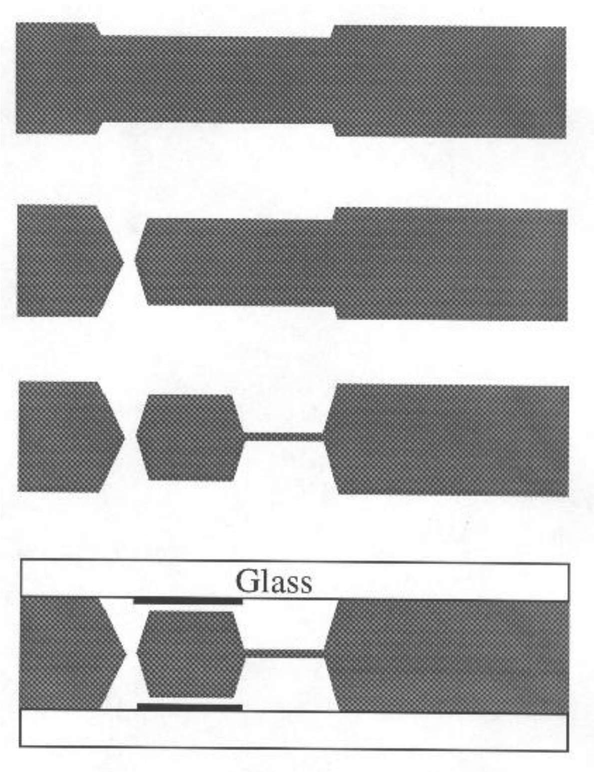


ZnO

- **Capacitive type**

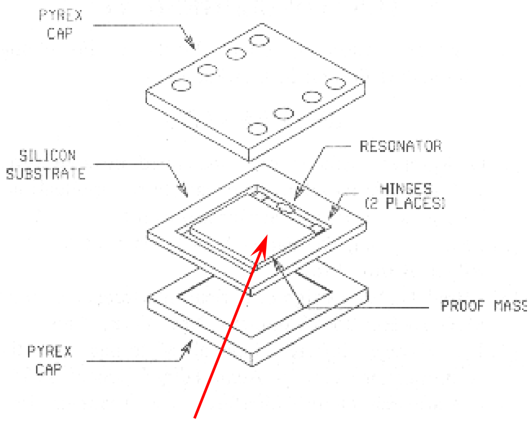
+ Part of the fabrication processes

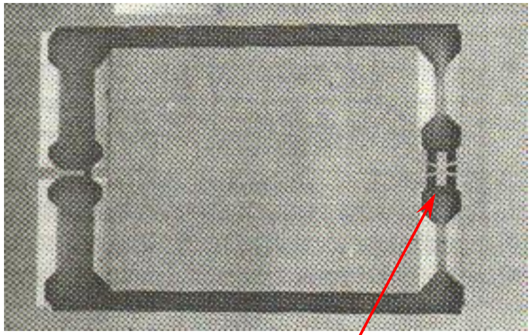




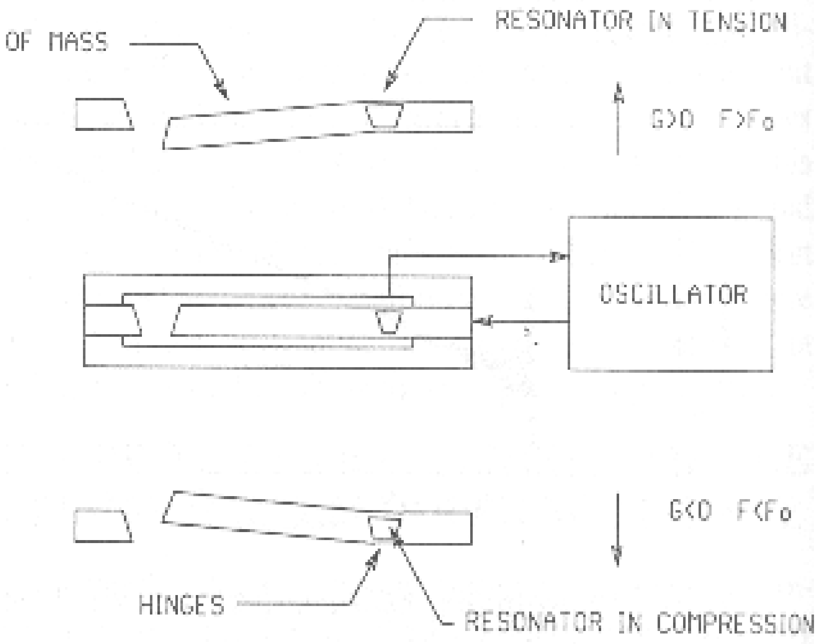
T. Sasayama, et al., Transducers '95, 1995.

- **Frequency type**





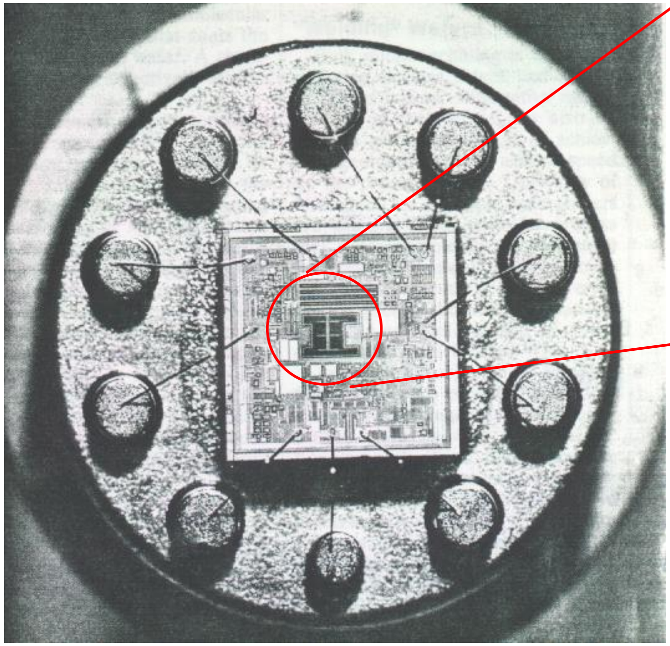
resonator



T.V. Roszhart, et al., Transducers '95, 1995.

Surface micromachined accelerometer

- In - plane detection



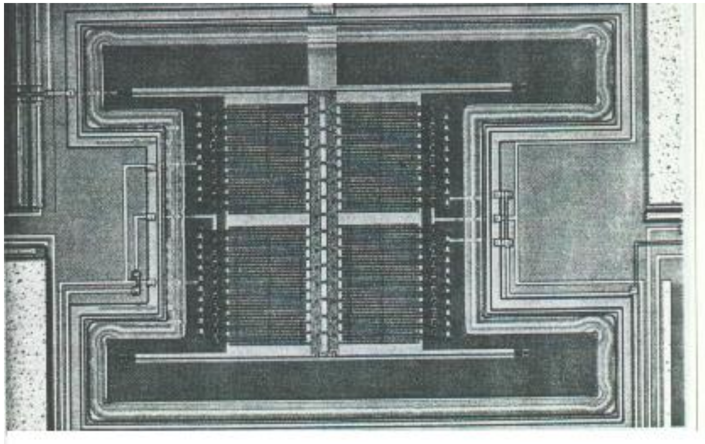
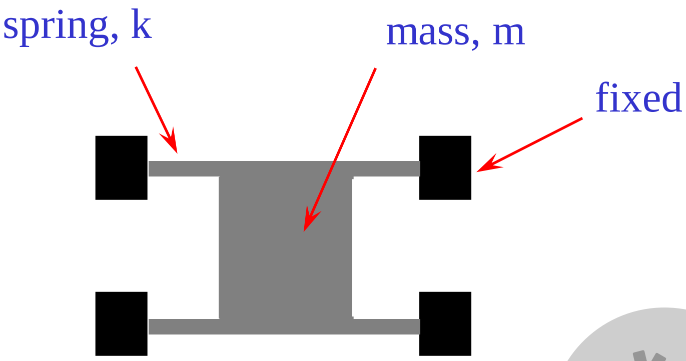


Figure source: L. O'Connor, Mechanical Engineering, 1992.

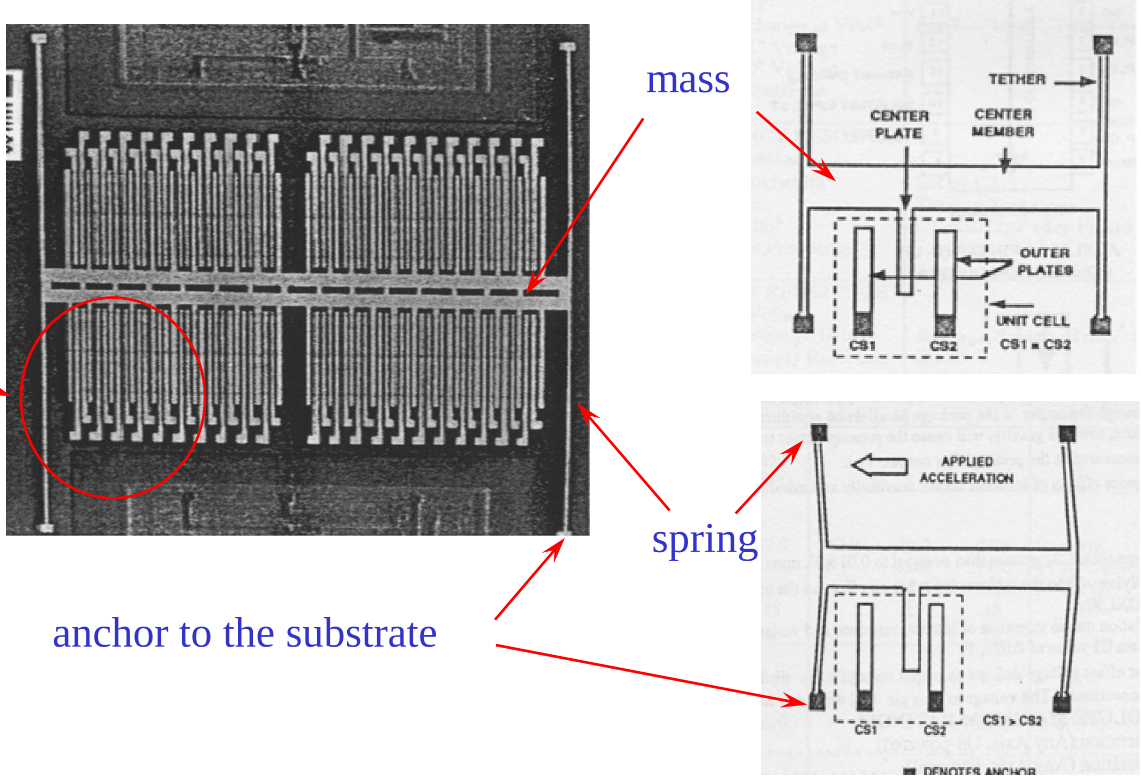


spring, k

mass, m

fixed

+ Due to the fabrication characteristic, the capacitive type sensing technique is more common for surface micromachined accelerometer



sensing element

mass

spring

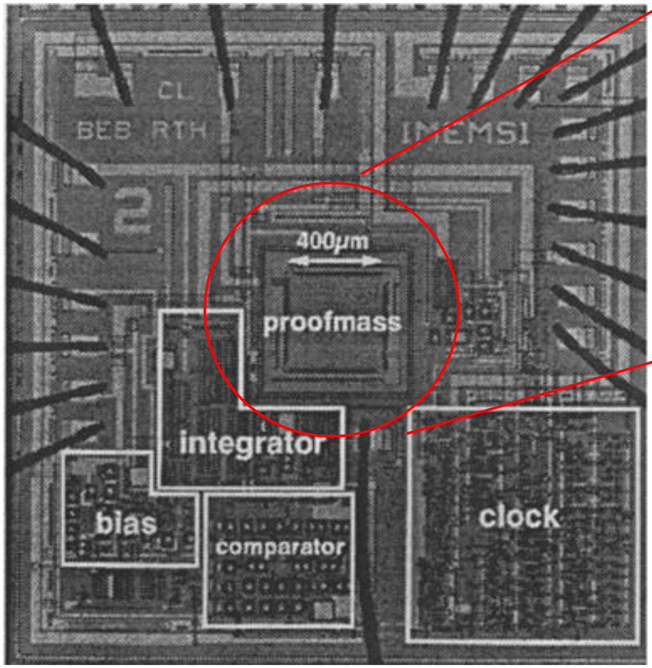
anchor to the substrate

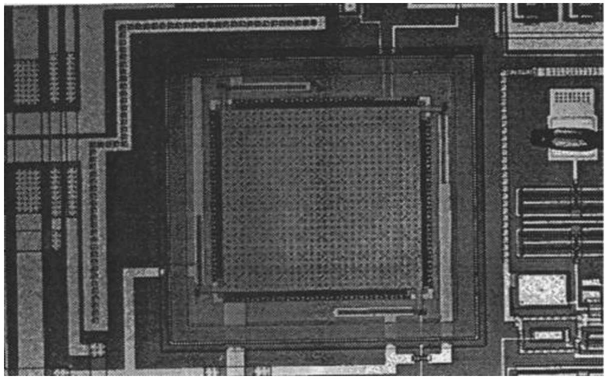
before accelerated

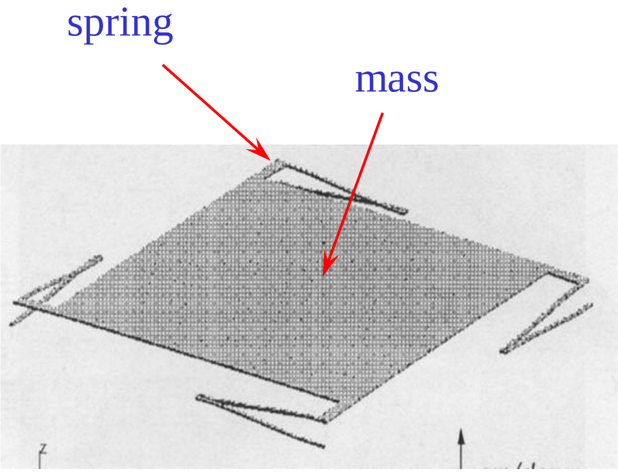
after accelerated

Figure source : Catalog for ADXL50 accelerometer, Analog Device Co.

- Out - of - plane detection





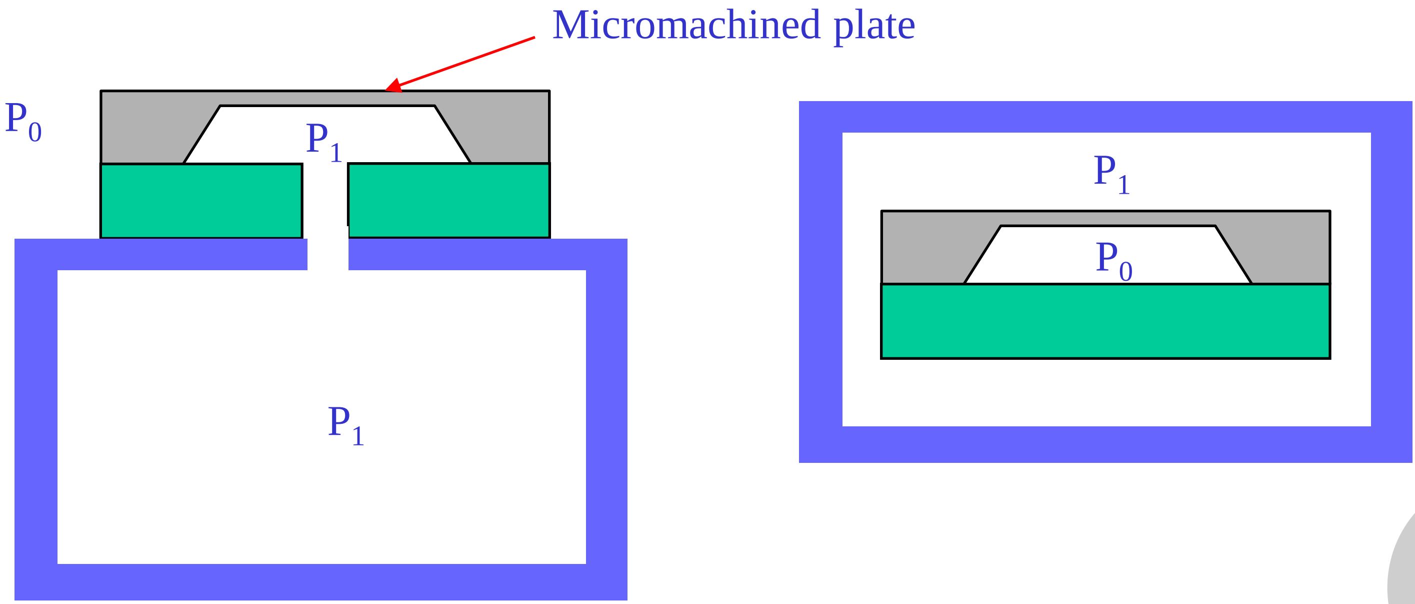


B.E. Boser, Monolithic surface-micromachined inertial sensor, 1995.

Pressure sensor

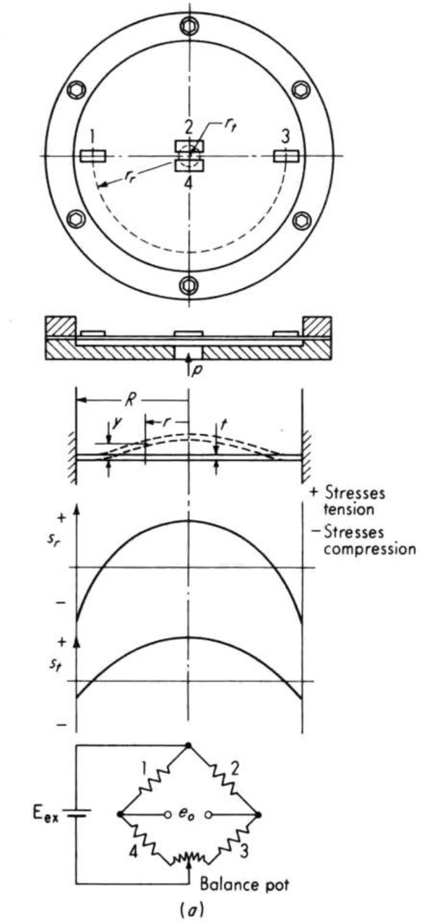
Basic concept

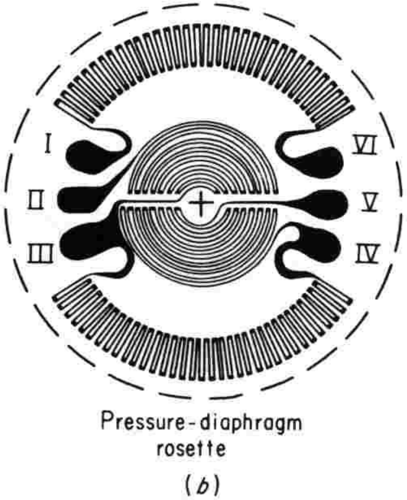
- Pressure sensor can be applied to detect (1) tire and oil pressure in automobile, and (2) blood pressure in human body, etc.
- Pressure sensor contains a deformable plate. The pressure is determined by the deformation of the plate



Conventional pressure transducer

- Elastic transducer

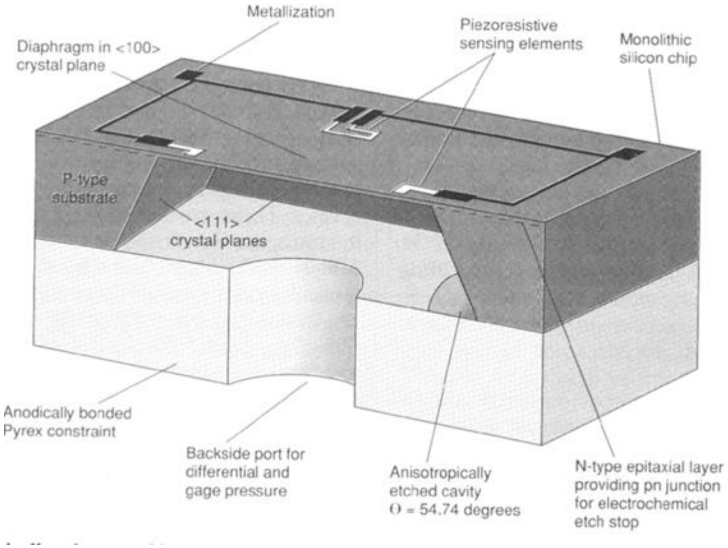


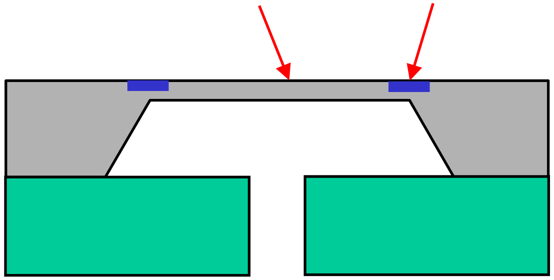


Measurement Systems 4th ed., E.O. Doebelin, 1990

Bulk micromachined pressure sensor

- Piezoresistive type





Micromachined plate

Piezoresistive sensing element

J. Bryzek, et. al., *Spectrum*, 1994

- Capacitive type

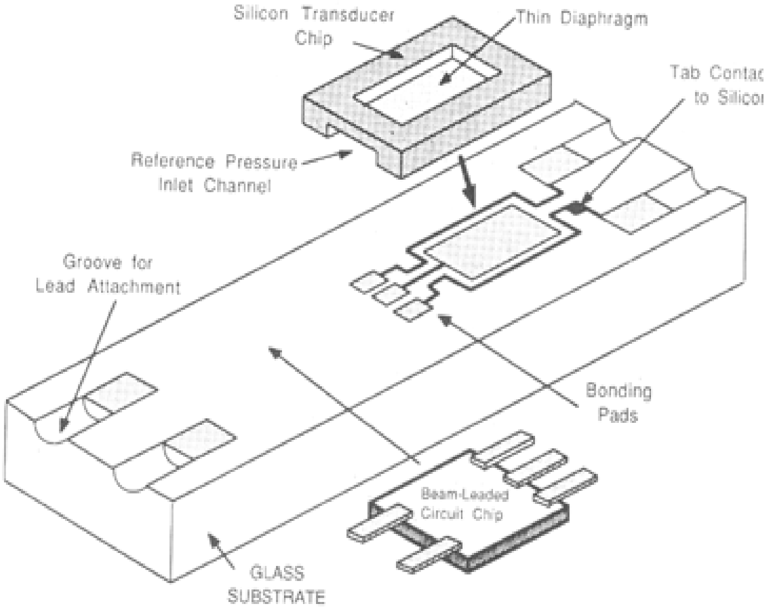
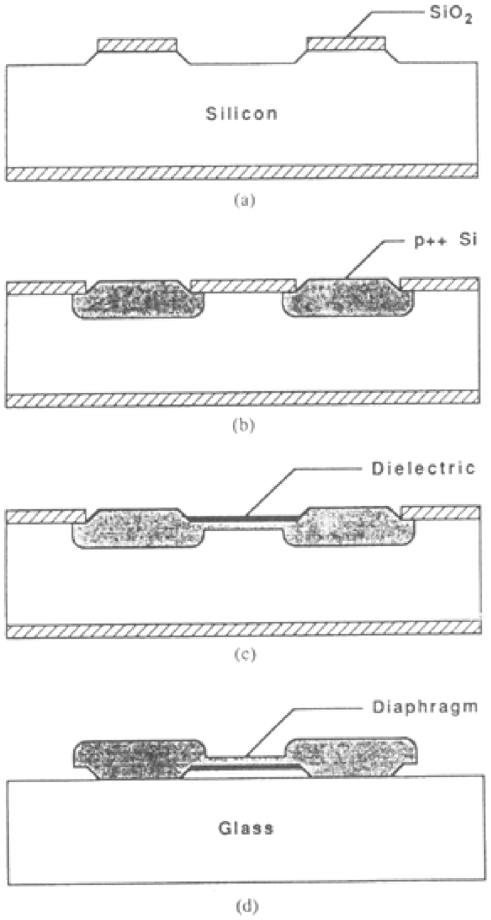


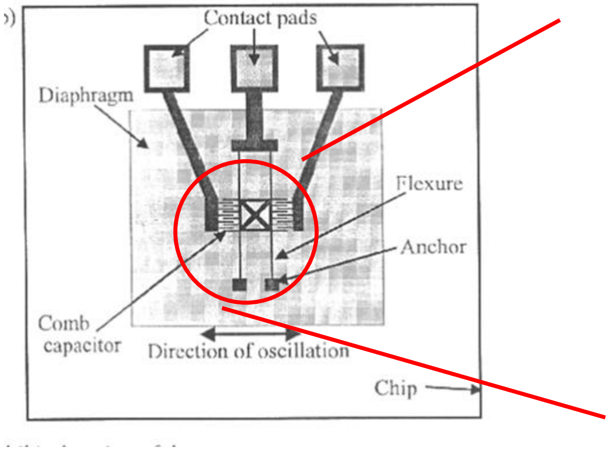
Fig. 2. Construction of a single ultraminiature sensing site.

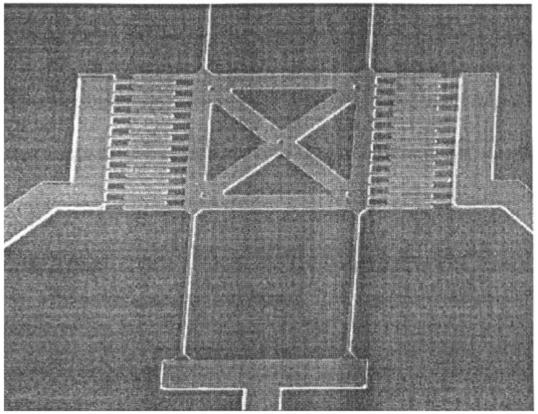


H.-L. Chau and K.D. Wise, IEEE Transactions on ED, 1988.

Bulk/Surface micromachined pressure transducer

- Good example to show the integration of the surface and the bulk micromachining
- **Resonant type :** The stiffness of the resonator varies with the pressure - the natural frequency of the resonator will change with the pressure

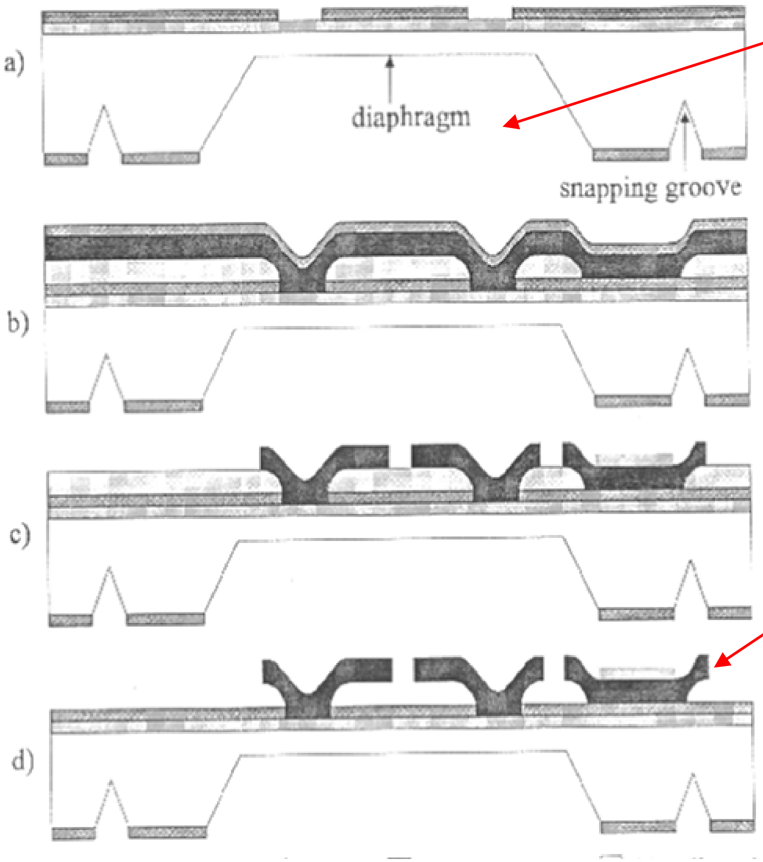




surface micromachined resonator

C.J. Welham, J.W. Gardner, and J. Greenwood, Transducer '95, 1995

- Fabrication processes

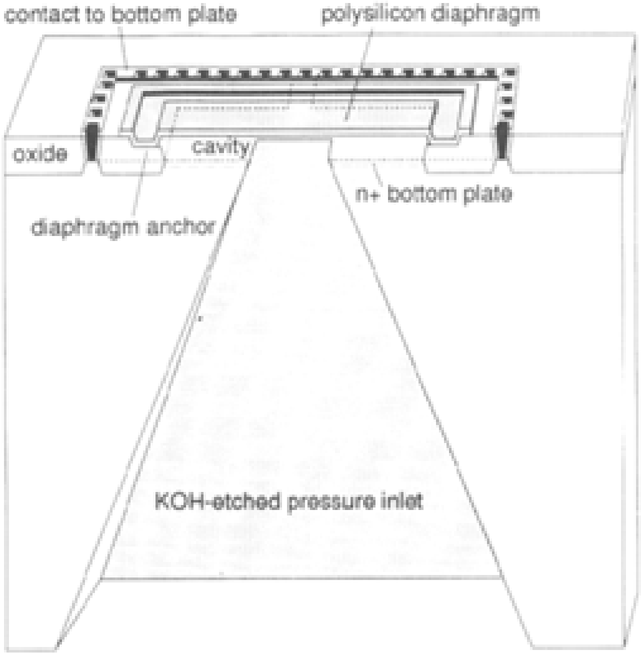


Bulk silicon etching

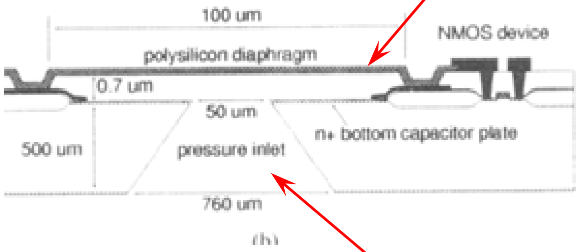
surface micromachined resonator

C.J. Welham, J.W. Gardner, and J. Greenwood, Transducer '95, 1995.

- Capacitive type



Air-gap-capacitor structure implemented using an existing



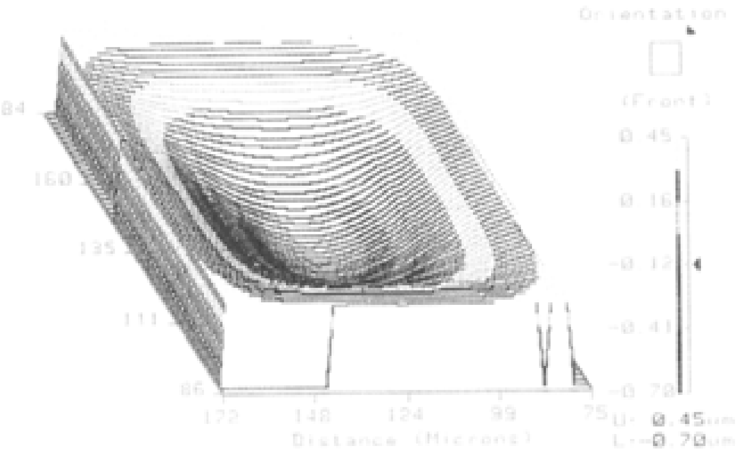
(b)

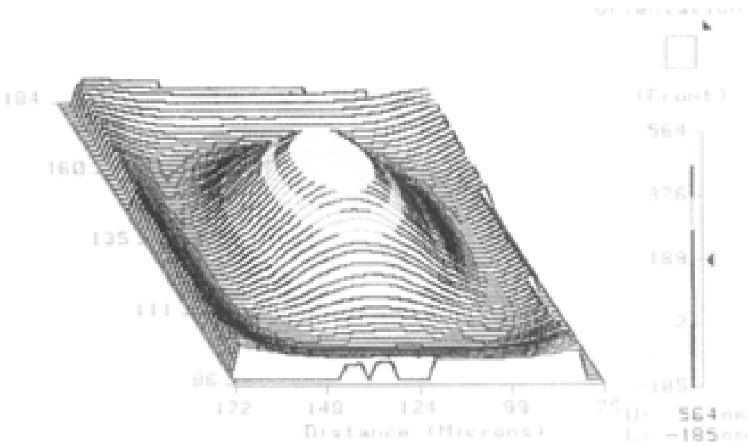
surface micromachined membrane (poly-Si)

Bulk silicon etching

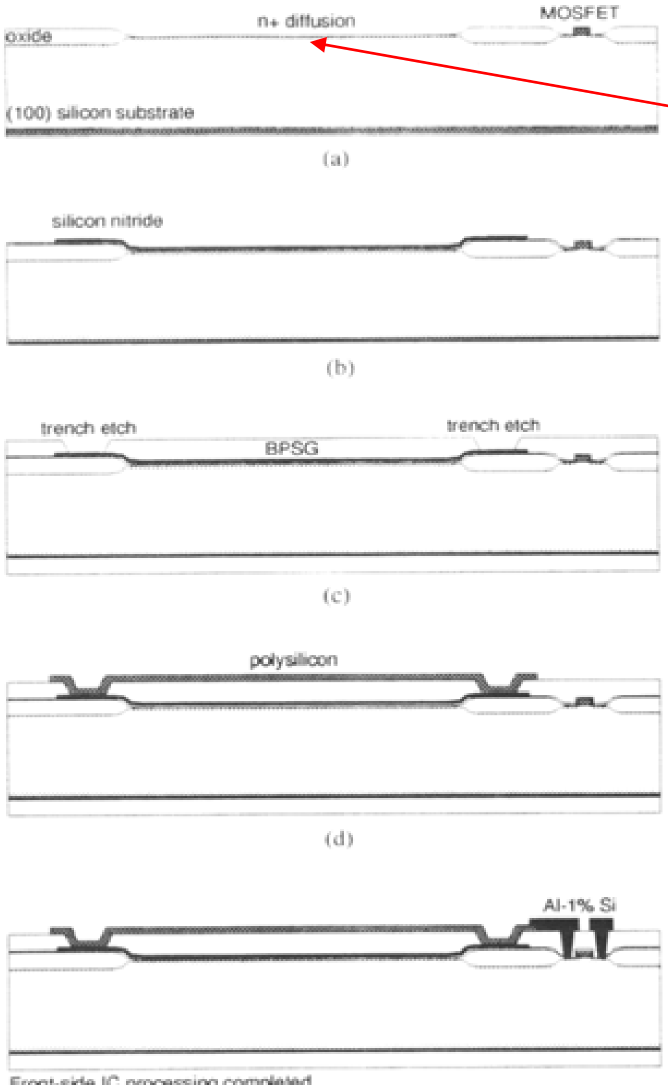
J.T. Kung and H.-S. Lee, J. of MEMS, 1992.

+ deformation of the plate measured through external optical system





- Fabrication processes



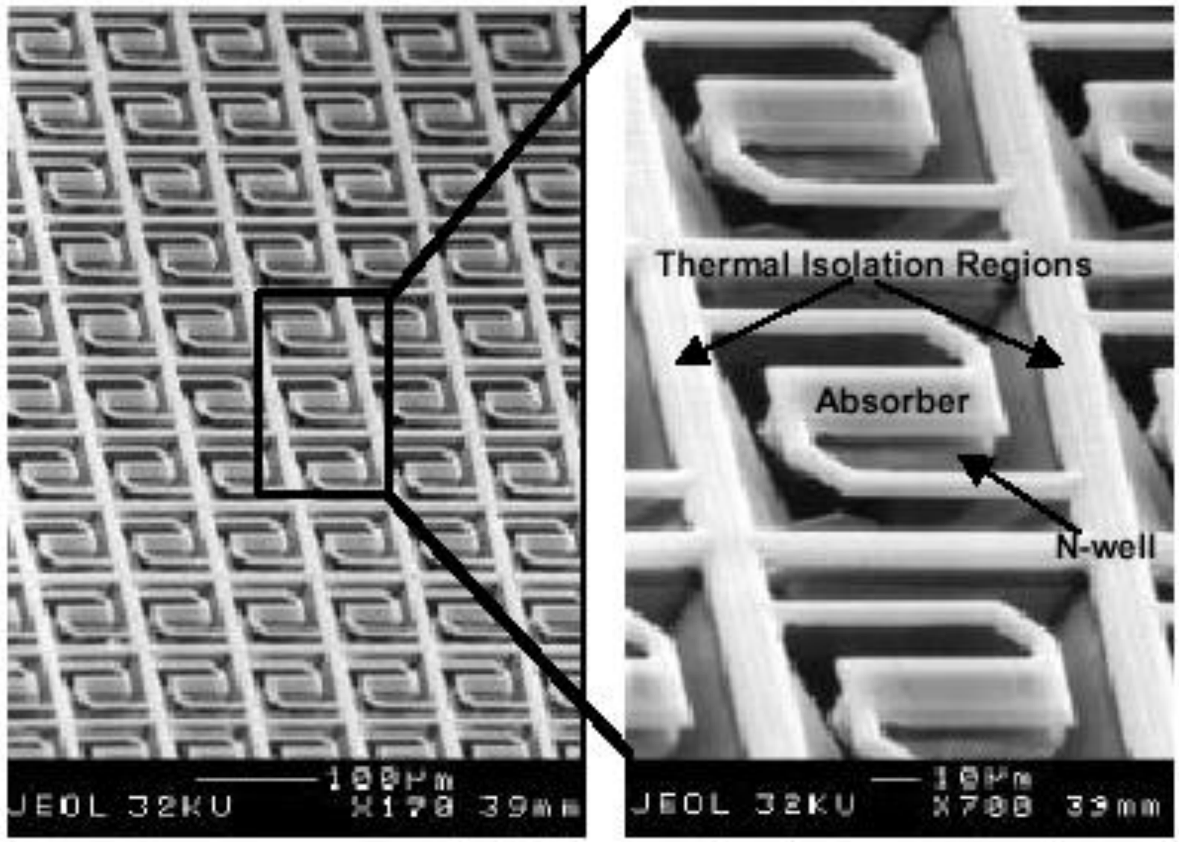
doped (phosphorus) layer) for bottom electrode

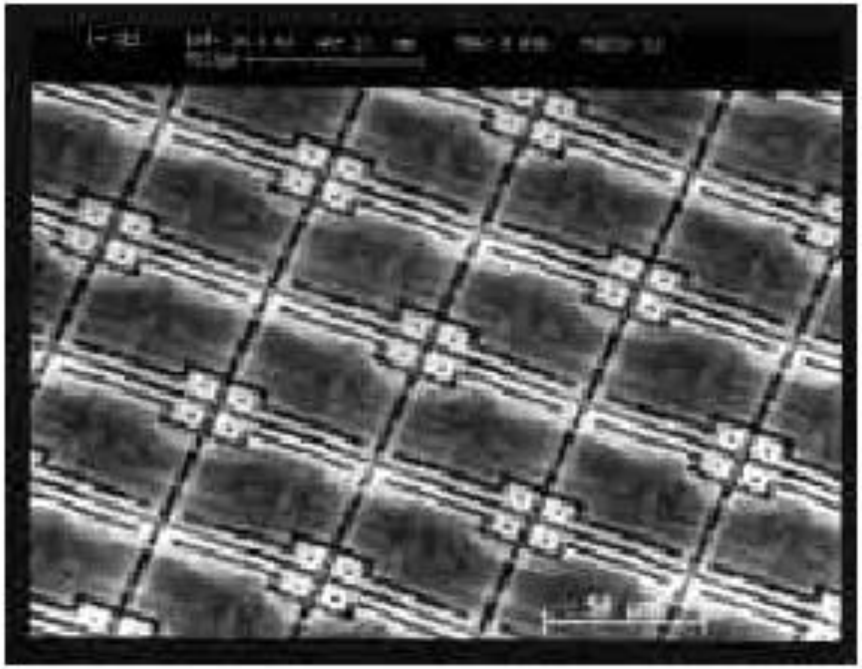
Thermal sensors

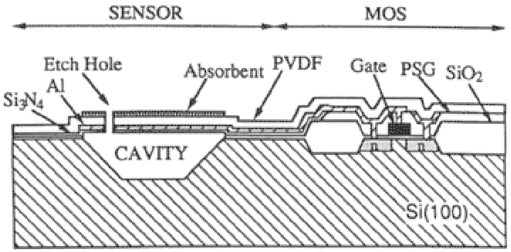
- Thermal sensors : sensors that measure physical quantities by
  - + physical properties to thermal quantities
  - + thermal quantities to electrical quantities
- In general, a thermal sensor operates in 2~3 steps
  1. Non-thermal signal to a heat flow
  2. Heat flow to a temperature difference
  3. Temperature difference to an electrical signal
- Applications of thermal sensors
  - + flow sensors (steps 1~3)
  - + infrared radiation sensors (steps 2~3)

- Better thermal isolation
- Small mass results in short response time
- Small mass results in higher sensitivity
- Distributed sensor through fabrication

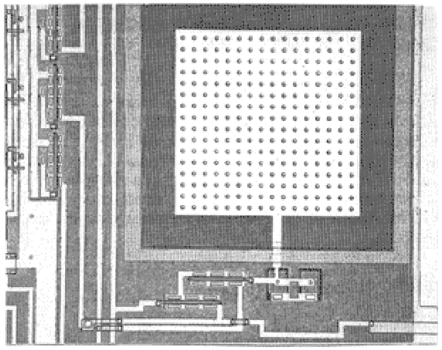
IR imager


Thermal Isolation Regions
Absorber
N-well
JEOL 32KU
100µm
X170 39mm
JEOL 32KU
10µm
X700 39mm




SENSOR
MOS
Etch Hole
Al
Si_3N_4
Absorbent
PVDF
Gate
PSG
SiO_2
CAVITY
Si(100)

(a)



(b)

Thermal Flow Sensors

- Thermal flow sensors are the most common flow sensor
- The basic concept for thermal flow sensor is the cooling of a hot object by the flow

$$Q = \rho A v C \Delta T$$

Q = heat dissipated into the fluid

ρ = density of the fluid

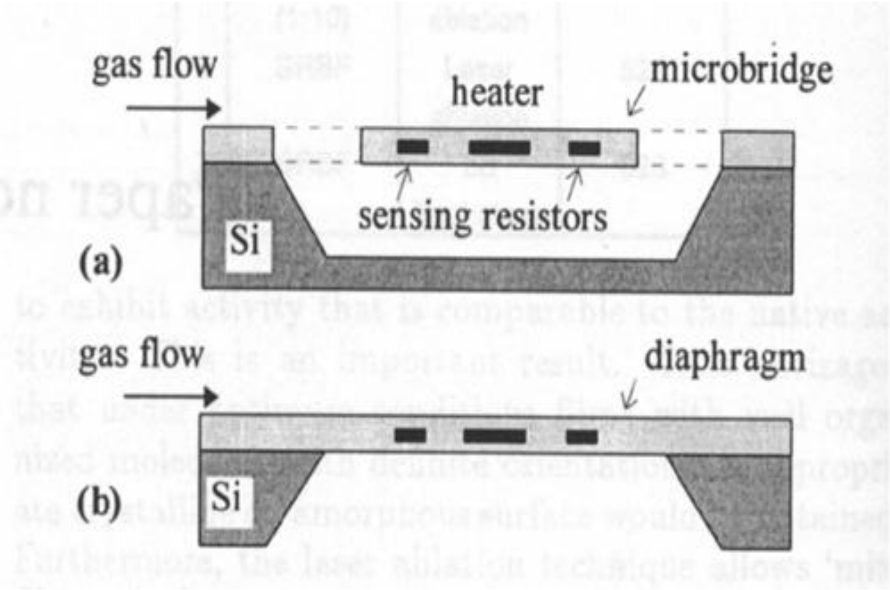
A = cross-sectional area of the flow

v = flow velocity

C = specific heat

- Better thermal isolation
- Small mass results in short response time

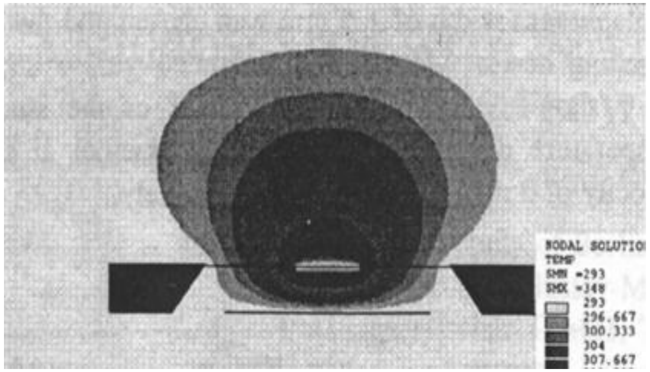
- Two most common structures for thermal flow sensors

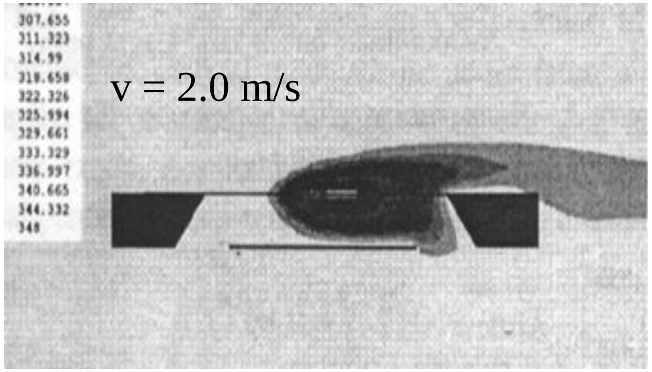


L. Qiu, E. Obermeier, and A. Schubert, Transducer '95, 1995

- The basic components of the thermal flow sensor contains one heater and two thermal sensors

- Temperature distribution near the heater and thermal sensor when flow velocity is 0.0 m/sec and 2.0 m/sec

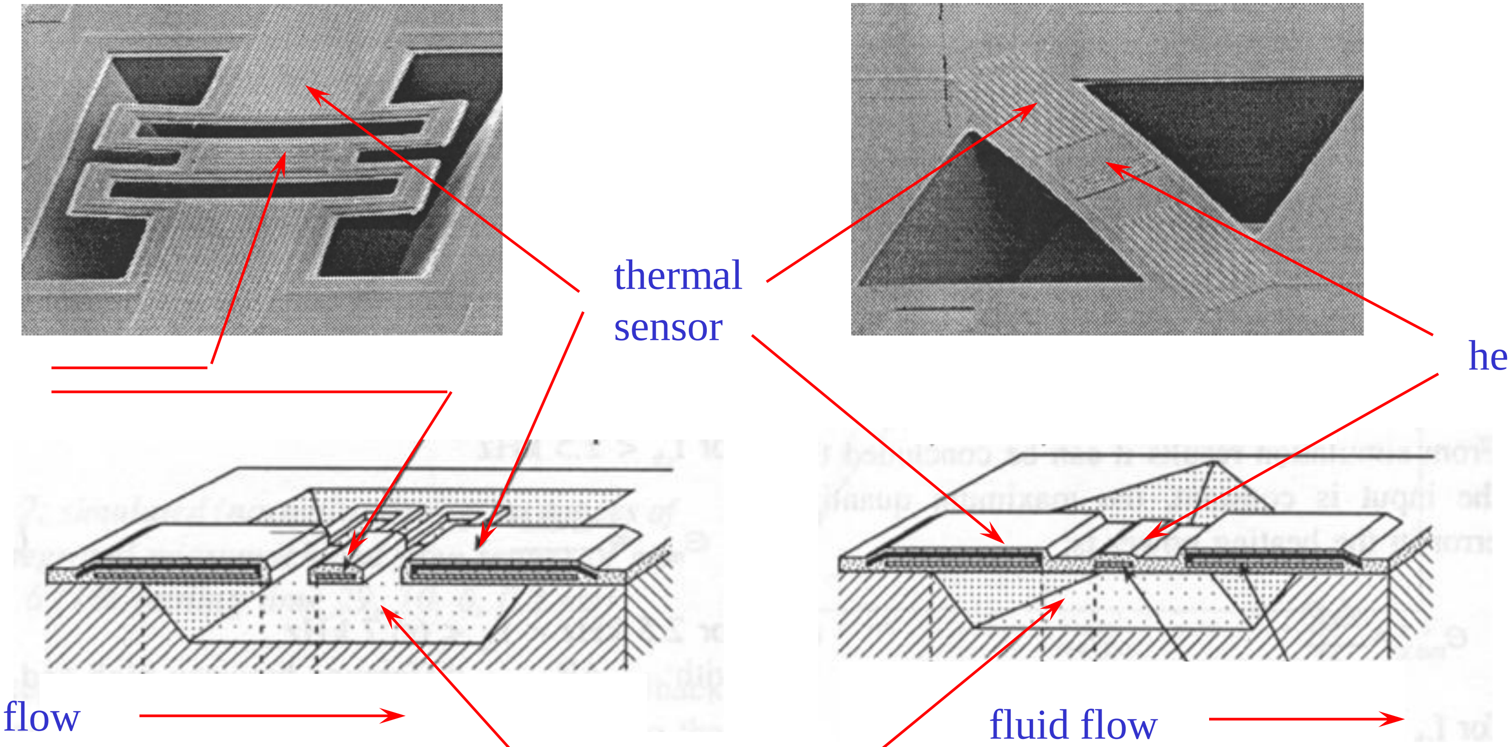




L. Qiu, E. Obermeier, and A. Schubert, Transducer '95, 1995

- The flow velocity is determined by the difference of the downstream and upstream temperature

- Two typical micromachined thermal flow sensor



heater

thermal
sensor

heater

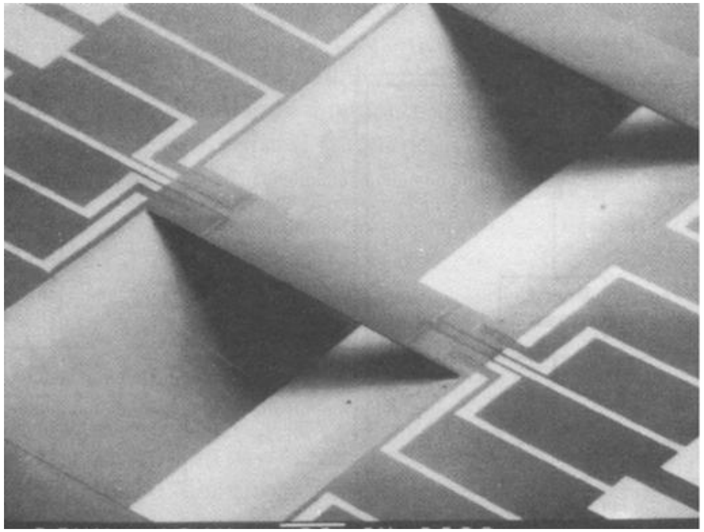
fluid flow

fluid flow

cavity for thermal isolation

F. Mayer, O. paul, and H. Baltes, Transducer '95, 1995

- Resonant bridge flow sensors



+ The sensor contains a resonant bridge which is driven at a temperature elevation of 20°C

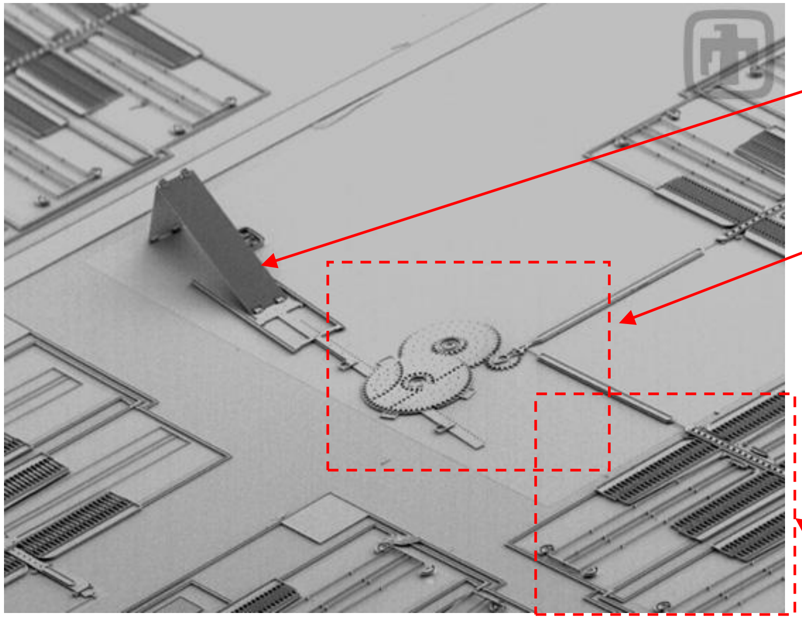
+ The resonant frequency of the resonating microbridge will shift

+ The bridge may be contaminated by particles within a real fluid - the resonant frequency will be shifted by this effect

S. Bowstra, et. al., Sensors and Actuators, 1990

Actuators

- **Actuators : Engine of the MOEMS, Moving parts**



Passive components

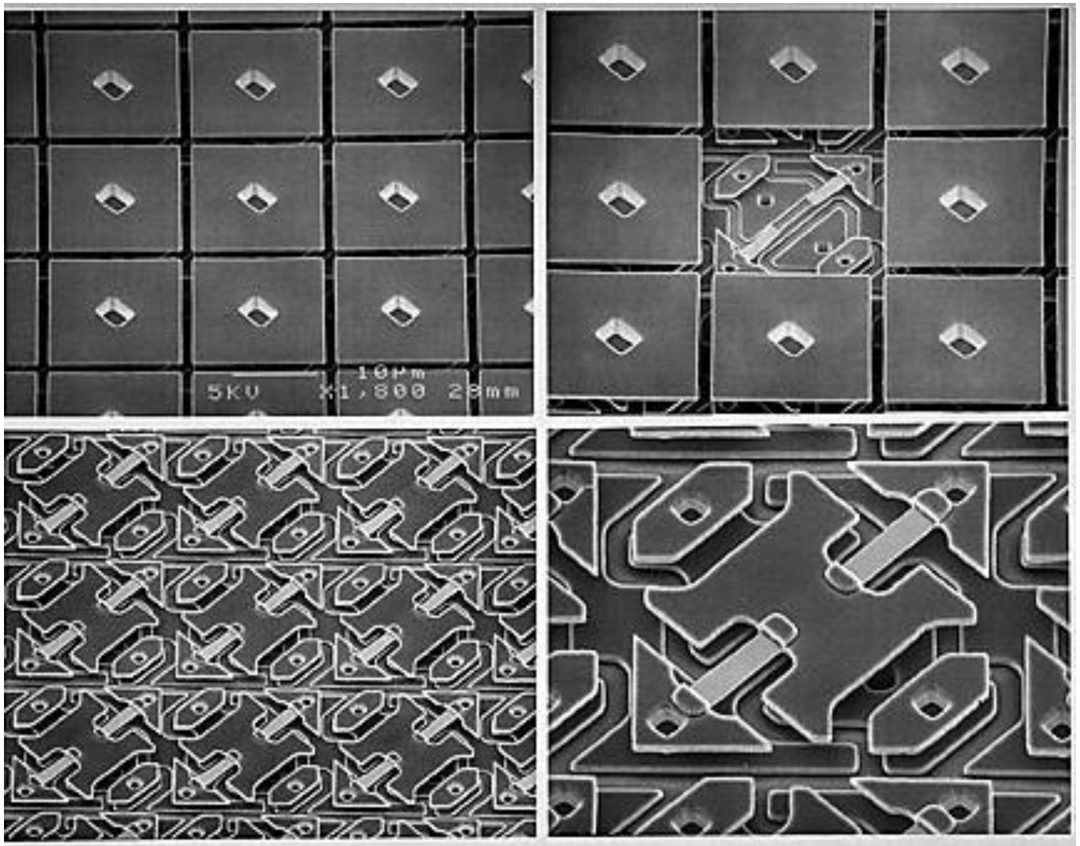
Transmission

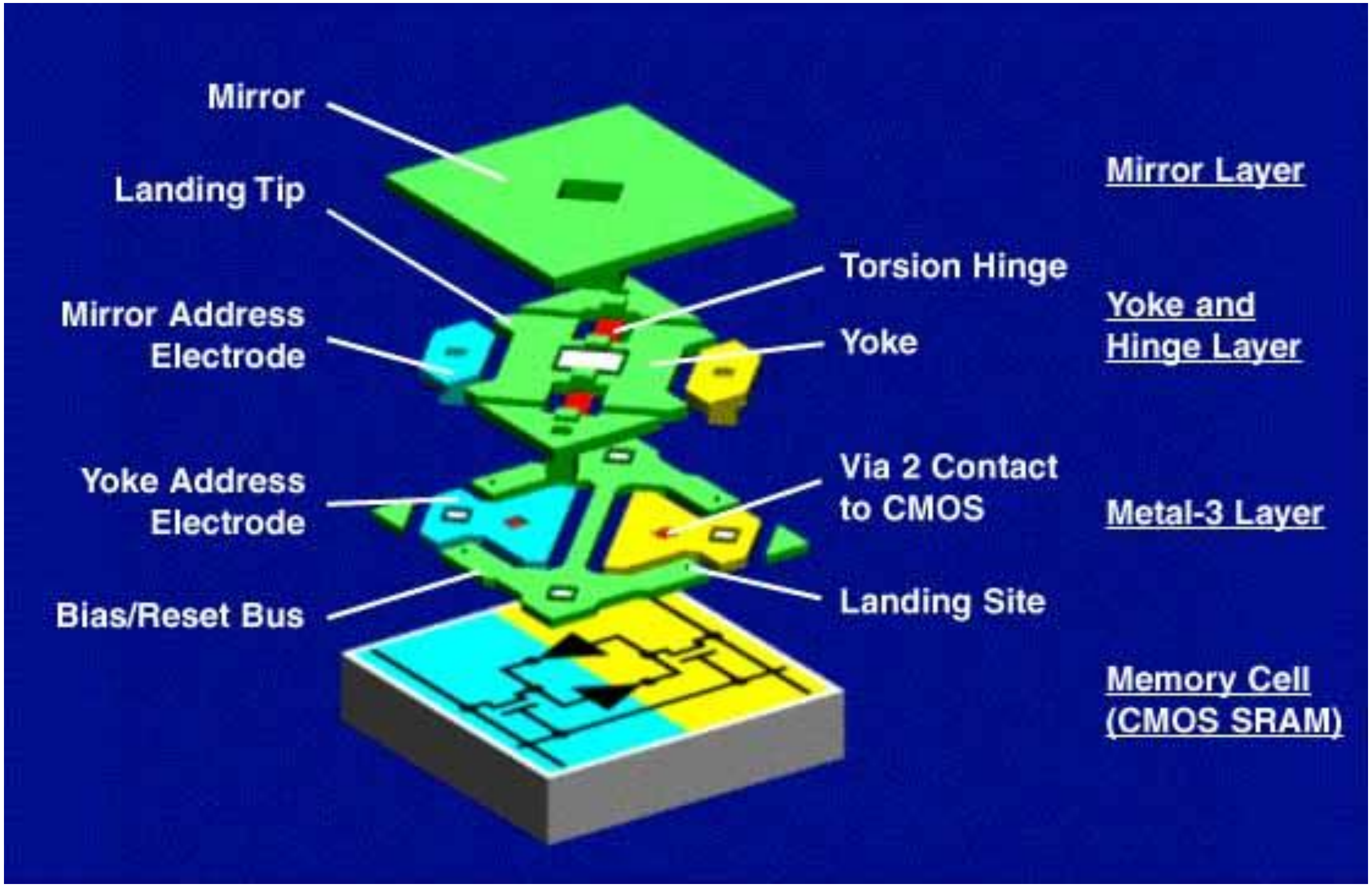
Actuator (Engine)

Sandia National Lab.

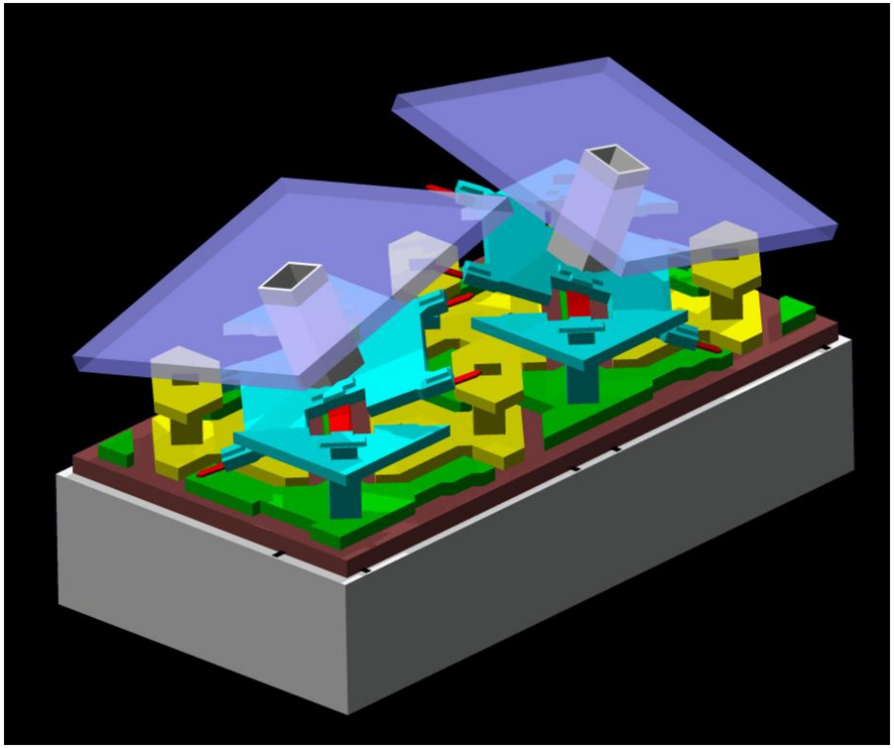
- In a more general way, "actuator" is named as an output transducer that initiate some action (S. Middelhoek, Silicon Sensors, 1989)
- Our discussion here will focus on the actuators to transfer the electrical signal to mechanical deformation
- Actuators can be characterized as out-of-plane (bulk micromachining) and in-plane (surface micromachining) motion
- Application of the micromachined actuators can be mechanical switch, scanning mirror, motors, positioner, microvalve, etc.

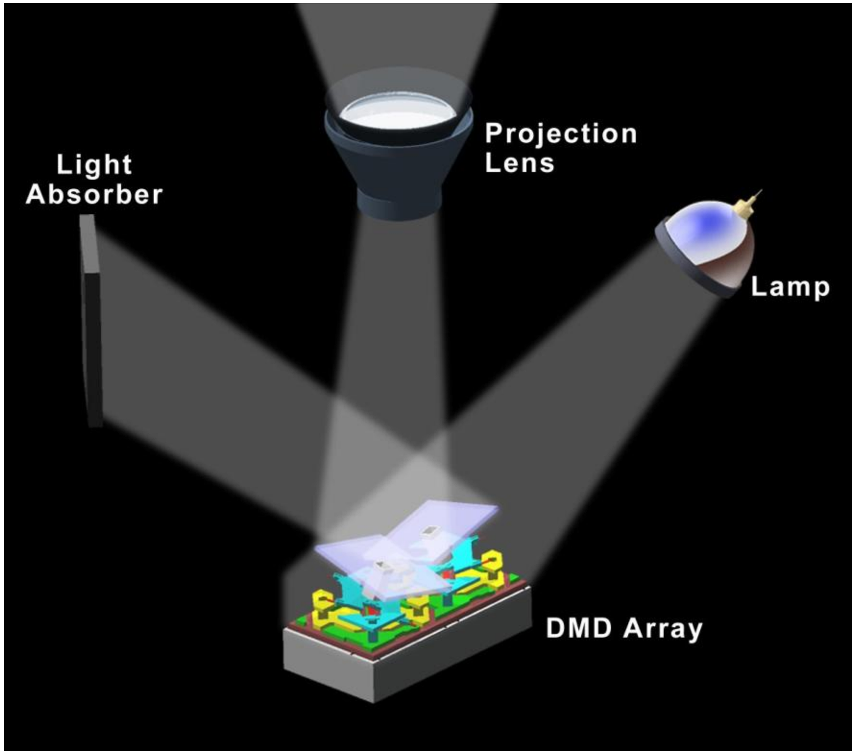
Application - TI DMD

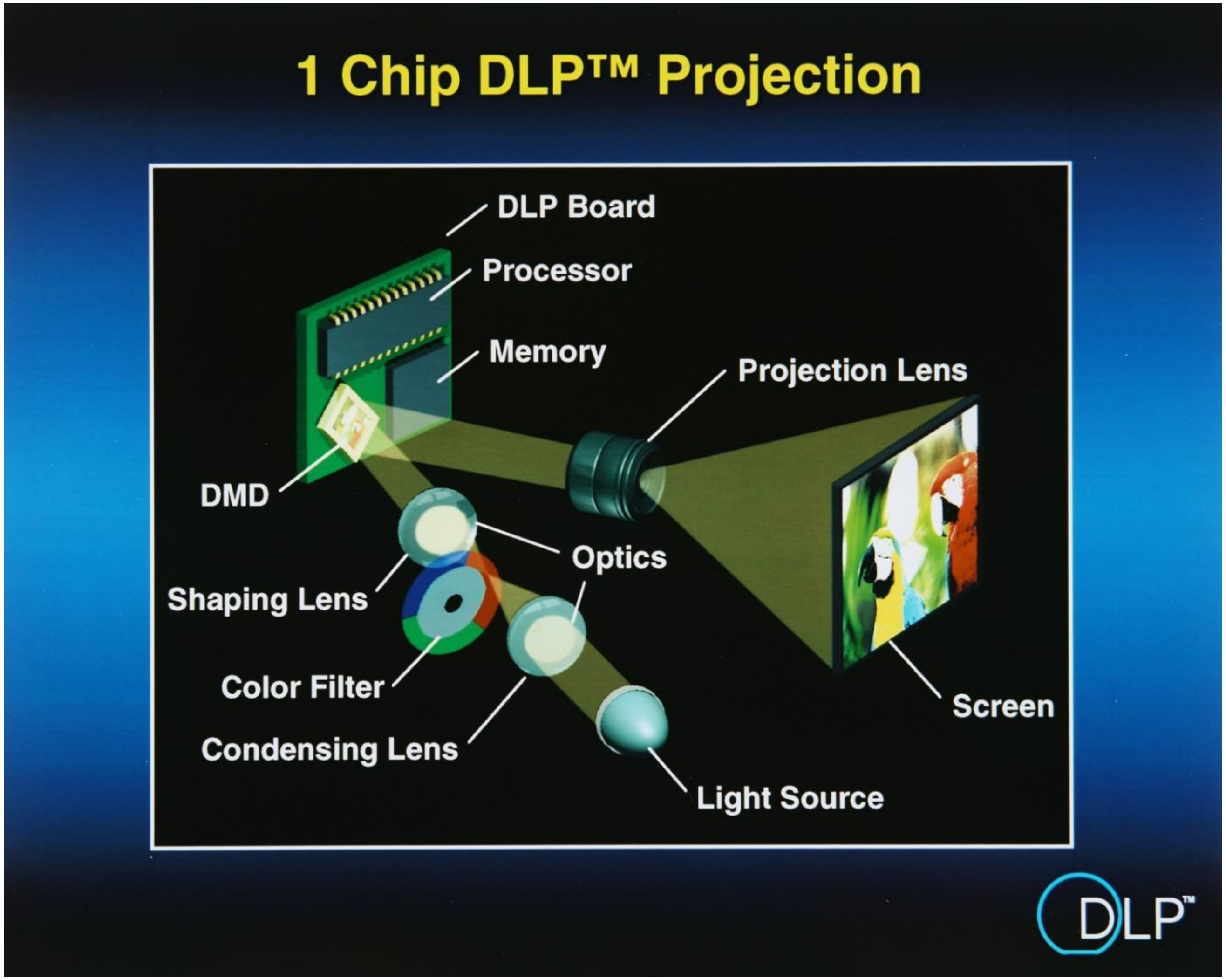



Mirror
Landing Tip
Mirror Address Electrode
Yoke Address Electrode
Bias/Reset Bus
Torsion Hinge
Yoke
Via 2 Contact to CMOS
Landing Site
Mirror Layer
Yoke and Hinge Layer
Metal-3 Layer
Memory Cell (CMOS SRAM)

MDL
NTHU




Light Absorber
Projection Lens
Lamp
DMD Array

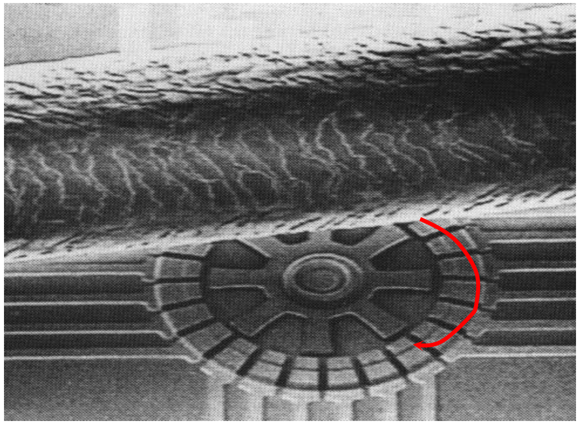


1 Chip DLP™ Projection

Classify The Motion of the Micro Actuator

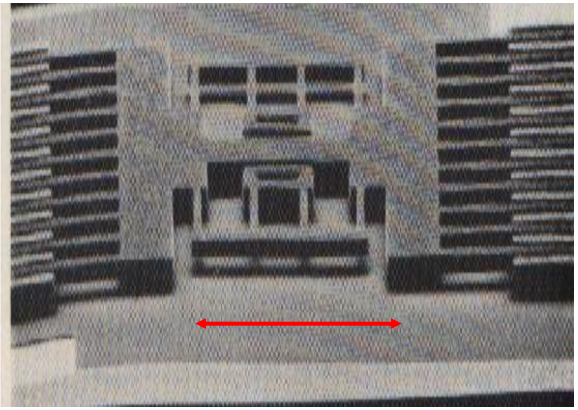
- In-plane motion

Angular



L-.S. Fan, Y.-C. Tai, and R. S. Muller, 1989.

Linear



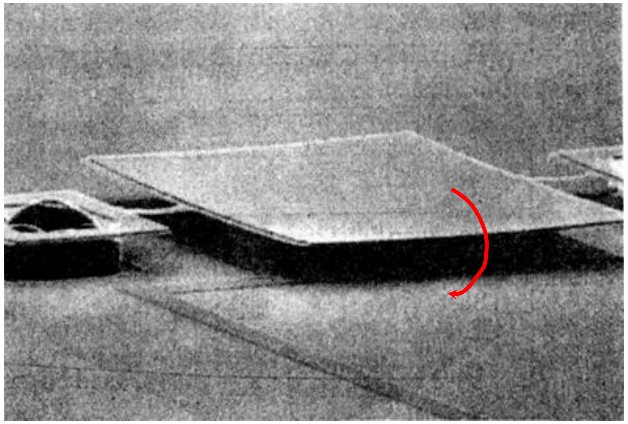
W.C. Tang, T.-C.H. Nguyen, and R.T. Howe, 1989.

MDL
NTHU

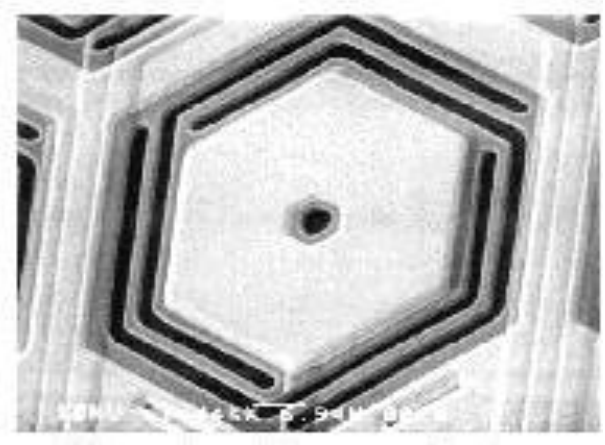
- Out-of-plane motion

Angular

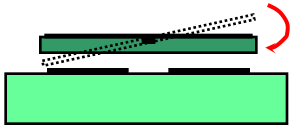
Linear

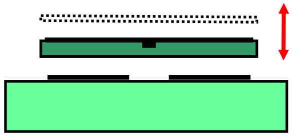


S.-W. Chung et. al., 1996



V. M. Bright, 1998

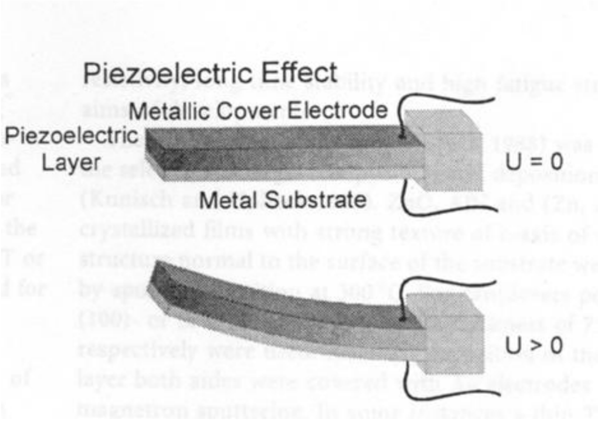




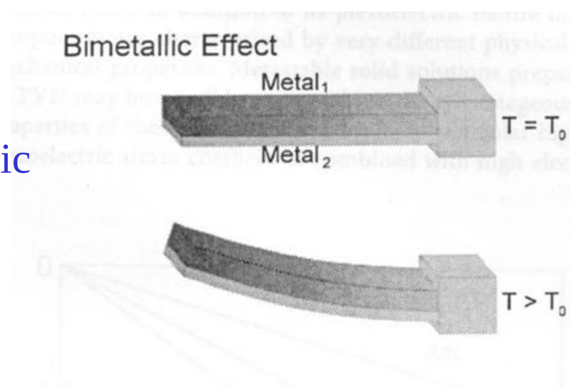
- Due to the fabrication characteristics, the bulk micromachined structures have more space to move out-of-plane

- Motion of the cantilever can be initiated through the following approaches,
  - + **electrostatic**
  - + **thermal**
  - + piezoelectric
  - + shape alloy
  - + magnetoresistive

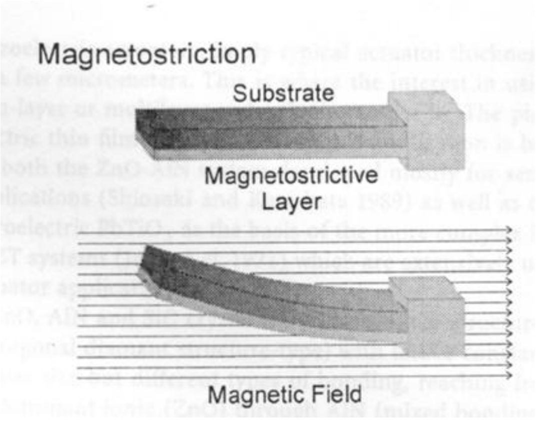
+ Four different approaches to actuated the micromachined cantilever



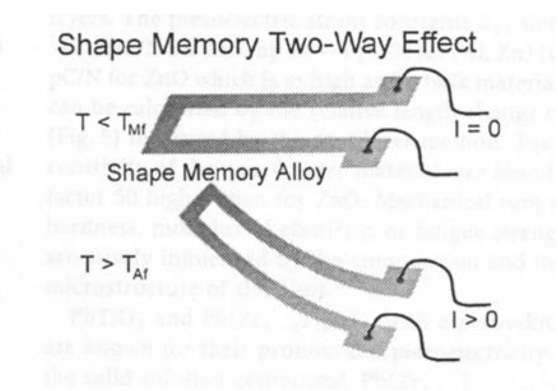
Piezoelectric type



Thernal (bilayer) type



Magnetic type



Shape alloy type

E. Quandt and H. Holleck, Microsystem Technologies, 1995

In-Plane Electrostatic Actuators

Gap closing electrodes

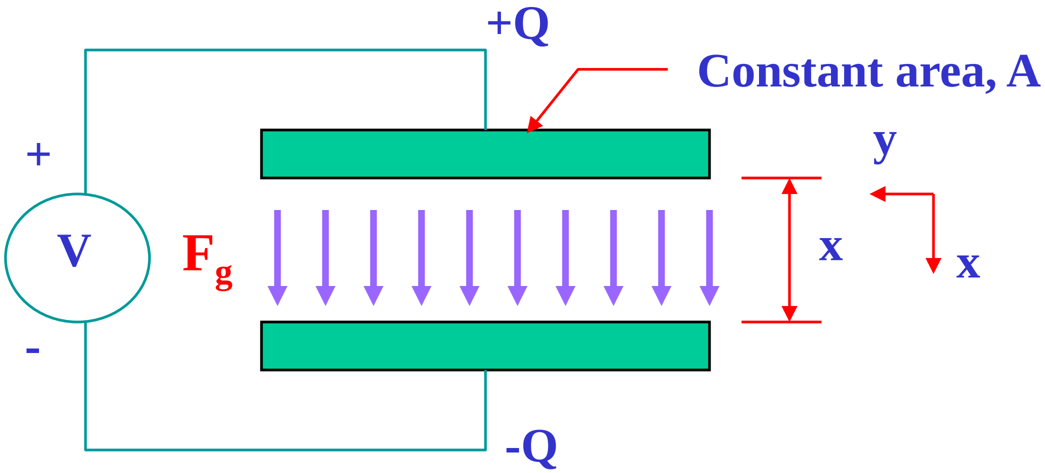
- **Energy**

$$U = CV^2/2$$

where C = εA/x

- **Electrostatic force**

$$F_x = -dU/dx$$



$$\Rightarrow \quad F_{gap} = \frac{1}{2}V^2\left(\frac{\varepsilon A}{x^2}\right)$$

Comb electrodes

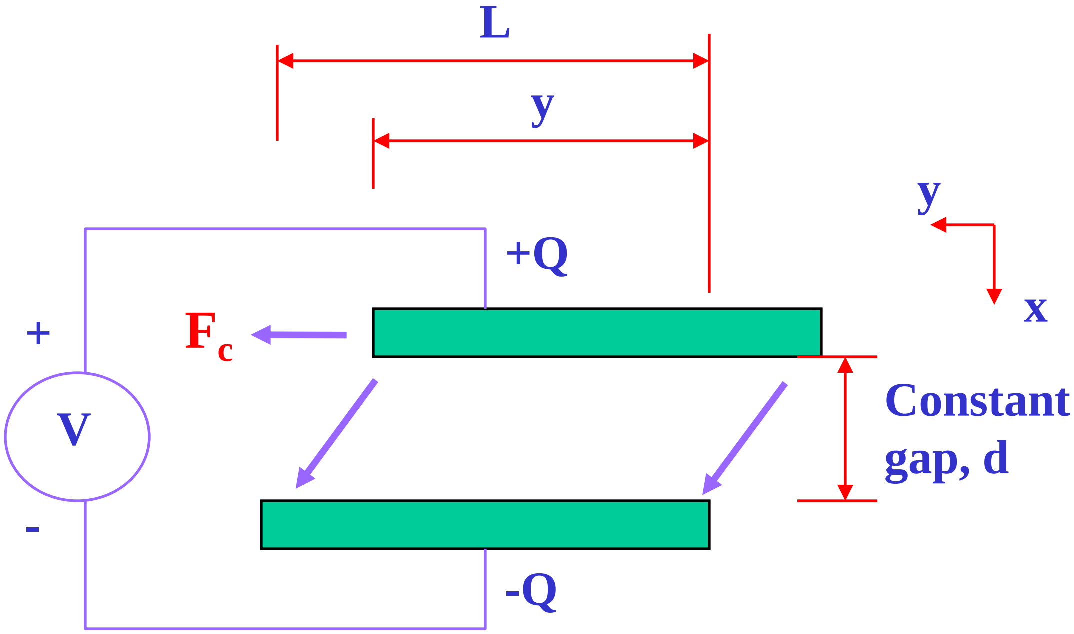
- **Energy**

$U = CV^2/2$

where $C = \varepsilon yz/d$

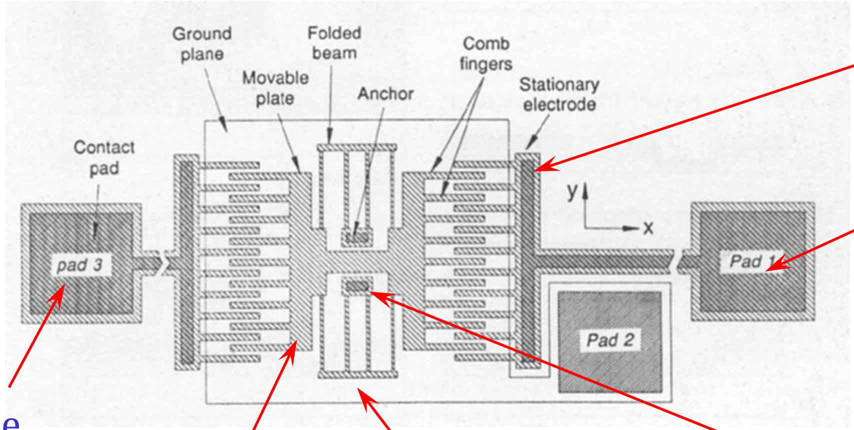
- **Electrostatic force**

$F_y = -dU/dy$



$$\Rightarrow \quad F_{comb} = \frac{1}{2}V^2\left(\frac{\varepsilon z}{d}\right)$$

Comb-drive actuator



stationary electrode

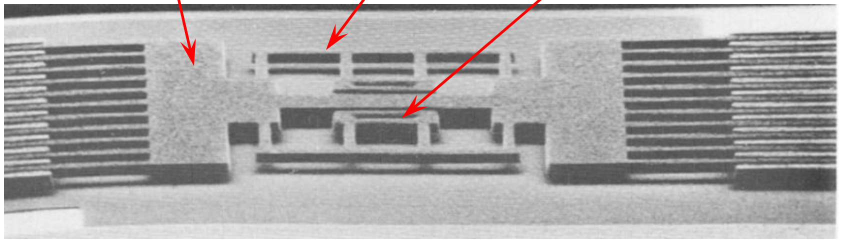
sense probe

drive probe

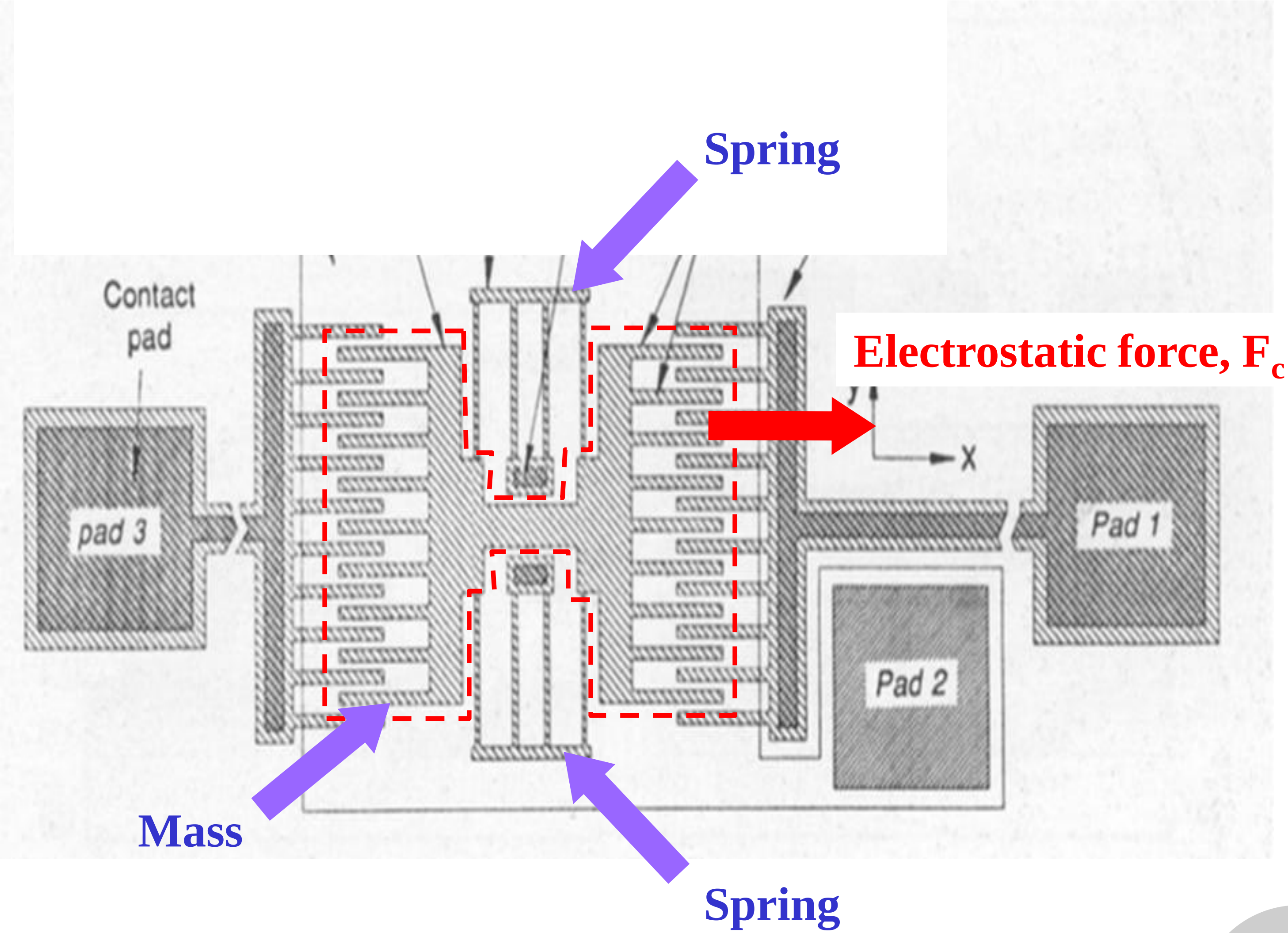
bond to the substrate

moving parts

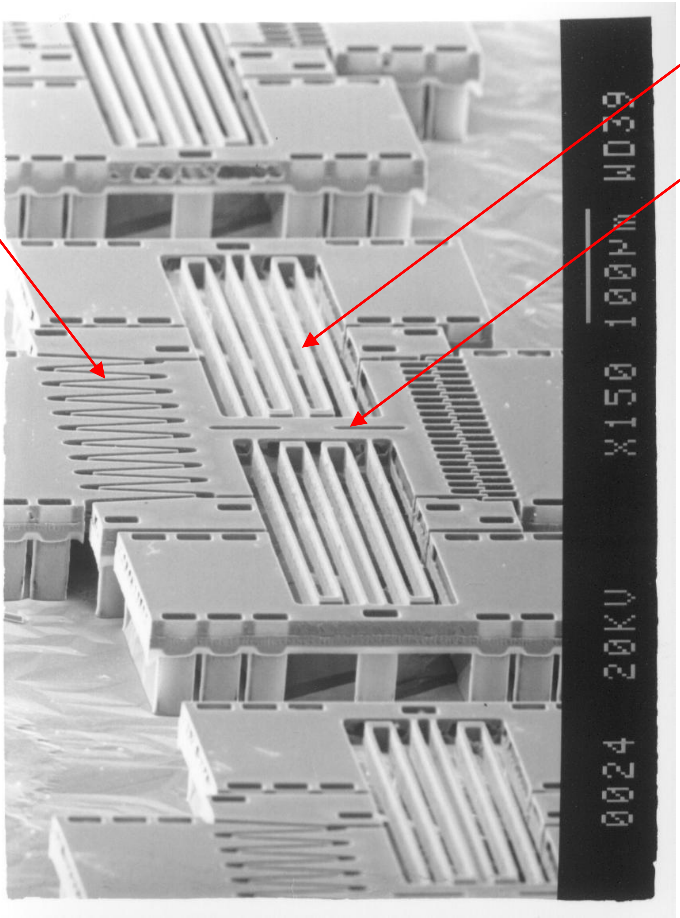
supporting frames



W.C. Tang, et. al., Sensors and Actuators, 1990.


Spring
Contact pad
pad 3
Electrostatic force, F_c
y
X
Pad 1
Pad 2
Mass
Spring

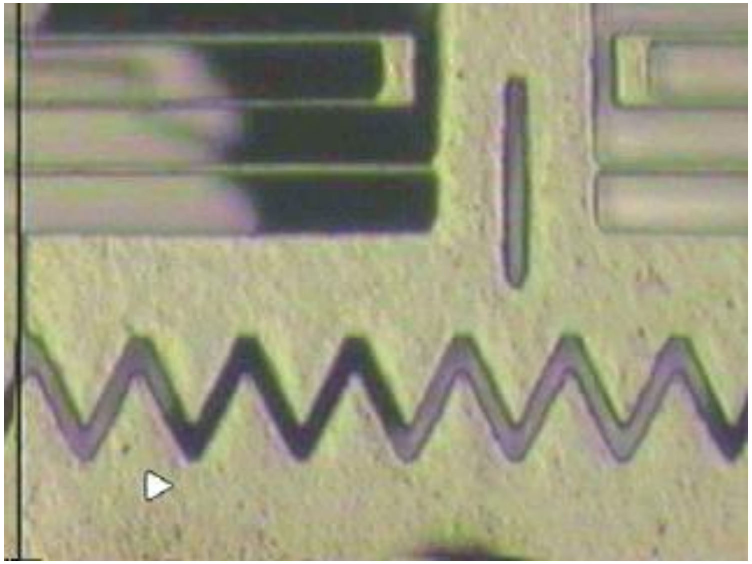
MDL
NTHU



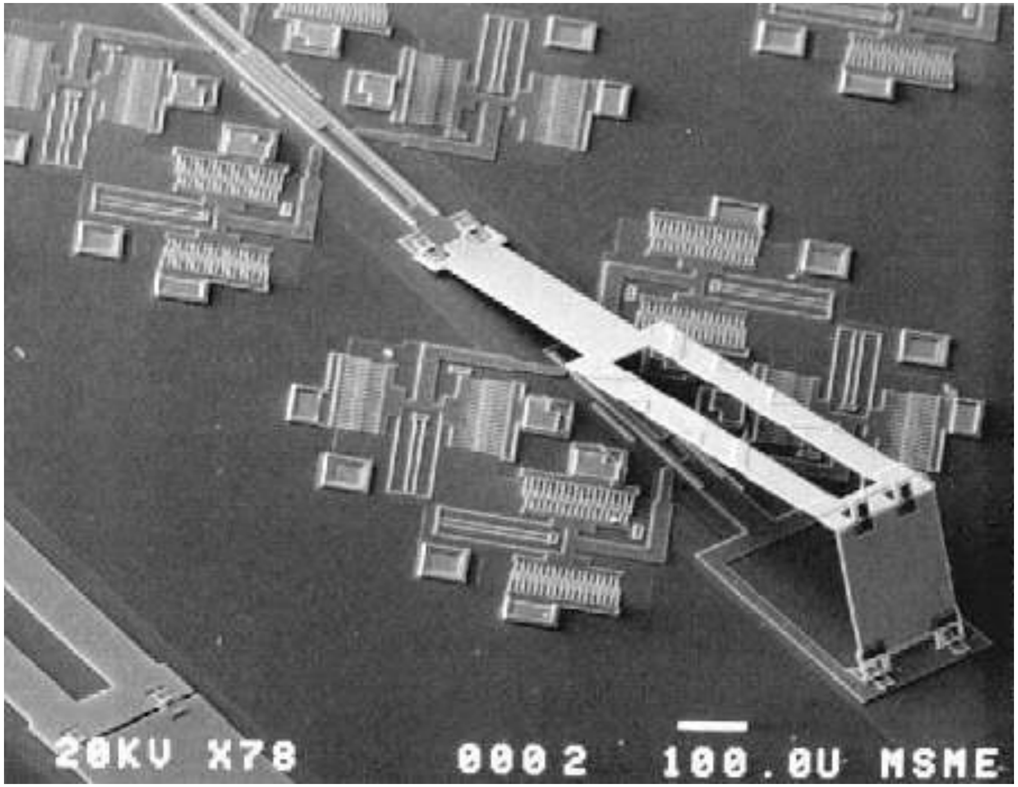
Comb electrode

Spring

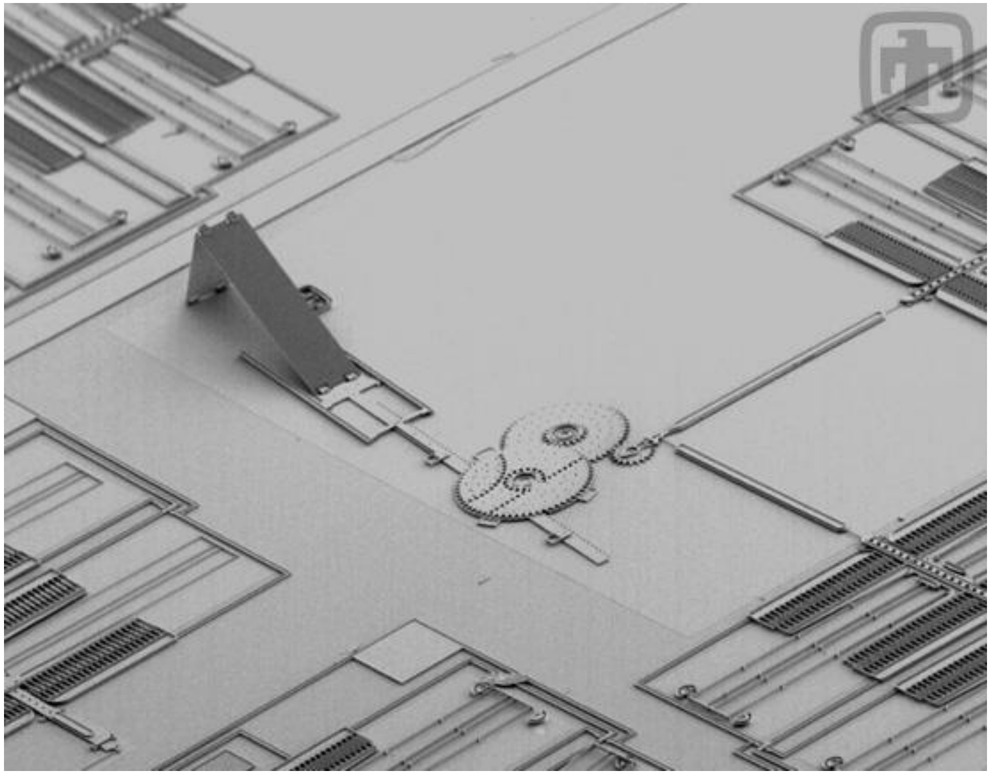
Moving stage



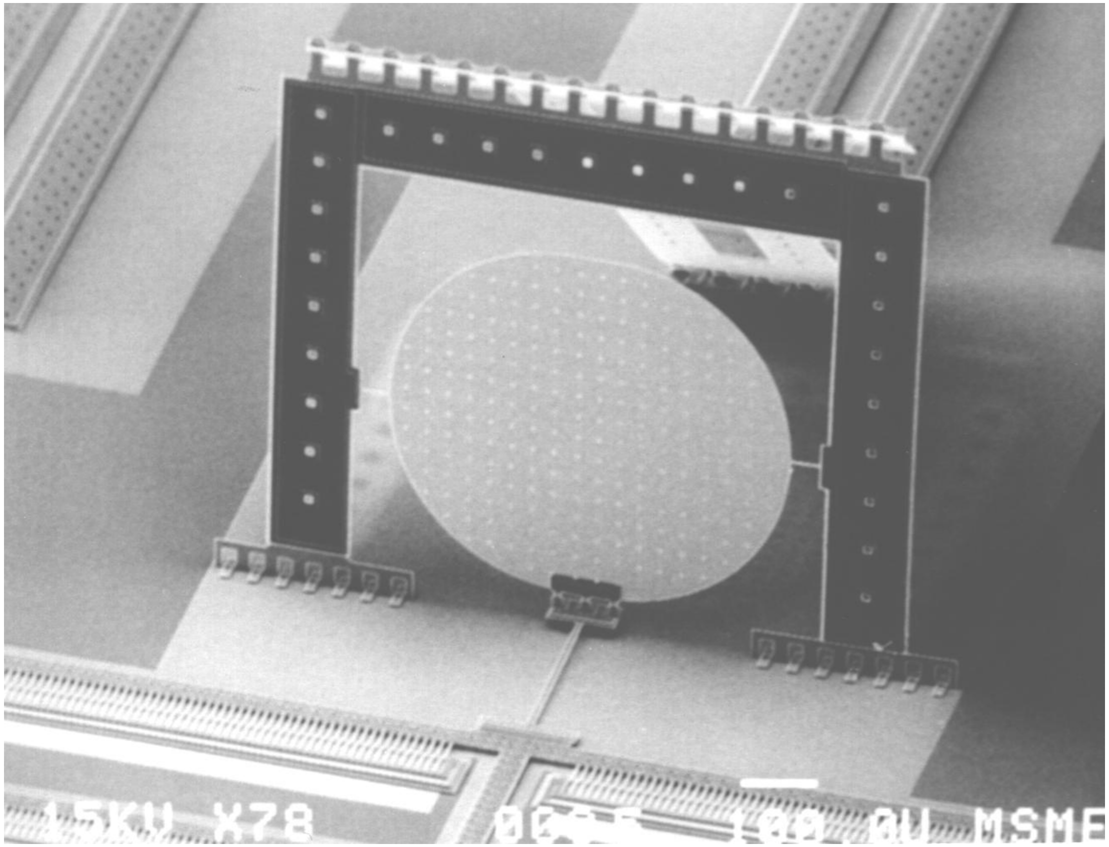
J. Hsieh, and W. Fang, the *ASME IMECE*, New York, NY, 2001



UC Berkeley



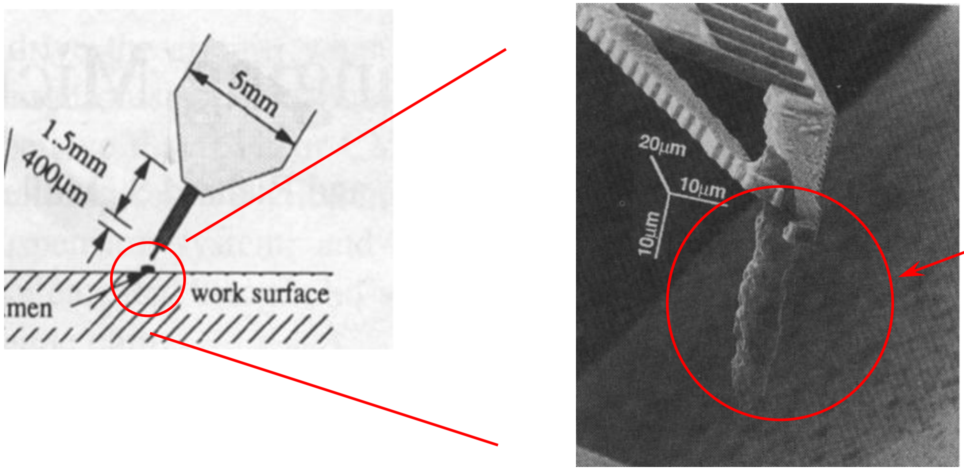
Sandia National Lab.



UC Berkeley

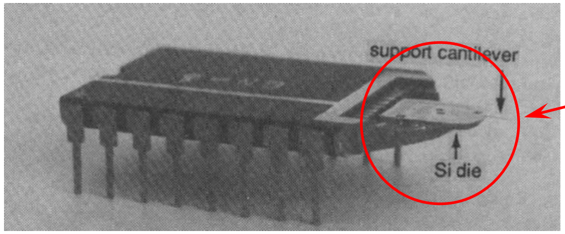
Microgripper

- Microgripper is fabricated by both surface and bulk micromachining



euglena

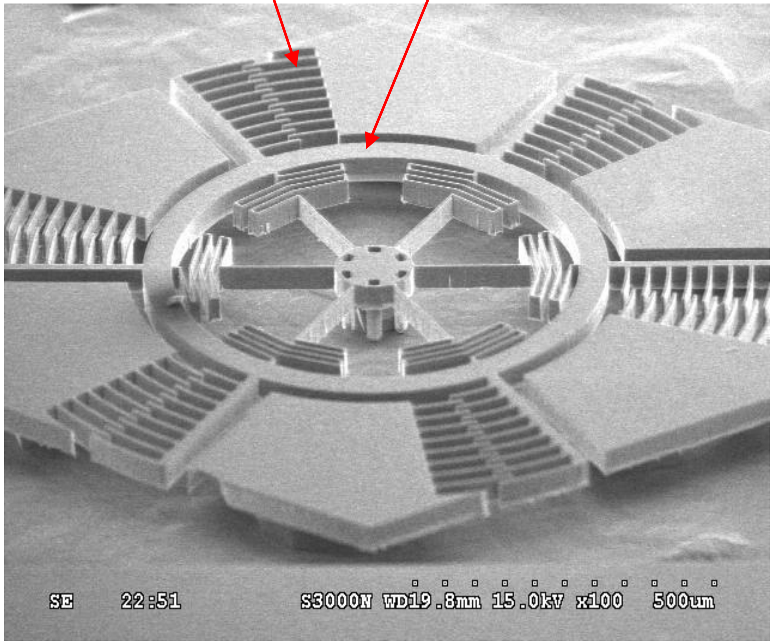
+ after standard IC packaging



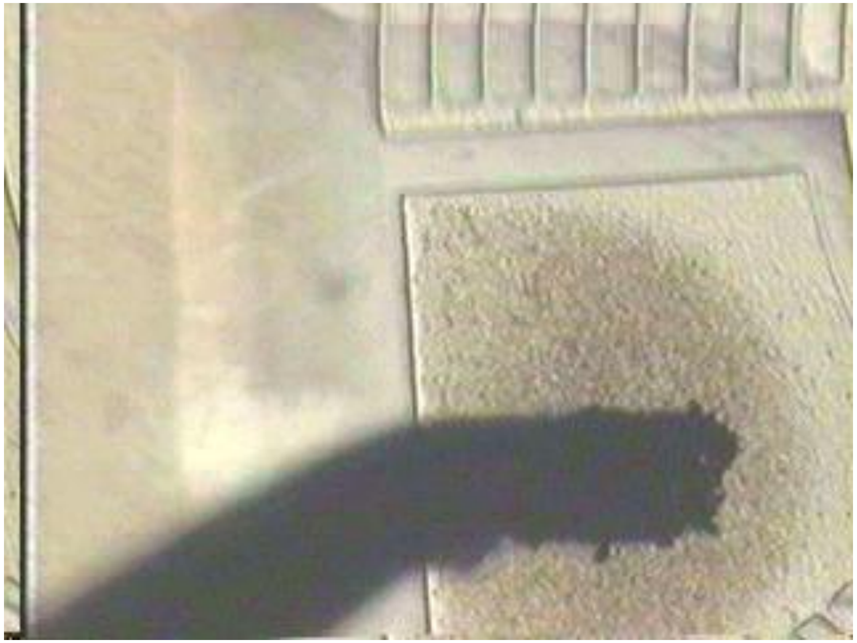
microgripper

C.-J. Kim, A.P. Pisano, and R.S. Muller, J. of MEMS, 1992.

Micro motor (comb)


Comb electrode

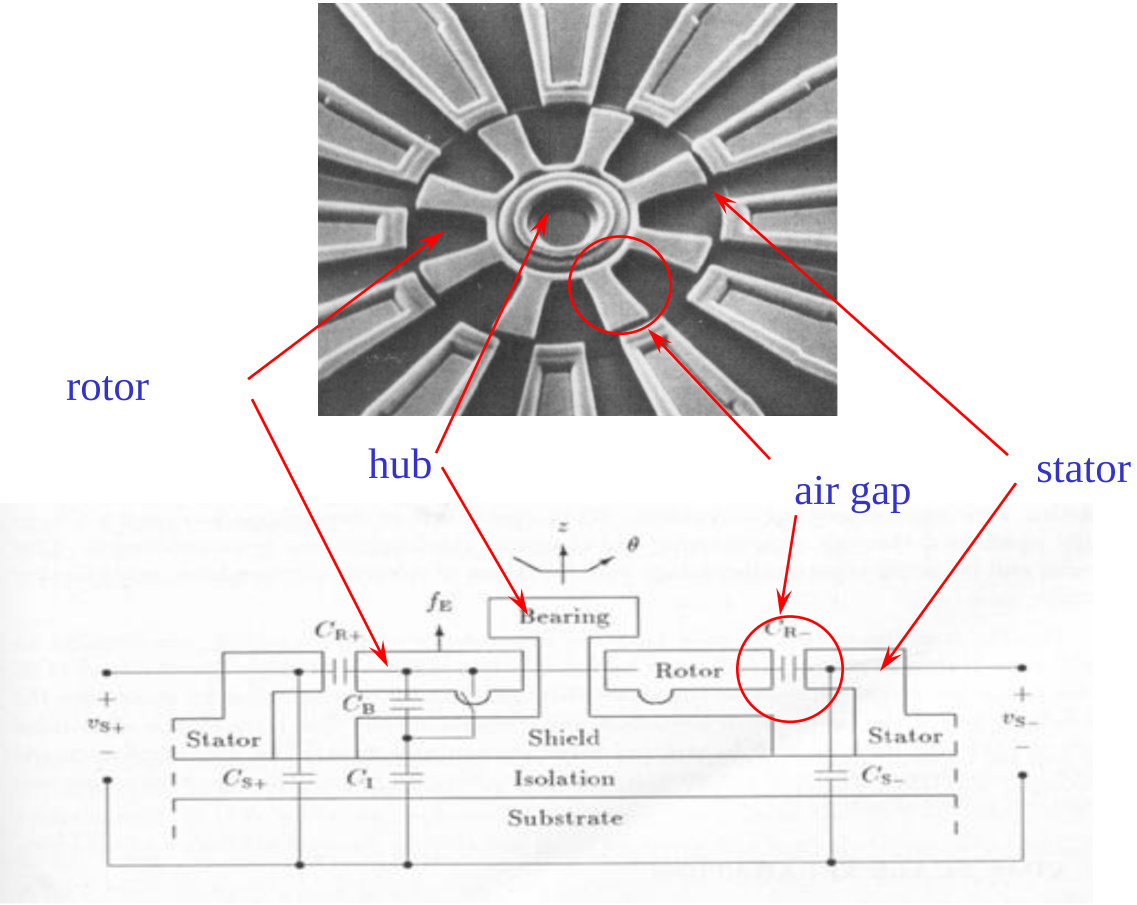
Moving platform



J. Hsieh, and W. Fang, the *SPIE Micromach. and Microfab.*, San Francisco, CA, 2001

Micro motor

- The motor is driven by several stators which are at its side



rotor

hub

air gap

stator

J.H. Lang, Integrated Micro-motion Systems edited by F. Harashima, 1989.

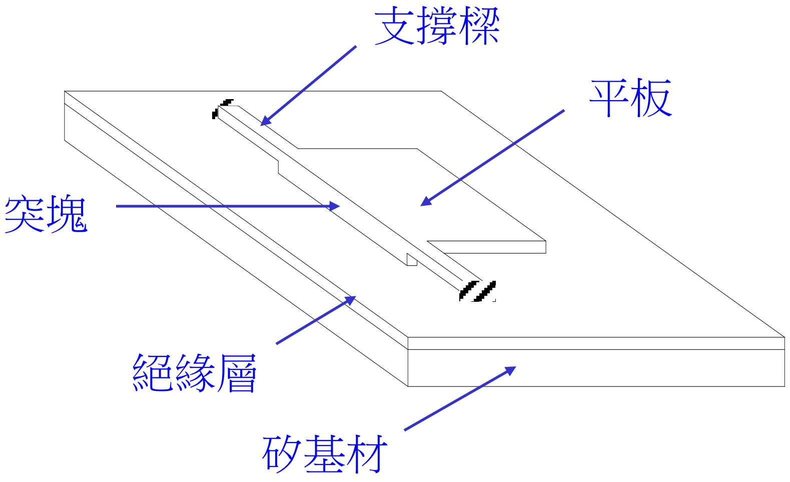
SDA (Scratch Drive actuator)

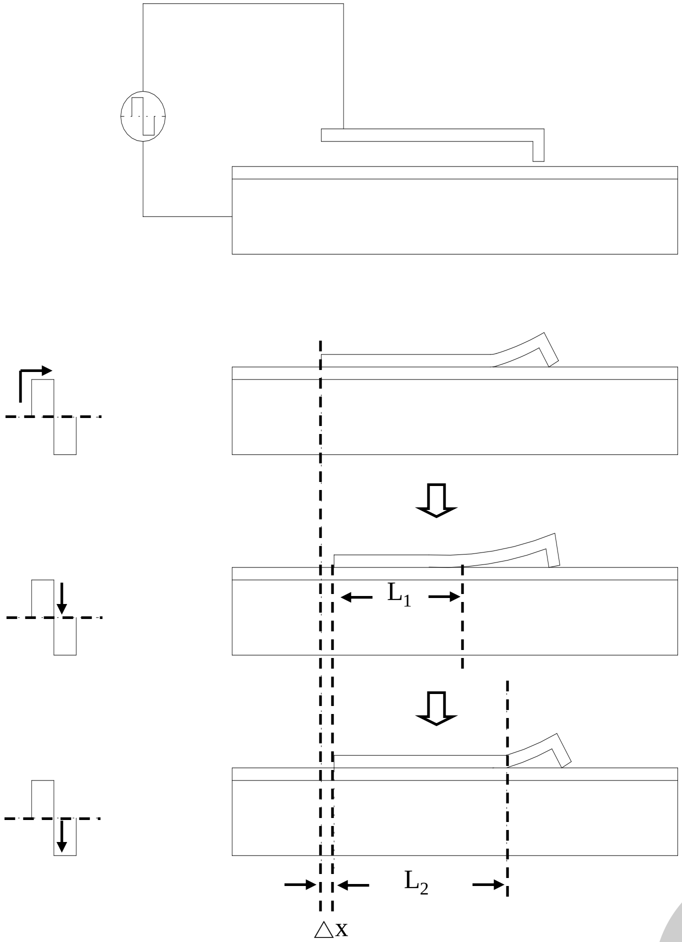
- SDA(scratch drive actuator)之設計

  靜電式驅動 : 30~150V

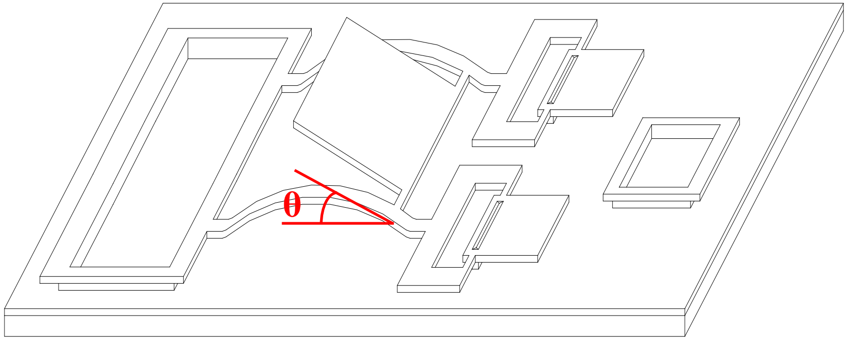
  單位行程 : 10nm

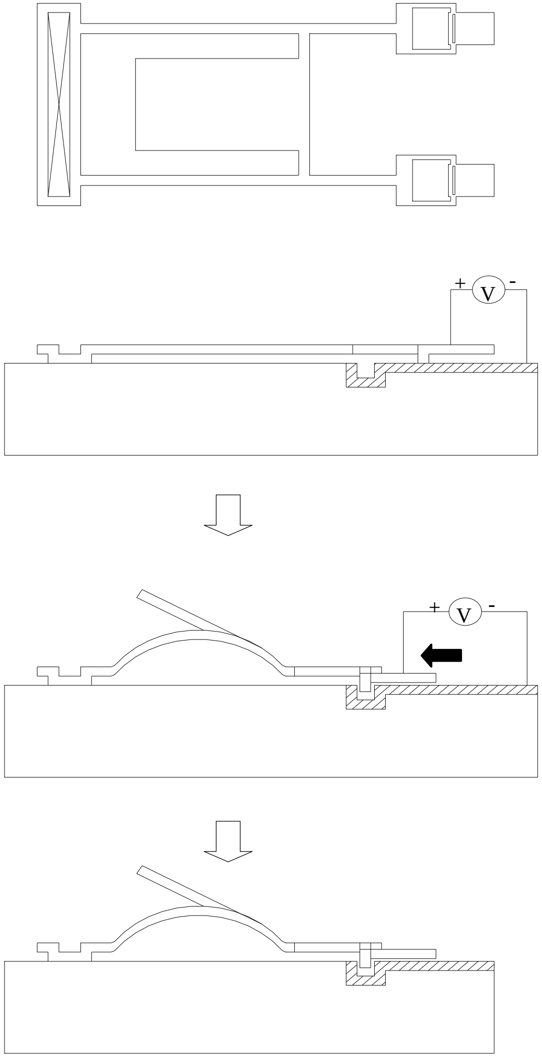
  出力大小 : 100μN



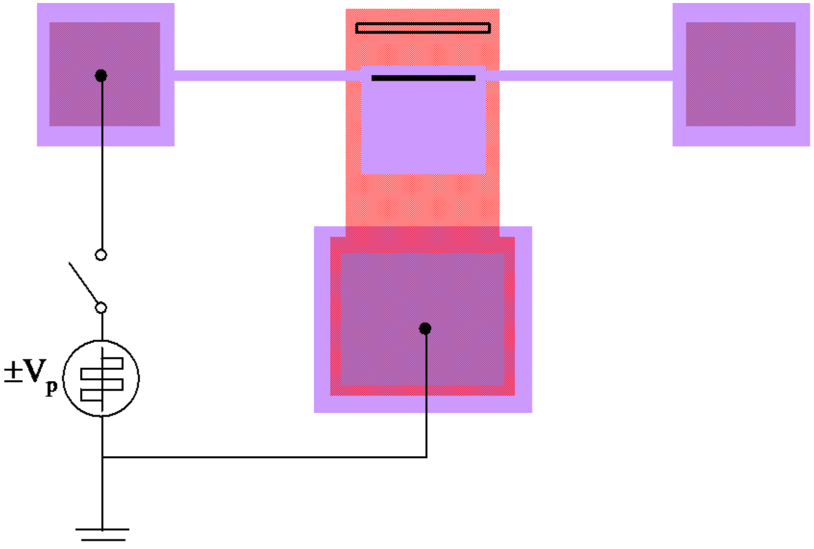


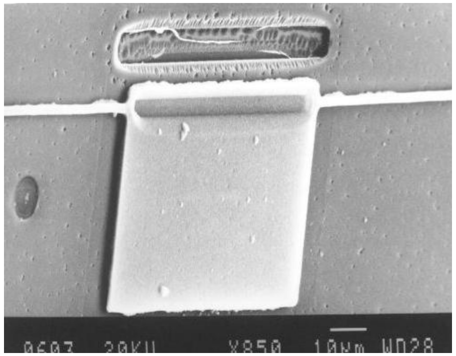
T.Akiyama, K. Shono
Sophia University, MEMS’93

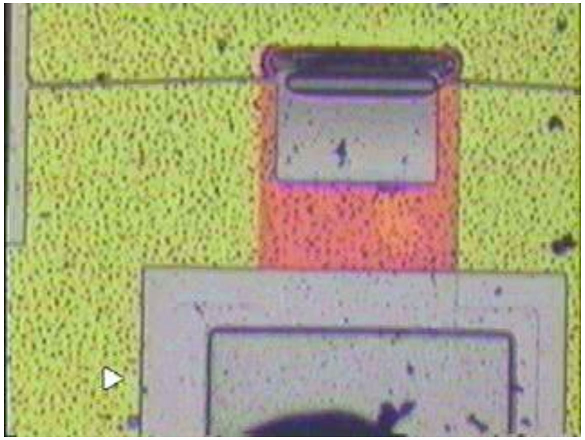

θ

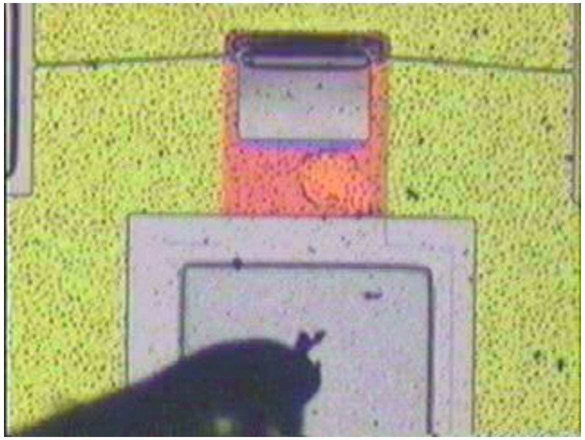

+
V
-
+
V
-

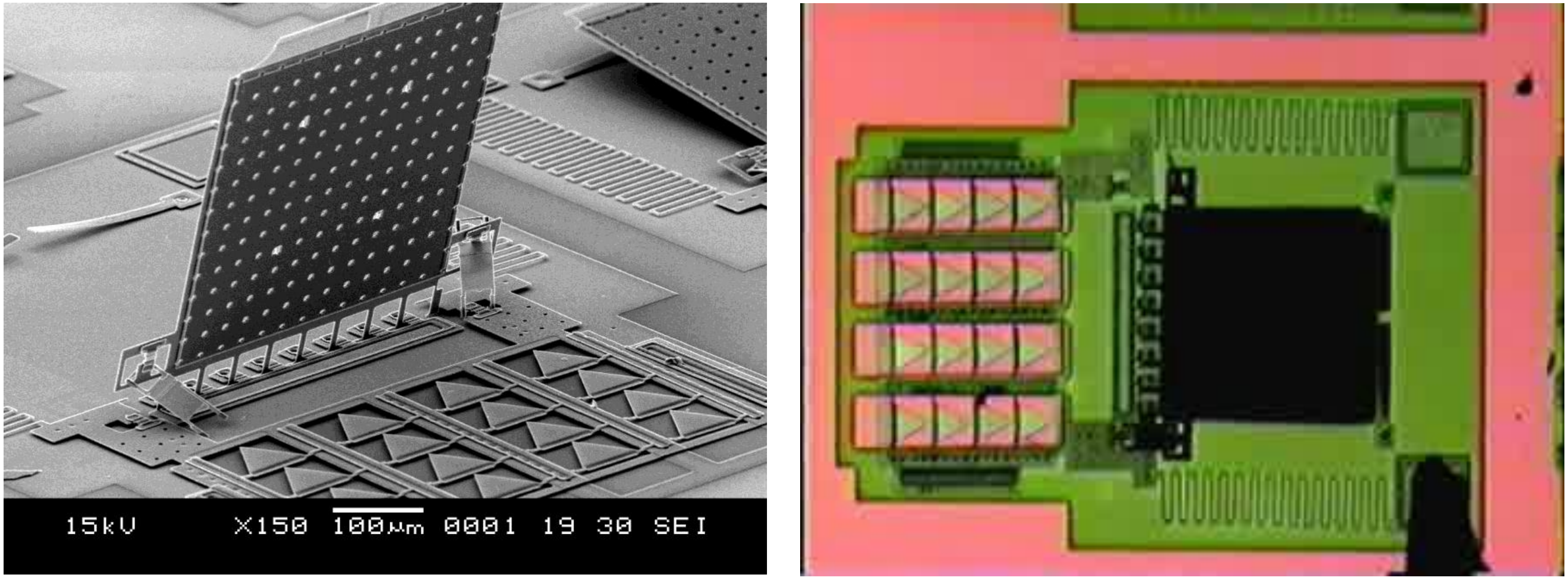
SDA 驅動測試











C.-Y. Wu, and W. Fang, 2002

Out-of-Plane Electrostatic Actuators

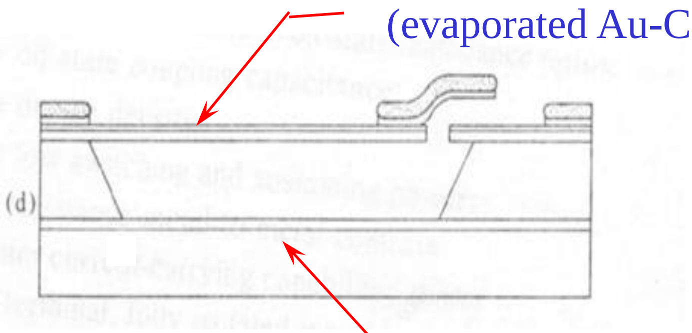
Mechanical switch

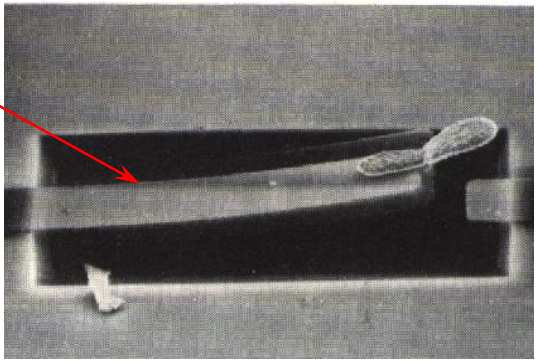
- **Mechanical switch**

  + micromachined switch proposed by Petersen at 1979 is an application of the electrostatic force linear actuator

  + the actuator - fabrication processes are shown in chap. 3

electrode 1
(evaporated Au-Cr)



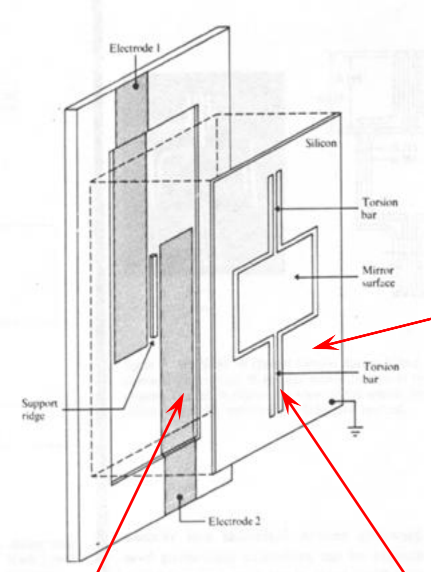


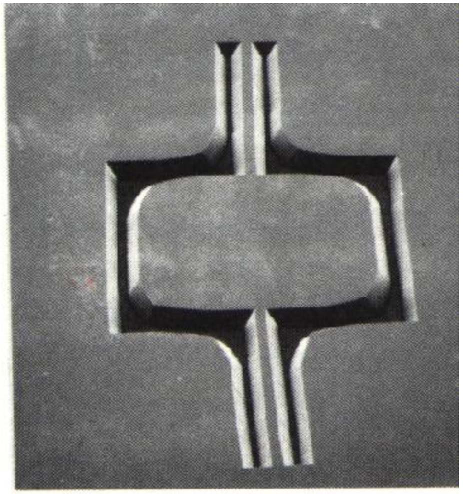
electrode 2 (p+ doped layer)

K.E. Petersen, IBM J. of Research and Development, 1979.

Torsional scanning mirror

- Torsional mirror can rotate about the torsional bar by the electrostatic force



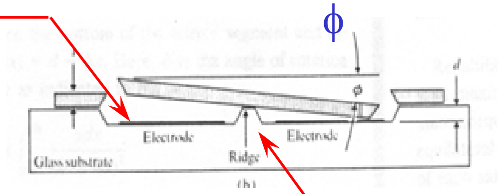


Torsional bar

SEM photo of the top substrate

Electrode

ϕ



After bonding

Ridge

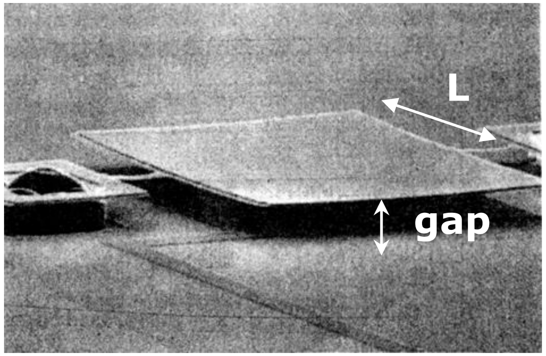
K.E. Petersen, IBM J. of Research and Development, 1980.

Design issues

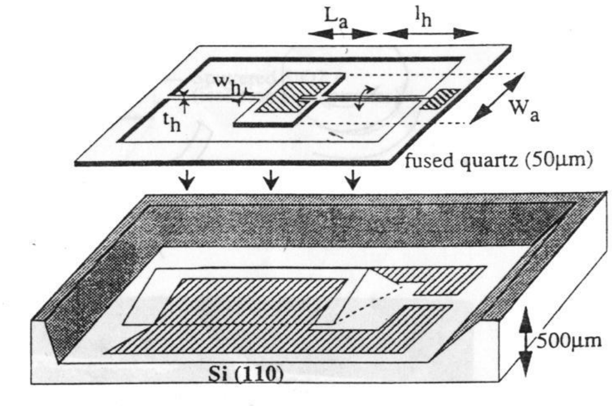
- Torsional actuator : out-of-plane angular motion

+ Surface device

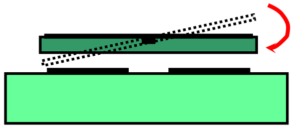
+ Bulk device

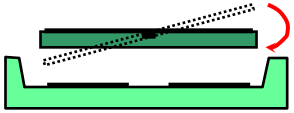


S.-W. Chung et. al., 1996



D. Chauvel et. al., 1997

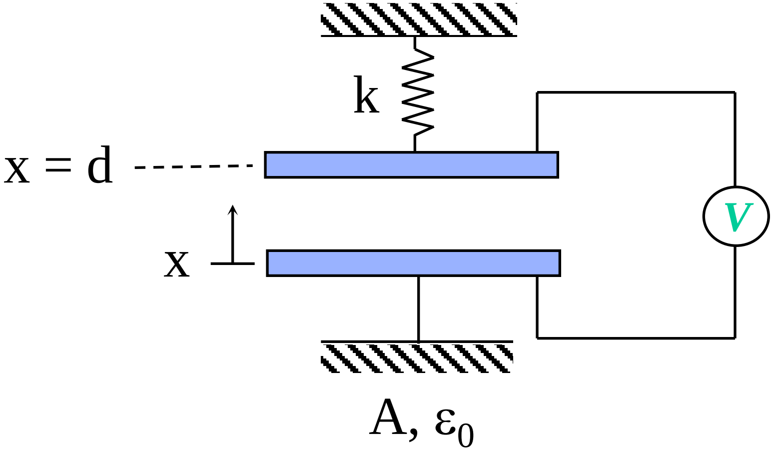




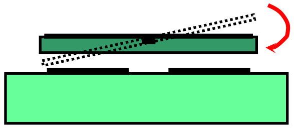
- Electrostatic force

electrostatic force : $F_{el} = \frac{1}{2}\varepsilon_0 A \frac{V^2}{x^2}$

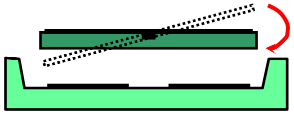
spring force : $F_{me} = k \cdot (d - x)$



- The general problems of the existing Micro Electrostatic Torsional Actuator (META)
  - Limitation of the rotating angle as well as the plate size (for surface device)
  - The demand of the large driving voltage (for bulk device)
  - Pull-in effect

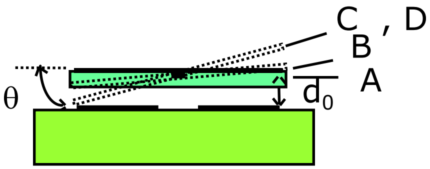


Surface device

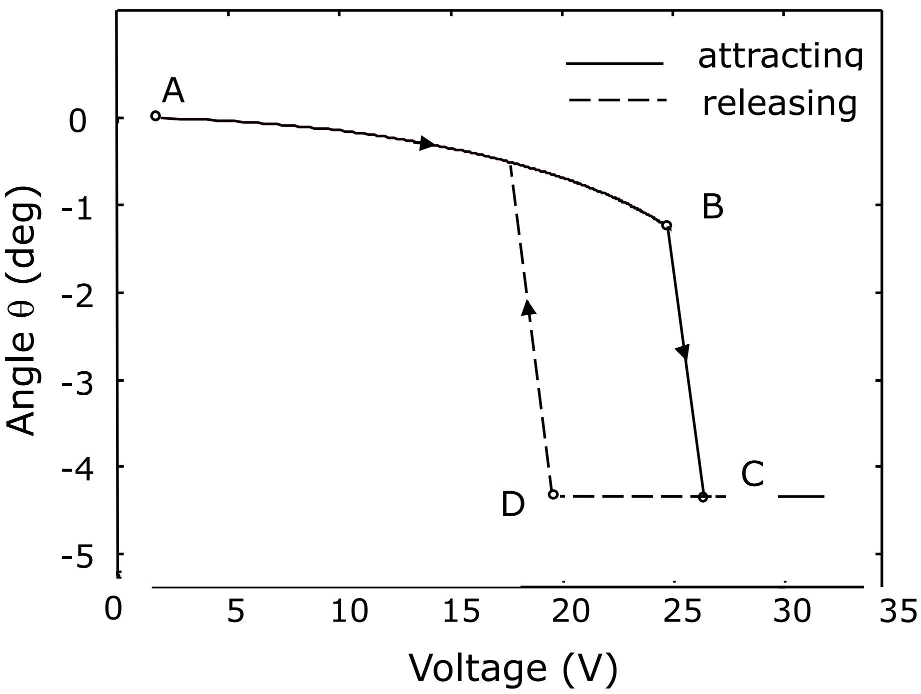


Bulk device

+ Pull-in effect

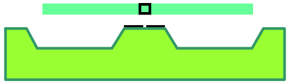


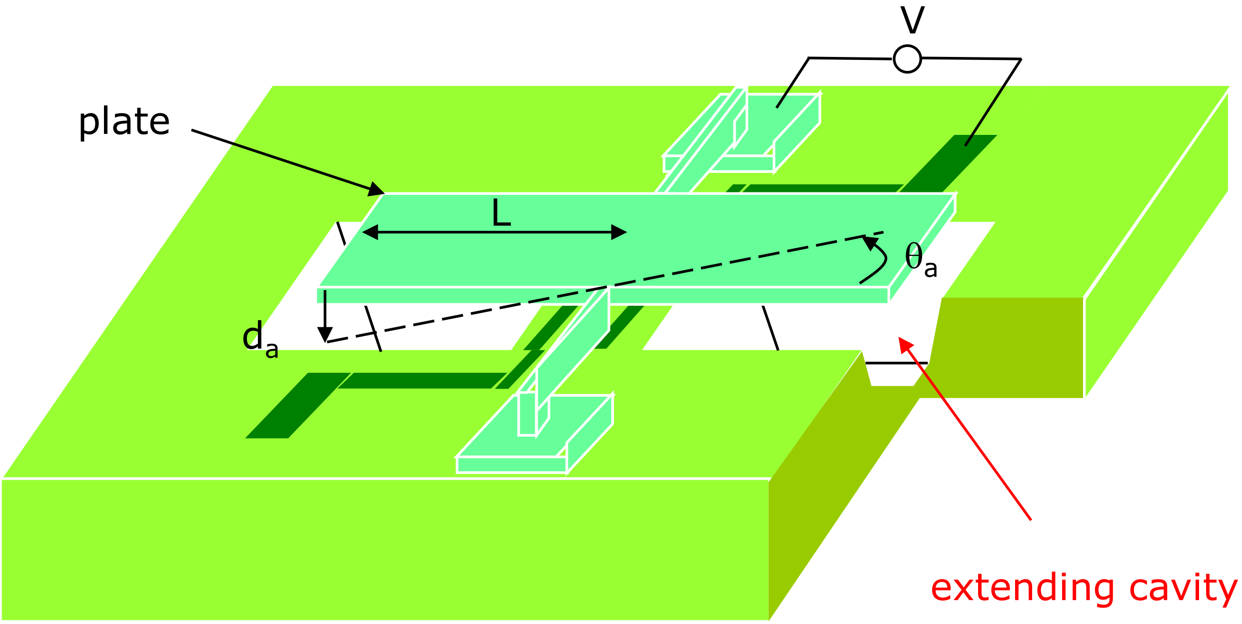
Typical operating θ-V curve



B -- C Pull-in
C -- D Hysteresis

- To overcome the size limitation of META

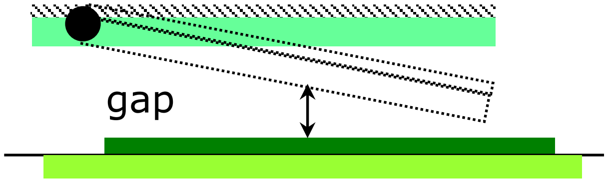




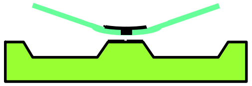
META with extending cavity

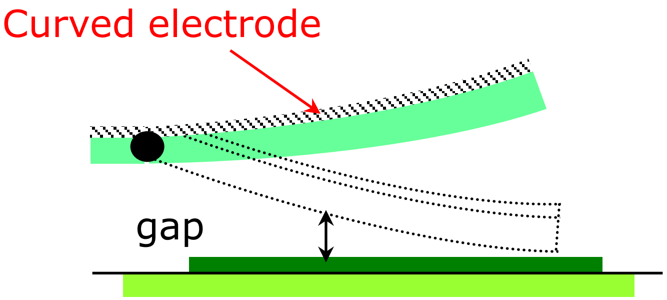
- To improve the electrostatic property of META

  - conventional ~
    gap decrease drastically



  - proposed ~
    gap decrease smoothly





Fabrication processes and results

- Integrating and surface process and front-side bulk etching

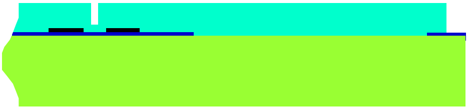
(a)

Deposit protection/isolation layer

↘ (b)

Define cavity and lower electrode

(c)



Pattern sacrificial layer

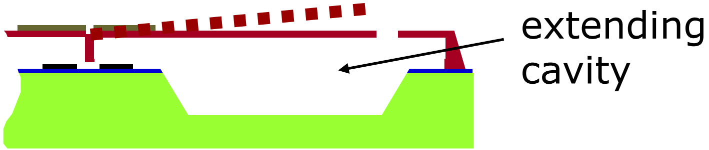
(d)

Pattern structural layer

(e)

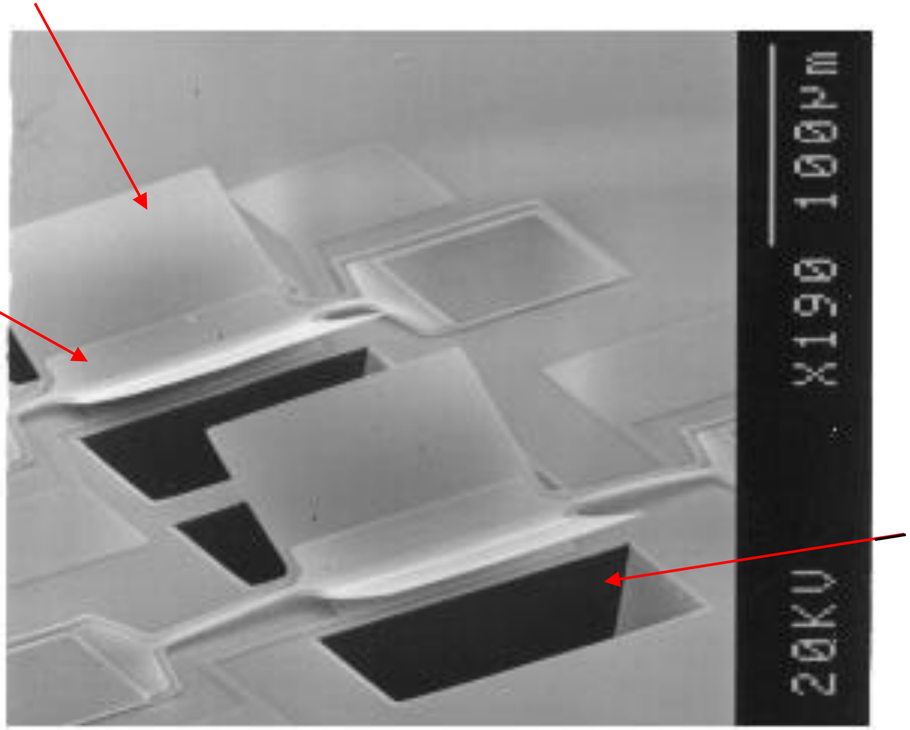
Pattern top electrode (option)
and then remove sacrificial layer

(f)



Releasing structure and etching Si

Fabrication processes

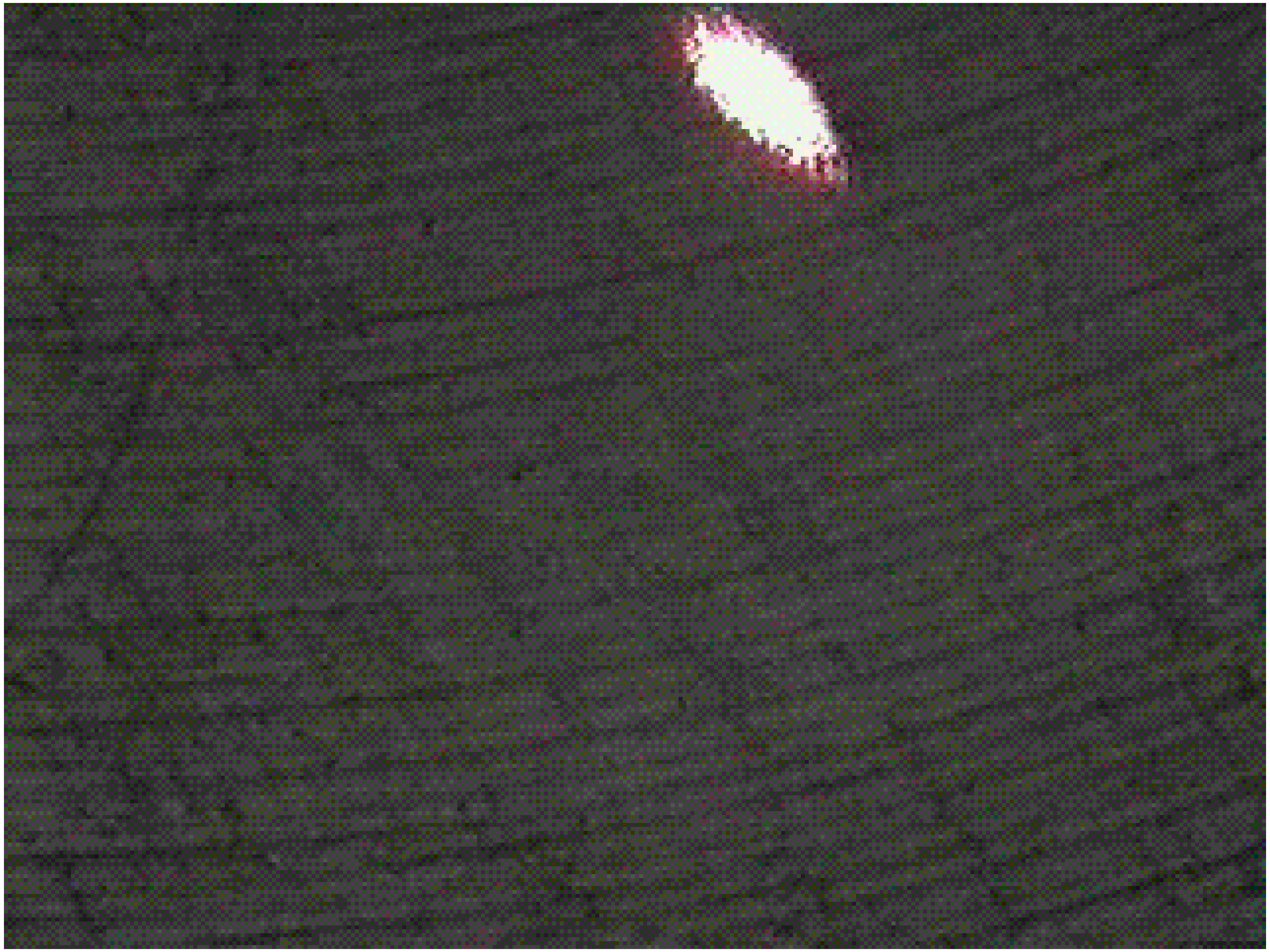


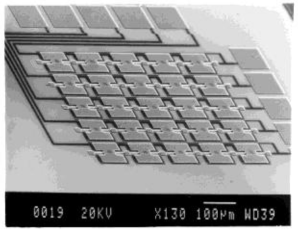
uncurved mirror plate

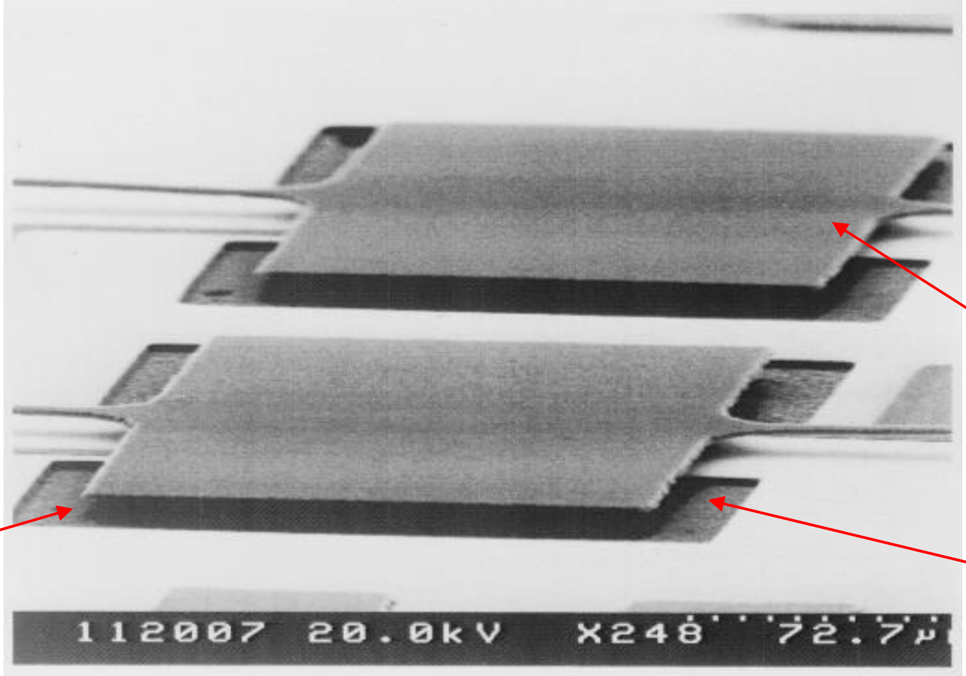
curved electrode

extending cavity

J. Hsieh and W. Fang, *Sensors and Actuators A*, 2000
J. Hsieh and W. Fang, *Transducers99*, 1999





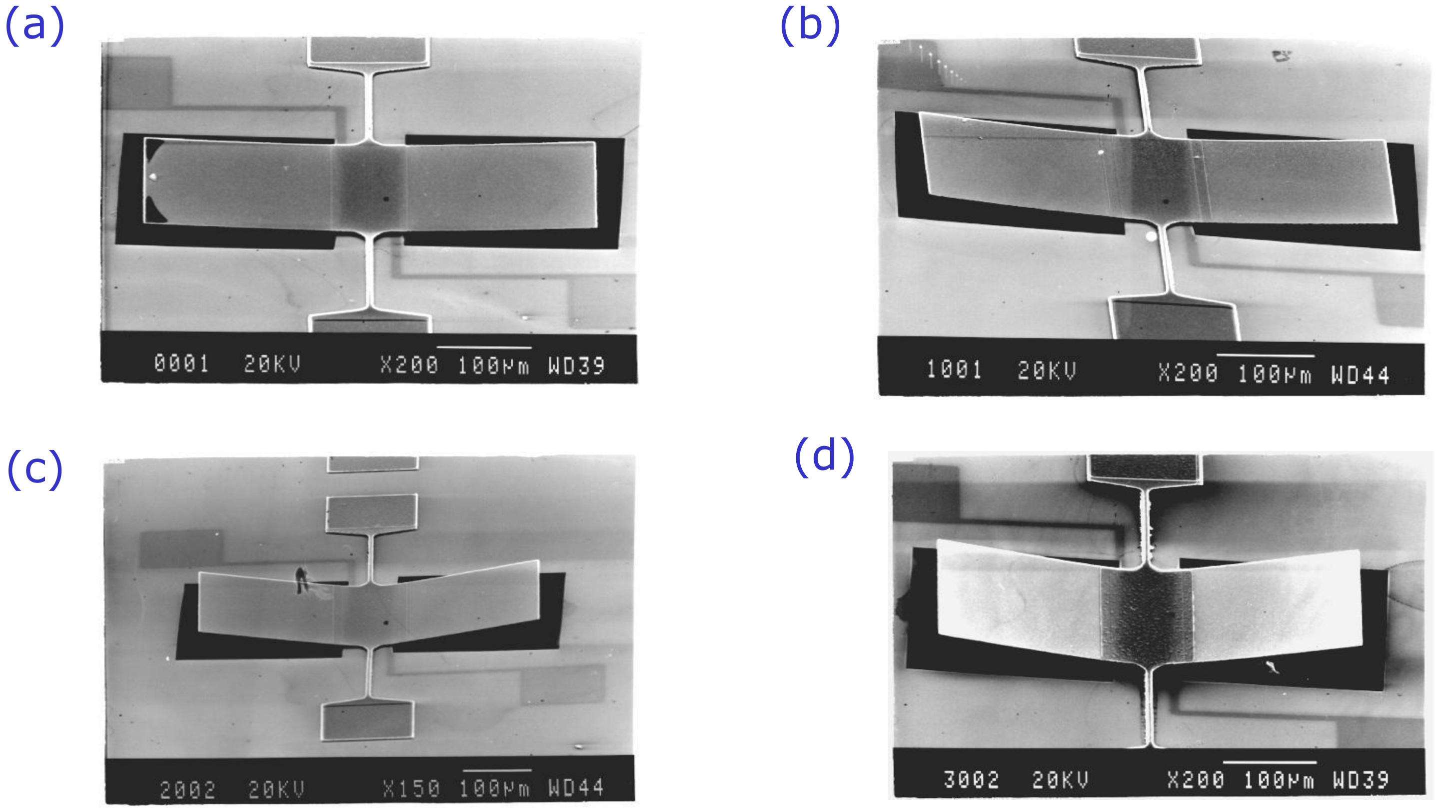


large gap

flat plate surface

extending cavity

META with extending cavity
(Al as plate material)

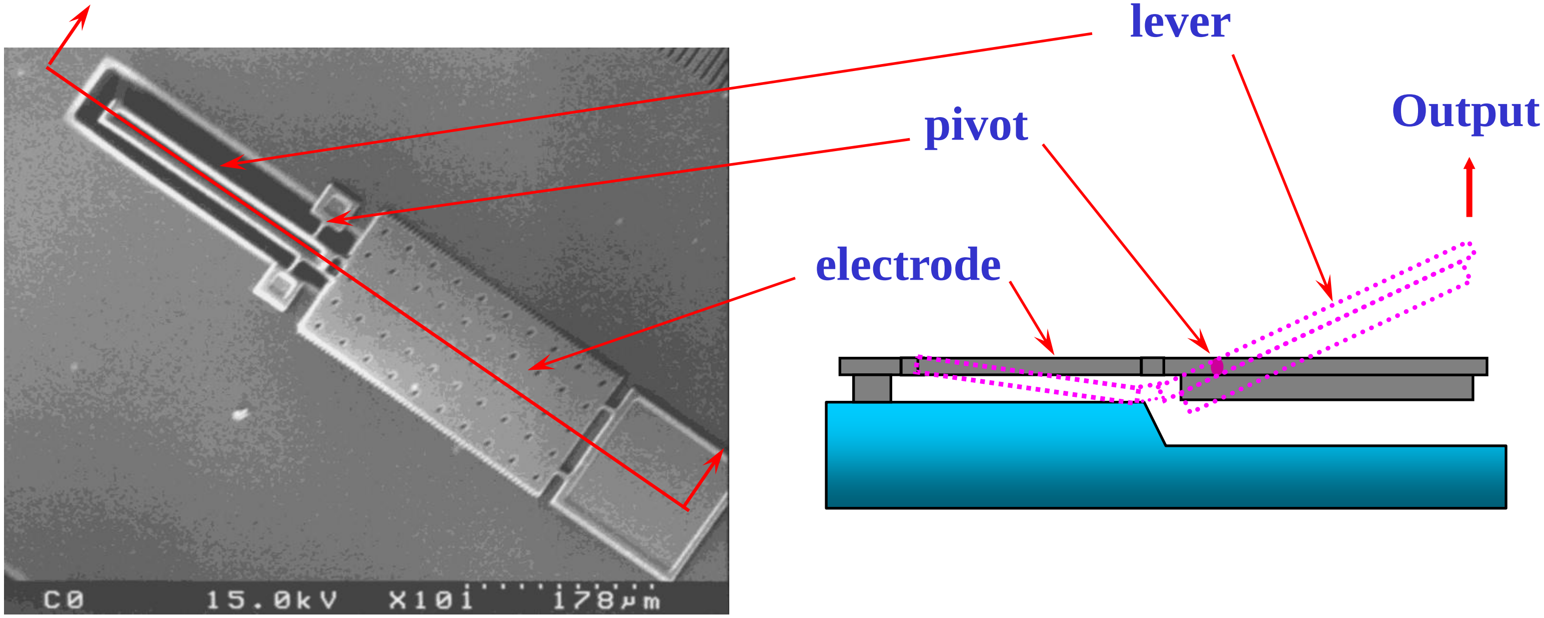


Fabricating result upon different top electrode thickness
(a) 0 (b) 0.1μm (c) 0.19μm (d) 0.3μm

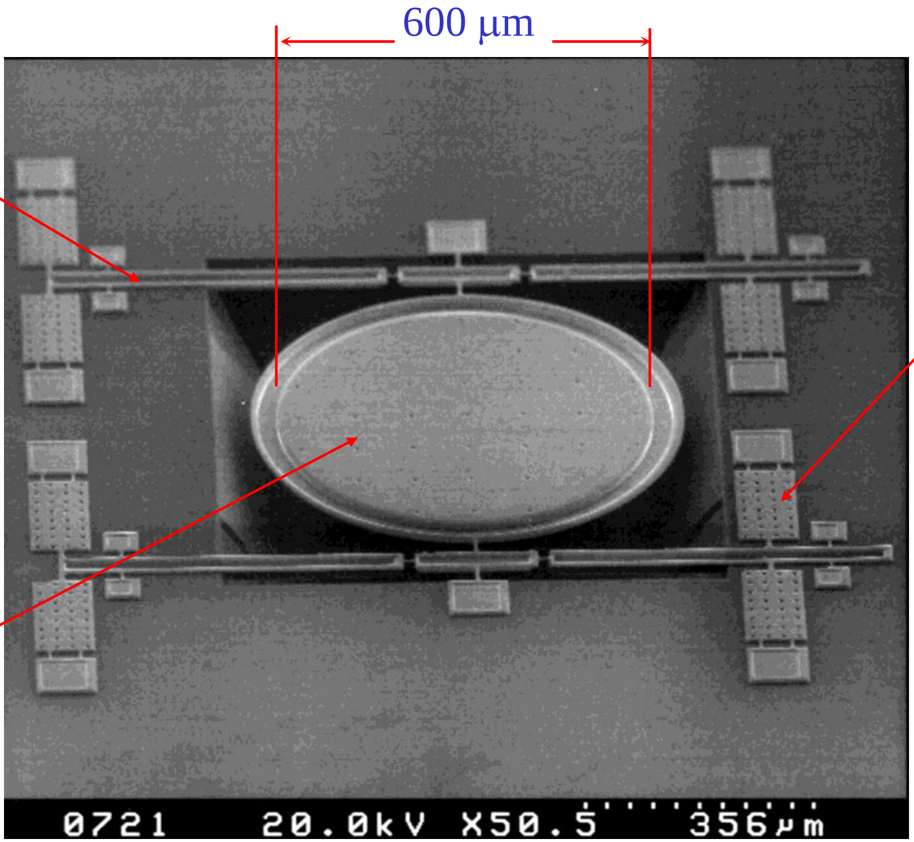
MDL
NTHU

Gap-closing Lever Actuator

- **EDLA Engine** (**E**lectrostatically-**D**riven-**L**everage **A**ctuator) :
  Out-of-plane Gap-closing Electrostatic Actuator



H.-Y. Lin, H. Hu, and W. Fang, *Transducers'01*, Munich Germany, 2001

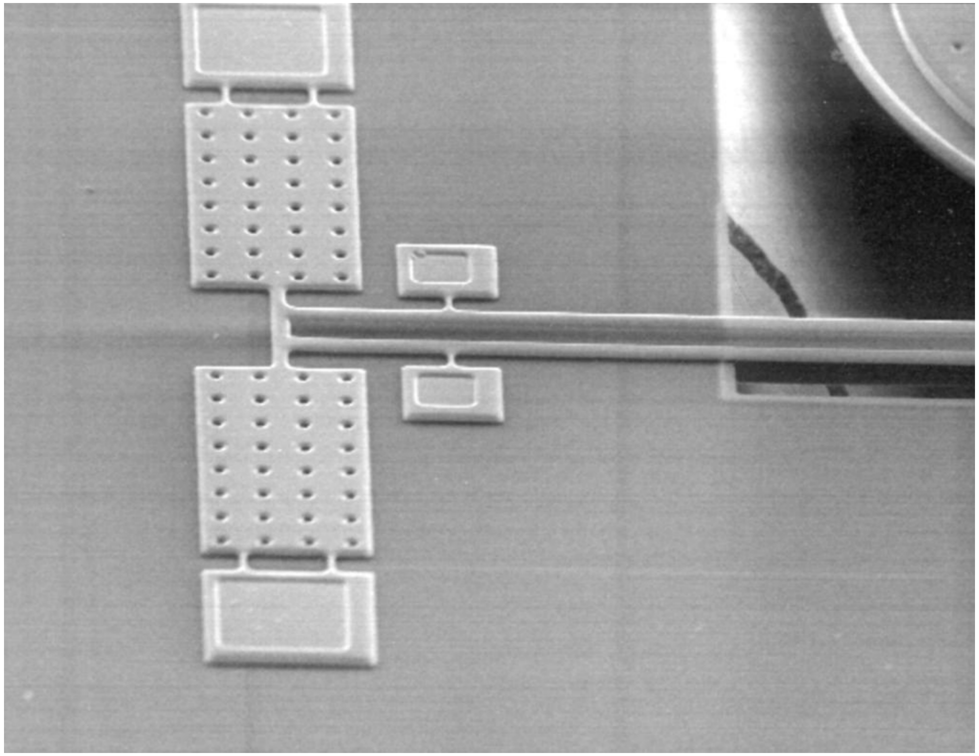


lever-mechanism

gap-closing
electrode

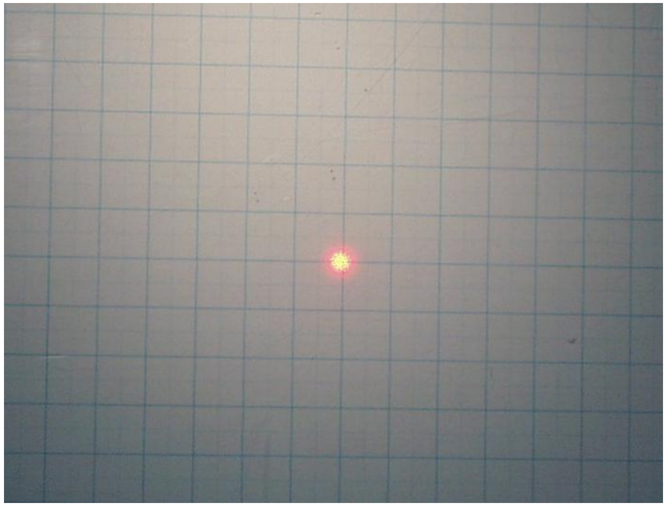
stiffened mirror with
reinforced frame

H.-Y. Lin and W. Fang, IEEE Optical MEMS 2000, 2000

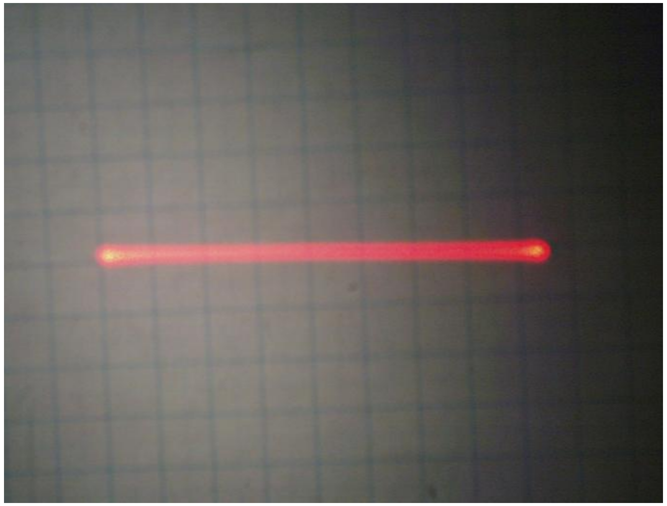


H.-Y Lin and W. Fang, ASME IMECE 2000, 2000

- Laser light scanning



Before scan



After scan at 17.7 KHz

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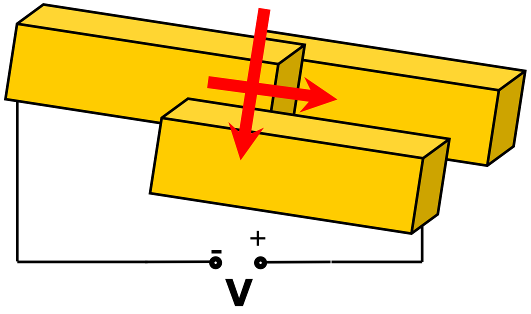
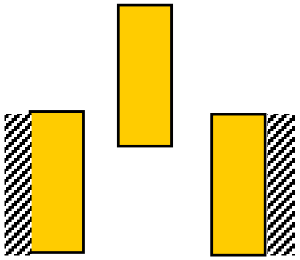
NTHU

Vertical comb



Side view



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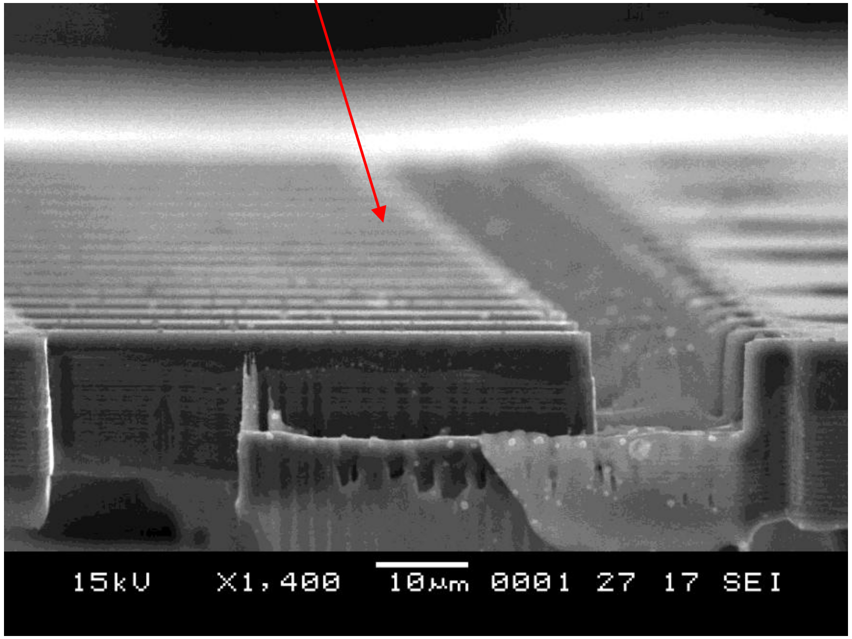
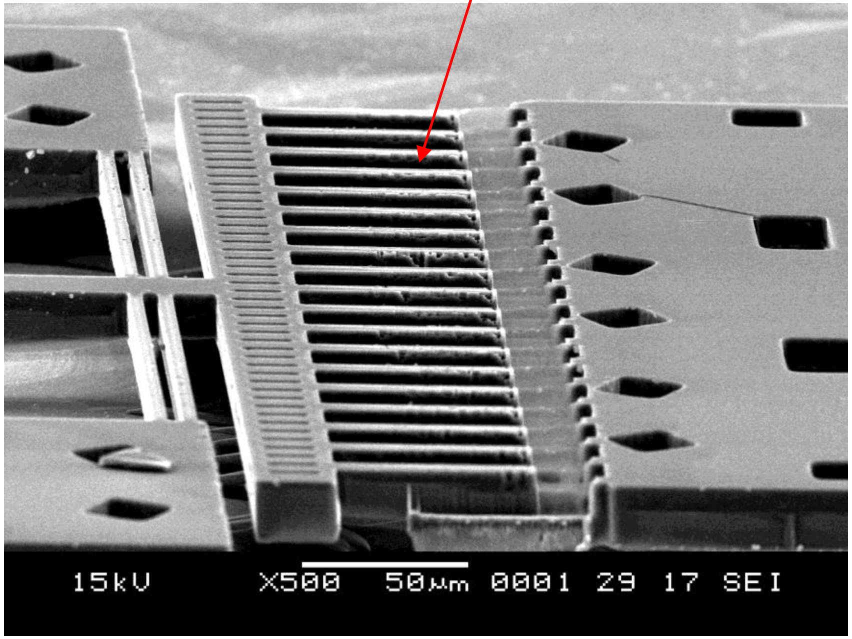
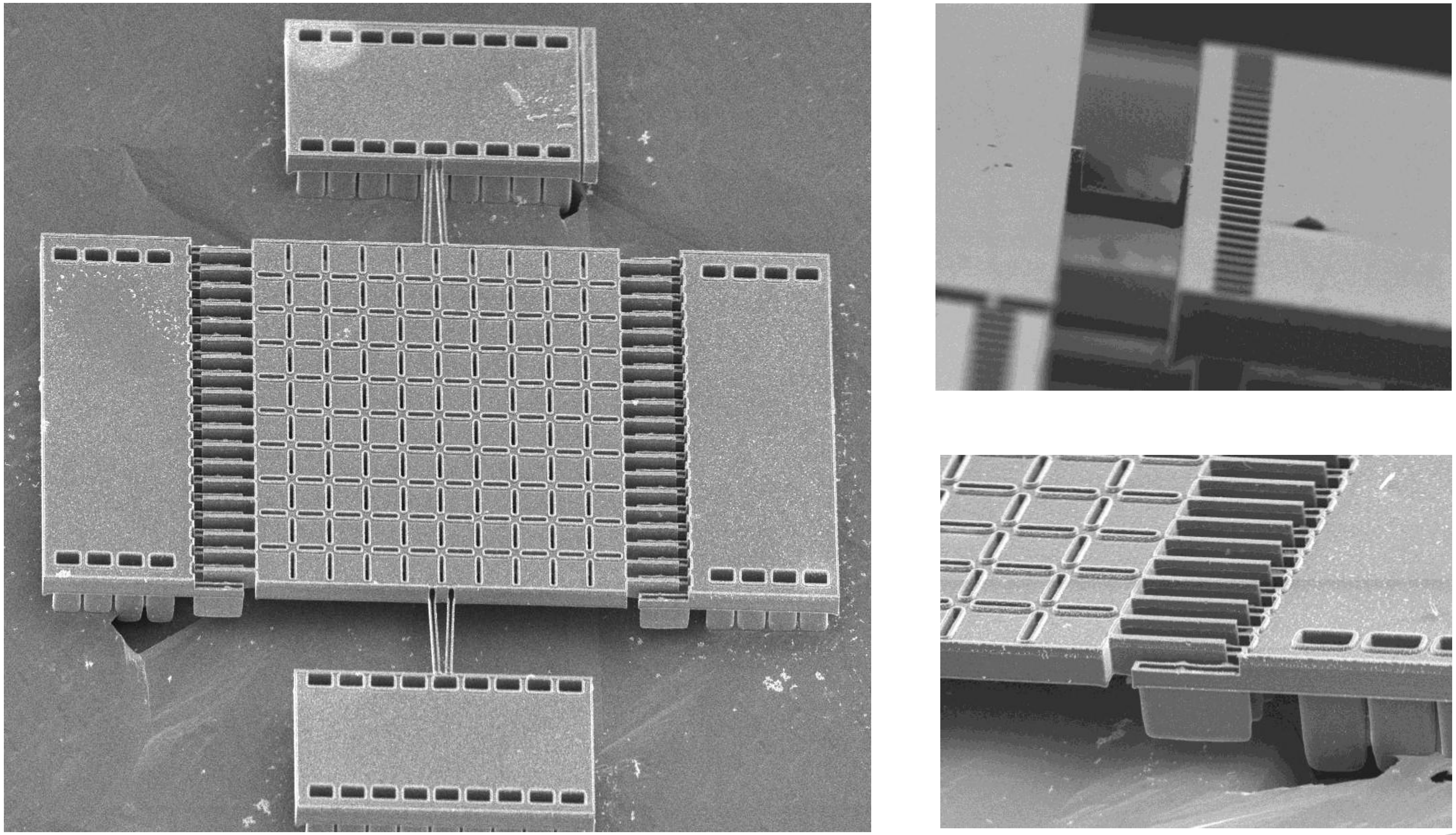
NTHU

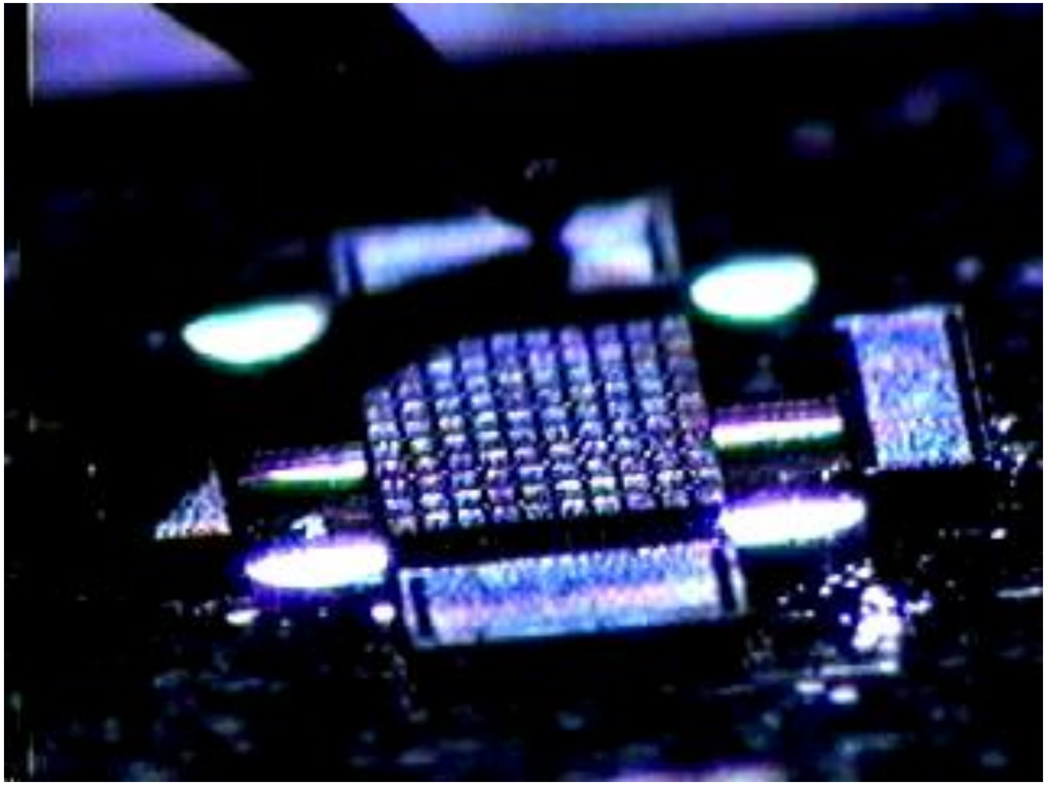

Comb electrode

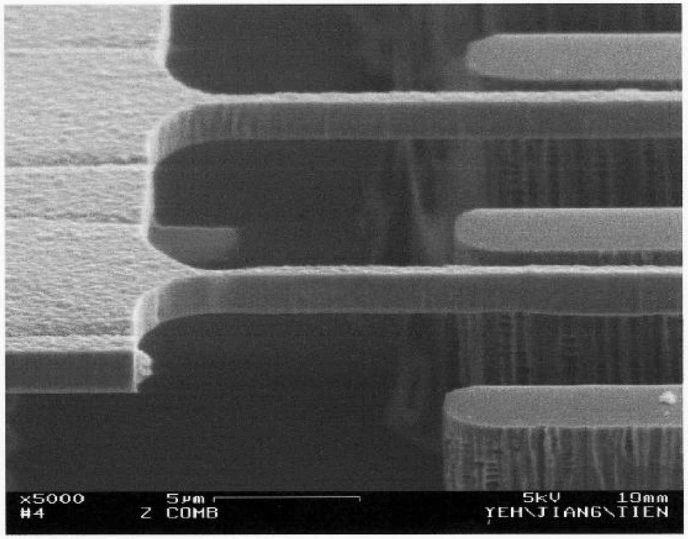

Comb electrode

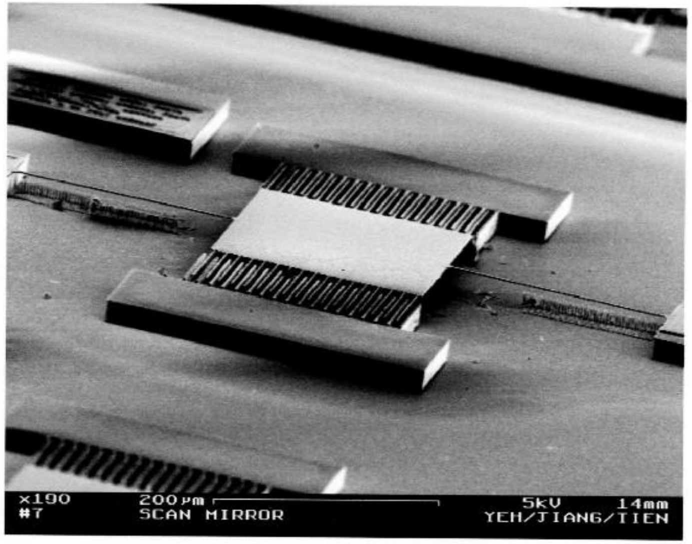
J. Hsieh, C.-C. Chu, M.-L. Tsai, and W. Fang, *IEEE Optical MEMS'02*, 2002



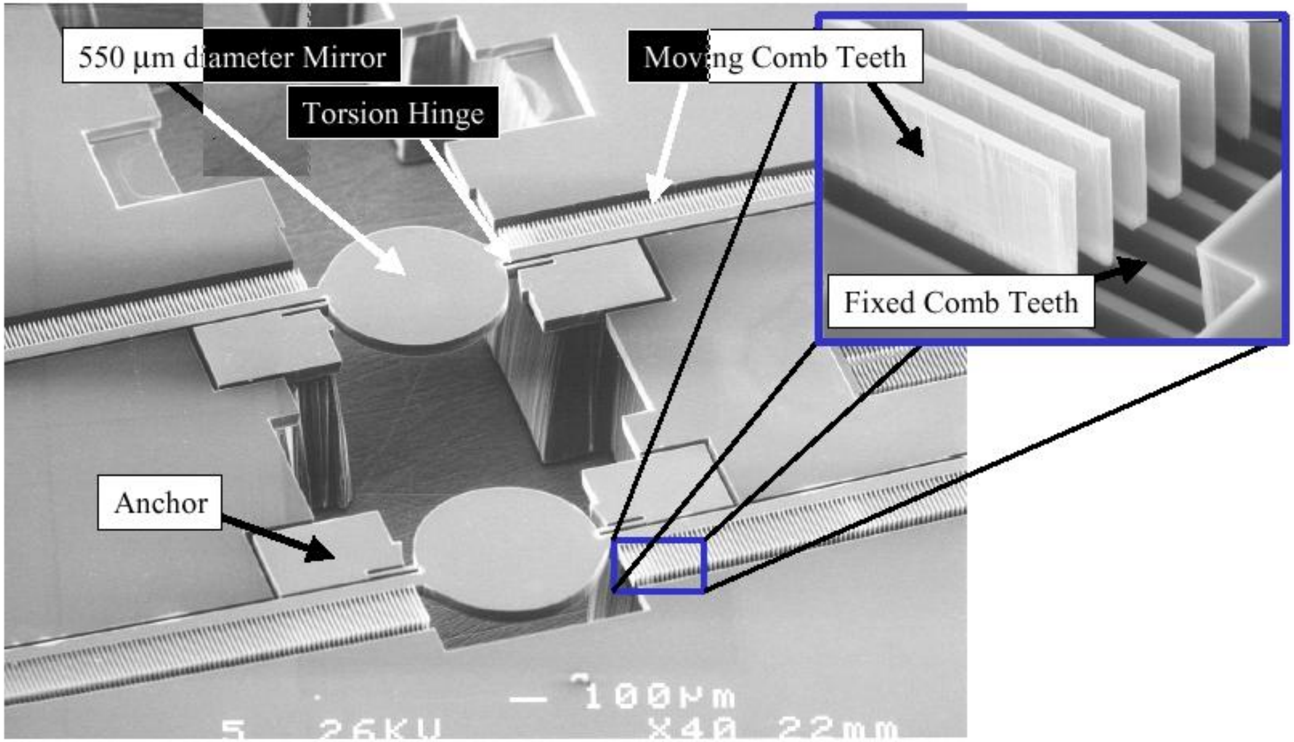
J. Hsieh, C.-C. Chu, M.-L. Tsai, and W. Fang, ***IEEE Optical MEMS'02*****, 2002**







J. A. Yeh et. al , University of Comell , 1999

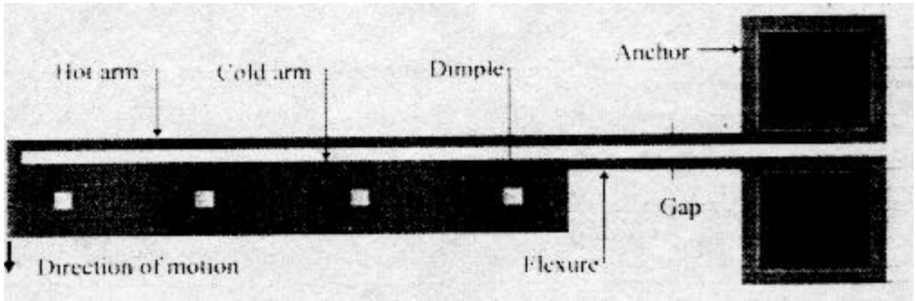


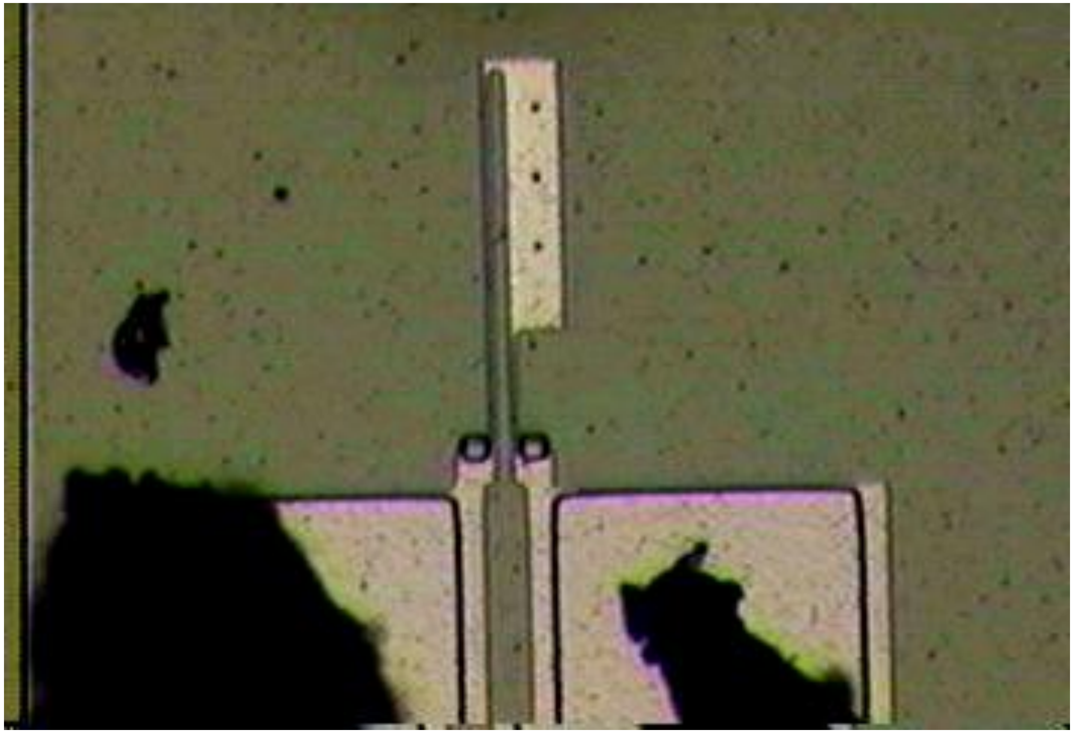
R. A. Conant et. al , UC Berkeley , 2000

In-Plane Thermal Actuators

Hot-cold arm thermal actuator

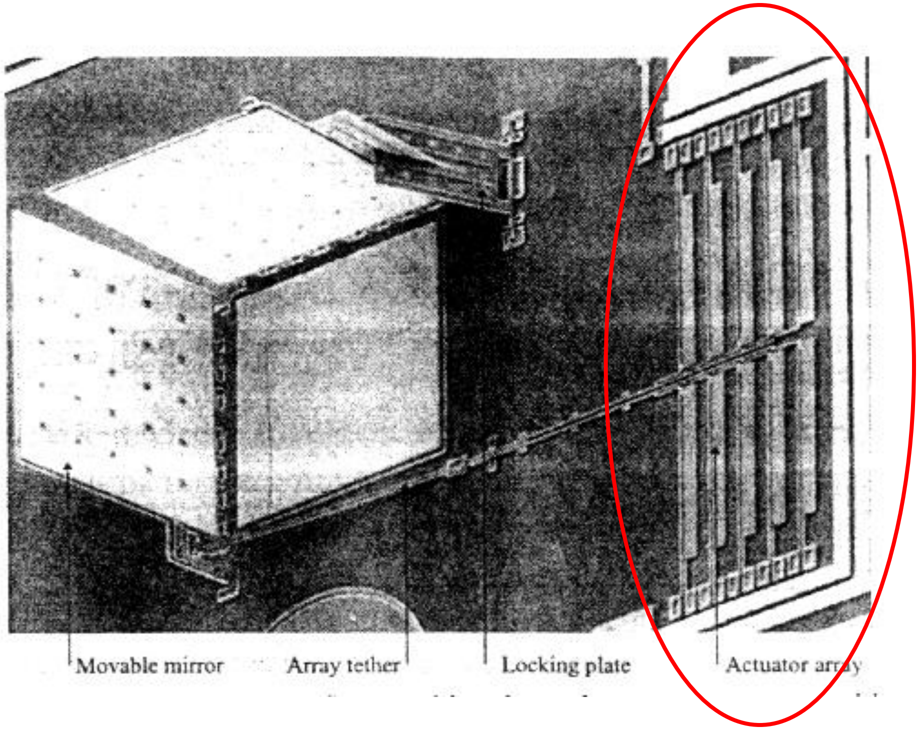
- 220μm長，2μm厚
- 2.94V， 3.86mA
輸出力4.4μN
- 最大變形量16μm
- 8μm at 300 Hz
- 1.75μm at 1 KHz





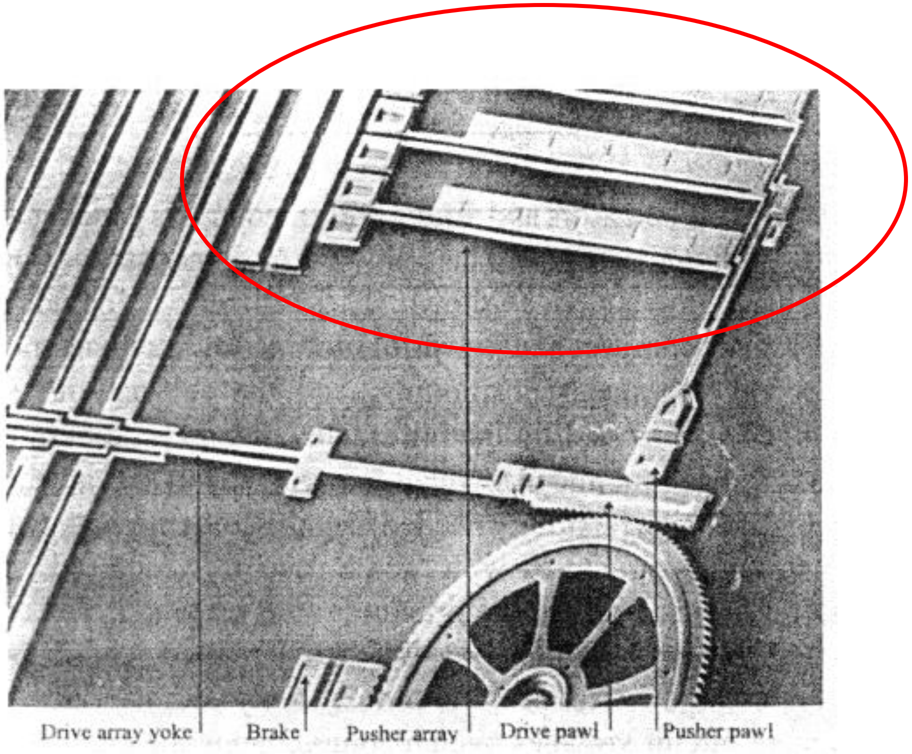
MDL
NTHU

- 單熱臂
- 入射光延原方向反射
- 3.5 mrad tolerance
- Au 膜
- 4.5µm plate thickness



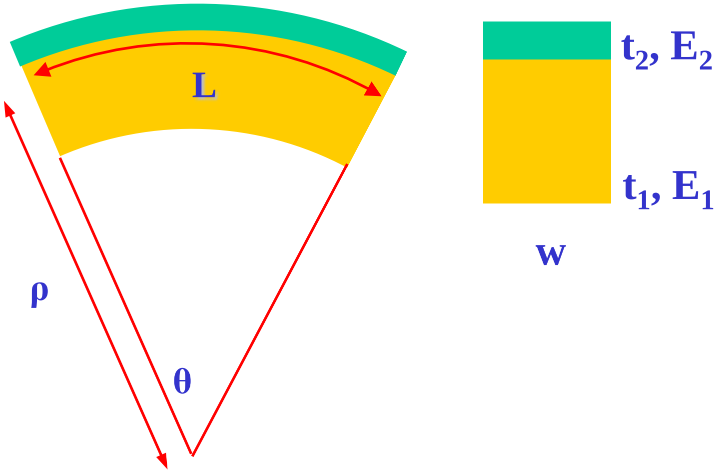
- 單熱臂
- 主微致動器驅動轉子
- 副微致動器頂住驅動齒桿
- 背向彎曲的應用

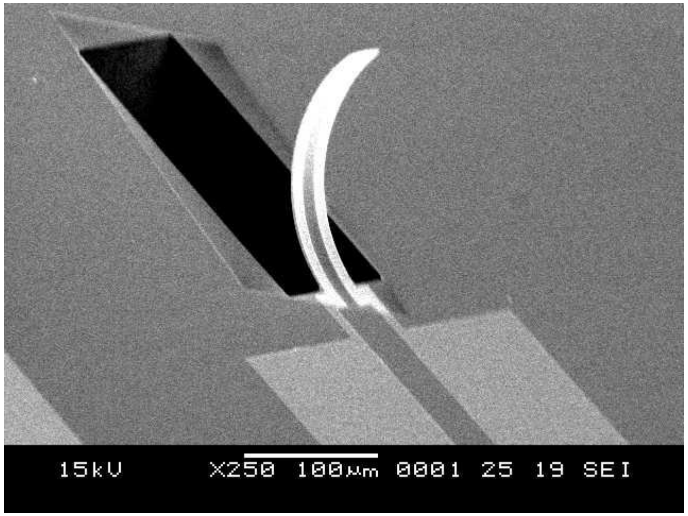
  - 7.5 V, 5 sec
- 驅動電壓 3.7 V



Out-of--Plane Thermal Actuators

Bimorph thermal actuator



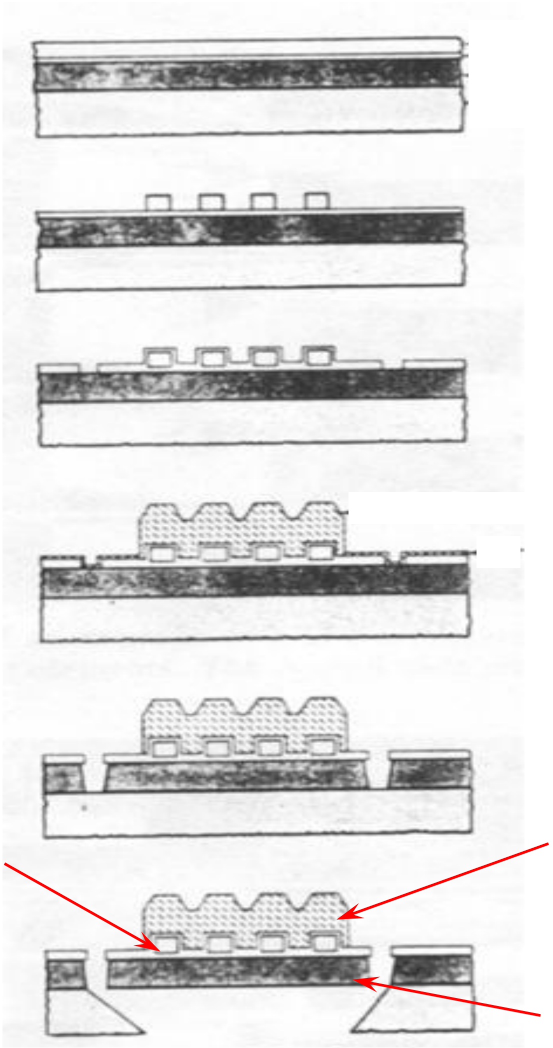


$$\rho = \frac{E_1 h\left(3m + k/n(1+n)^2\right)}{6(\sigma_2 + m\sigma_1)}$$

where $\frac{E_2}{E_1} = m \qquad \frac{t_2}{t_1} = n \qquad h = t_1 + t_2$

$$k = 1 + 4mn + 4mn^3 + 6mn^2 + m^2 n^4$$

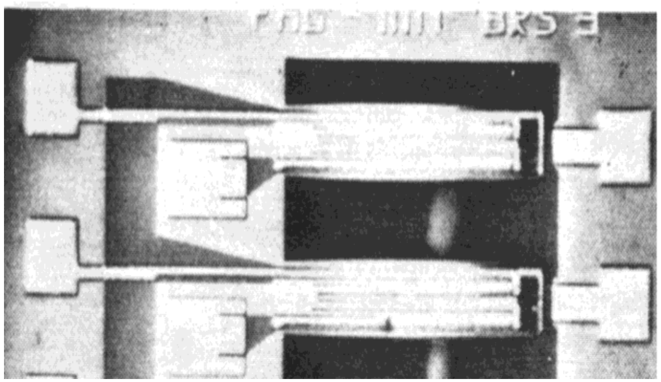
Bimorph thermal actuator



Heater
(polysilicon)

Layer 1 (Au)

Layer 2 (p+ silicon)

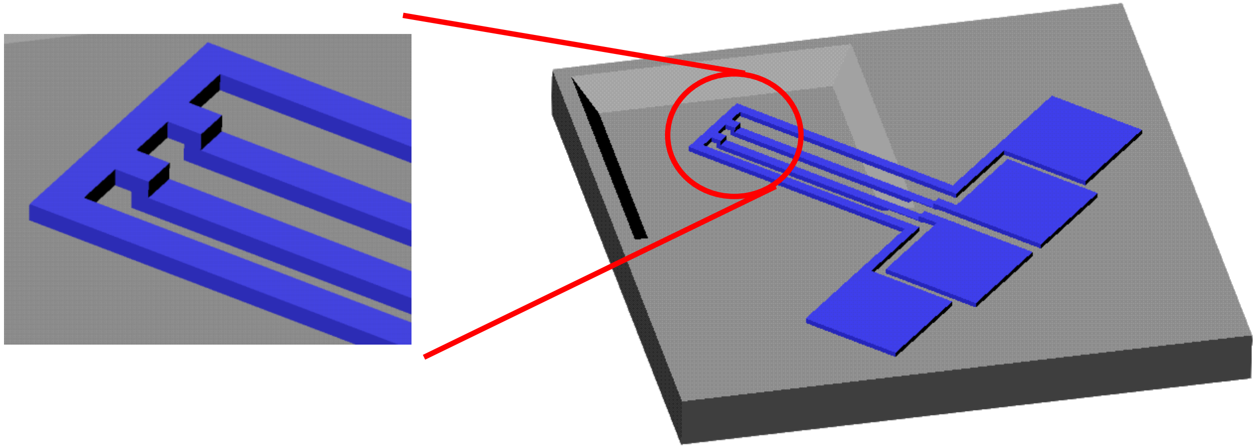


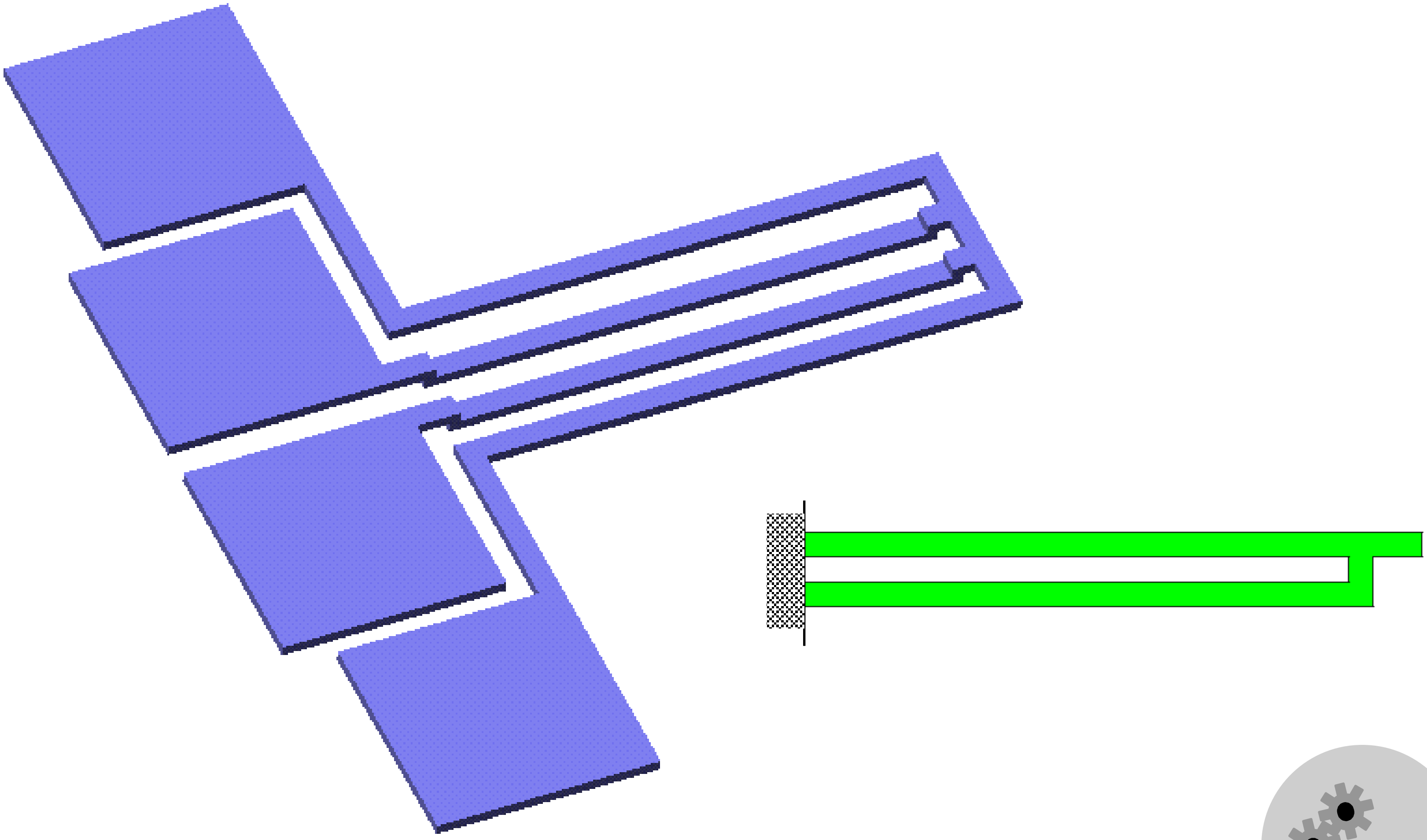
W. Riethmuller and W. Benecke, IEEE Trans. on ED, 1988.

MDL
NTHU

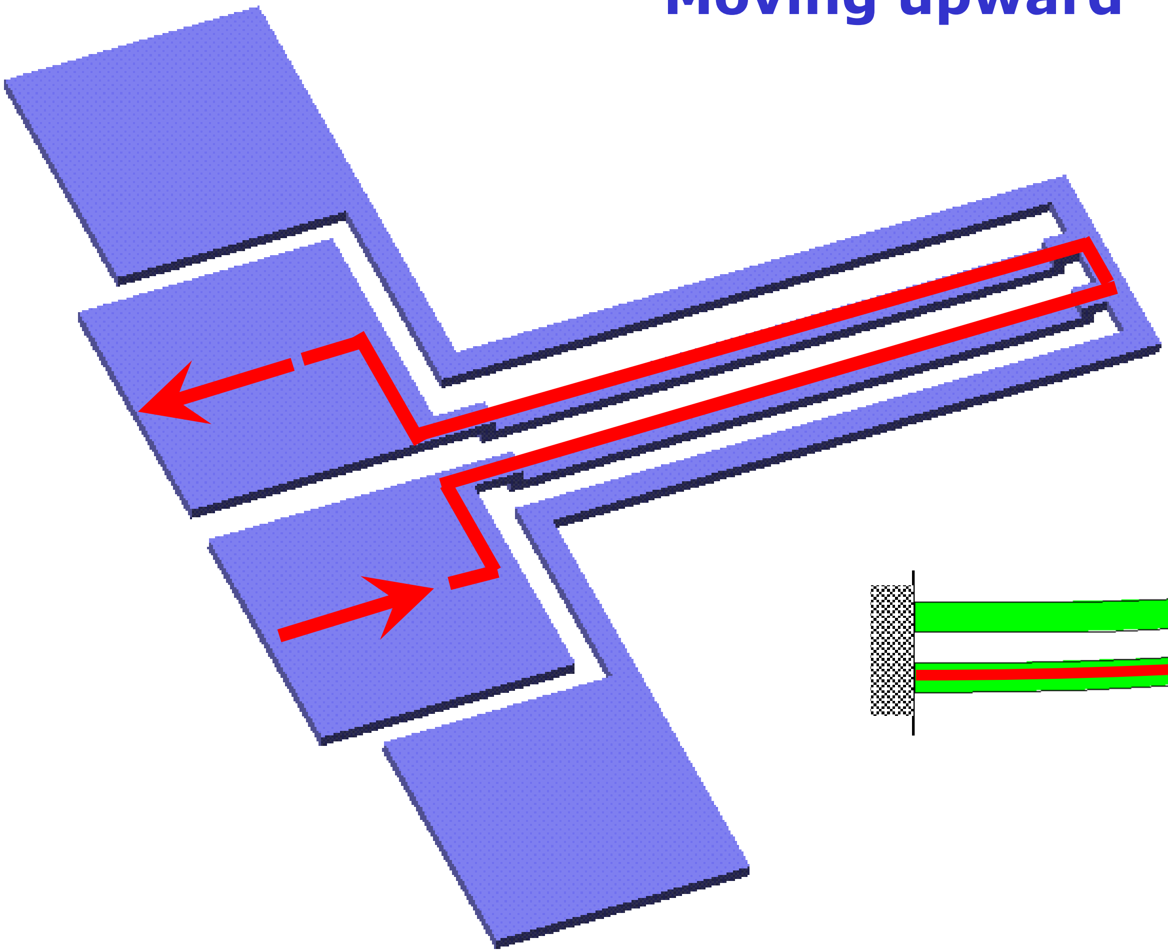
Single layer thermal actuator

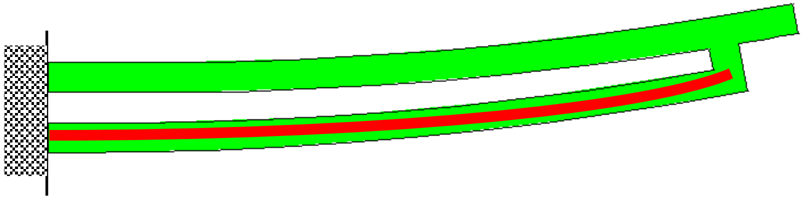
- 採單一結構層，增加元件壽命
- 具有雙向致動的能力
- 使用粗細相同的樑，可改善致動器性能及提高製程良率



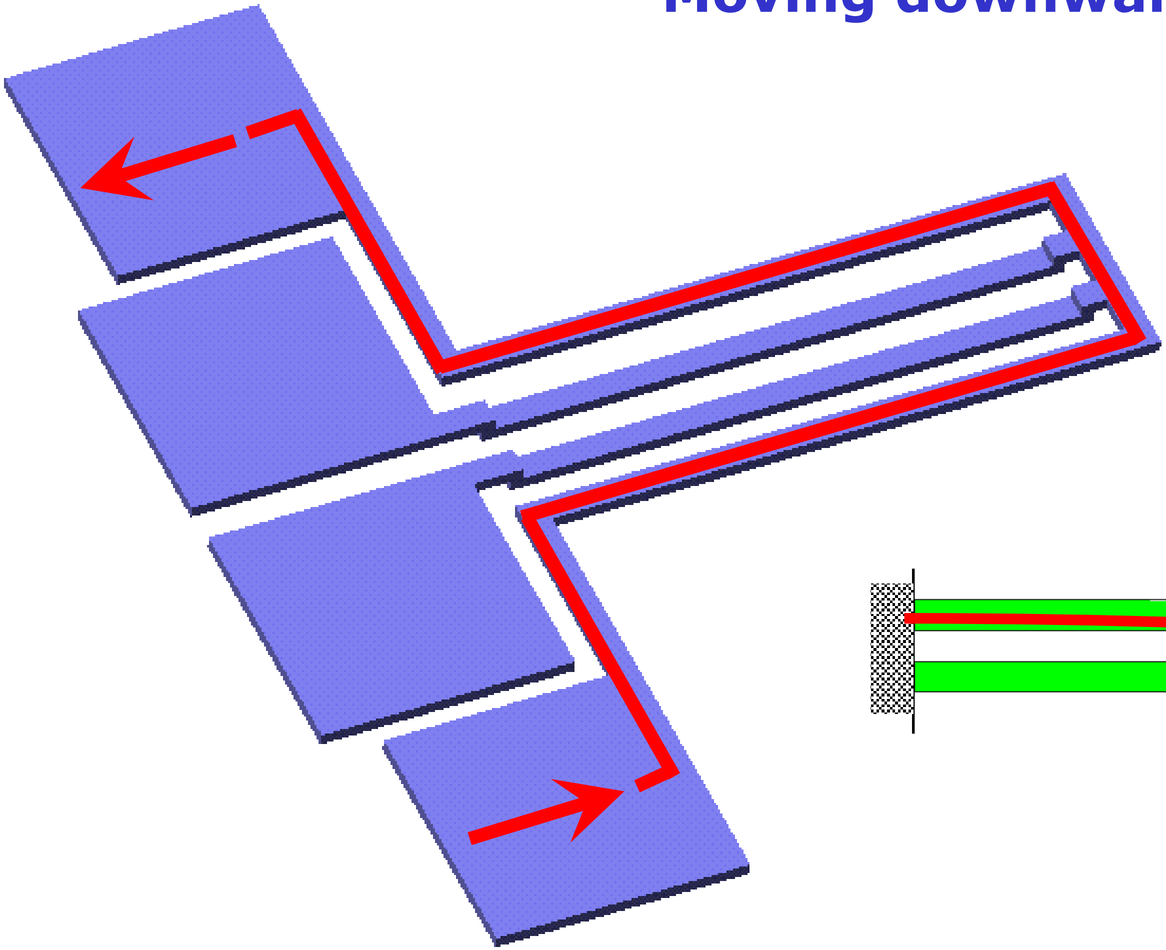


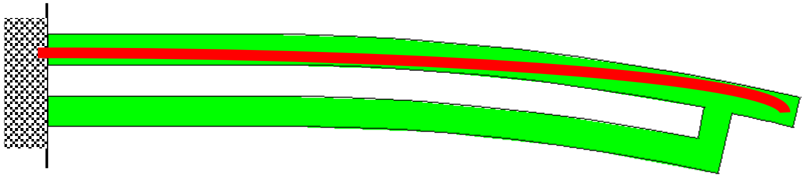
Moving upward



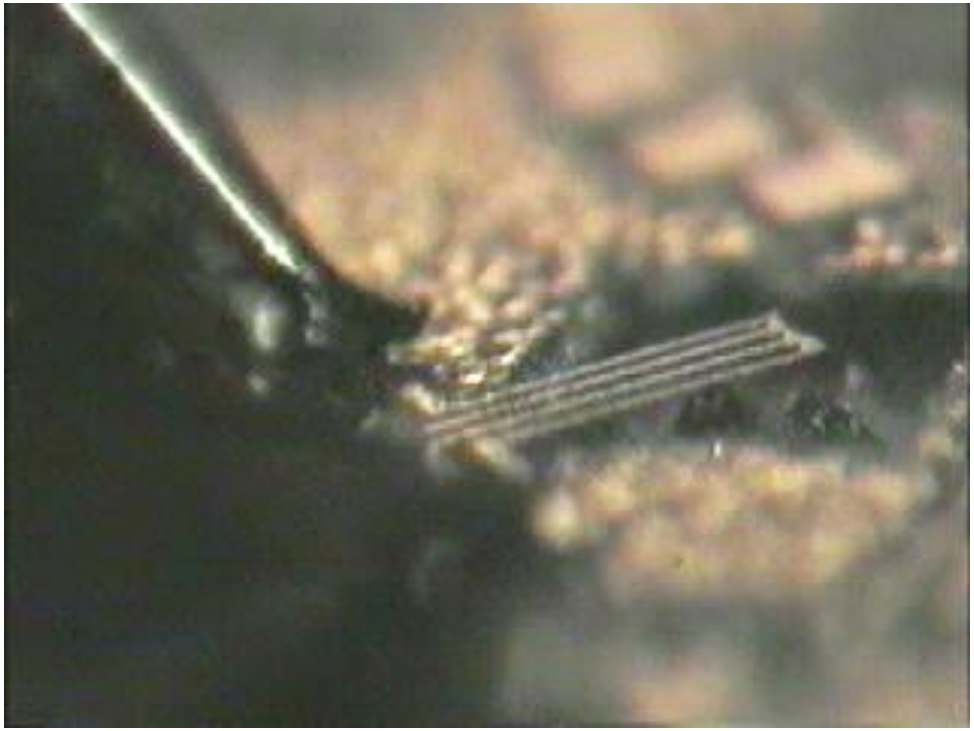


Moving downward





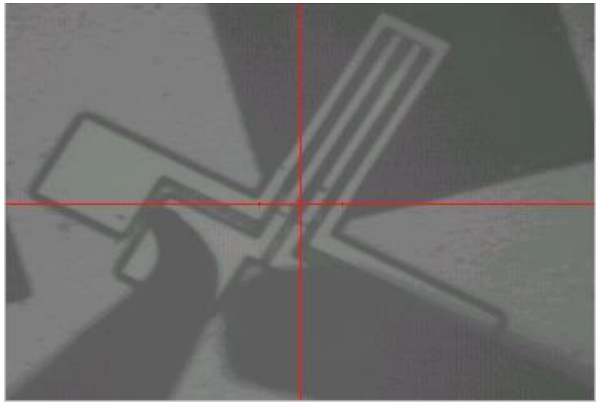
Static drive



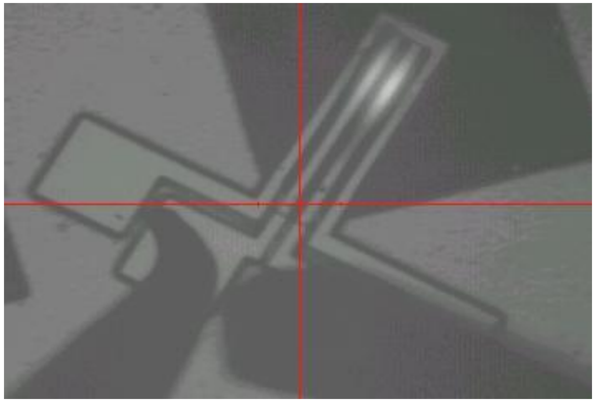
Applying voltage：0~7V

Beam length：240 μm
Beam width：10 μm

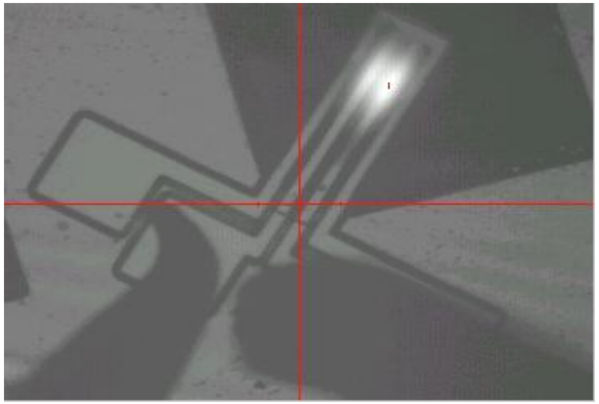
- **Temperature distribution**



V_{appl} ： 6.5V

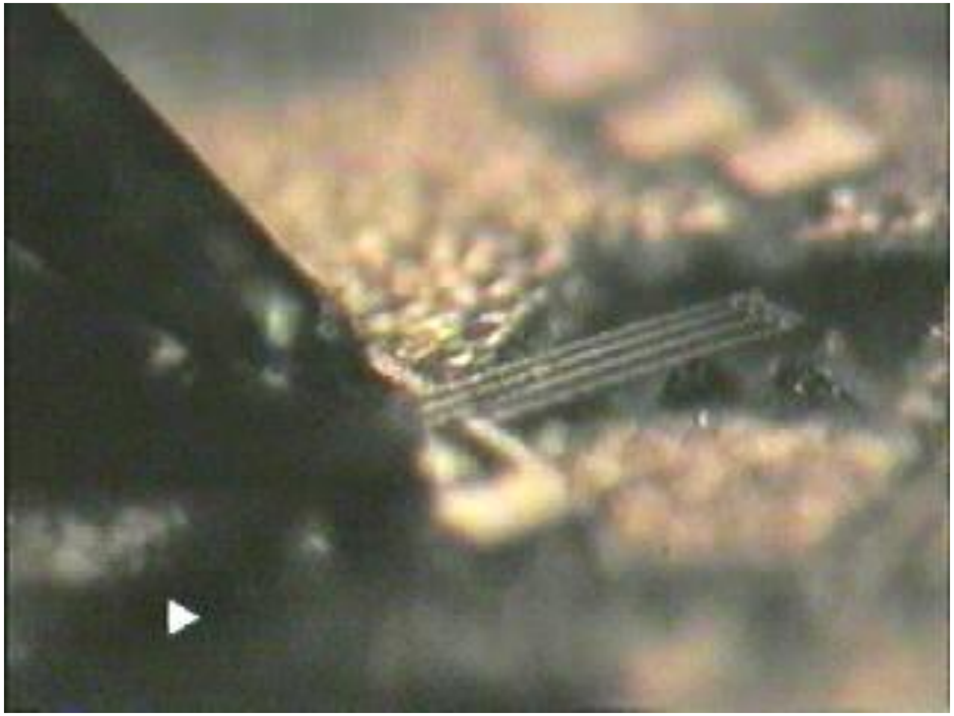


V_{appl} ： 6.7V



V_{appl} ： 6.85V

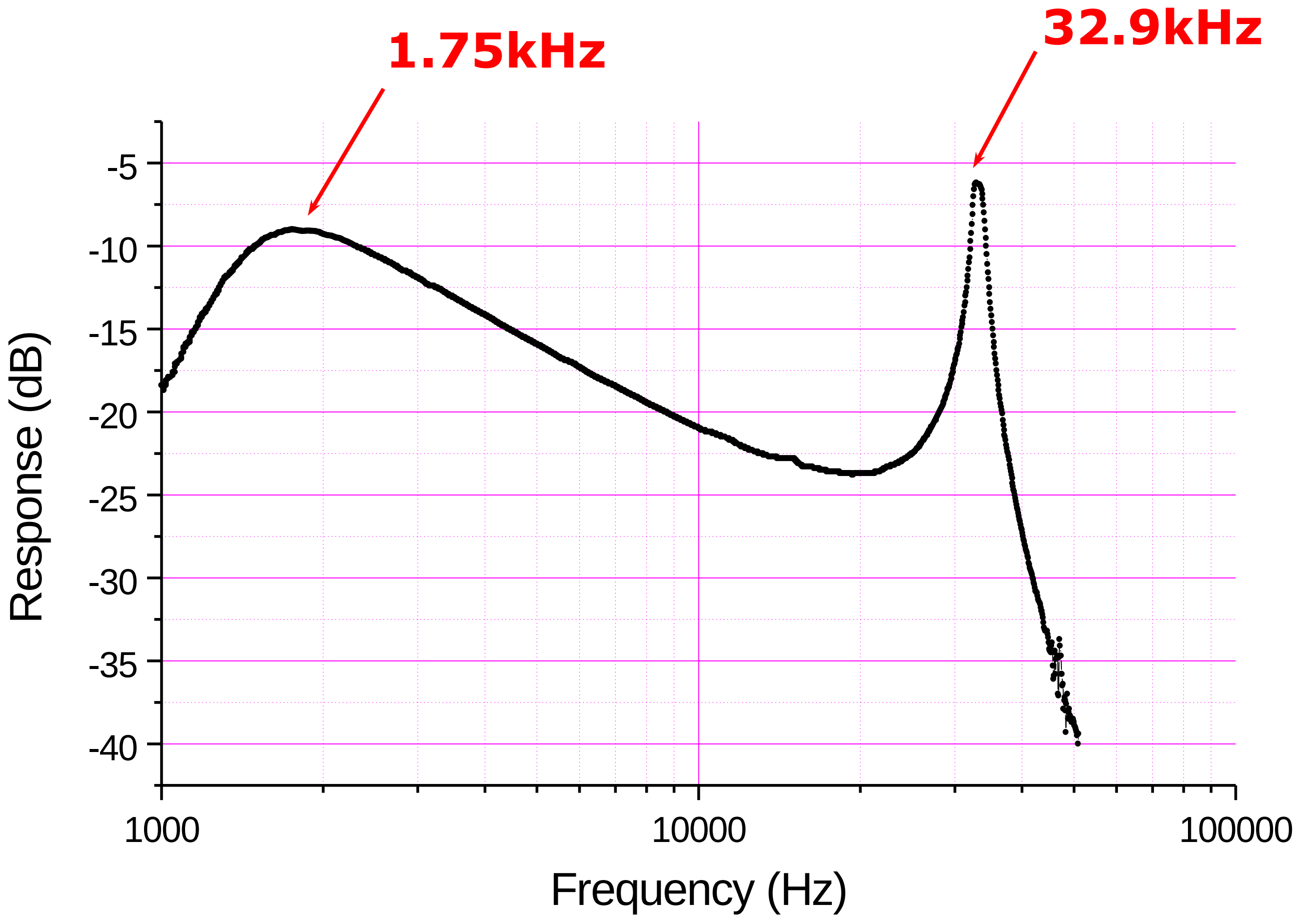
Dynamic drive



Applying voltage：5V
Driving freq : 0~200 Hz

Beam length：240 μm
Beam width：10 μm

Frequency response



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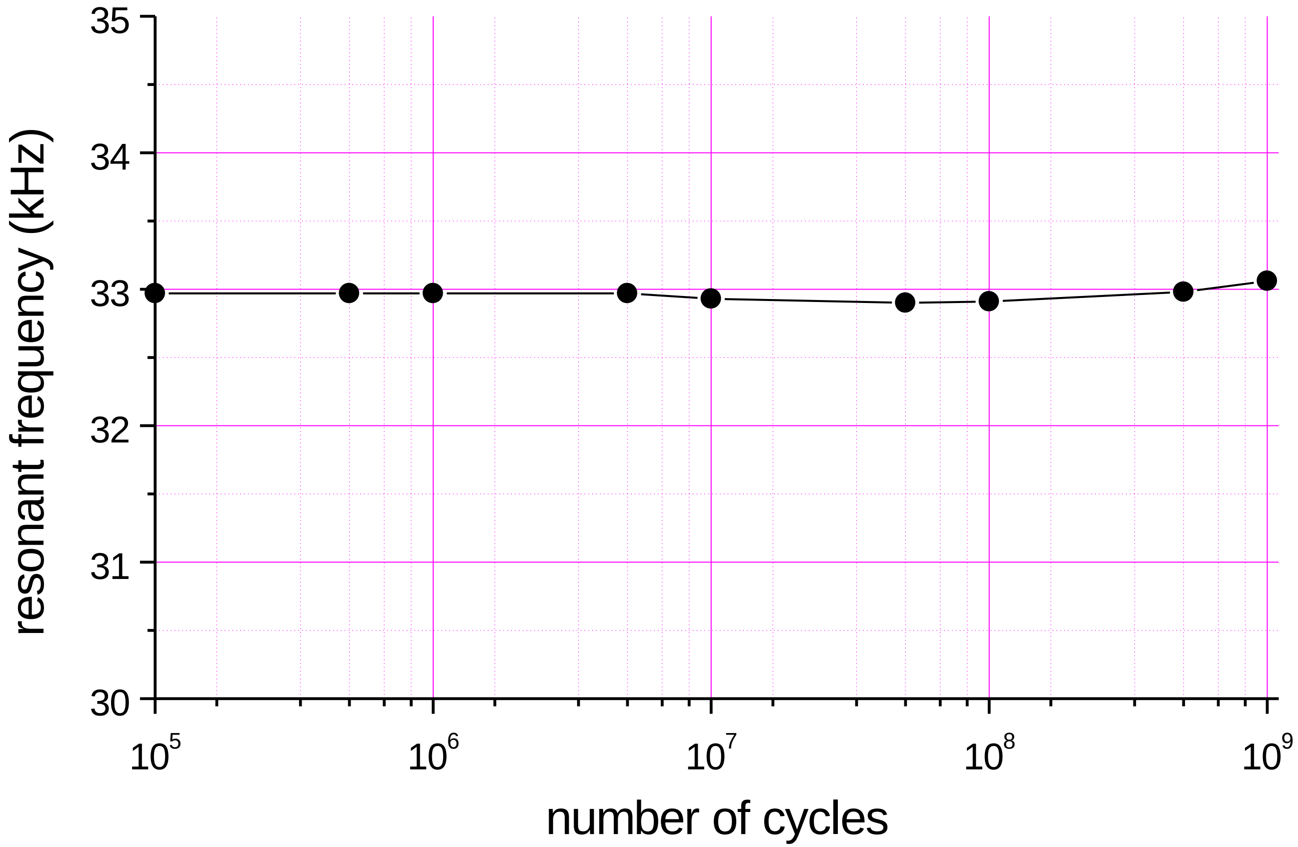
NTHU

Reliability test

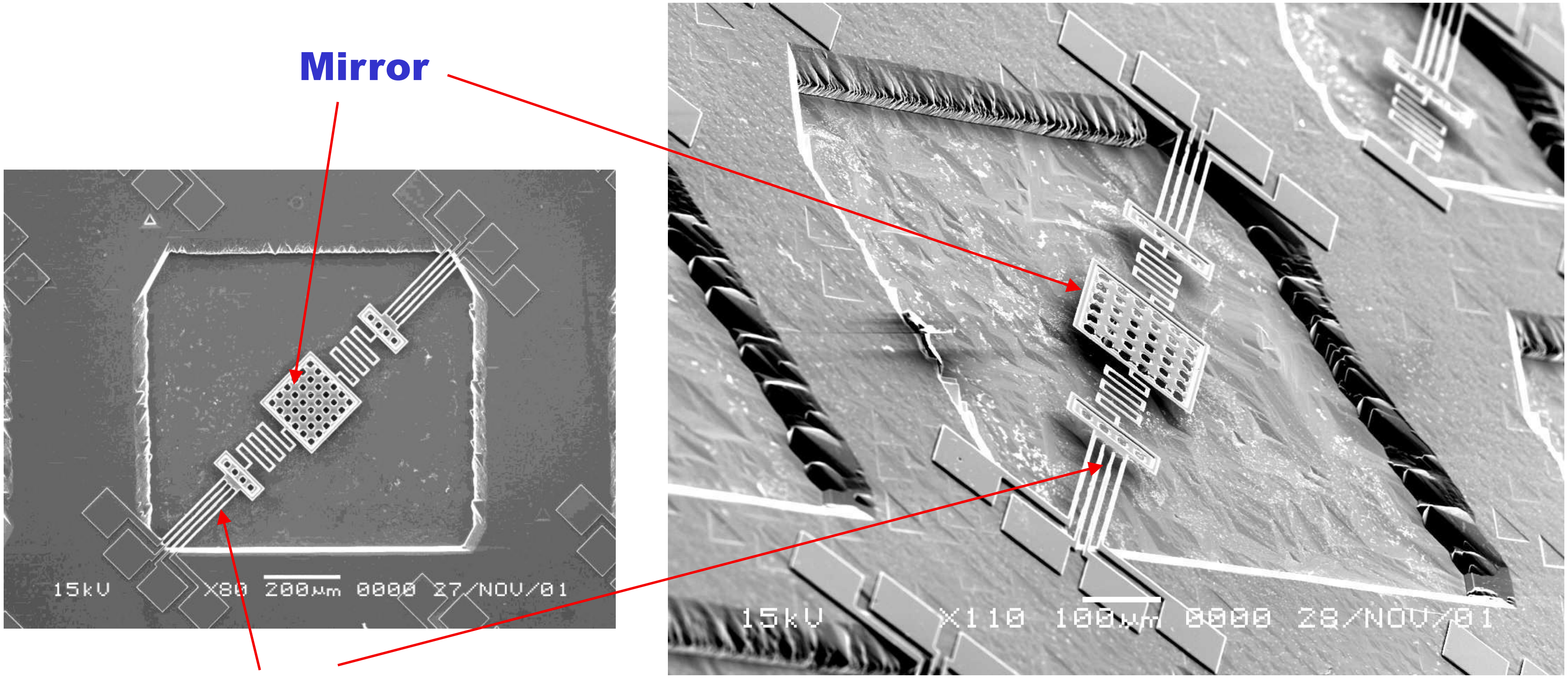


V_{appl}： 2.25V **Driving freq： 32.9kHz**

MDL
NTHU

Application - 1D scanner

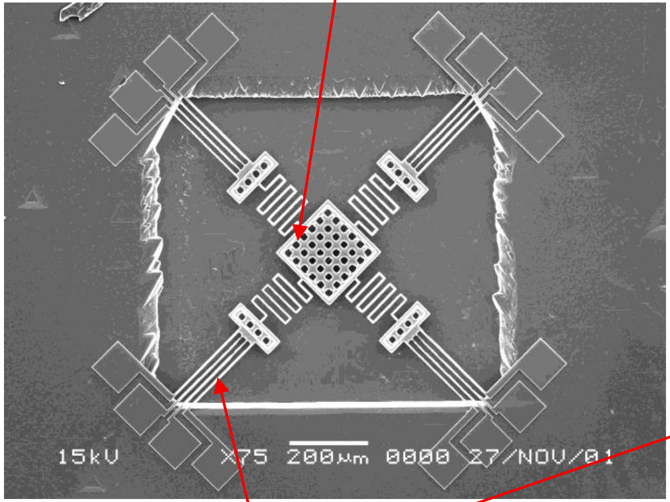
Mirror

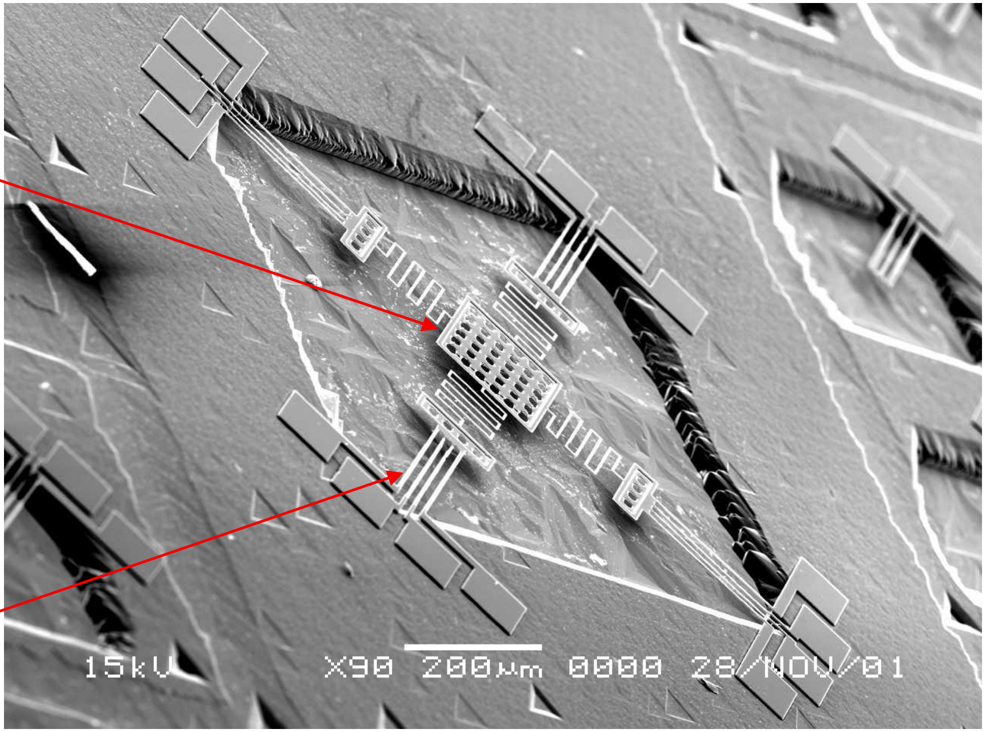


Thermal actuator

Application - 2D scanner

Mirror





Thermal actuator