Testing of Micromachined Structures

方維倫 教授
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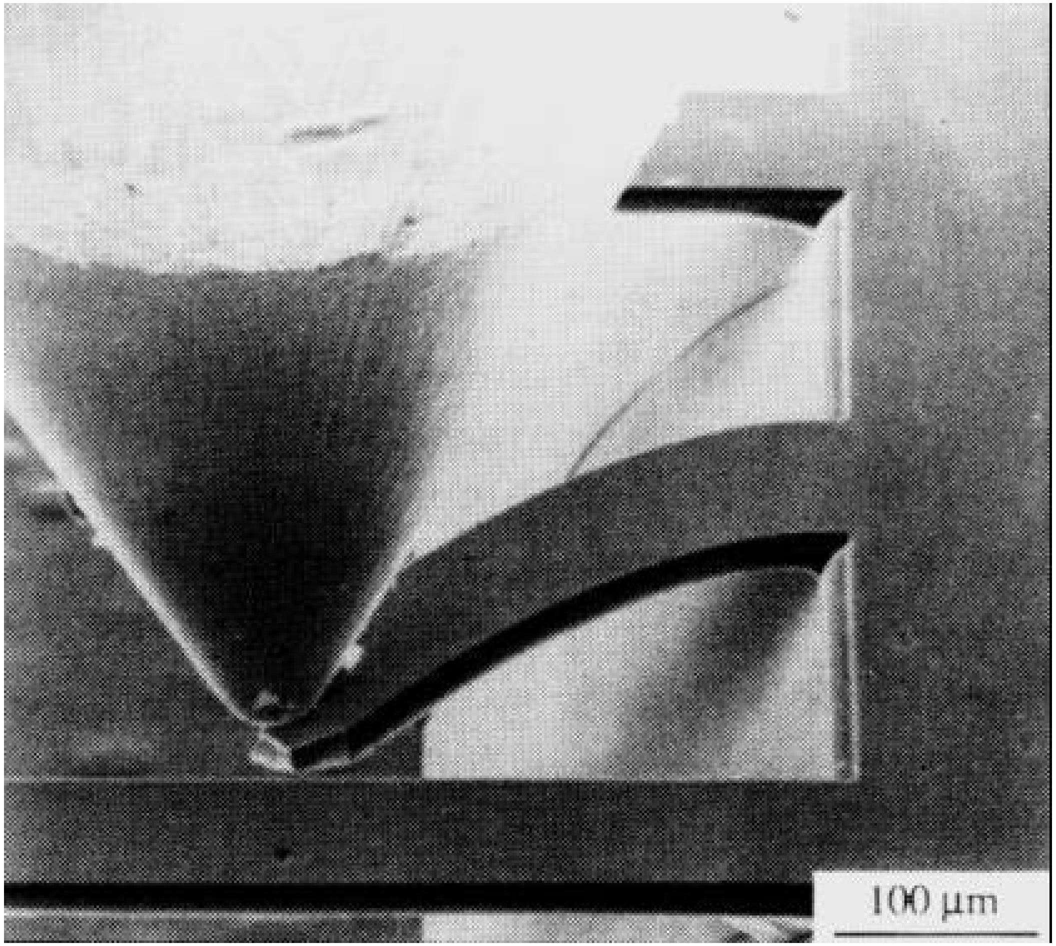
Micro Devices Laboratory
Power Mechanical Engineering Dept.
National Tsing Hua University

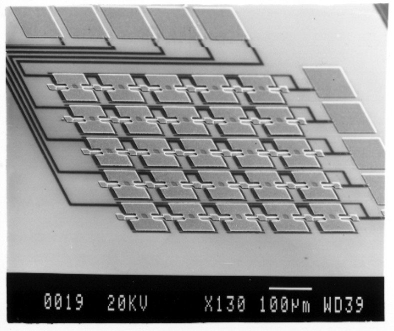
MDL
NTHU

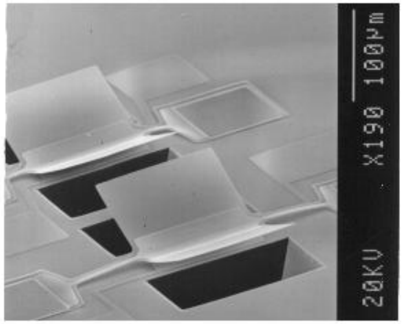


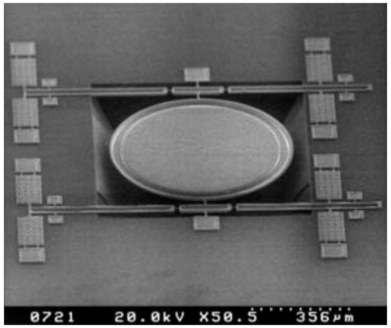
J.-A. Schweitz, 1992

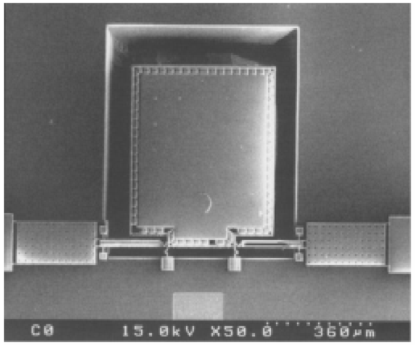
Thin Film Devices

Scanners for display

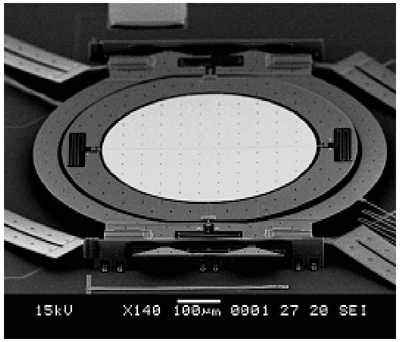




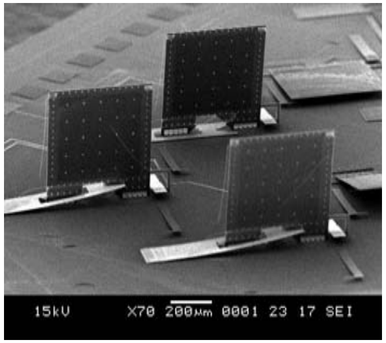




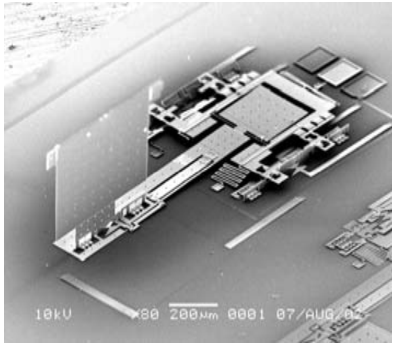
2D Optical Switch



3D Optical Switch



2D Optical Switch



VOA

J. Hsieh and W. Fang, *Transducers'99*, Japan, 1999

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

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

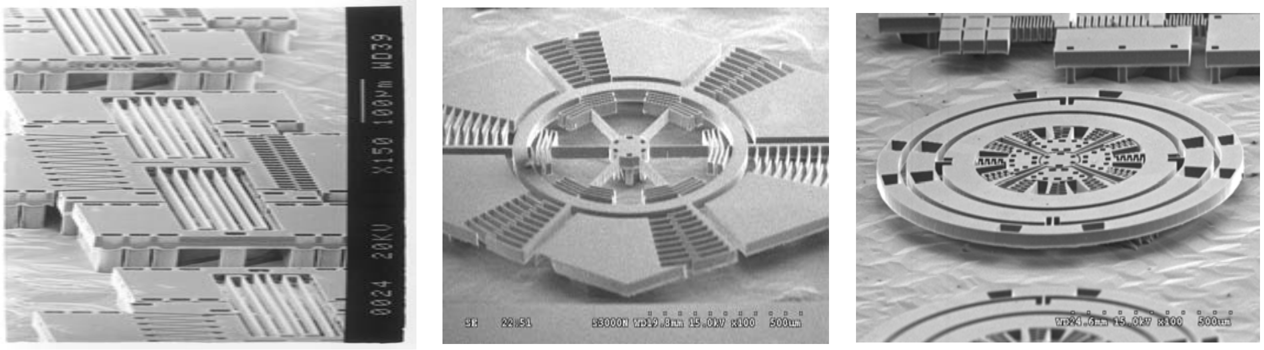
H.-Y. Lin, M.-C. Wu, and W. Fang, *Transducers'01*, Germany, 2001

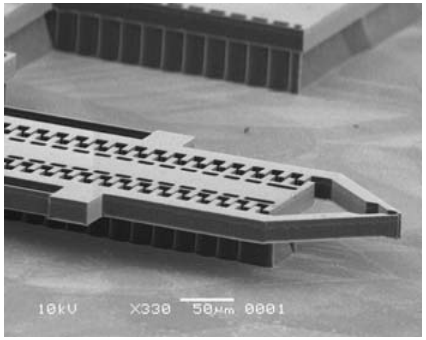
W.-C. Chen, J. Hsieh, and W. Fang, *IEEE MEMS'02*, Las Vegas, NV, 2002

Y.-P. Ho, M. Wu, H.-Y. Lin and W. Fang, *IEEE Optical MEMS*, Switzerland, 2002

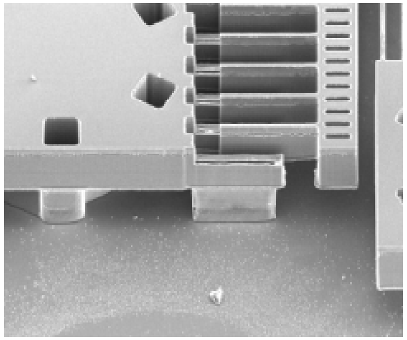
Thick (HARMs) Devices

Inertia sensors

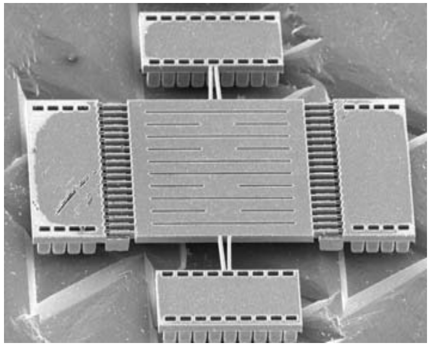




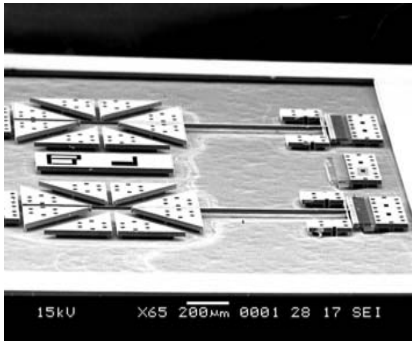
Gripper



Vertical comb



Optical scanner



VOA

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

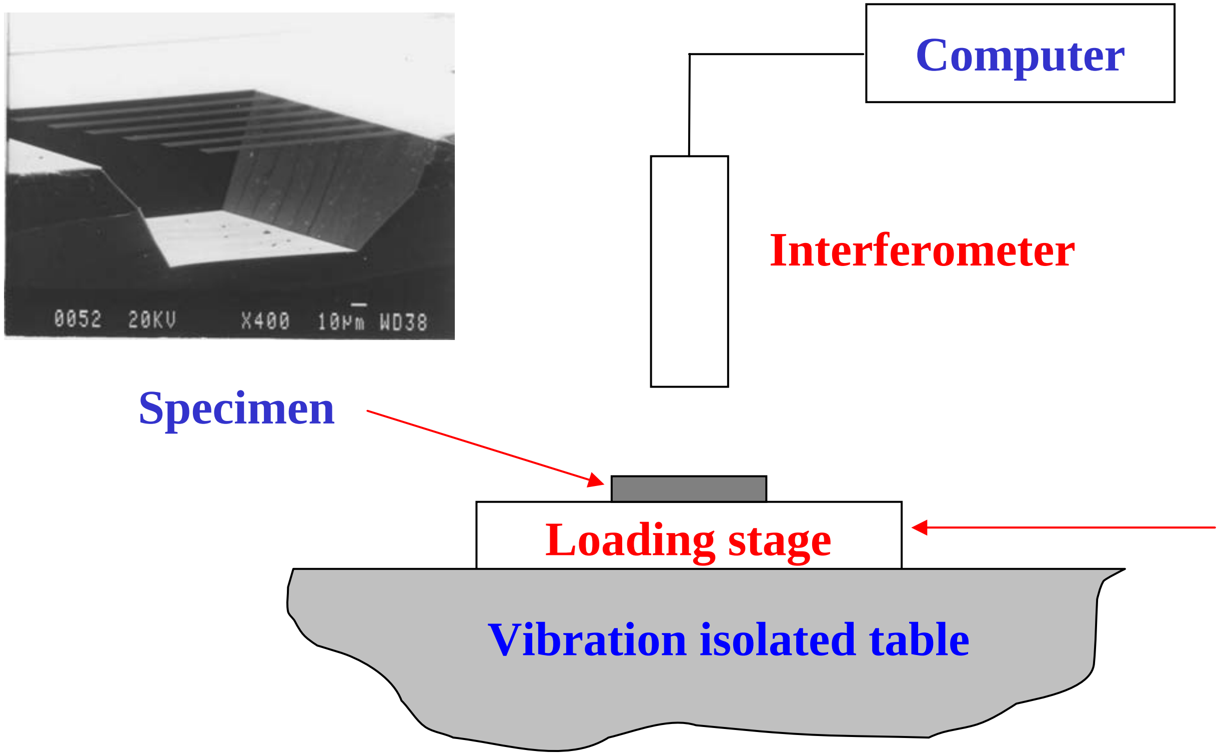
J. Hsieh and W. Fang, *JMM*, 2001

J. Hsieh, C.C. Chiu, J.M. Tsai, and W. Fang, *IEEE Optical MEMS*, Switzerland, 2002

J. M. Tsai, J. Hsieh, and W. Fang, *IEEE Optical MEMS*, Switzerland, 2002

- **Static test**
  - + Devices
  - + Material properties
- **Dynamic test**
  - + Devices
  - + Material properties

Static Testing Platform



Computer

Interferometer

Specimen

Loading stage

Vibration isolated table

Residual stresses

Heating stage

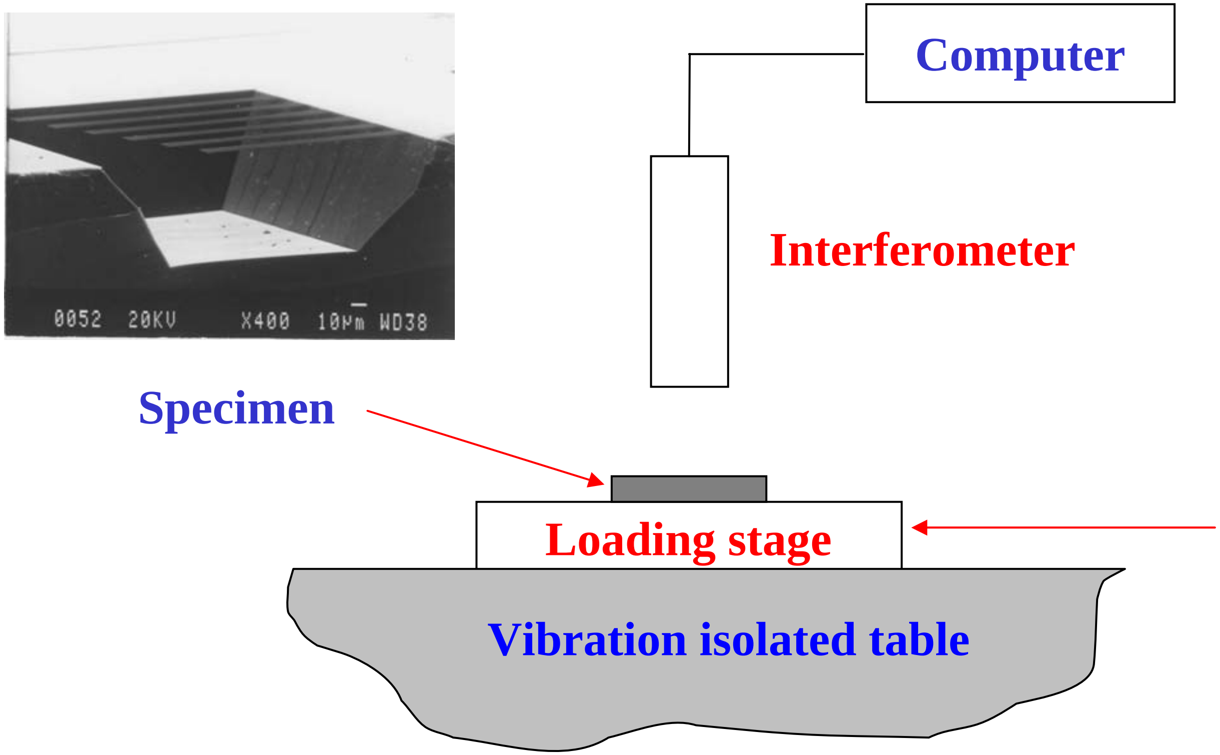
Electromagnetic stage

Pressure source

Indenter

- Static test
  - + Devices
  - + Material properties
- Dynamic test
  - + Devices
  - + Material properties

Static Testing Platform



Computer

Interferometer

Specimen

Loading stage

Vibration isolated table

Residual stresses

Heating stage

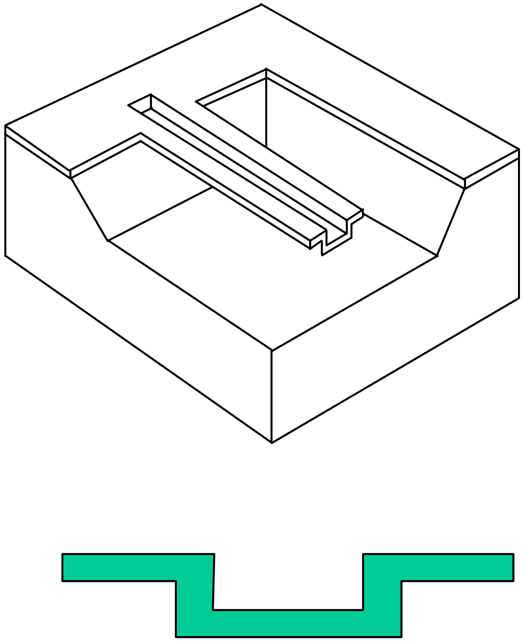
Electromagnetic stage

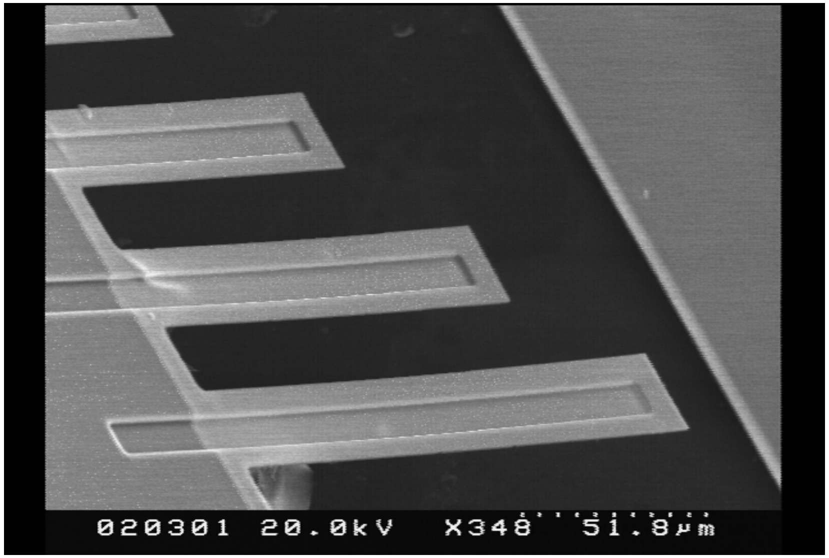
Pressure source

Indenter

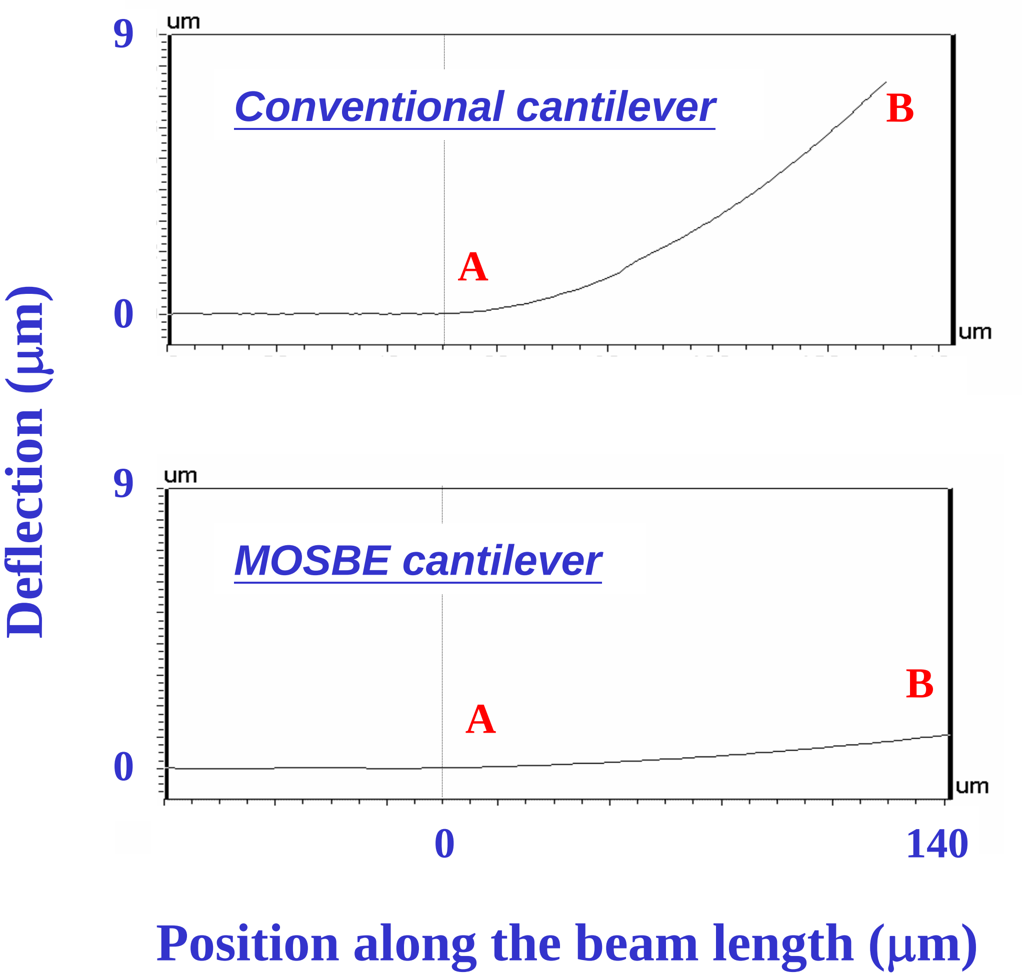
Self loaded by residual stress

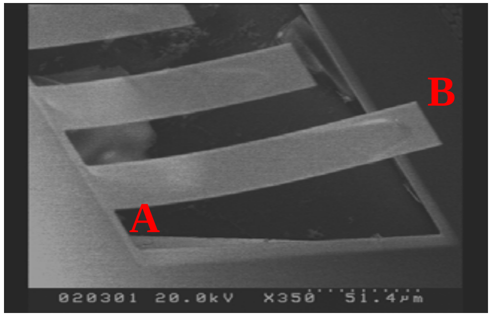
- **Stiffness test of the cantilever**

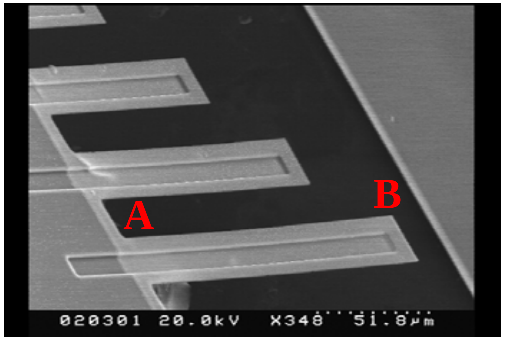




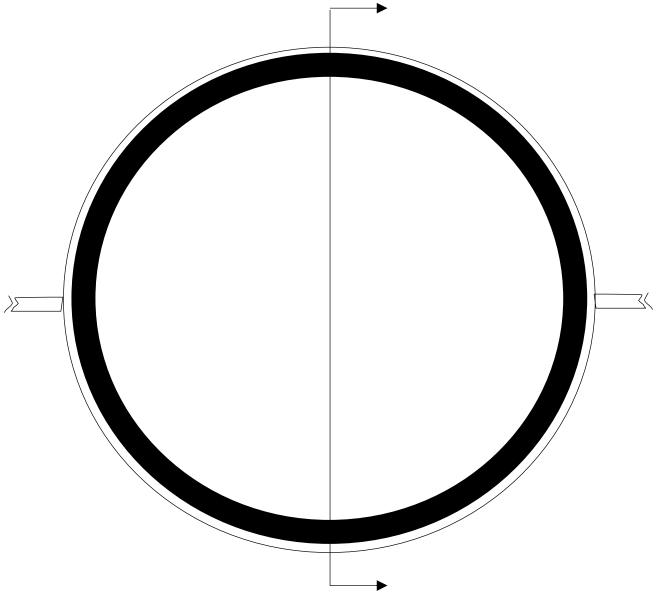
H.-Y. Lin and W. Fang, *J. of Micromechanics and Microeng.*, 2000

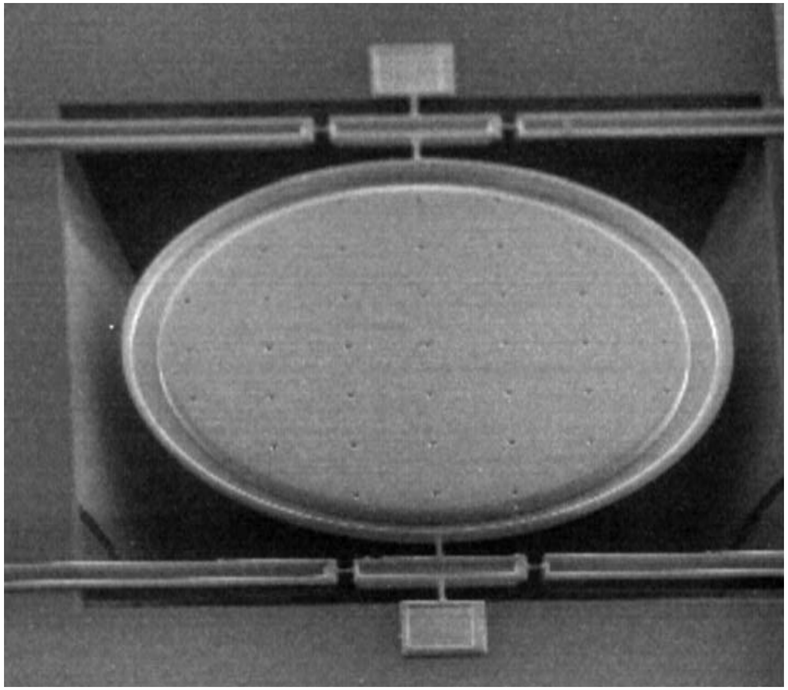

Deflection (μm)
9
um
0
Conventional cantilever
A
B
um
9
um
0
MOSBE cantilever
A
B
um
0
140
Position along the beam length (μm)


B
A
020301 20.0kV X350 51.4μm


A
B
020301 20.0kV X348 51.8μm

- **Stiffness test of the mirror**

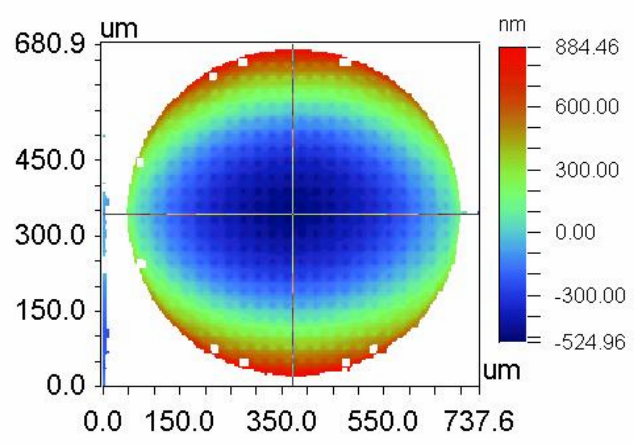




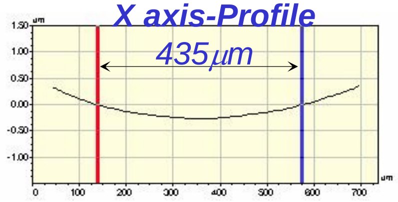
Reinforced folded frame

H.-Y. Lin and W. Fang, the *ASME IMECE*, Orlando, FL, 2000

MUMPs mirror

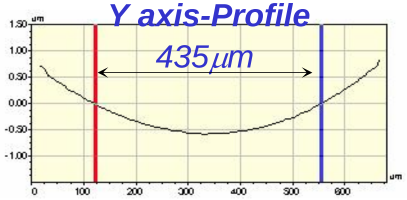


X axis-Profile



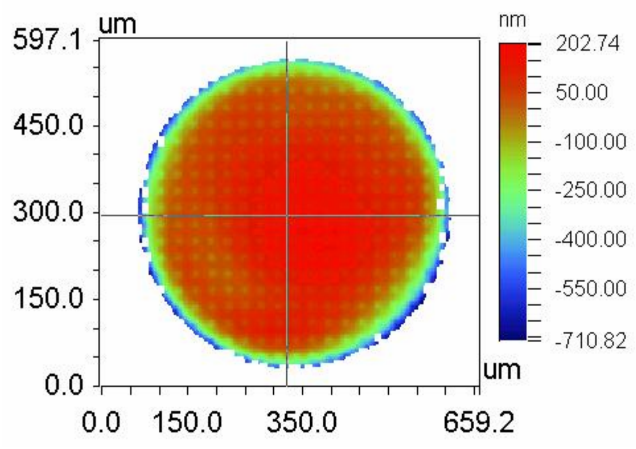
ρ : 93mm

Y axis-Profile

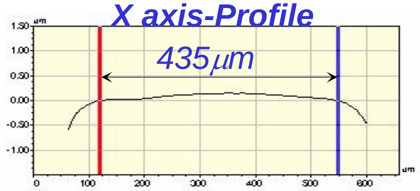


ρ : 41mm

MOSBE mirror

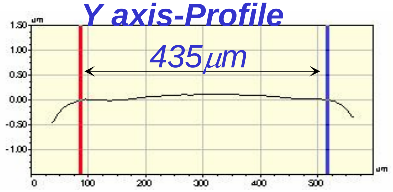


X axis-Profile



ρ : 153mm

Y axis-Profile



ρ : 179mm

H.-Y. Lin and W. Fang, the *ASME IMECE*, Orlando, FL, 2000

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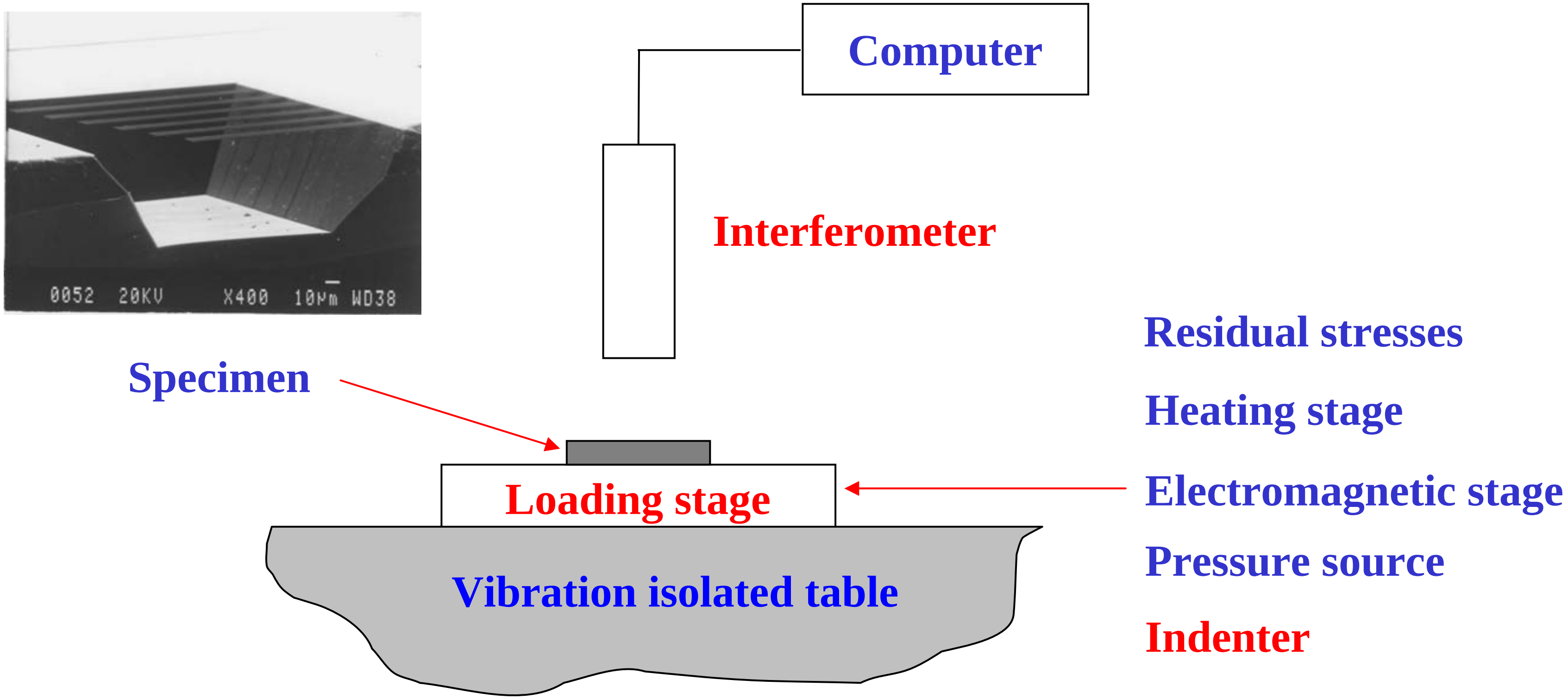
Static Testing Platform



Computer

Interferometer

Specimen

Loading stage

Vibration isolated table

Residual stresses

Heating stage

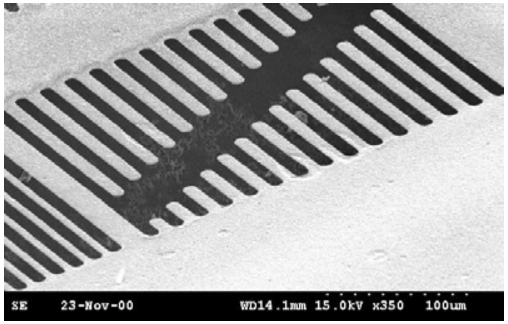
Electromagnetic stage

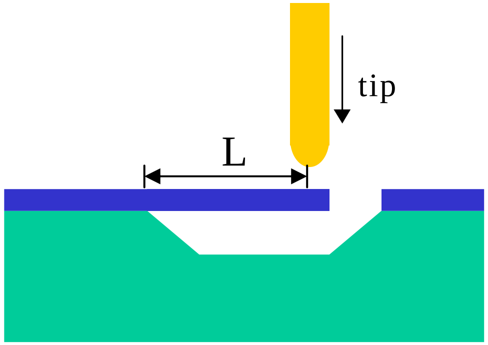
Pressure source

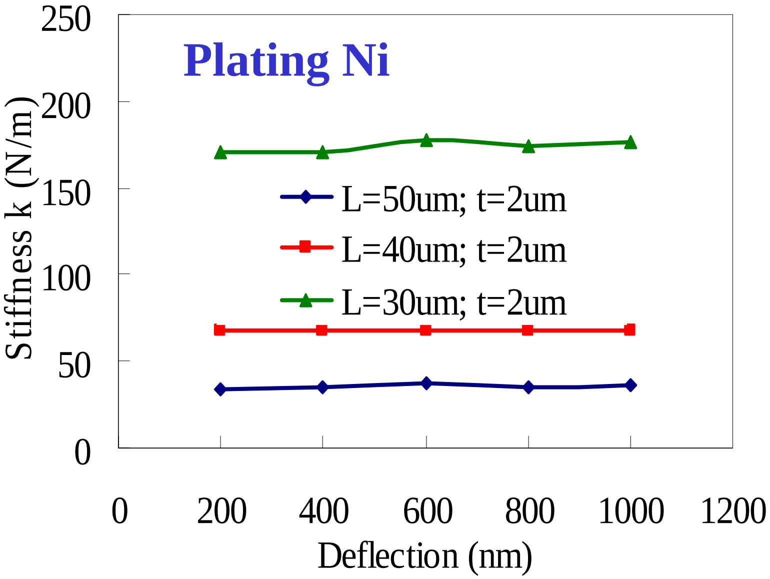
Indenter

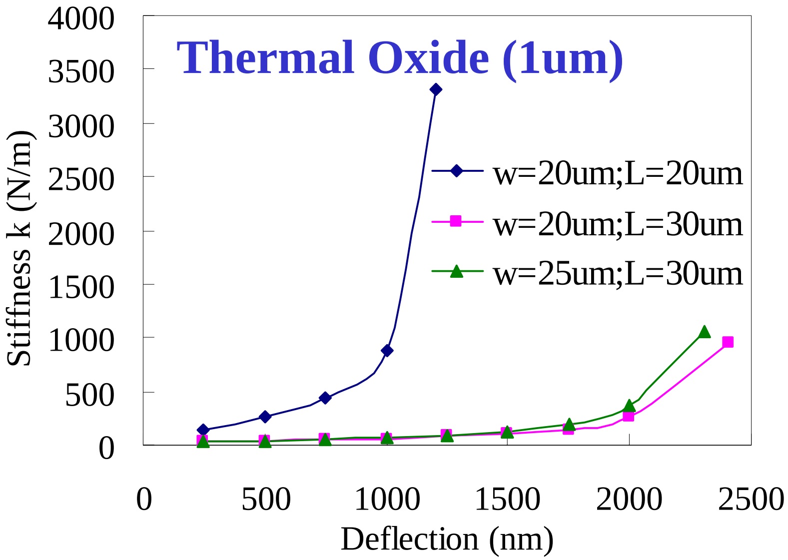
External loaded by nano-indenter

- Stiffness test of the cantilever



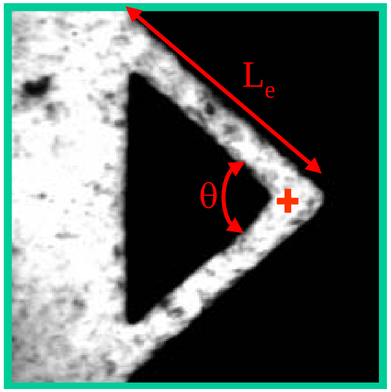


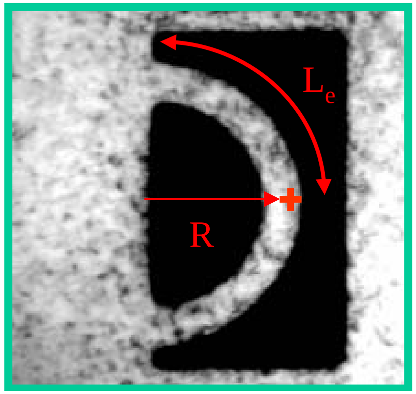


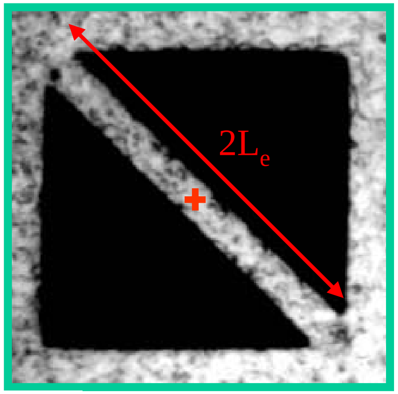


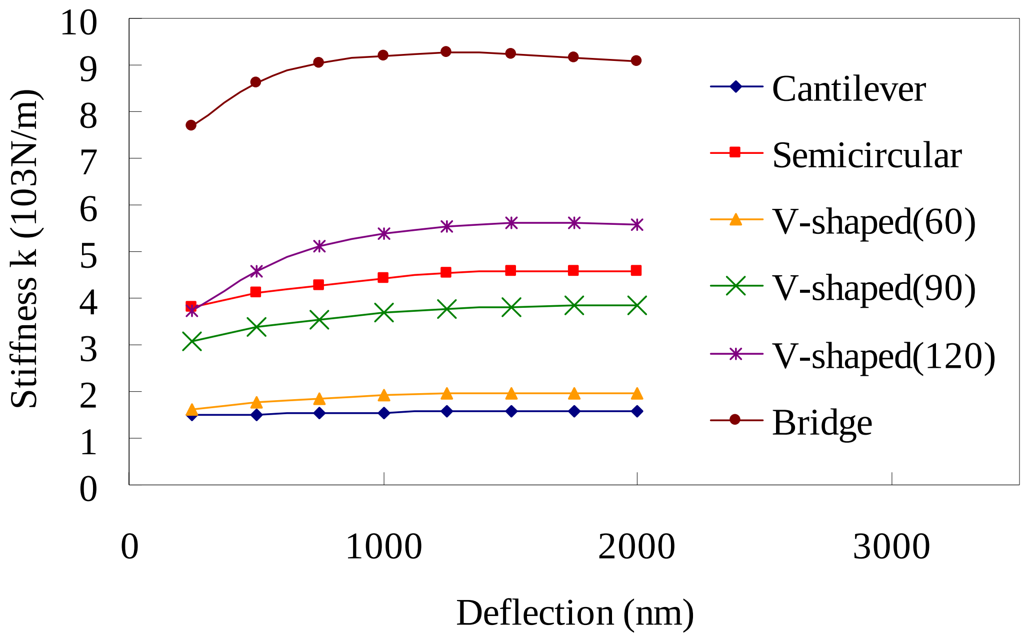
MDL
NTHU

- **Stiffness test of various structures**





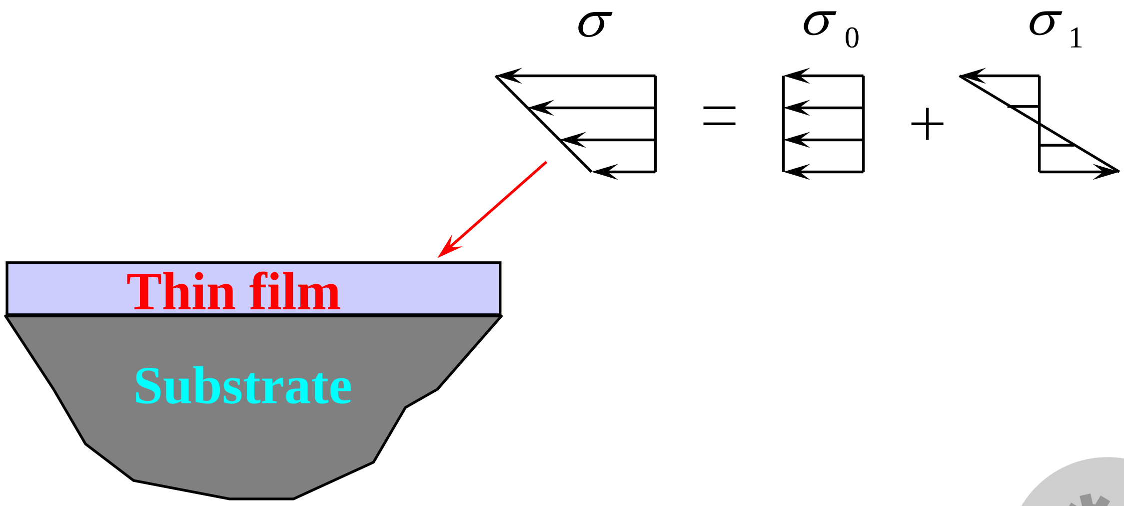




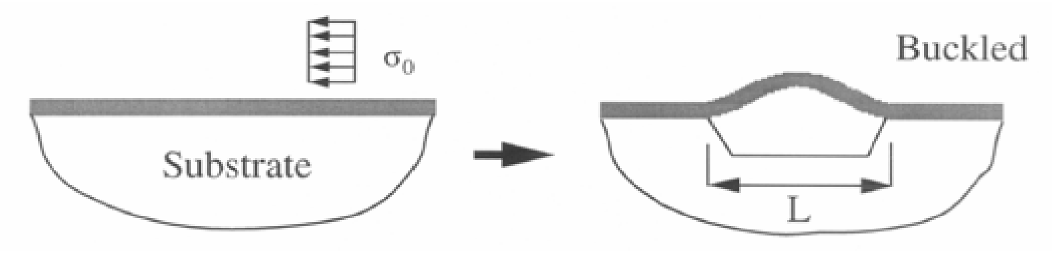
- **Static test**
  - **+ Devices**
  - **+ Material properties – Residual stresses**
- **Dynamic test**
  - **+ Devices**
  - **+ Material properties**

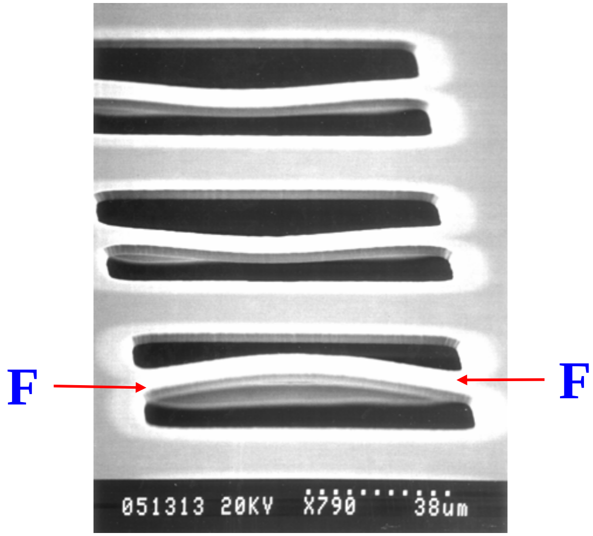
Residual stress

- Compression $-\sigma_0$
- Tension $+\sigma_0$
- Gradient σ_1



Buckle Beam Method





- **Idealization: critical beam length**

$L < L_{cr}$ unbuckled
$L > L_{cr}$ buckled

where $$L_{cr} = 2\pi\sqrt{\frac{EI}{\sigma_0 A}}$$

Guckel, Randazzo, and Burns, *J. of Applied Physics*, 1985

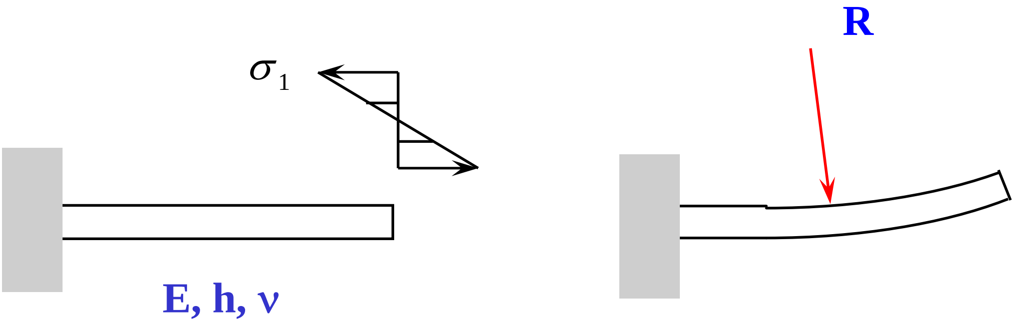
W. Fang, and J.A. Wickert, *J. of Micromechanics and Microeng.*, 1994

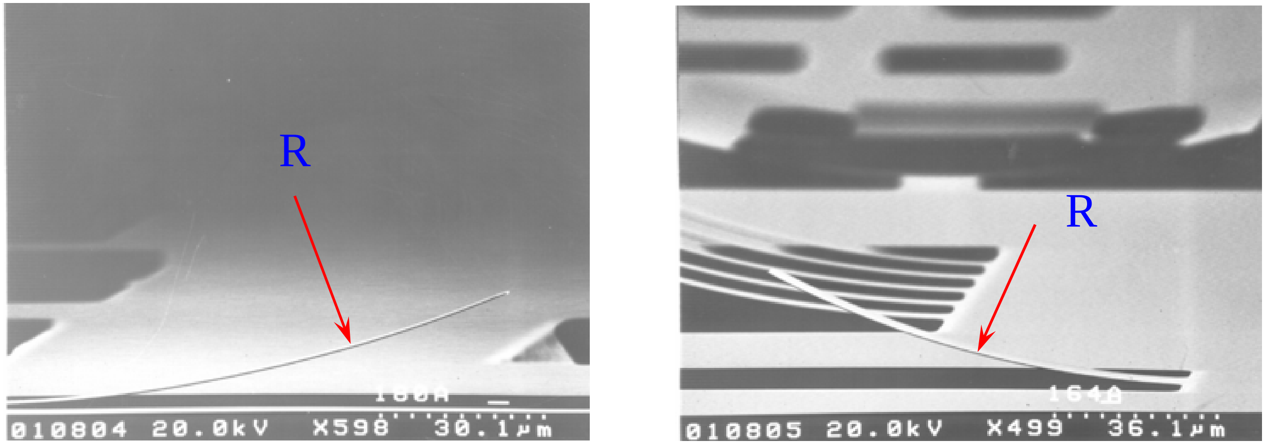
Cantilever Beam Method

- Gradient residual stress σ_1 will lead to a bending moment on the test cantilever

- Gradient residual stress is determined by the radius of curvature R of the bent cantilever

$$\sigma_1 = \frac{Eh}{2R}$$



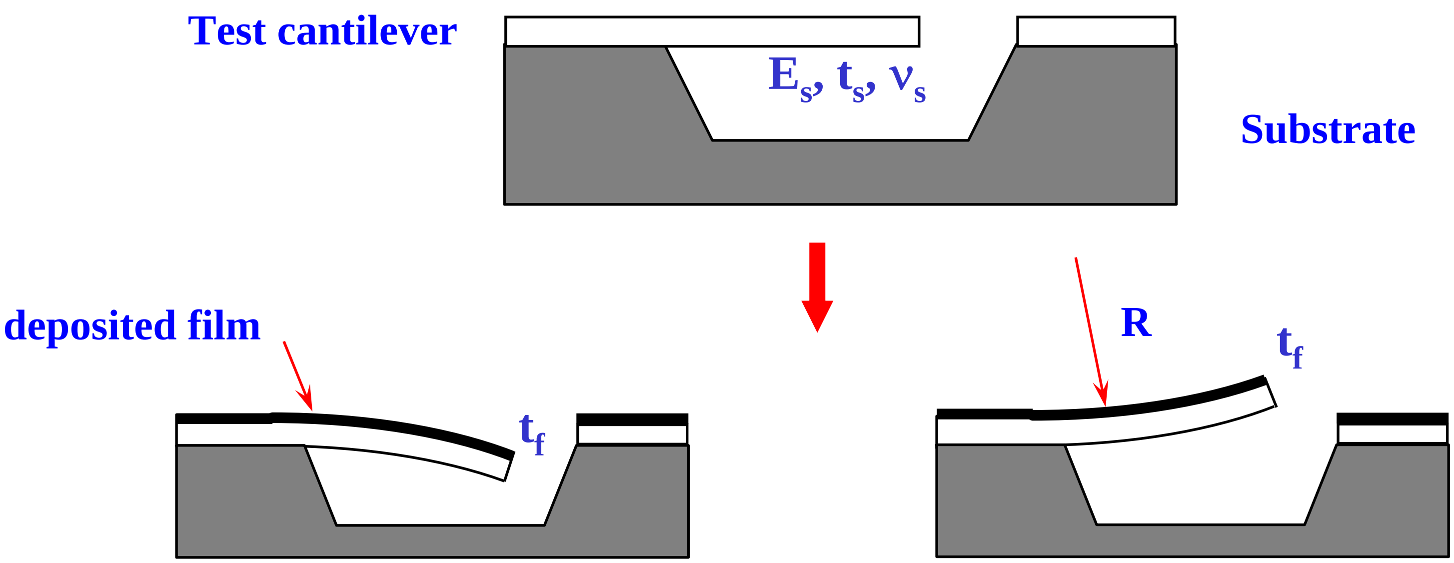


Y.-L. Chen, J.-S. Shie, and W. Fang, 1997

Bilayer beam technique

$$\sigma_0 = \frac{E_s (t_s)^2}{6 R t_f (1 - \nu_s)}$$

measured

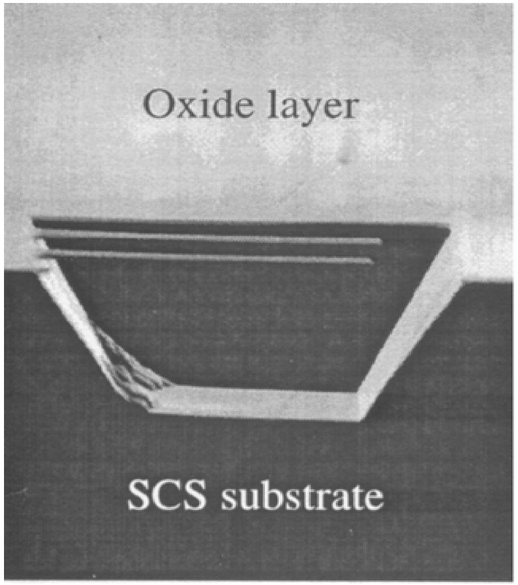


Compression

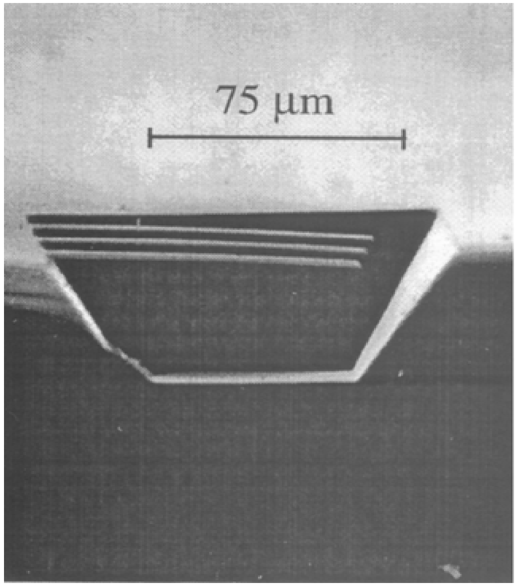
Tension

W. Fang and J.A. Wickert, J. of Micromech. and Microeng.,1995

- **Bilayer beam technique can be applied to measure residual stress of thin films whose thickness are too small to fabricate micromachined structures**



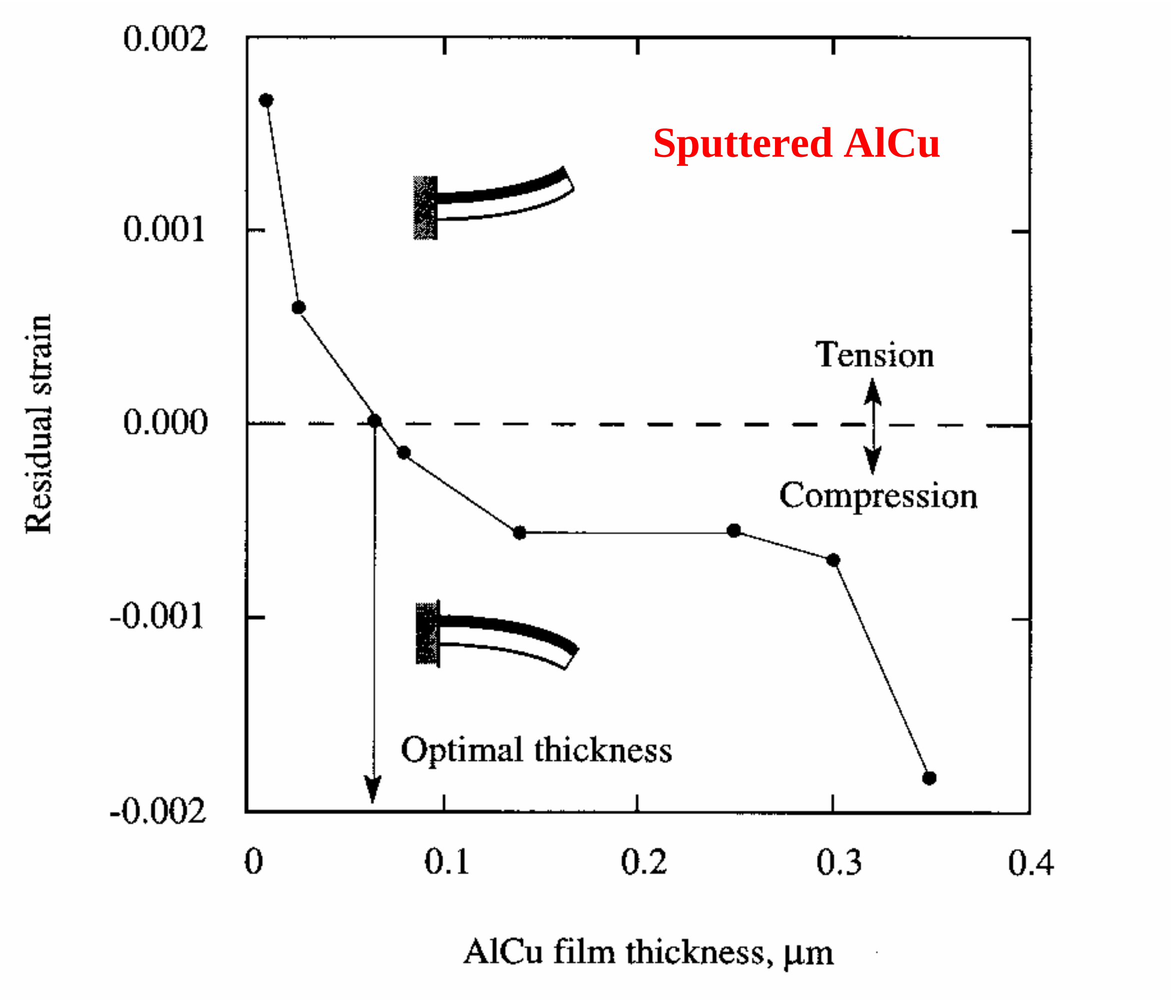
SiO_2 test cantilever



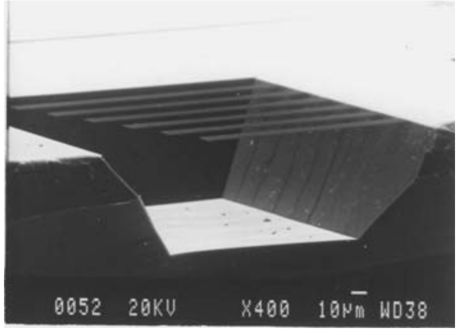
Test cantilever deposited with a 15 nm thick *DLC* film

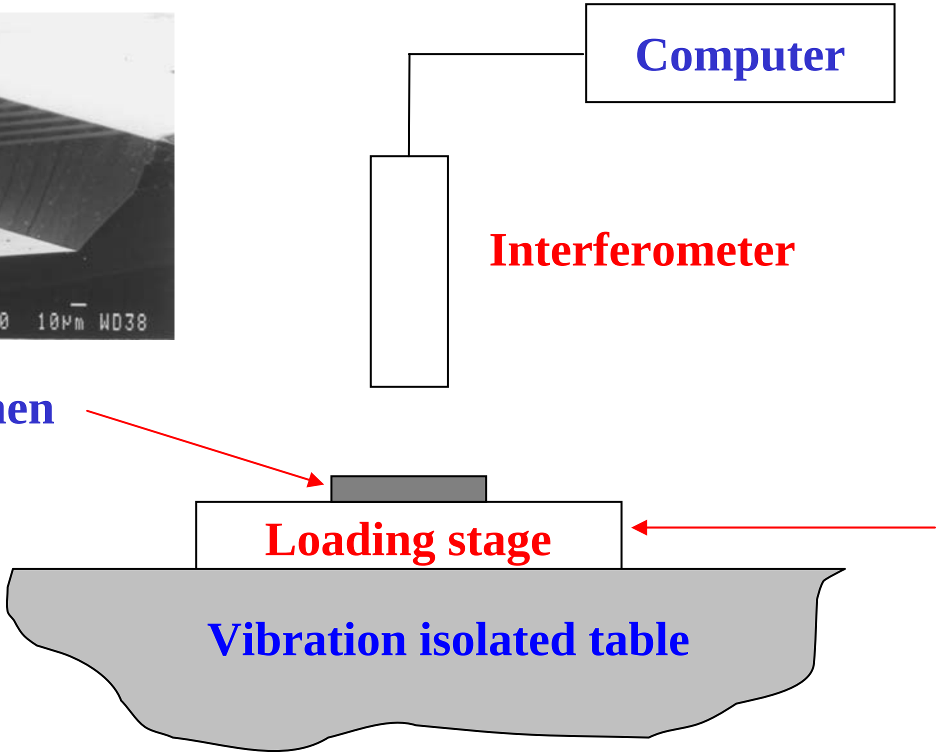
W. Fang and J.A. Wickert, *J. of Micromechanics and Microengineering*, 1995

- **Variation of the residual strain with the thickness of *AlCu* film**



Static Testing Platform





Computer

Interferometer

Specimen

Loading stage

Vibration isolated table

Residual stresses

Heating stage

Electromagnetic stage

Pressure source

Indenter

Pressure load

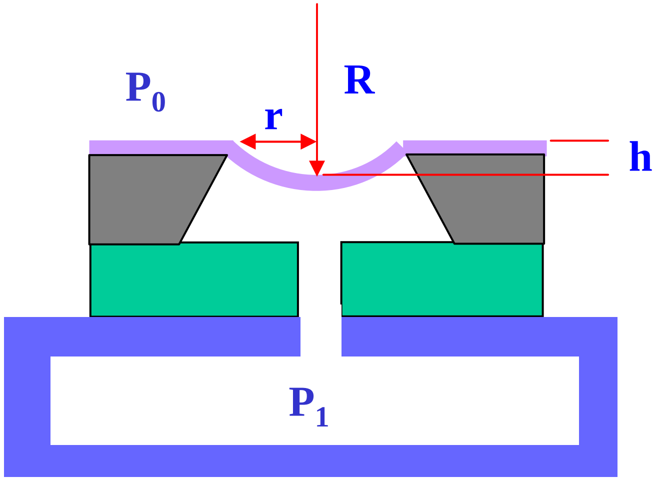
- **Load-deflection test**

Residual stress

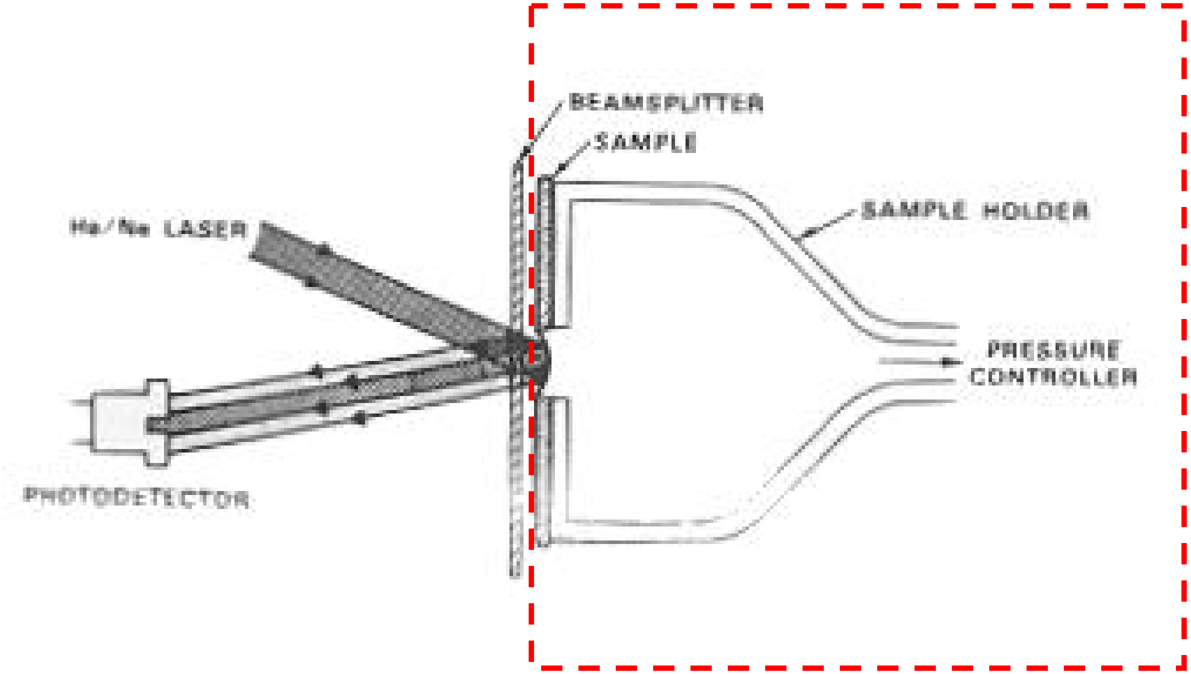
Young's modulus

$$p = \frac{4t\sigma_0}{r^2}h + \frac{8t}{3r^4}\frac{E}{1-\nu}h^3$$

Deflection amplitude of the membrane

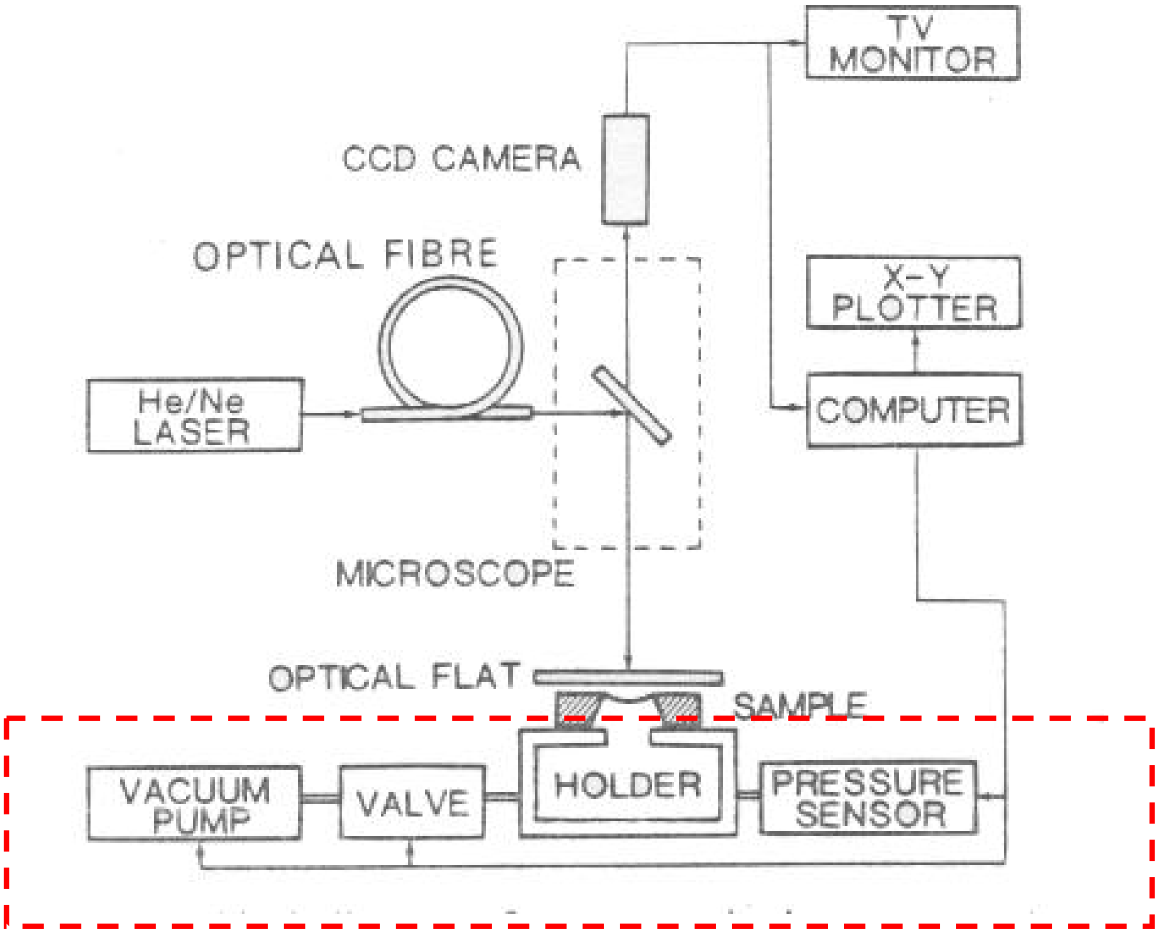


- Measurement system



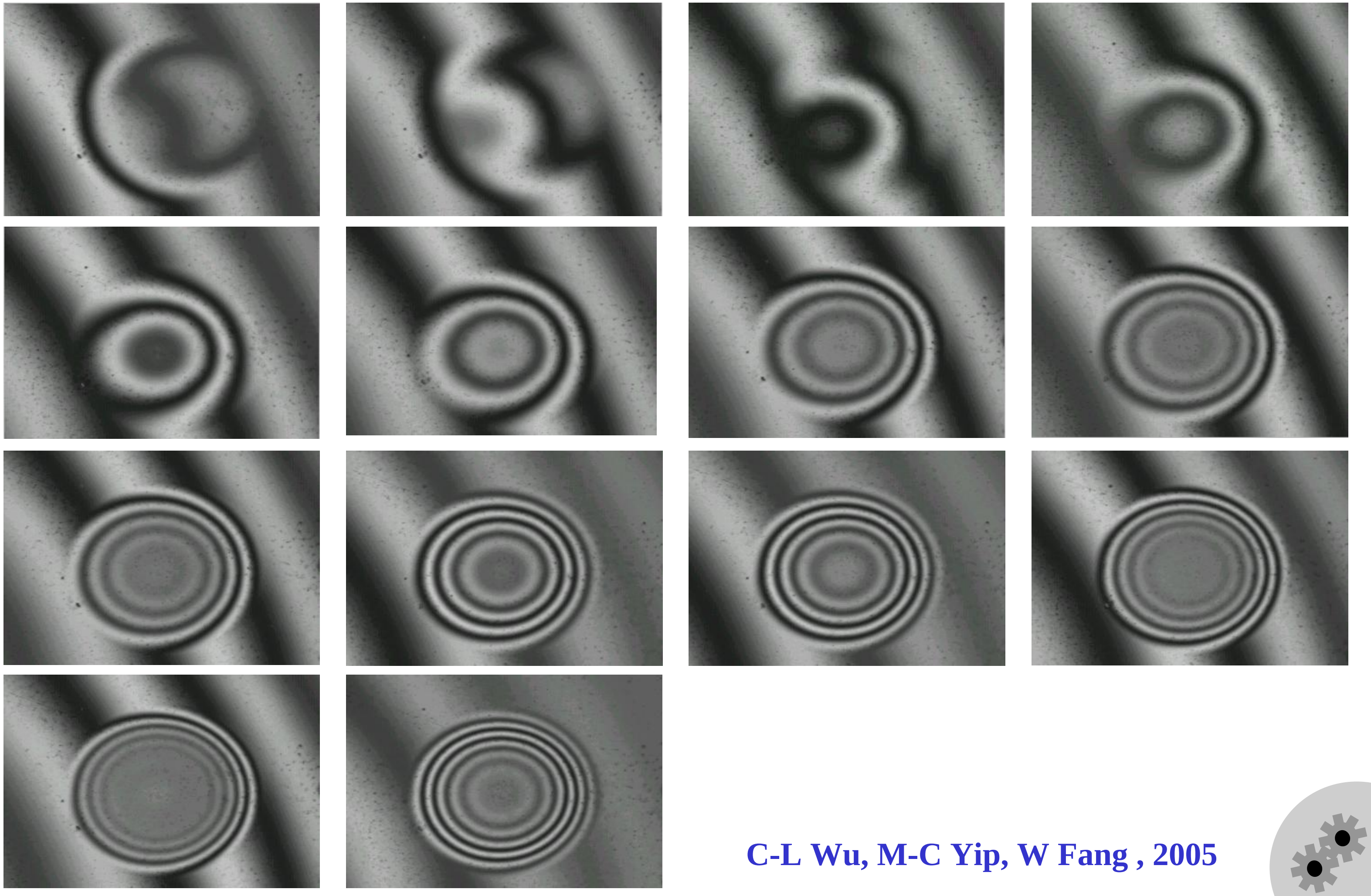
Setup for external load

- **Measurement system**



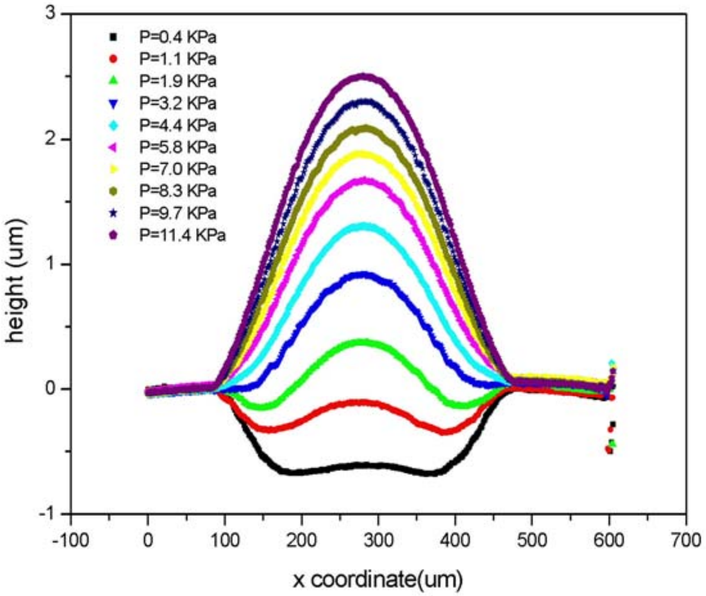
Setup for external load

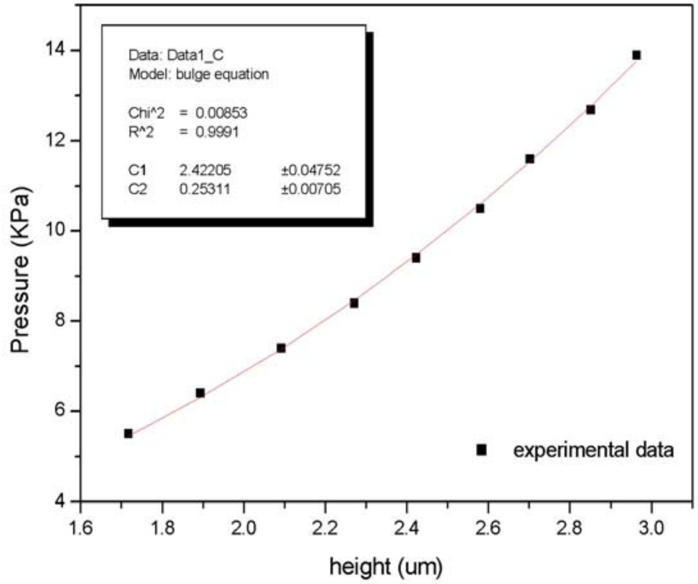
•Bulge test



C-L Wu, M-C Yip, W Fang , 2005

•Bulge test

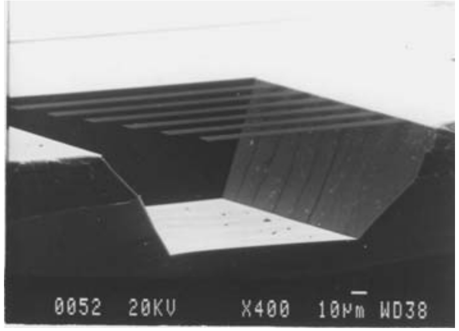


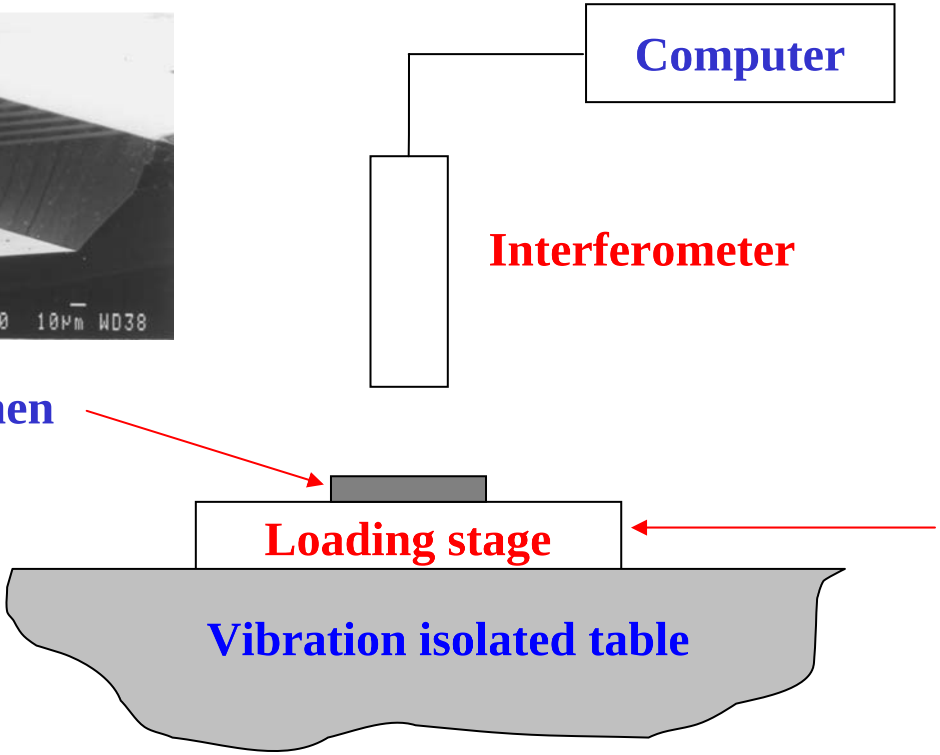


C-L Wu, M-C Yip, W Fang , 2005

- Static test
  - + Devices
  - + Material properties – CTE
- Dynamic test
  - + Devices
  - + Material properties

Static Testing Platform





Computer

Interferometer

Specimen

Loading stage

Vibration isolated table

Residual stresses

Heating stage

Electromagnetic stage

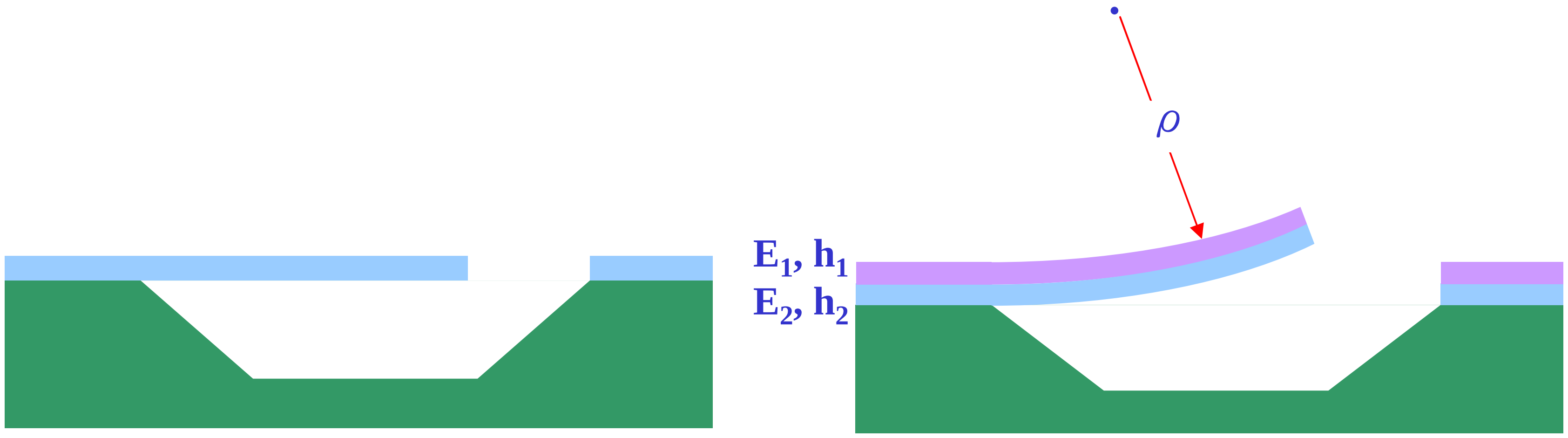
Pressure source

Indenter

Bi-layer approach

- **Bilayer - analysis**

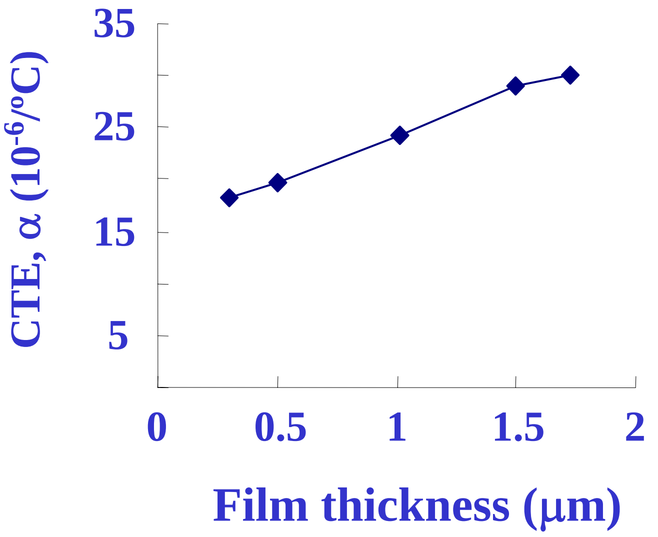
$$\frac{1}{\rho}=\frac{6\cdot\Delta T\cdot\Delta\alpha\cdot(1+m)^2}{h\cdot\left[3\cdot(1+m)^2+(1+m\cdot n)\cdot\left(m^2+\frac{1}{m\cdot n}\right)\right]}$$

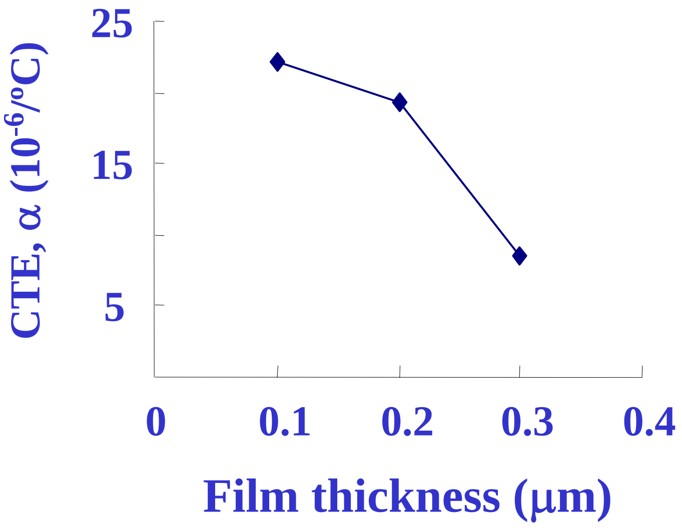


W. Fang, H.-C. Tsai, and C.-Y. Lo, *Sensors and Actuators A*, 1999

W. Fang and C.-Y. Lo, *Sensors and Actuators A*, 2000

- **Sputtered Al**
- **E-gun Ti**





Bulk Al : 23.6 × 10^{-6}/°C

Bulk Ti : 8.4 × 10^{-6}/°C

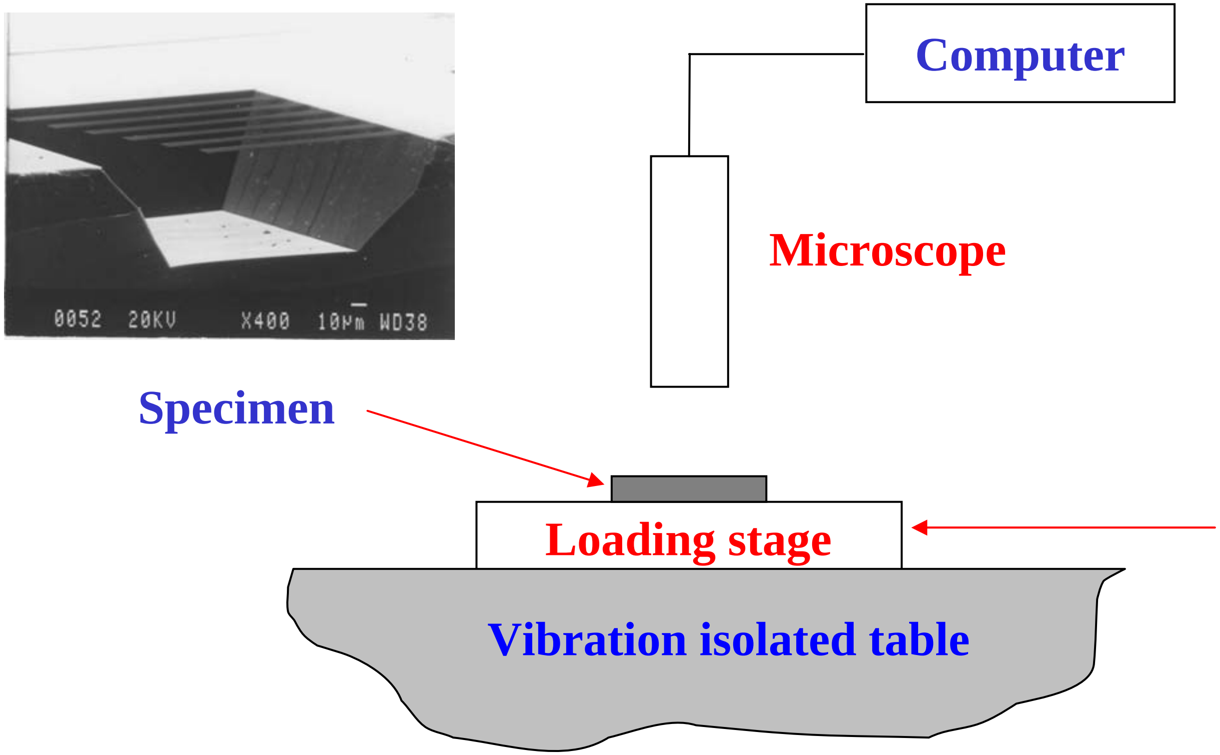
- **Results**

	SiO_2	W	Ti	Al
0.1μm			22.21×10^{-6}	
0.2 μm			19.4×10^{-6}	
0.3 μm			9.04×10^{-6}	18.23×10^{-6}
0.5 μm		5.6×10^{-6}		19.61×10^{-6}
1 μm	0.25×10^{-6}			24.14×10^{-6}
1.5 μm				28.92×10^{-6}
1.73 μm				29.97×10^{-6}

- **Static test**
  - + Devices
  - + Material properties – Elastic modulus

- **Dynamic test**
  - + Devices
  - + Material properties

Static Testing Platform



Computer

Microscope

Specimen

Loading stage

Vibration isolated table

Residual stresses

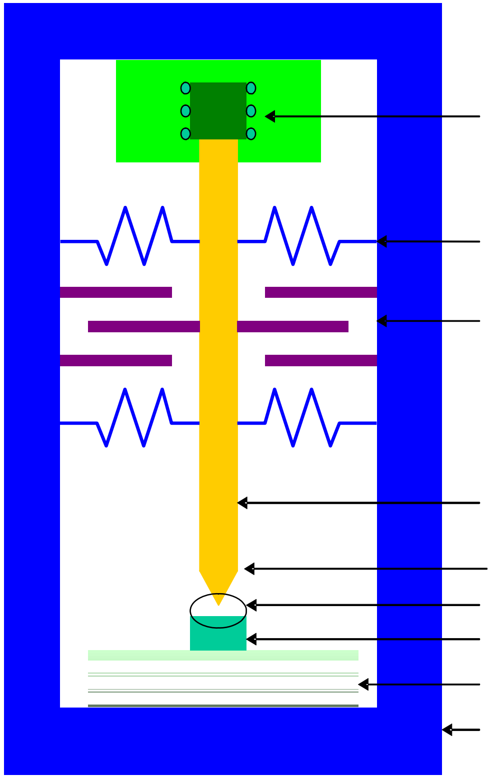
Heating stage

Electromagnetic stage

Pressure source

Indenter

- **Nanoindentation system**



Loading actuator

Support spring, K_s

Displacement sensor, D_i

Probe, m

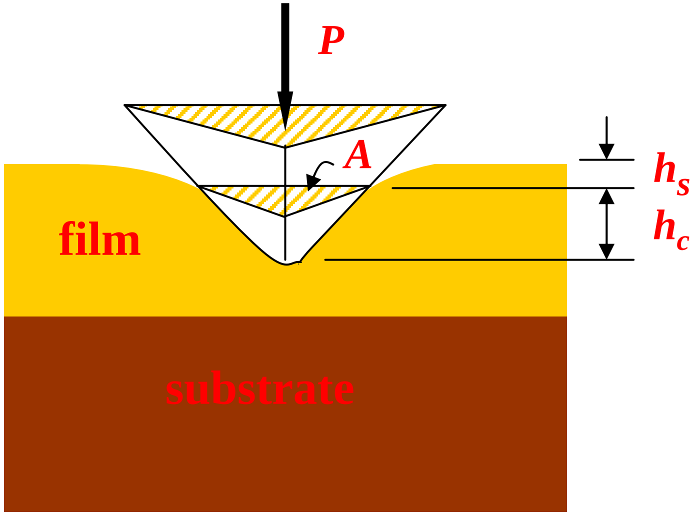
Diamond tip

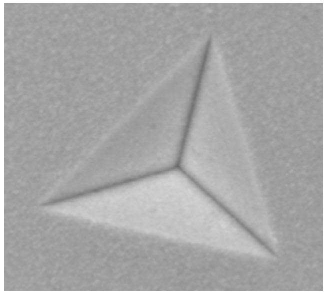
Contact, S and D_s

Sample

Stage

Load frame, K_f



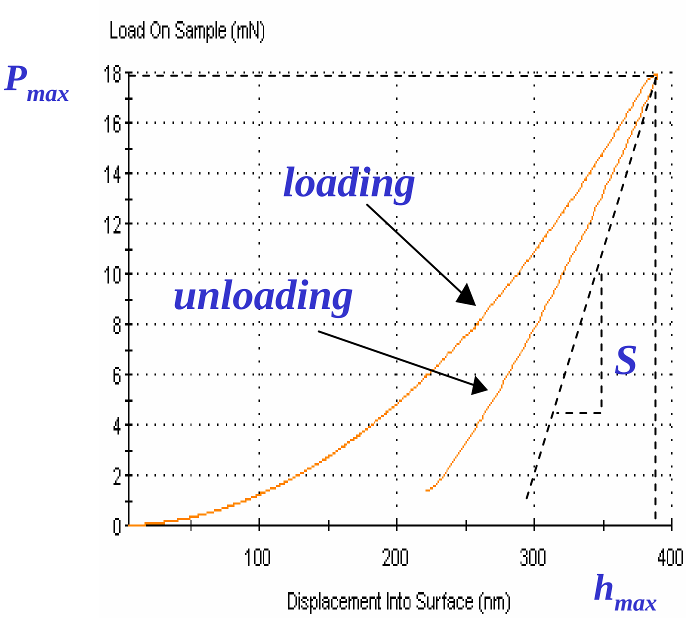


Berkovich tip geometry

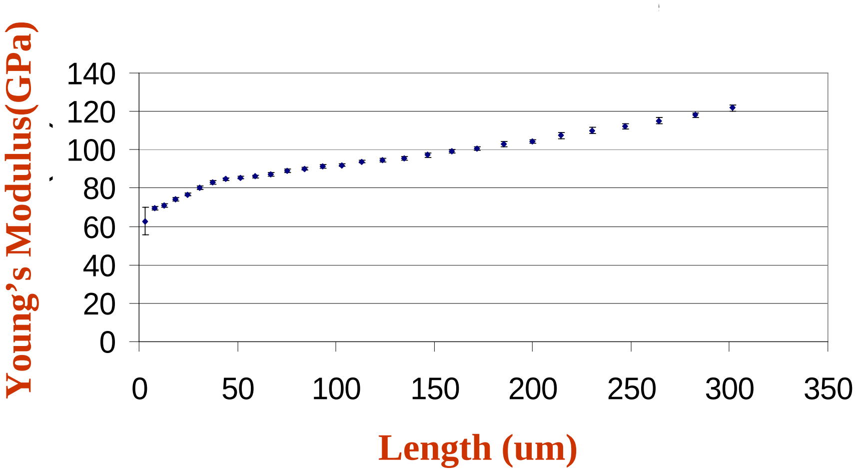
- **Principle**

  + measured parameter: tip load and displacement

  + extracted properties: H & E

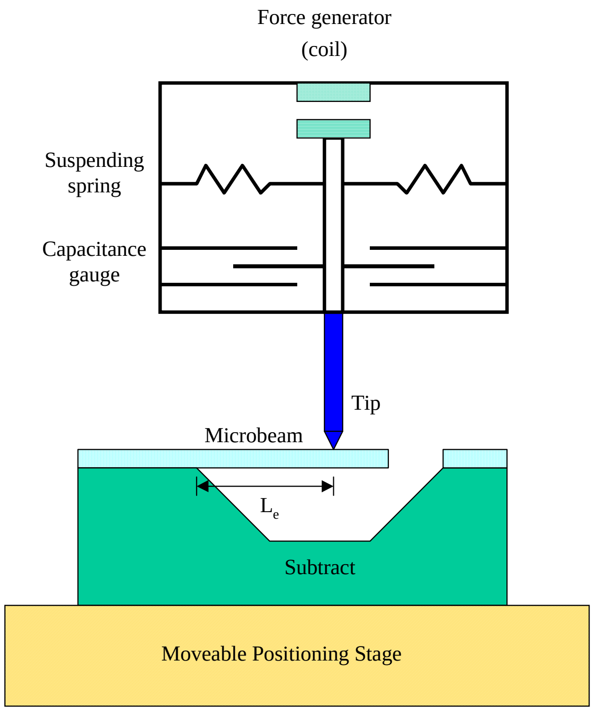


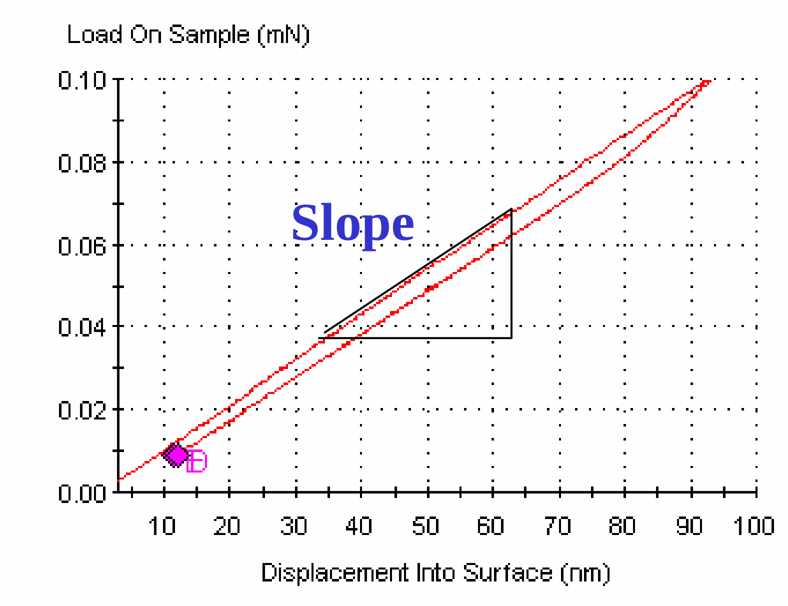
Typical example: 0.84 μm SiO_2 film



E_{ave}= 88GPa (5%~10% of film thickness)

Nanoindentation system for bending beam test



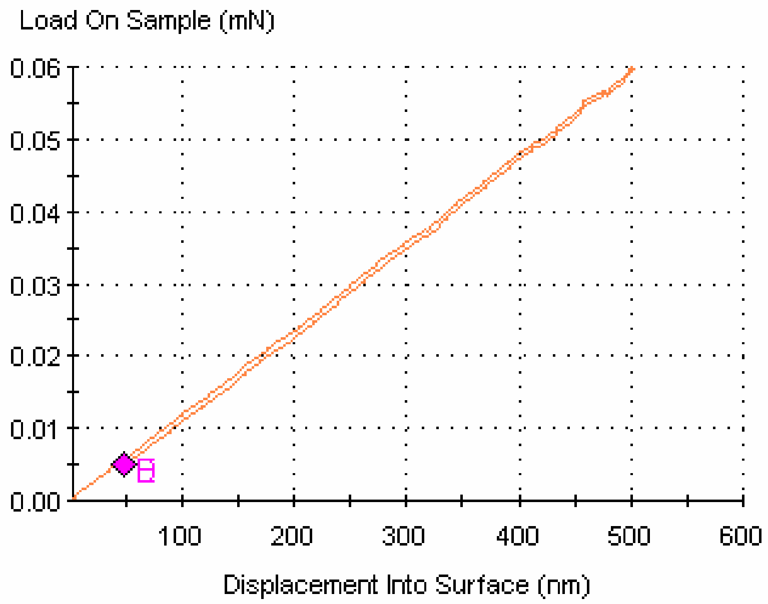


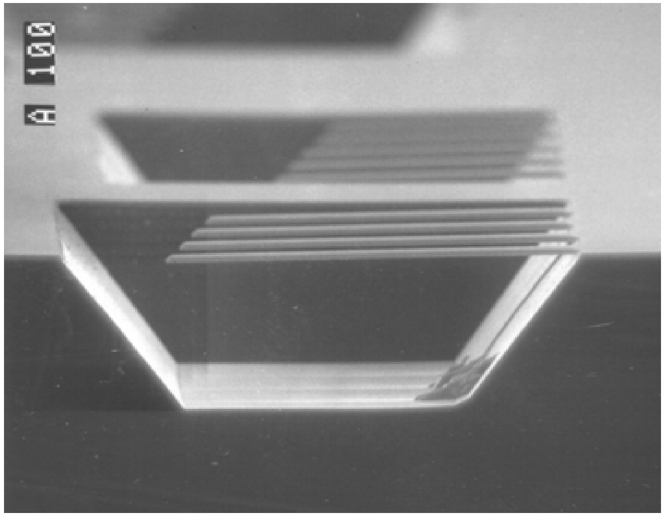
→ **Slope is the stiffness of cantilever**

$$E = \frac{4l^3}{wt^3}\frac{P}{\delta}$$

MDL
NTHU

- **Stiffness test of the SiO_2 cantilever**



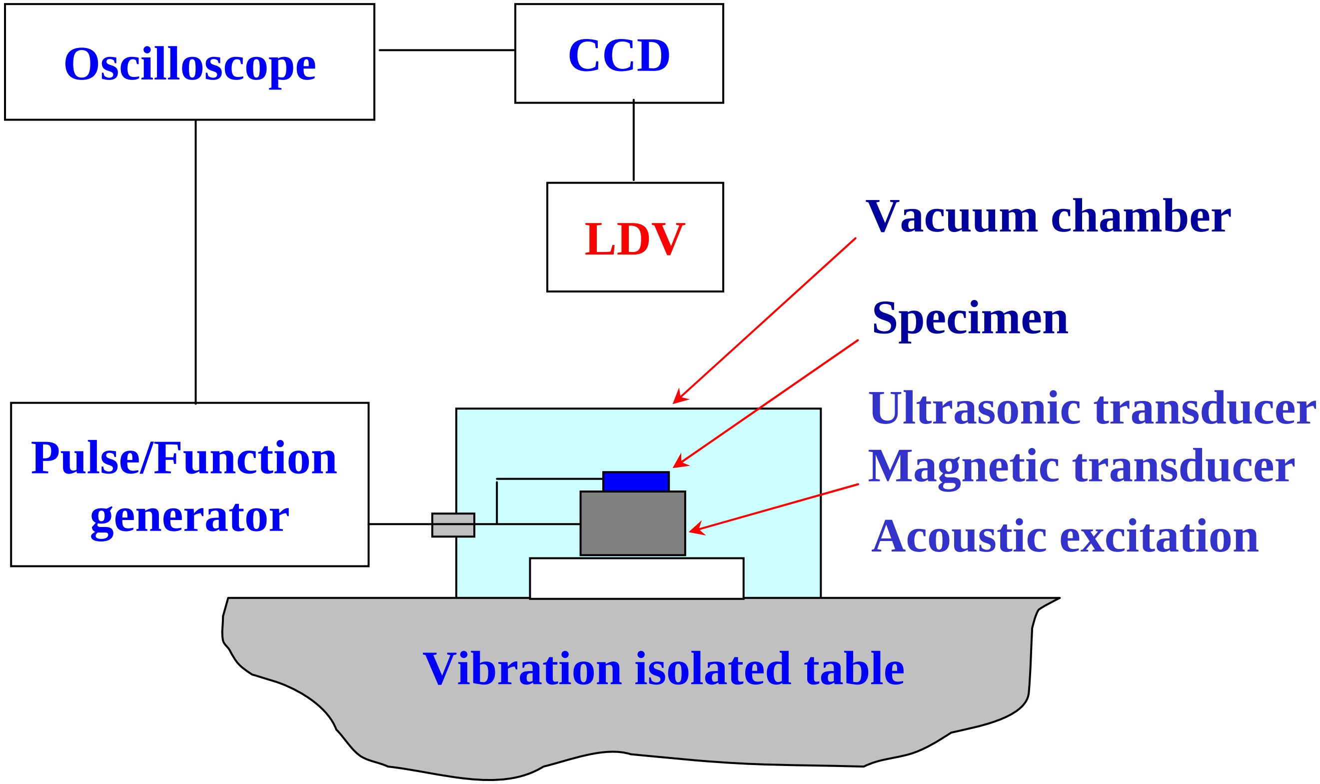


E = 71.3 GPa

- **Static test**
  - + Devices
  - + Material properties

- **Dynamic test**
  - + Devices
  - + Material properties

Dynamic Testing Platform



Oscilloscope

CCD

LDV

Vacuum chamber

Specimen

Ultrasonic transducer

Magnetic transducer

Acoustic excitation

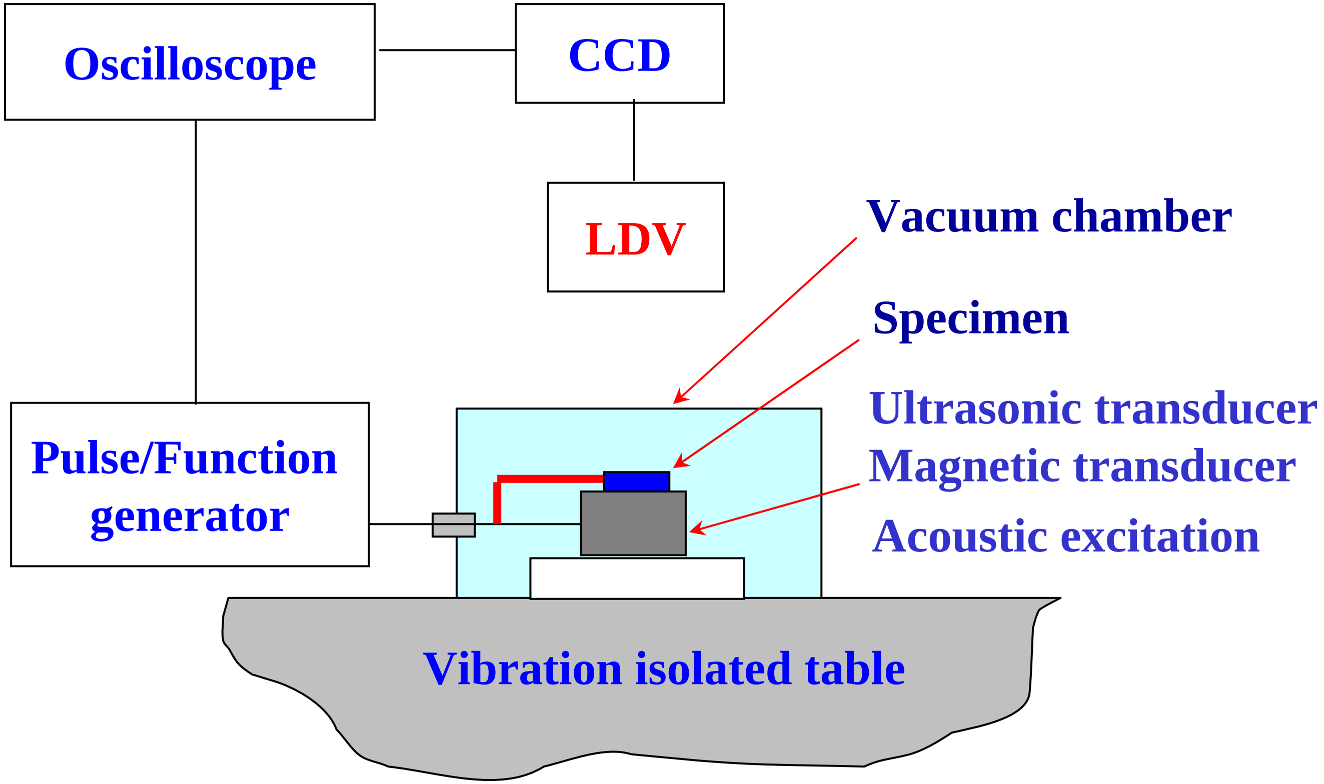
Pulse/Function generator

Vibration isolated table

W. Lai and W. Fang, *Sensors and Actuators A*, 2001

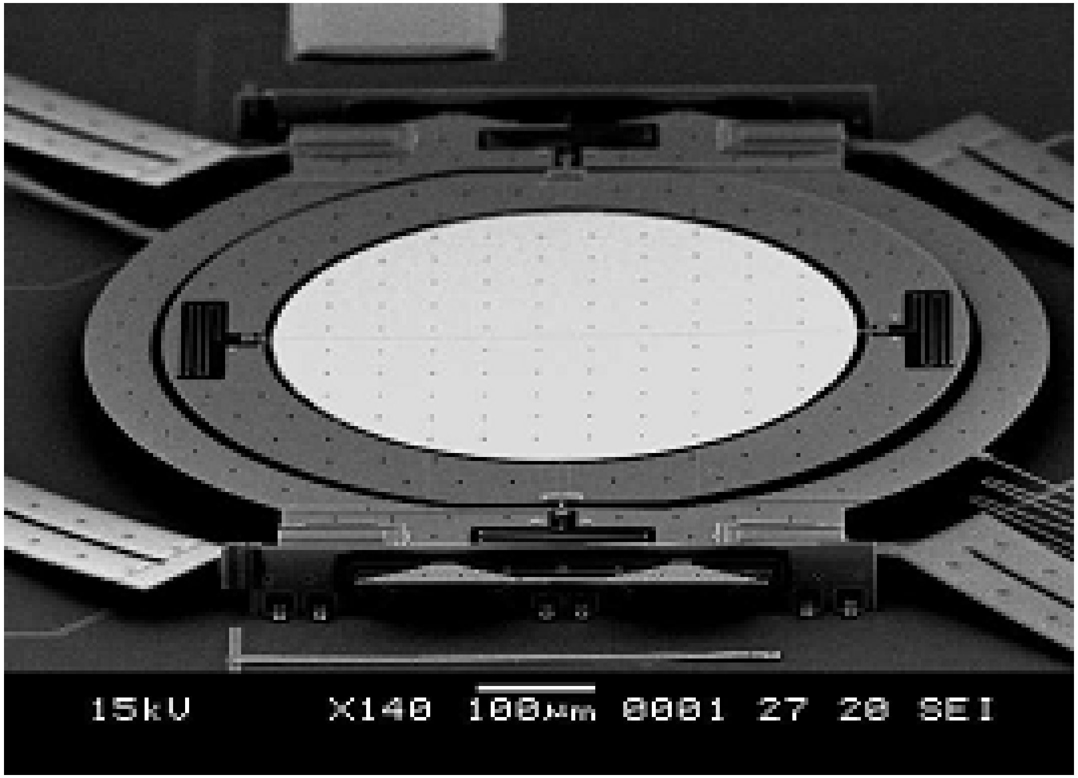
- Static test
  - + Devices
  - + Material properties
- Dynamic test
  - + Devices
  - + Material properties

Dynamic Testing Platform

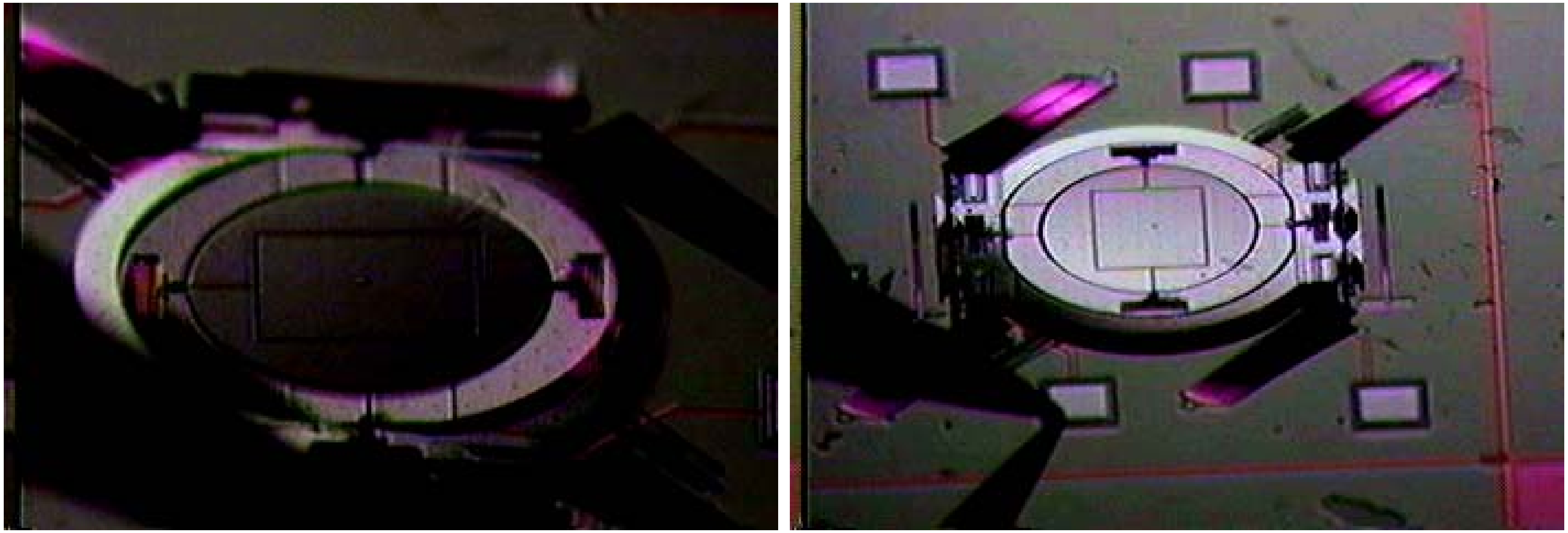


W. Lai and W. Fang, *Sensors and Actuators A*, 2001

Electrostatic actuator: optical scanner



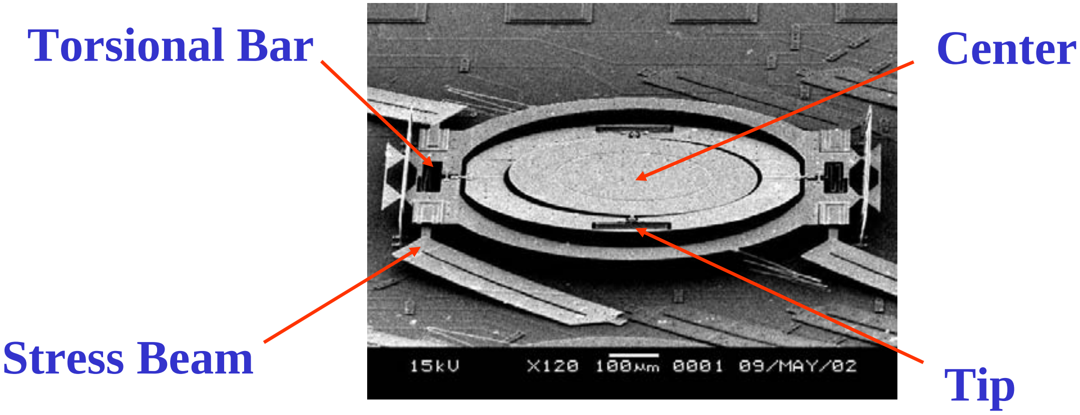
Y.-P. Ho, M. Wu, H.-Y. Lin and W. Fang, *IEEE Optical MEMS '02*, 2002

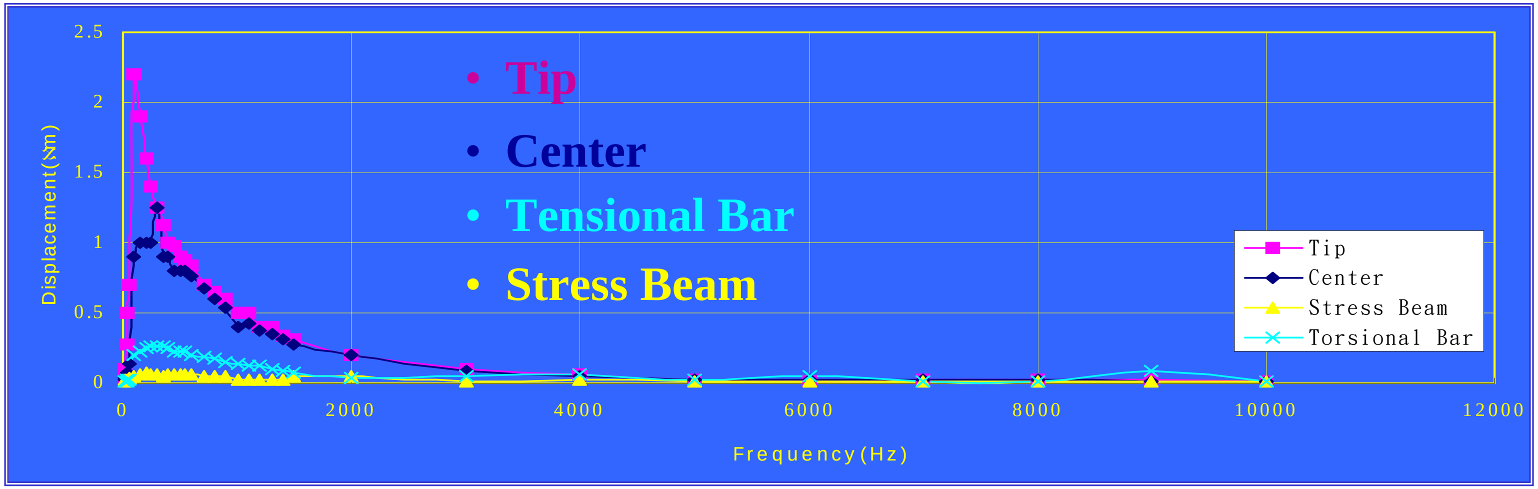


Y.-P. Ho, M. Wu, H.-Y. Lin and W. Fang, *IEEE Optical MEMS ‘02*, 2002

- **Frequency response**

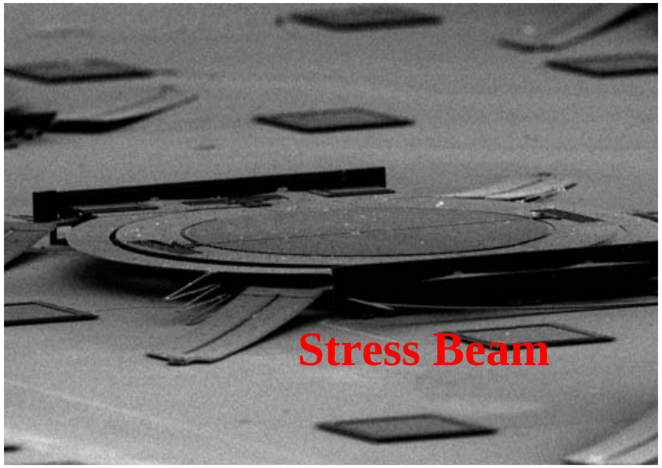
Driving Outer Ring

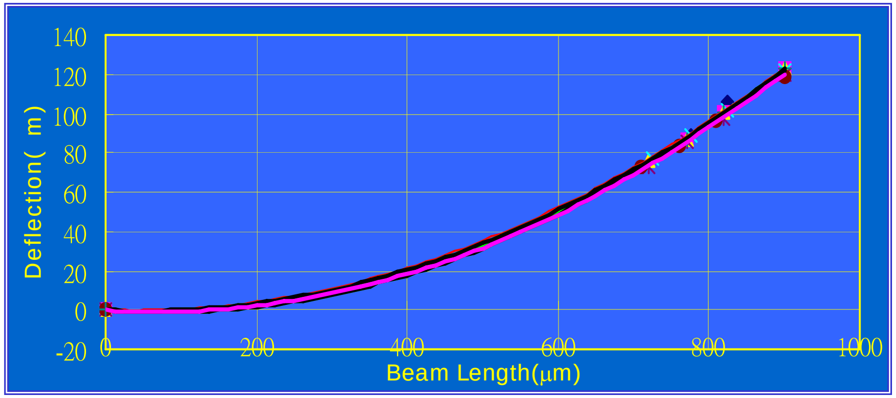


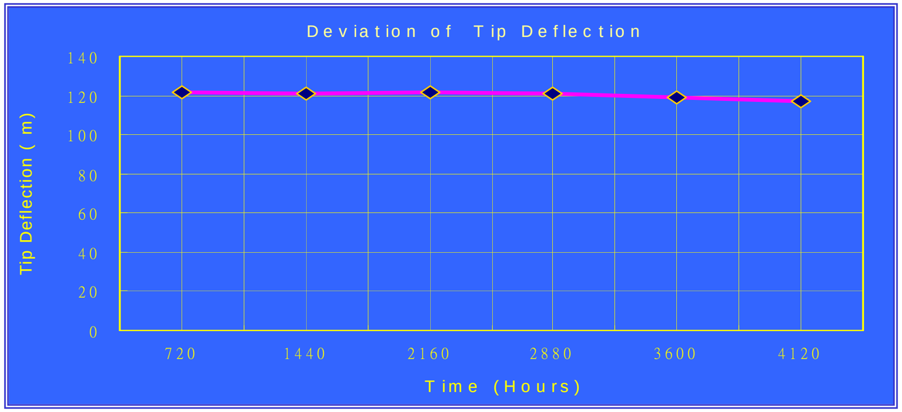


Coupling problem – the torsional & wobble motion

- **Reliability test**



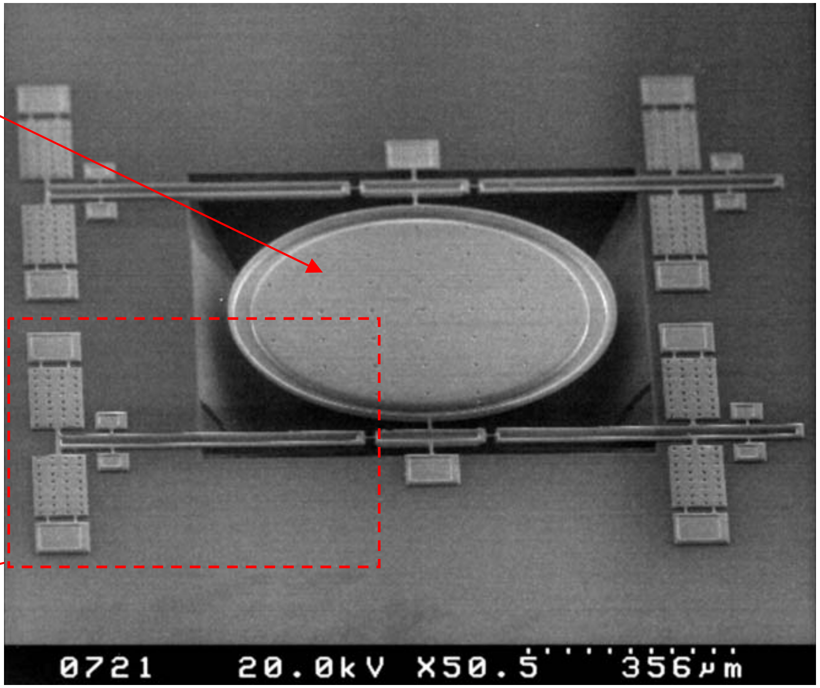




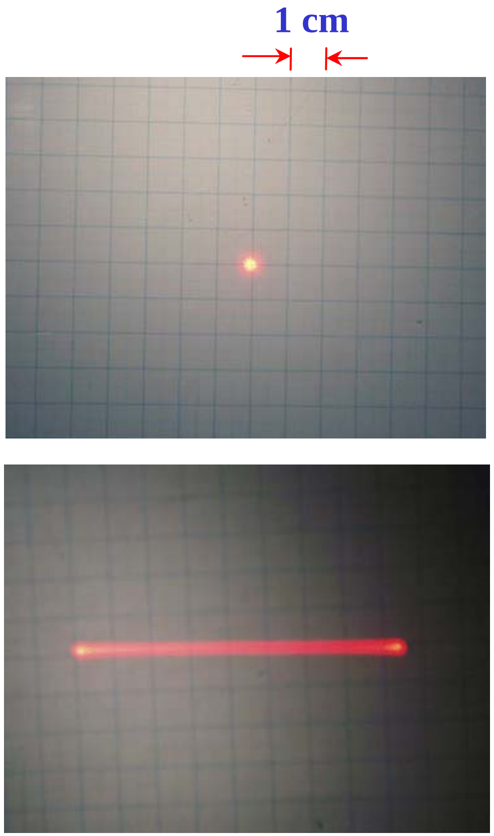
MDL
NTHU

Electrostatic actuator: optical scanner

Mirror (Follower)

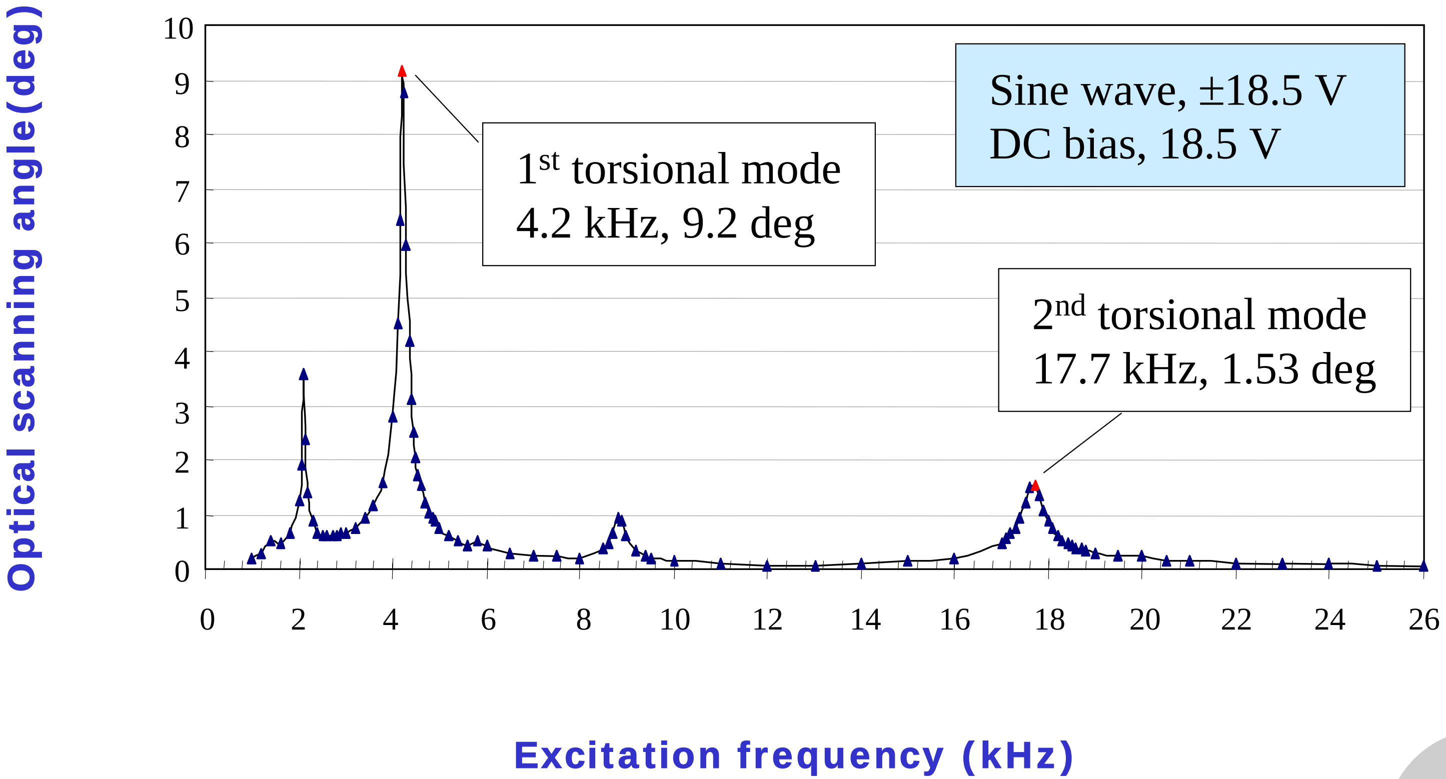


EDLA engine (Driver)



H.-Y. Lin and W. Fang, *IEEE Optical MEMS*, Kauai, Hawaii, 2000
H.-Y. Lin and W. Fang, the *ASME IMECE*, Orlando, FL, 2000

- **Measured frequency response**

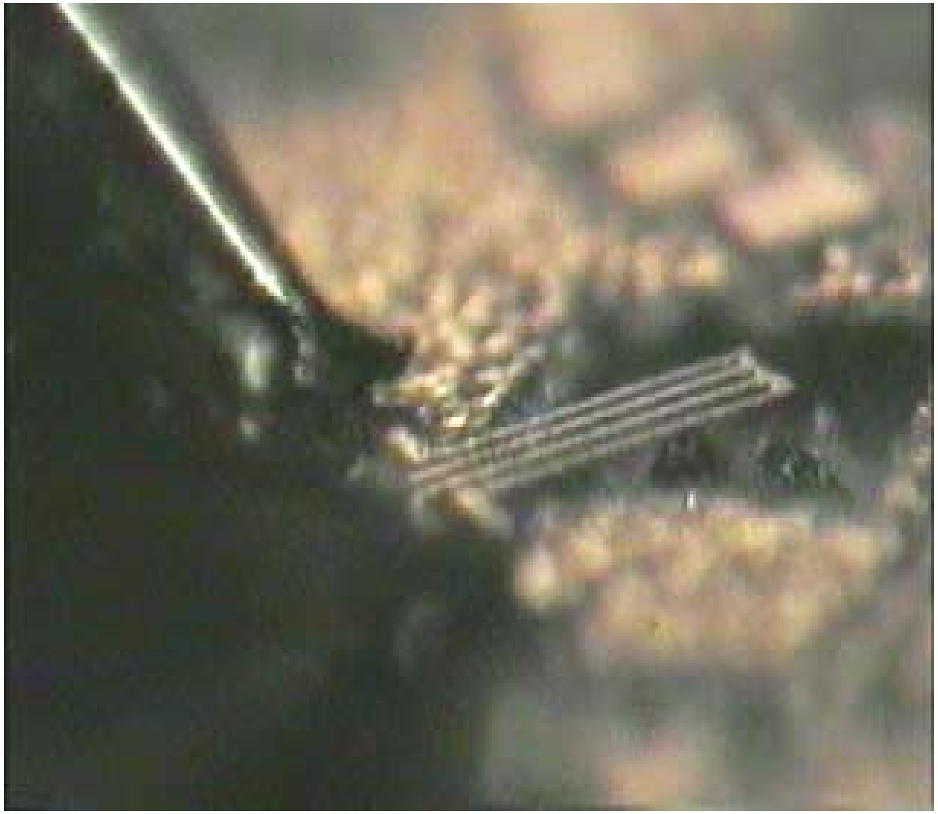


Sine wave, ±18.5 V
DC bias, 18.5 V

1st torsional mode
4.2 kHz, 9.2 deg

2nd torsional mode
17.7 kHz, 1.53 deg

Electrothermal actuator

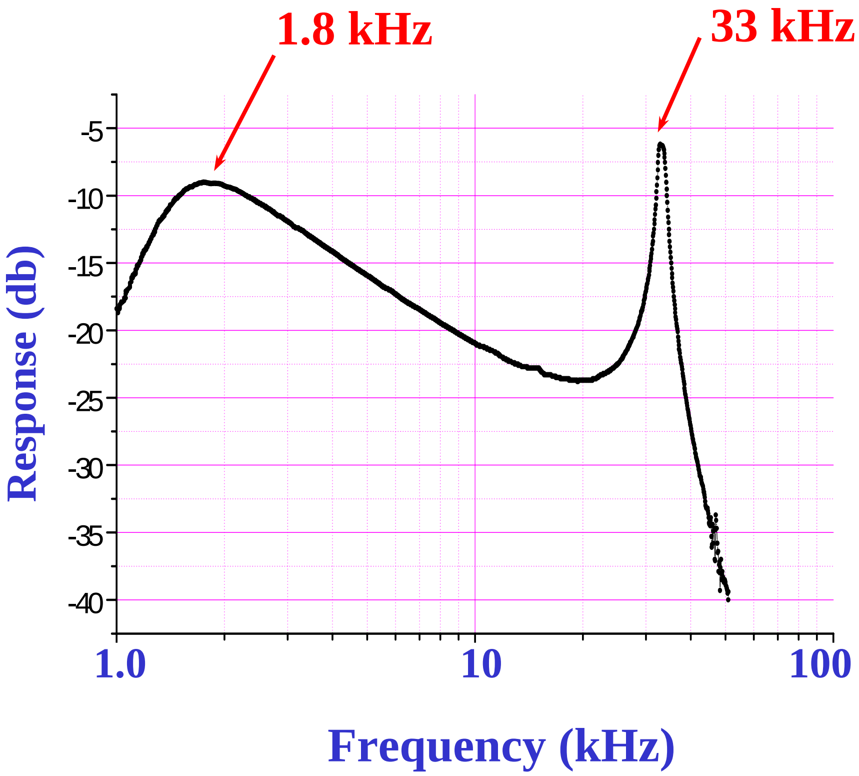


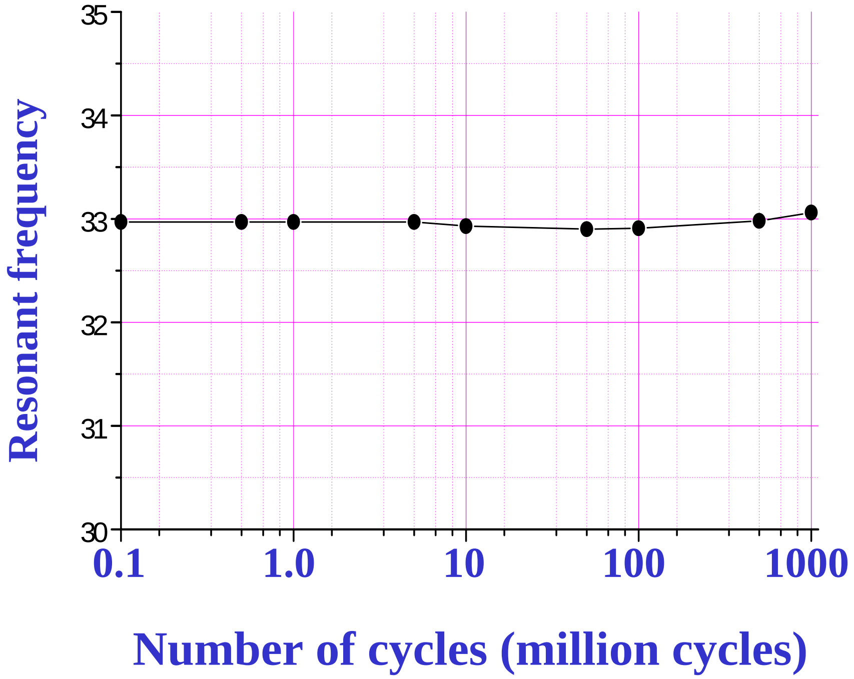
- **Mono layer – long life time**
- **Bi-direction (DC mode)**
- **High frequency (AC mode)**

Driving voltage : 5 volts

Output displacement : 7 μm

W.-C. Chen, J. Hsieh, and W. Fang, *IEEE MEMS'02*, Las Vegas, NV, 2002

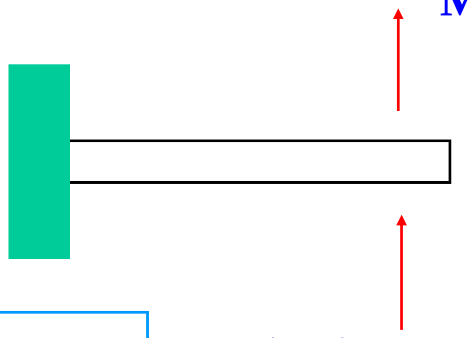

1.8 kHz
33 kHz
Response (db)
-5
-10
-15
-20
-25
-30
-35
-40
1.0
10
100
Frequency (kHz)


Resonant frequency
35
34
33
32
31
30
0.1
1.0
10
100
1000
Number of cycles (million cycles)

- **Static test**
  - **+ Devices**
  - **+ Material properties**
- **Dynamic test**
  - **+ Devices**
  - **+ Material properties – Resonant frequency, damping coefficient**

- When the excitation frequency of the structure coincides with its natural frequencies, its response will become extremely large

- In general, the vibration test requires a excitation source and a measurement device



Measurement

Accelerometer
Strain gauge
Eddy current
Optical

Vibration

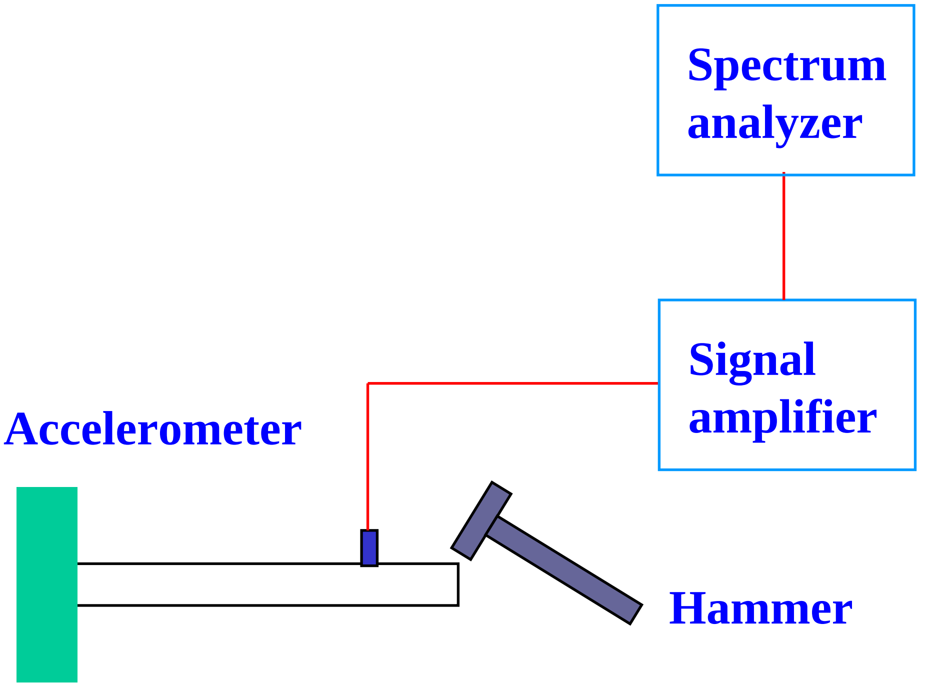
Excitation

Hammer
Shaker
Magnetic source
Noise generator

- **Example 1**

  + Structure excited by a hammer and detect by an accelerometer

  + In principle, all of the vibration modes will be excited after impact



Spectrum analyzer

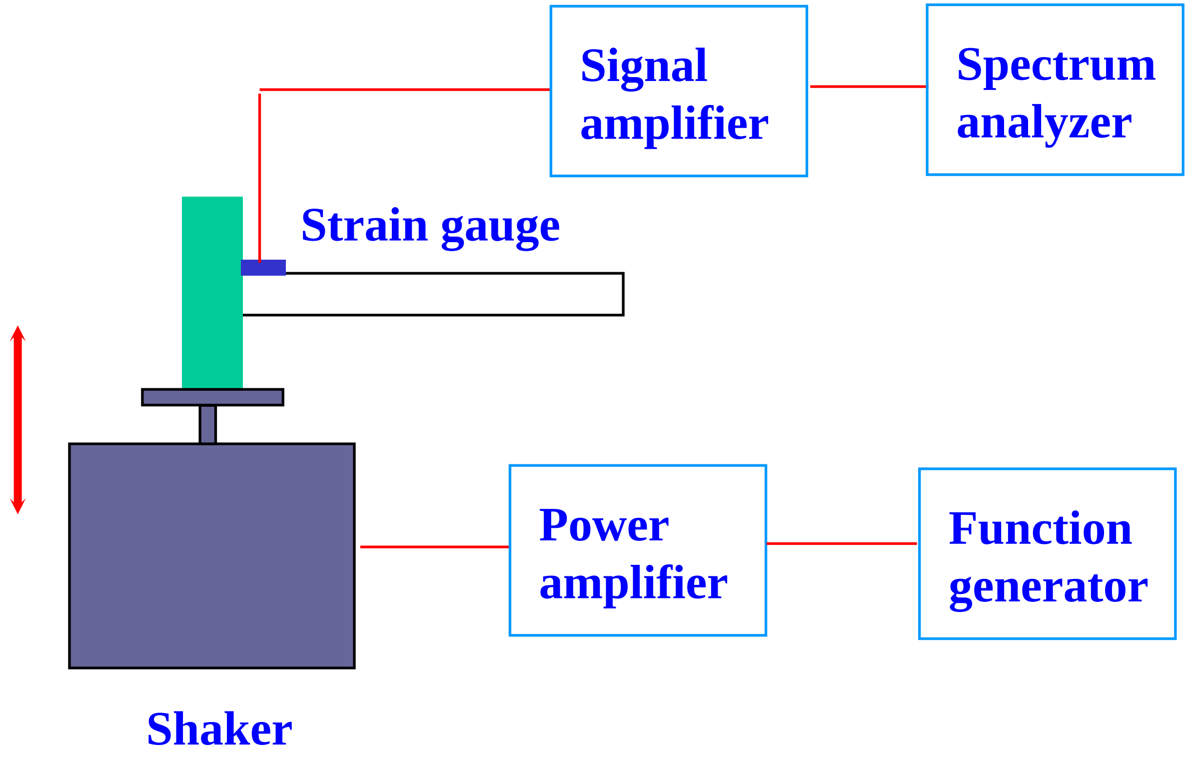
Signal amplifier

Accelerometer

Hammer

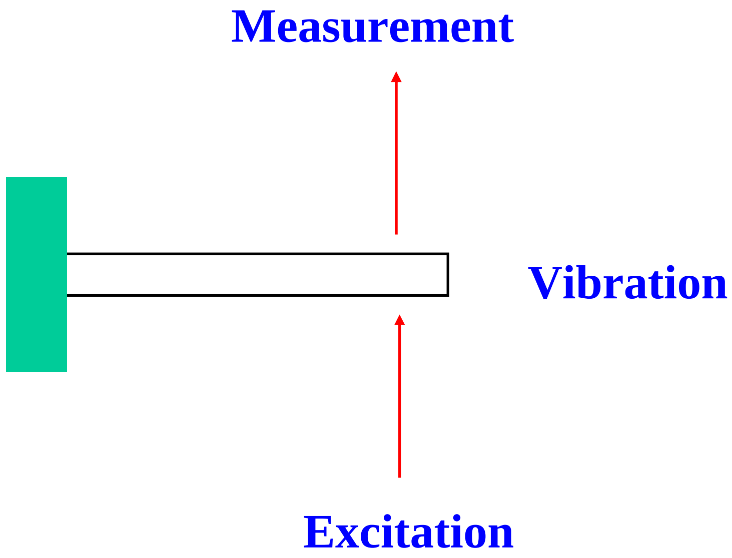
- **Example 2**

+ Structure excited by a shaker and detect by a strain gauge

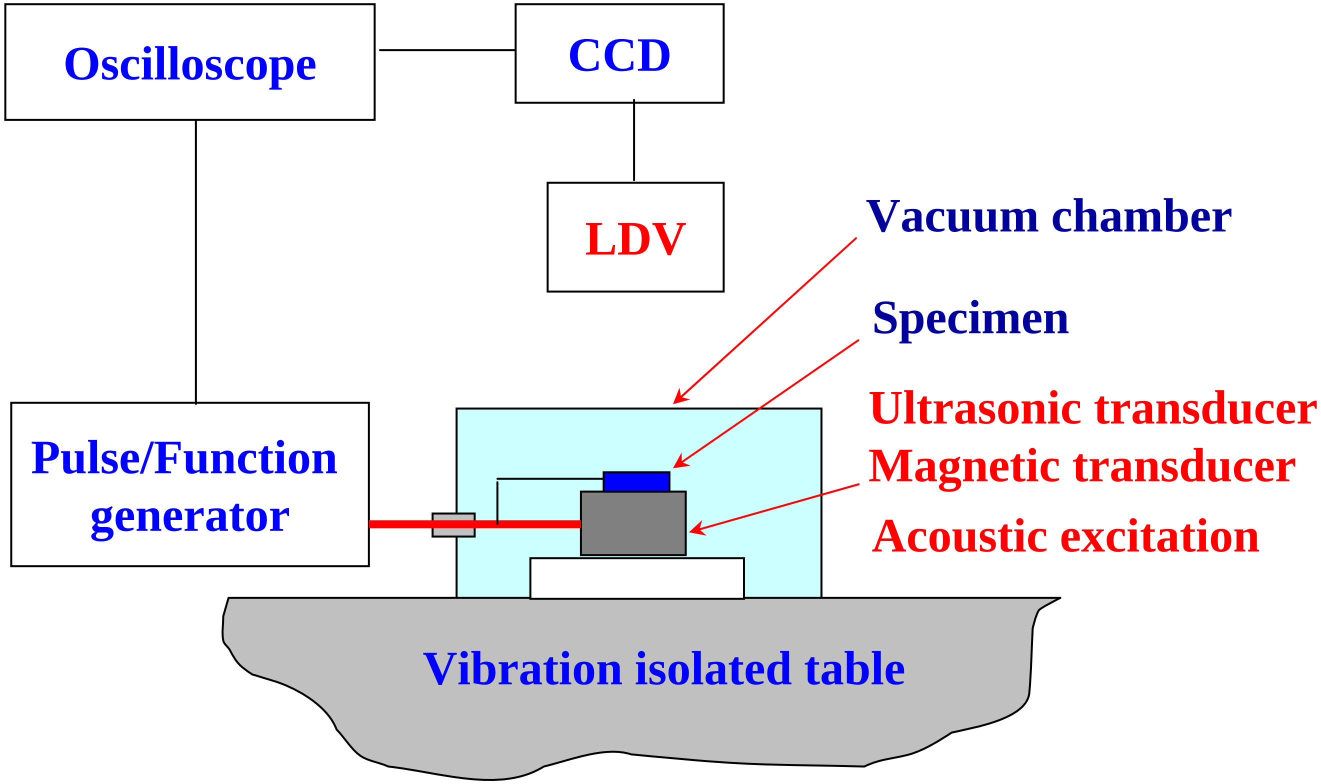


- **How to excite?**

- **How to sense?**



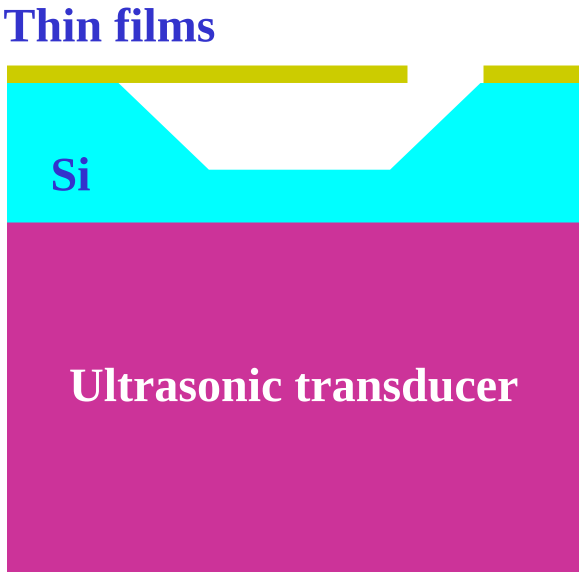
Dynamic Testing Platform

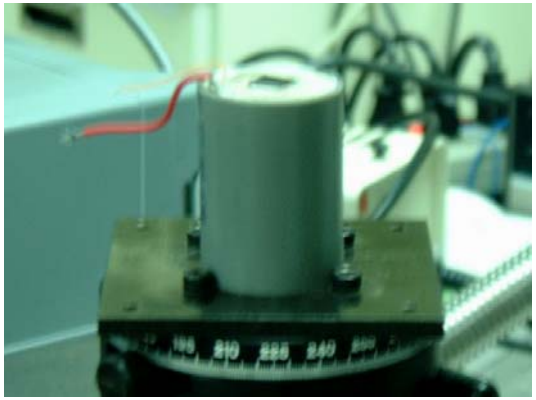


W. Lai and W. Fang, *Sensors and Actuators A*, 2001

Ultrasonic transducer

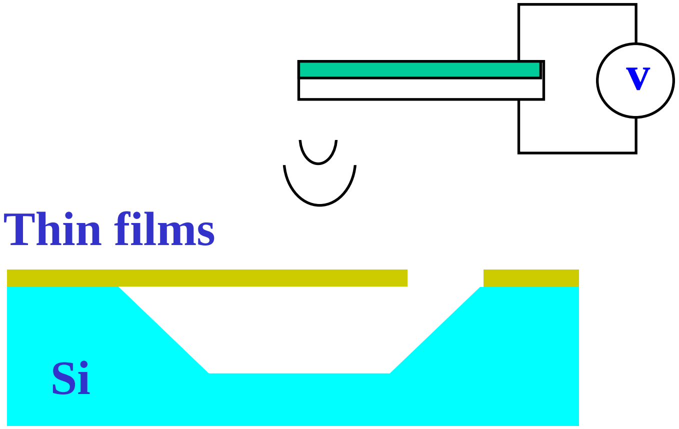
- **Ultrasonic Transducer: Pulse and Harmonic excitations**
- **The frequency range of the excitation can reach ~10 MHz**





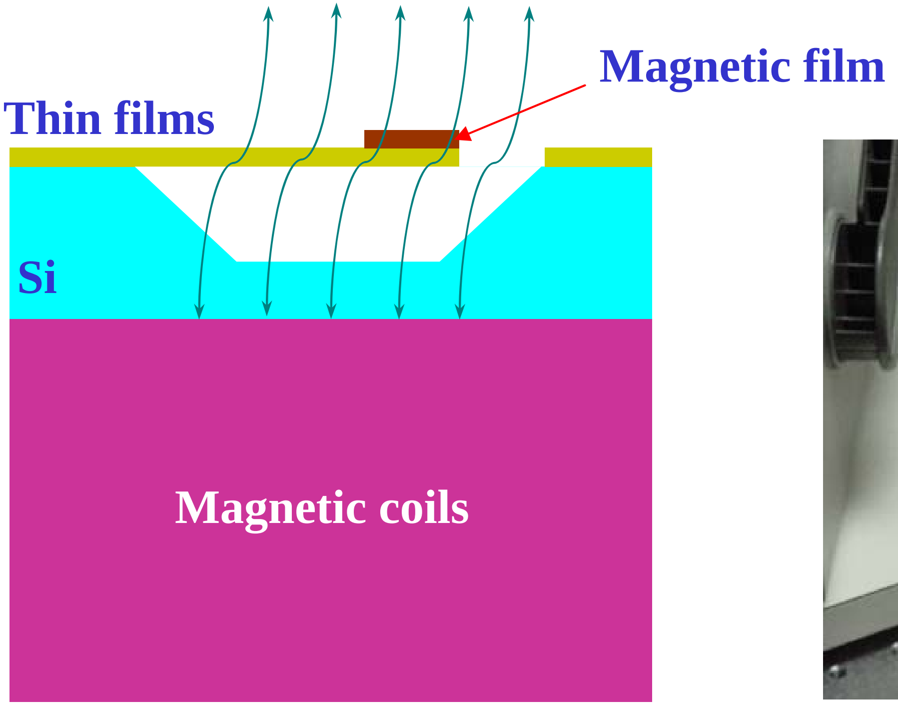
Acoustic excitation

- The frequency range of the wave generated by a loudspeaker is around 20 Hz ~ 20 KHz
- The frequency range of the wave generated by a piezoelectric transducer is around 0 ~ 1.2 MHz



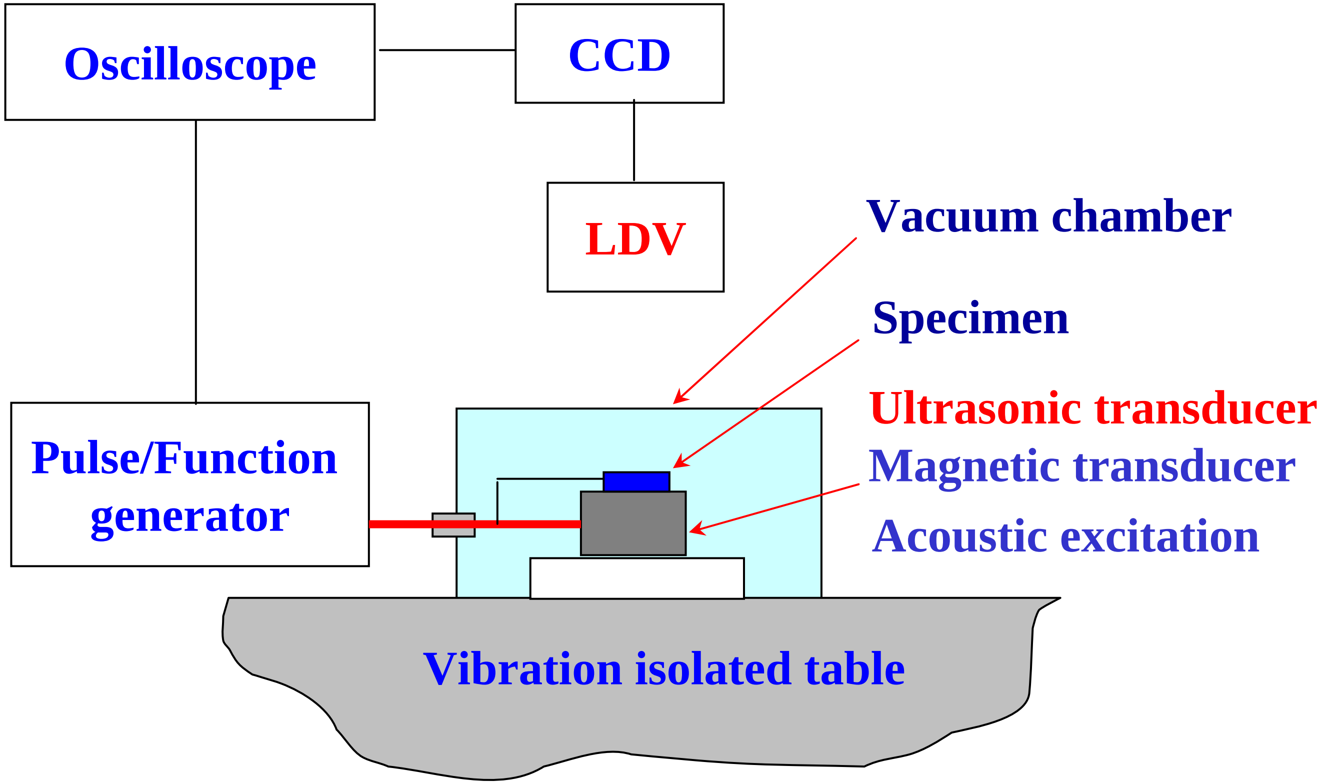
Magnetic transducer

- An magnetic coil is used to generate magnetic force – harmonic excitation only



H.-C. Tsai and W. Fang, *AVS conference*, 2000

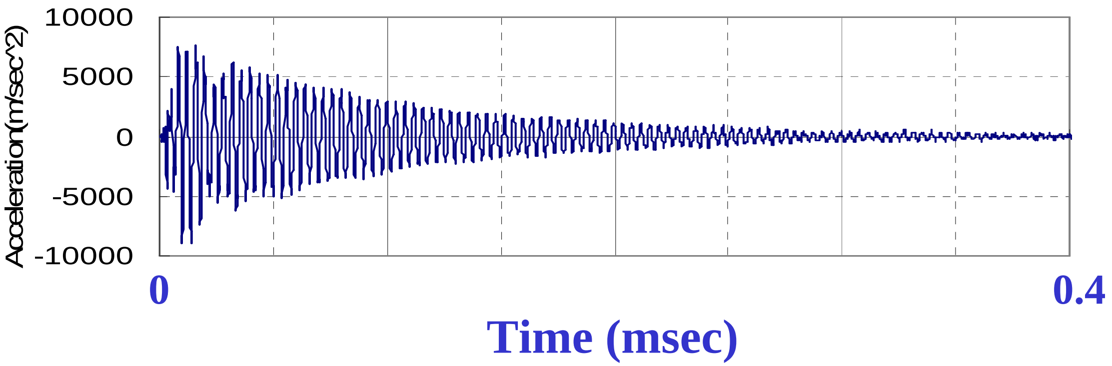
Dynamic Testing Platform



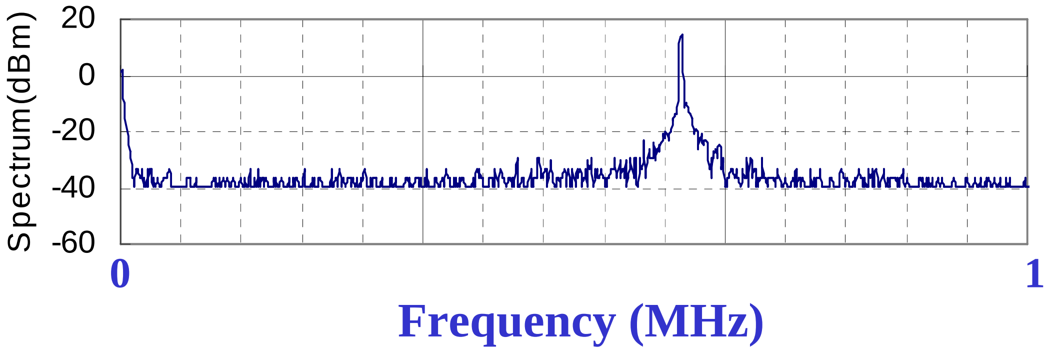
W. Lai and W. Fang, *Sensors and Actuators A*, 2001

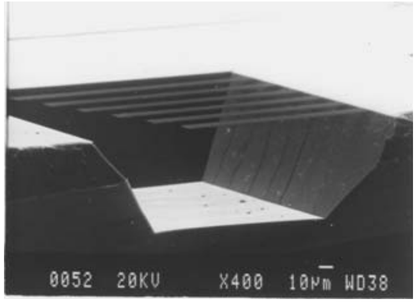
Resonance frequency/ Damping coefficient

- **Time domain**



- **Frequency domain**

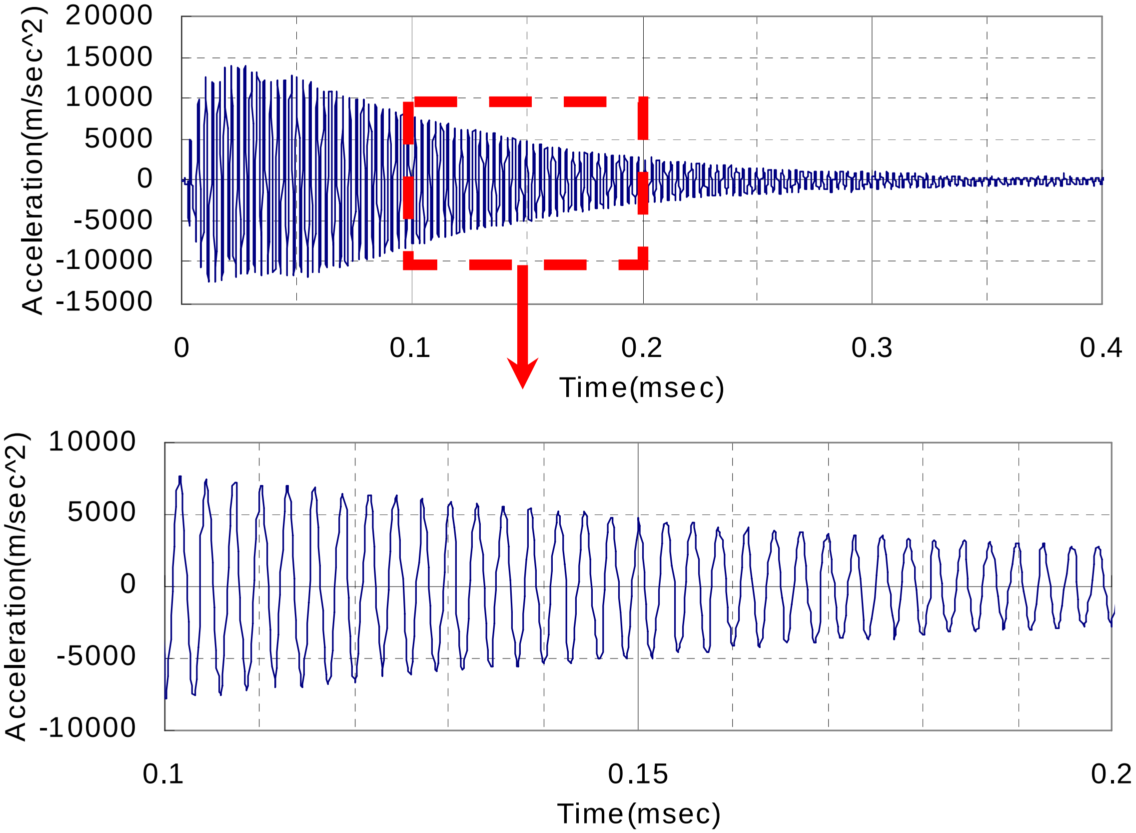




test cantilever

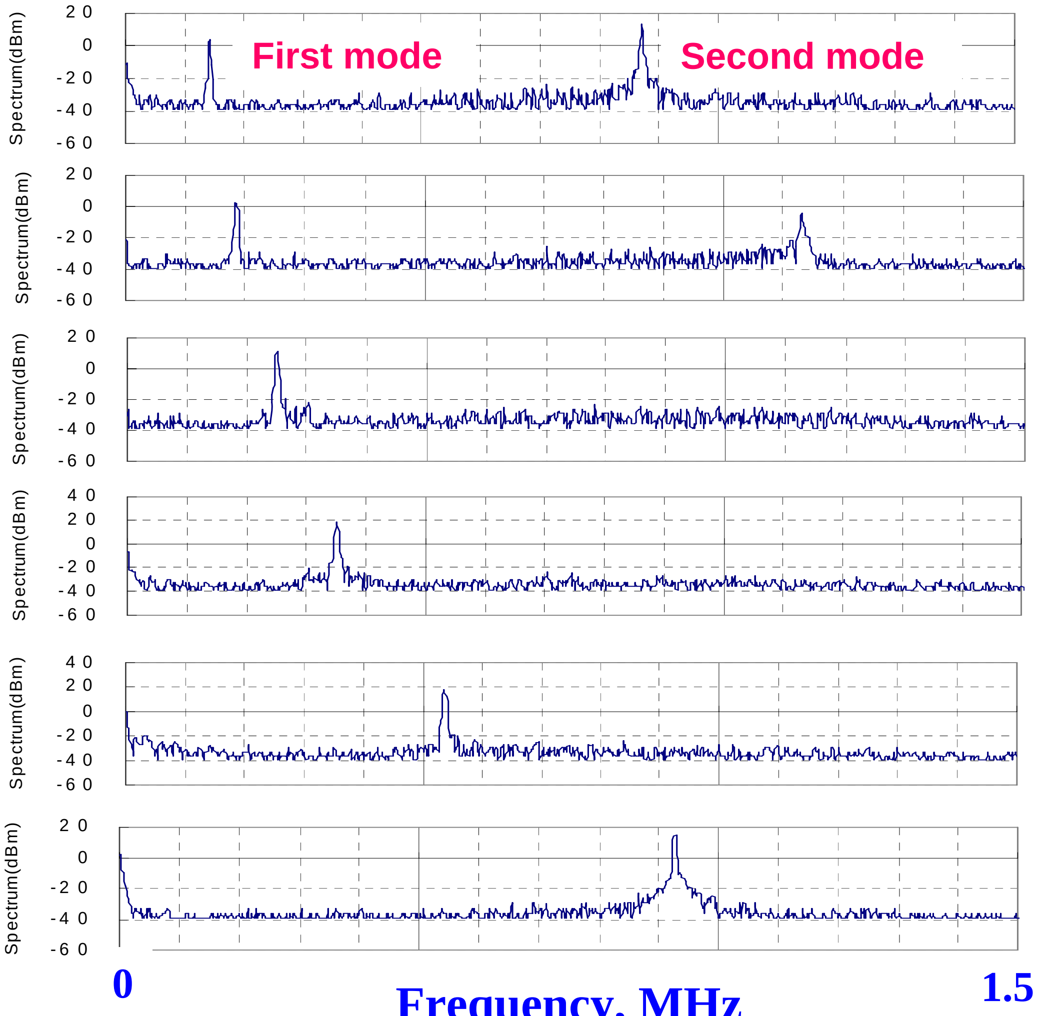
W. Lai, Y. Ho, and W. Fang, the *ASME IMECE*, New York NY, 2001

- **Time domain response**



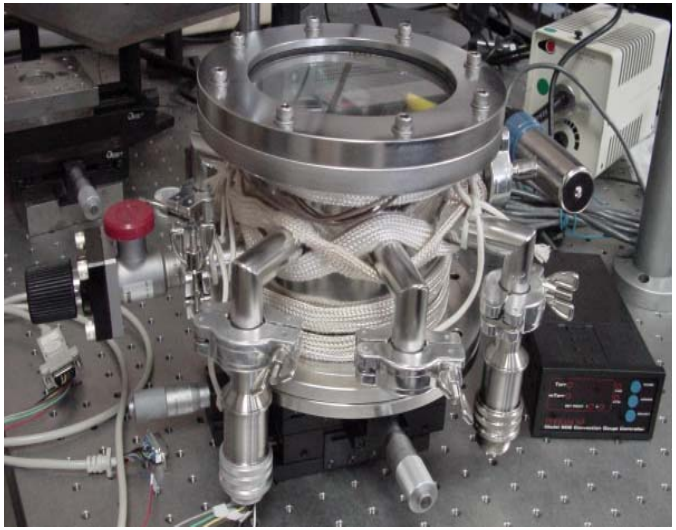
Results

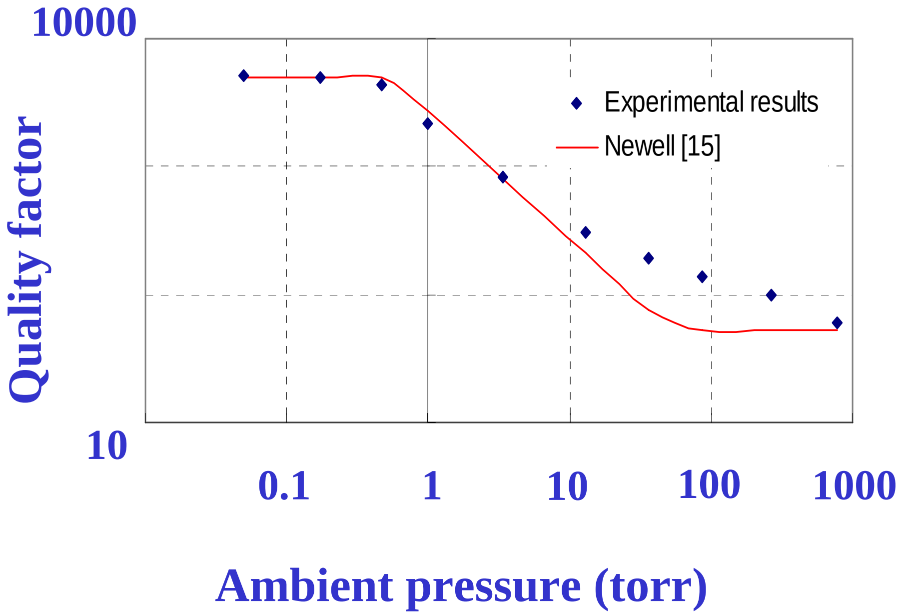
- **Frequency domain response**



Frequency, MHz

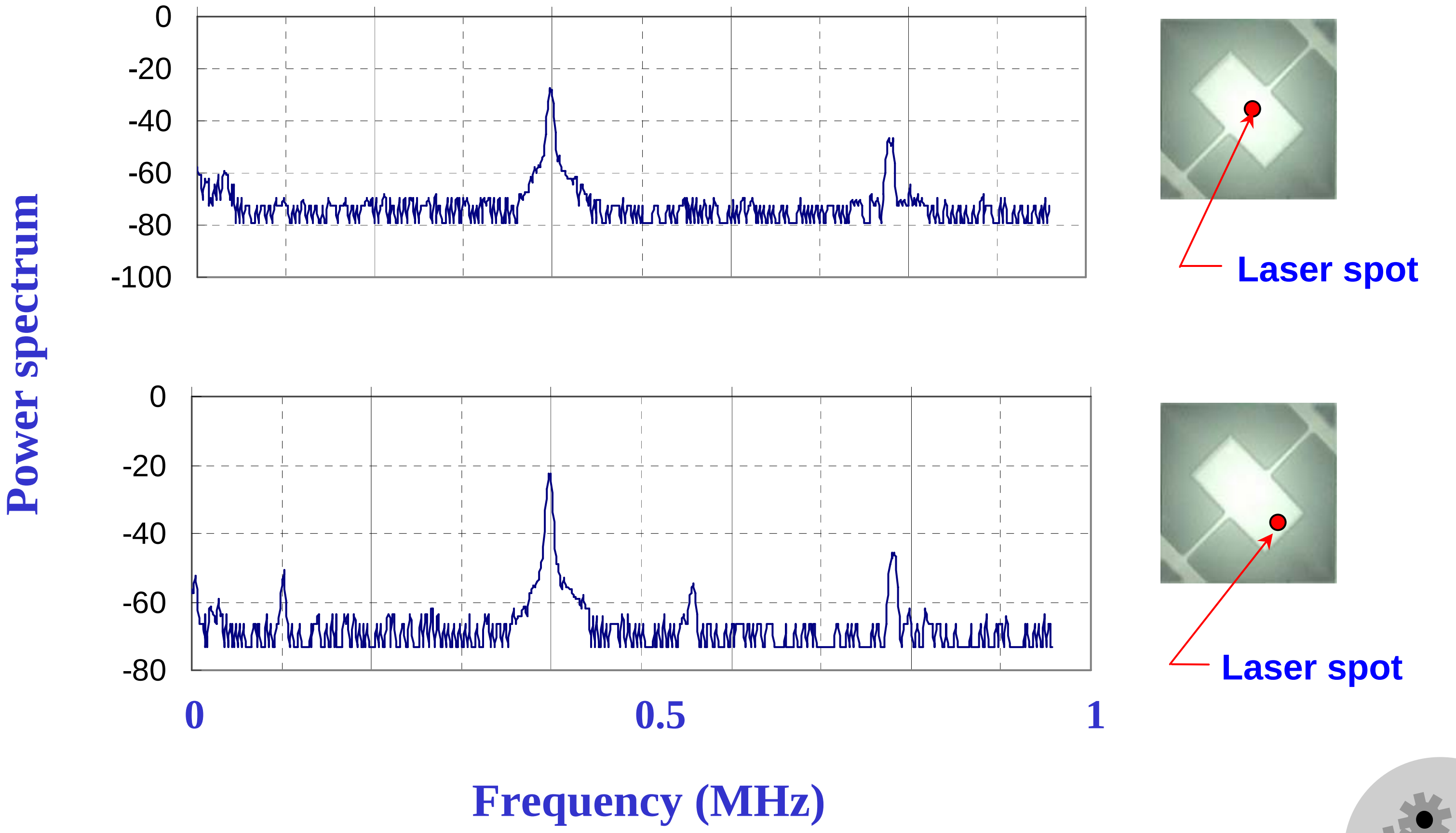
- **Variation of the quality factor with the ambient pressure**





W. Lai, Y. Ho, and W. Fang, the *ASME IMECE*, New York NY, 2001

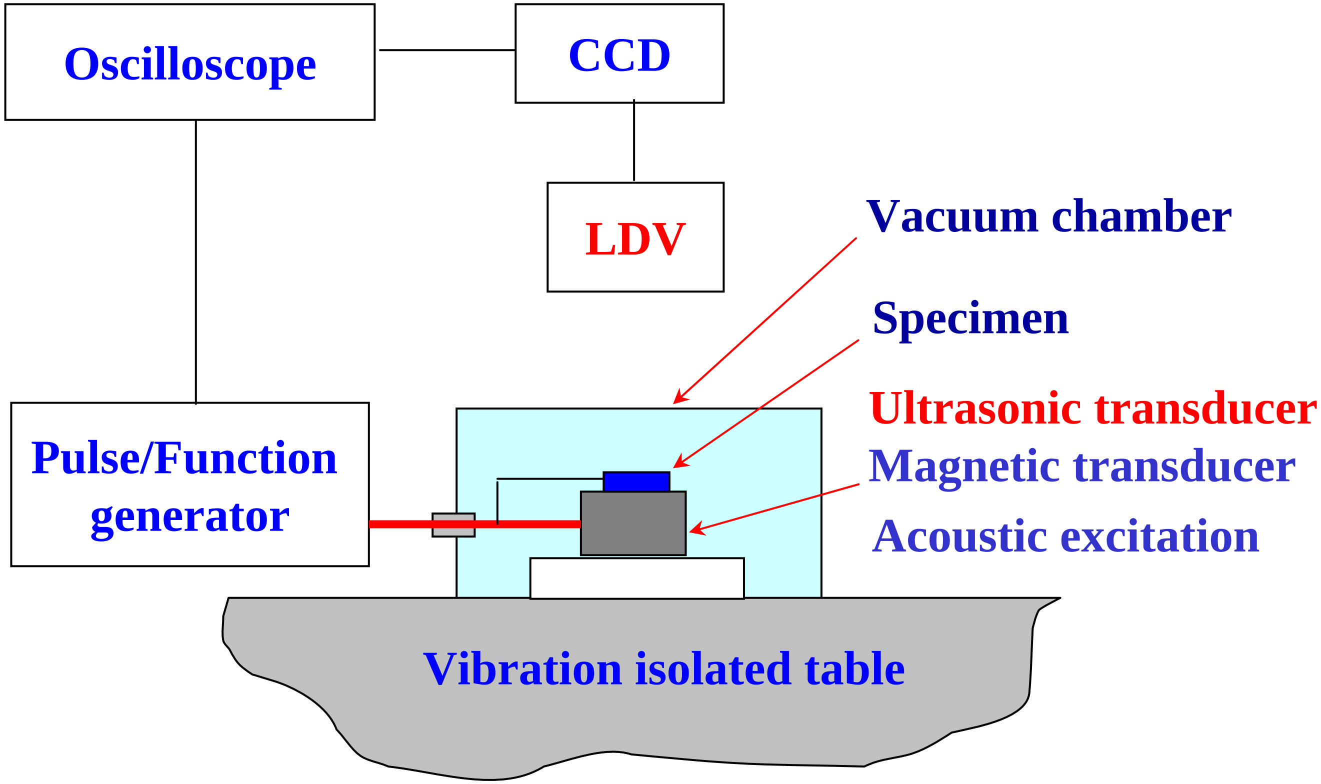
- **Dynamic behavior of complicated structure**



- Static test
  - + Devices
  - + Material properties

- Dynamic test
  - + Devices
  - + Material properties – Young’s modulus,
    Poisson’s ratio

Dynamic Testing Platform



W. Lai and W. Fang, *Sensors and Actuators A*, 2001

Thin film material properties

- Young’s modulus **E**, Shear modulus **G**, and Poisson’s ratio **ν**

Bending mode

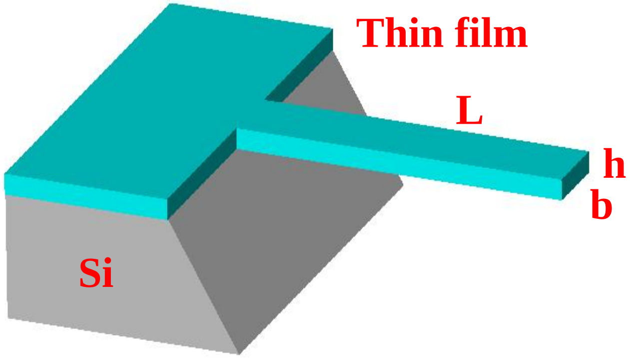
$$E = C_1(L, h, \rho) f_B^2$$

Geometry and material constants

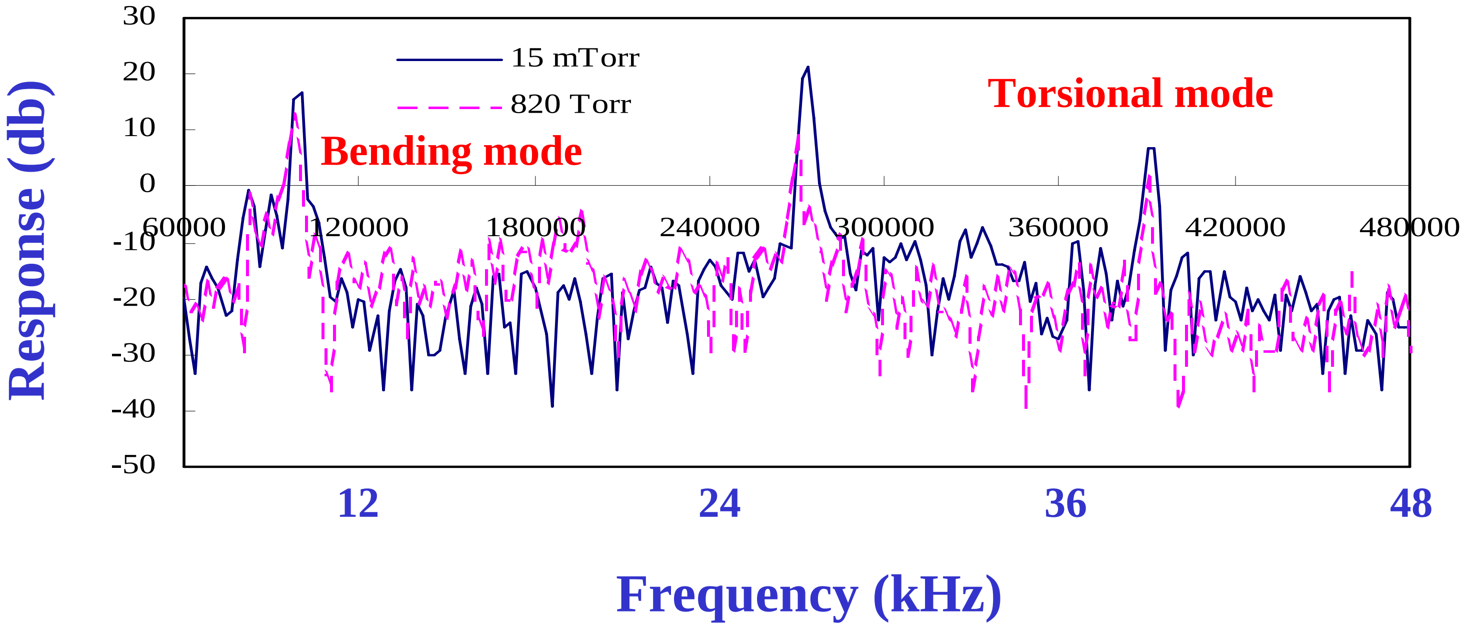
$$G = C_2(L, h, b, \rho) f_T^2$$

Torsional mode

$$\upsilon = \frac{E}{2G} - 1$$



- **Measured Young's modulus for SiO_2 film : E = 57 Gpa (bulk : 70 Gpa)**
- **Measured Poisson's ratio for SiO_2 film : ν = 0.202 ± 0.021 (bulk : 0.17)**



H.-C. Tsai, W. Lai, and W. Fang, the *ASME IMECE*, New York NY, 2001

Summary

- Static test
  - \+ Devices
  - \+ Material properties

- Dynamic test
  - \+ Devices
  - \+ Material properties

Geometry and Boundary Considerations

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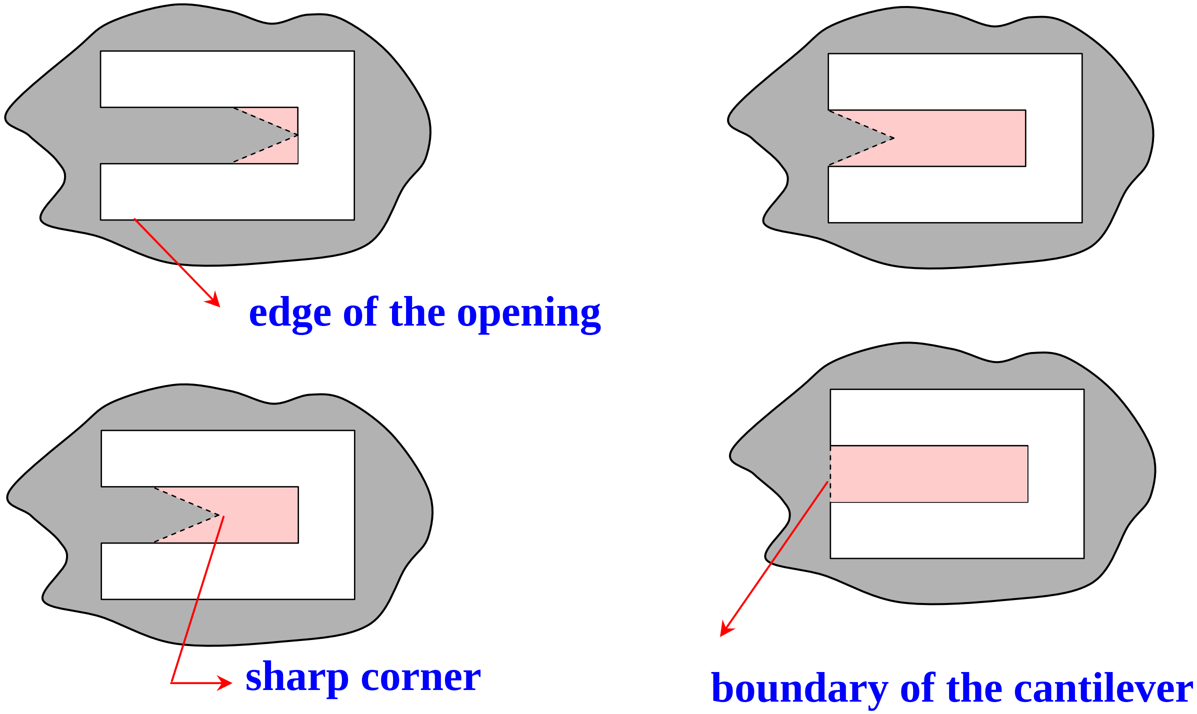
Cross section of the test beams

H.-H. Hu and W. Fang, Sensors and Actuators A, 2001

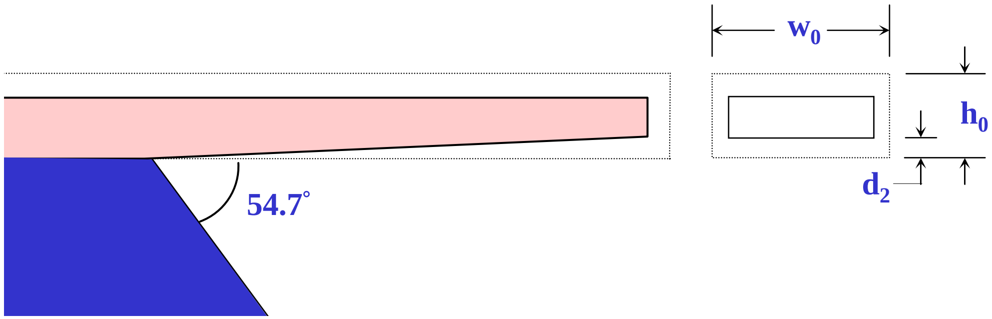
- For (100) Si substrate

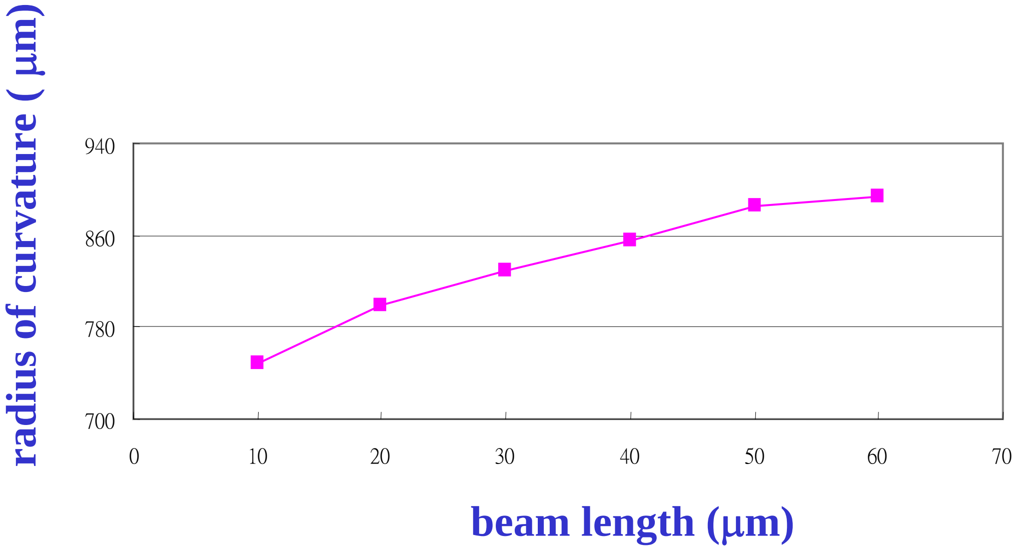


edge of the opening

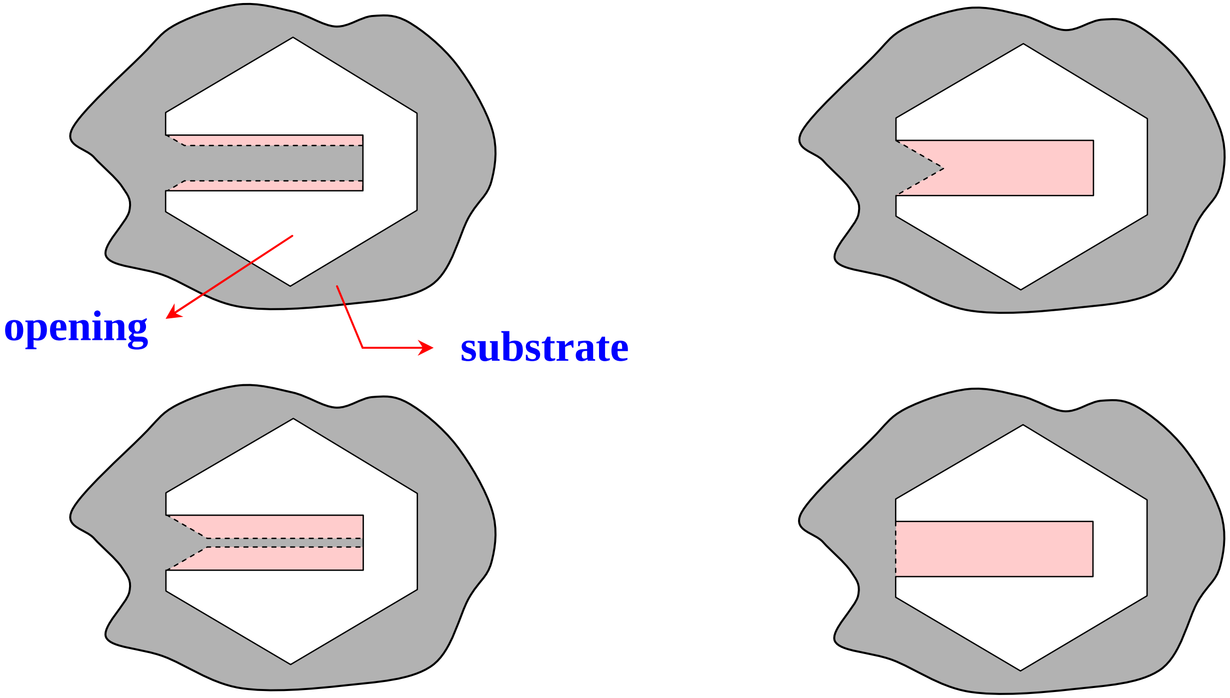
sharp corner

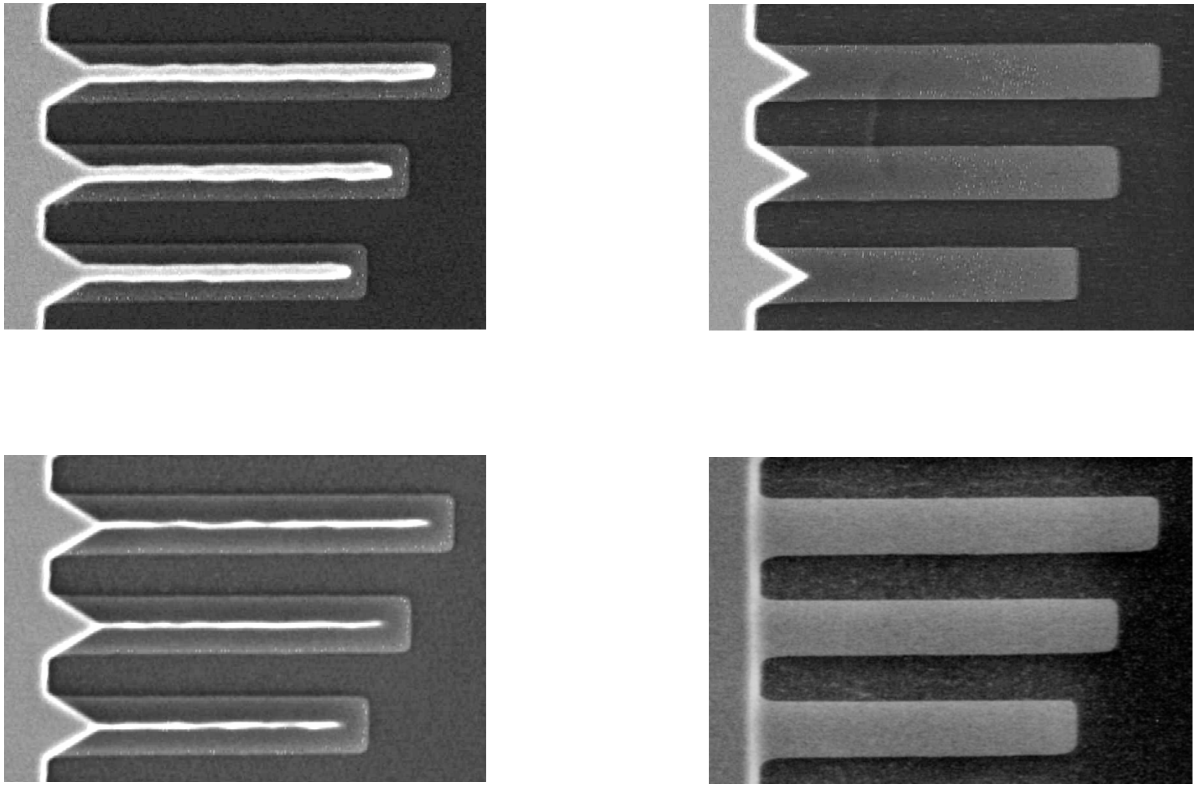
boundary of the cantilever

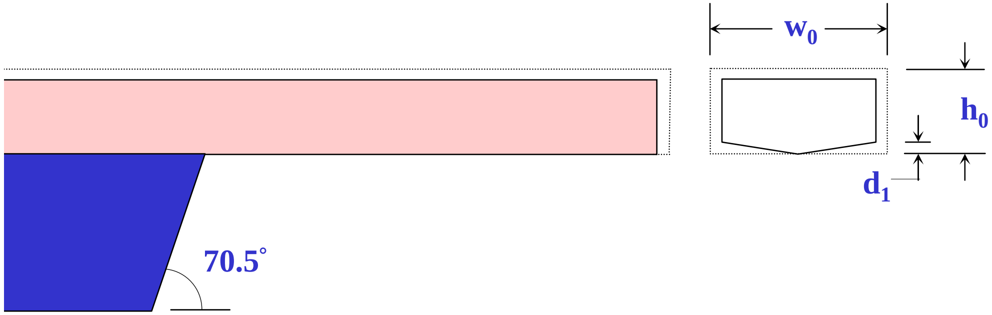

w0
h0
d2
54.7°


radius of curvature (μm)
940
860
780
700
0
10
20
30
40
50
60
70
beam length (μm)

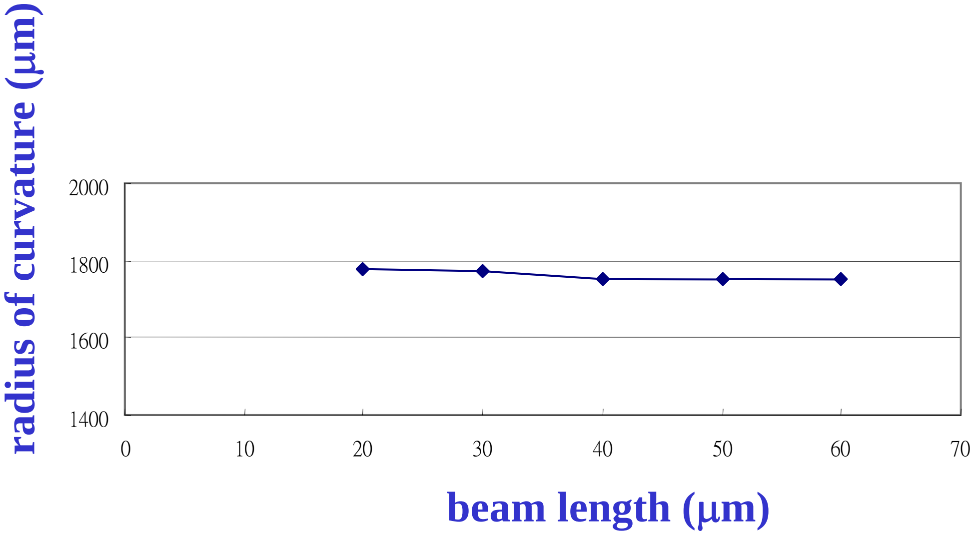
- **For (111) Si substrate**







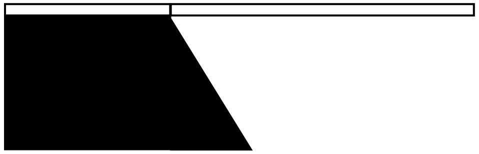
w_0
h_0
d_1
70.5°



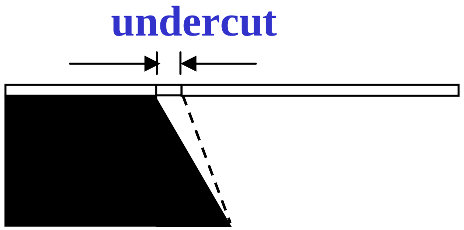
radius of curvature (μm)
2000
1800
1600
1400
0
10
20
30
40
50
60
70
beam length (μm)

Boundary Conditions - I

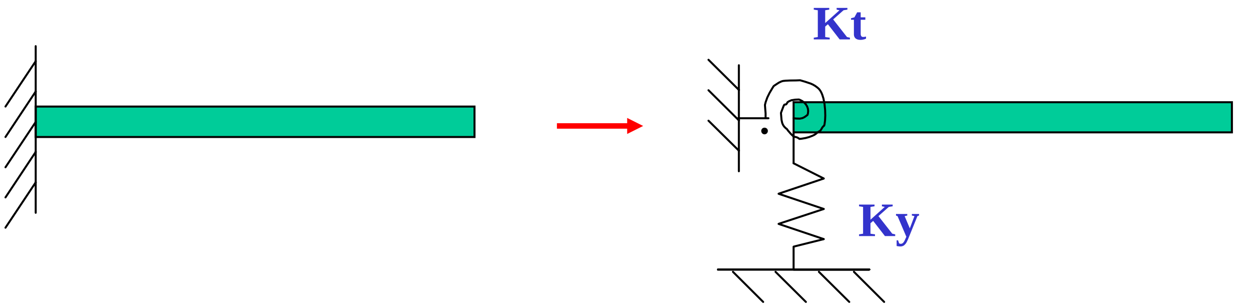
- Bulk process – half plane, undercut



Halfplane

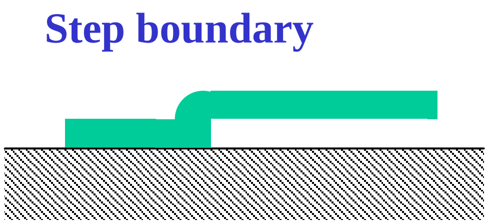


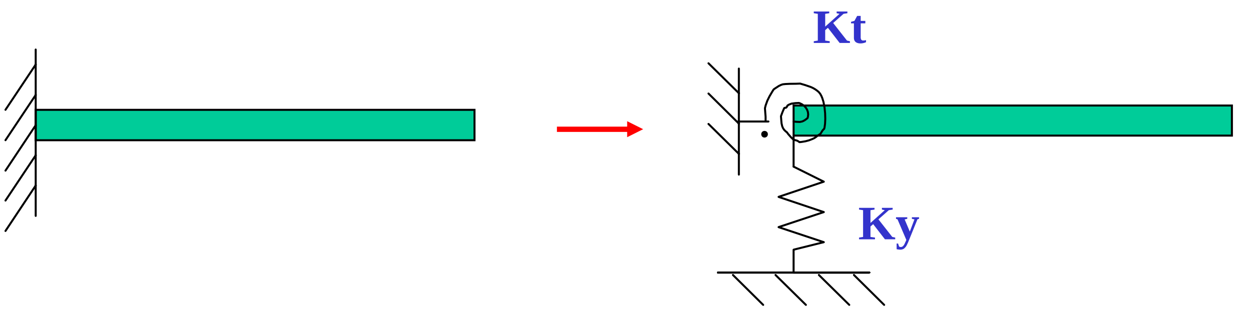
Undercut



Boundary Conditions - II

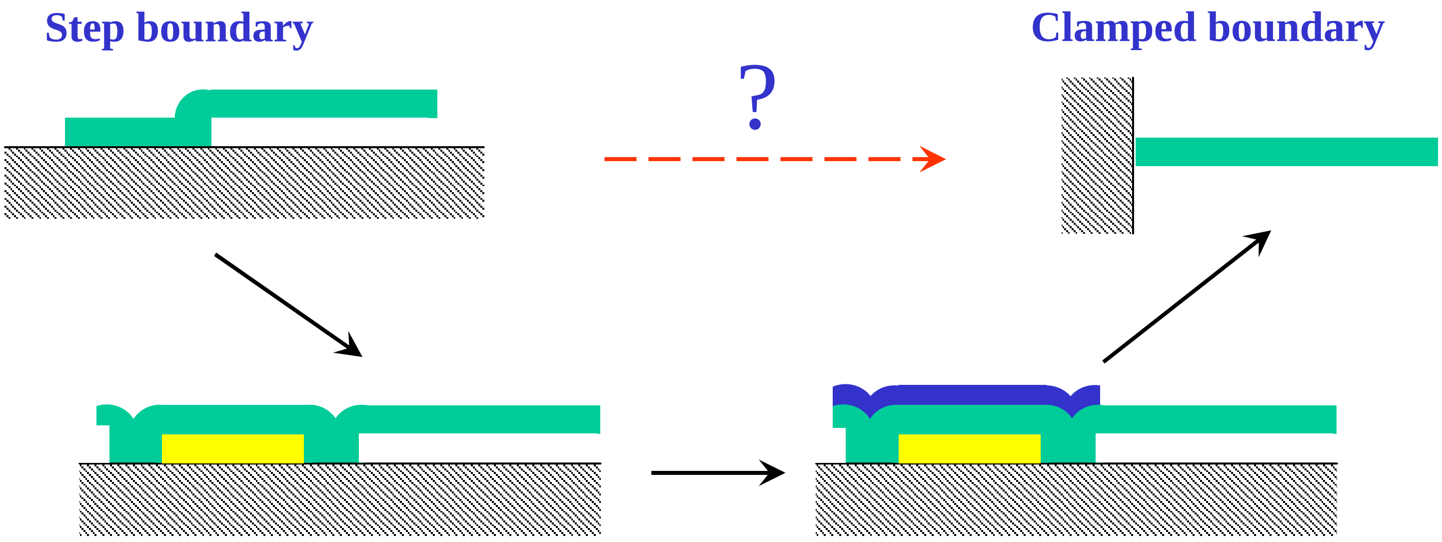
- Surface process – step





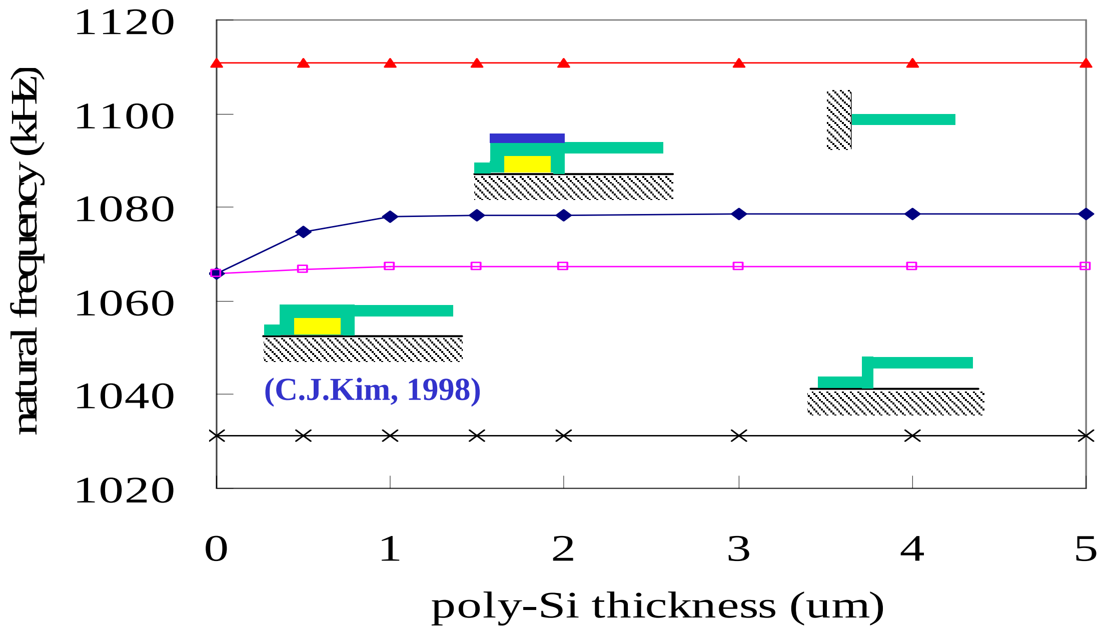
Boundary Reinforcement

- **For 2 poly surface processes**



C.J.Kim, 1998

- # FEM simulation



	Ideal	Step	Plane	Stack
Natural frequency	**1110690**	**103180**	**1065990**	**1078310**
Error	**0 %**	**7.25 %**	**4.02 %**	**2.91 %**

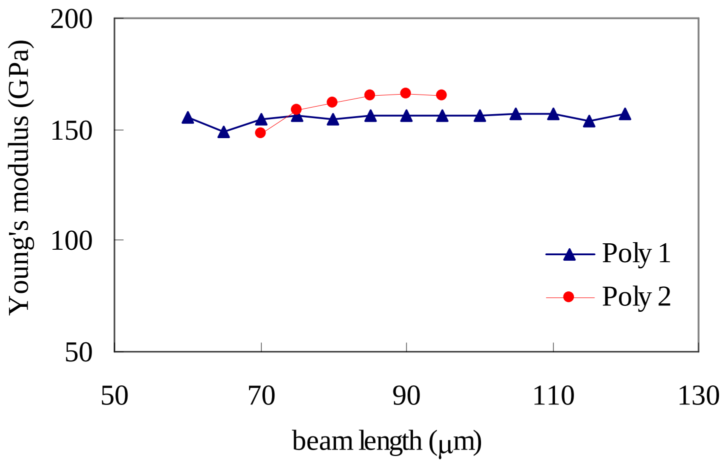
MDL
NTHU

Measurement – elastic modulus of poly-Si

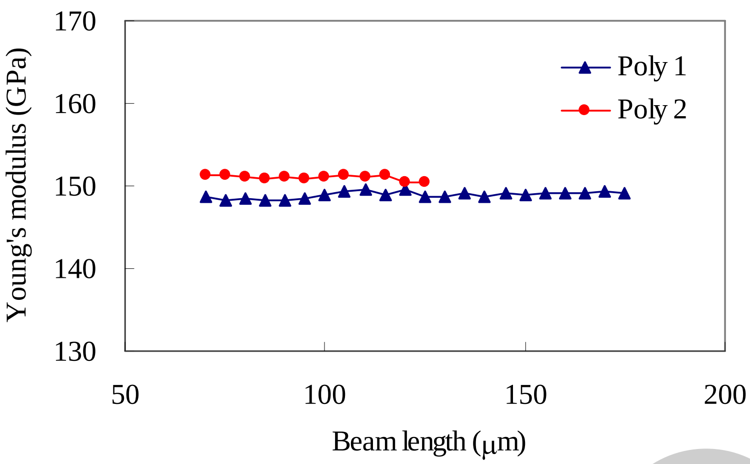
+ $E_{Poly1} = 148.9 \pm 0.7$ GPa, in MUMPs 55

+ $E_{Poly2} = 151.0 \pm 0.7$ GPa, in MUMPs 55

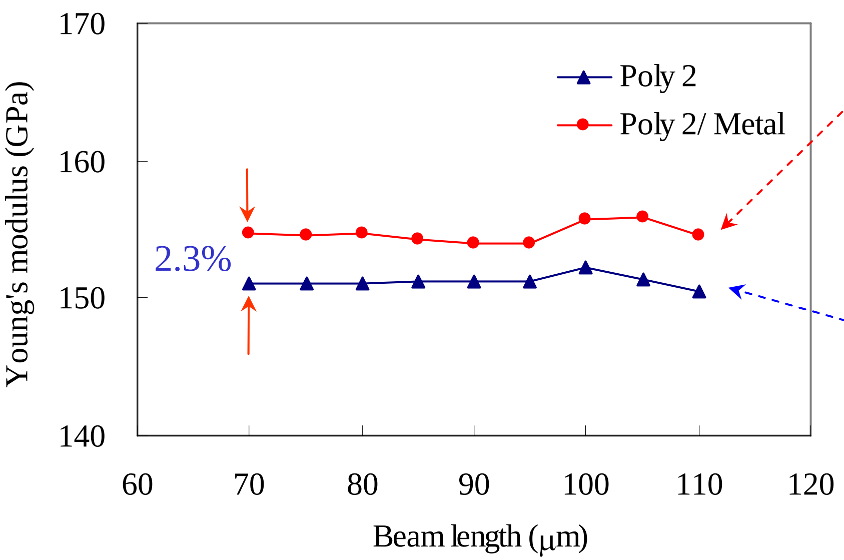
MUMPs 51

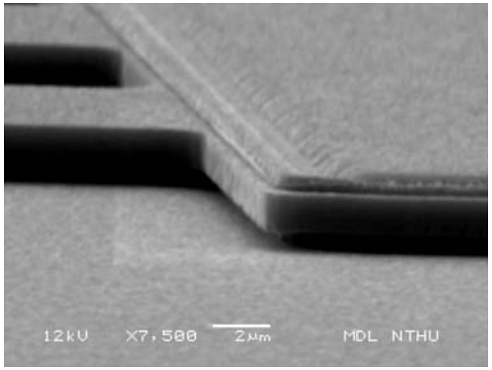


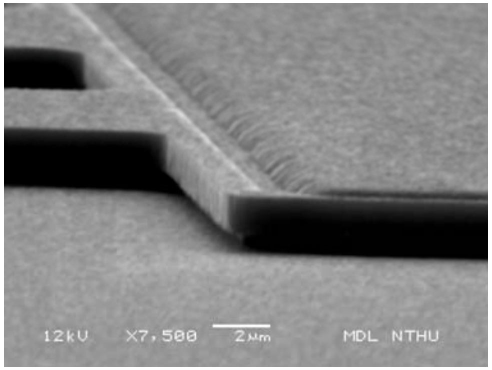
MUMPs 55



- **Comparison of the measured elastic modulus for different boundary condition**

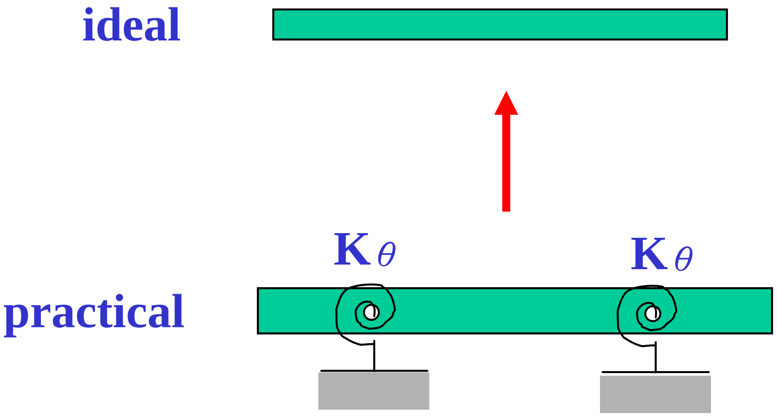


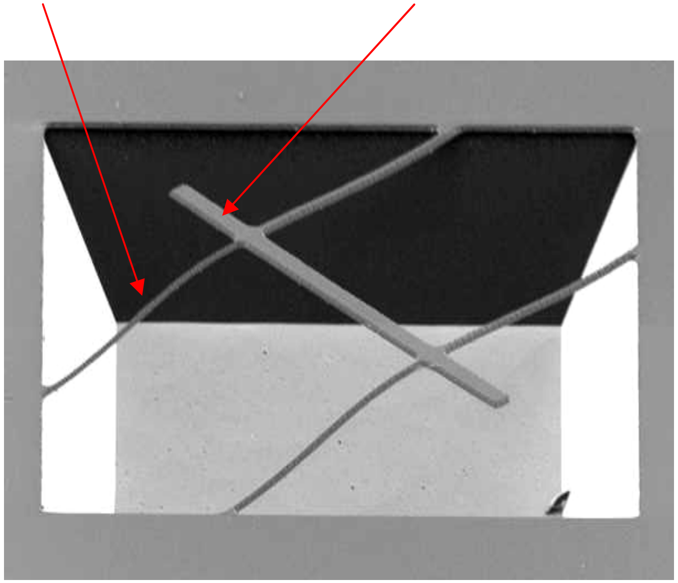




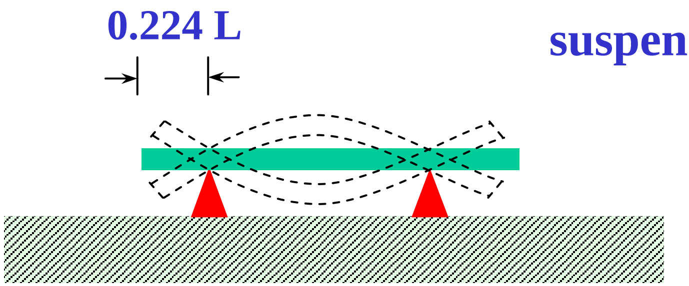
Elastic modulus of thin film

Free-Free Beam

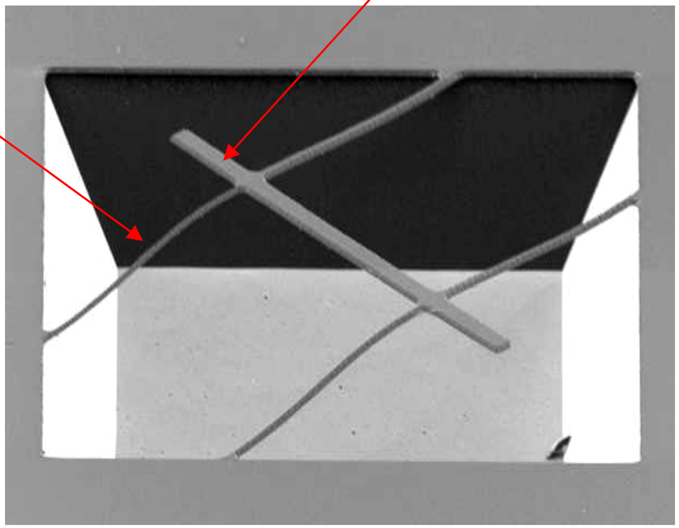




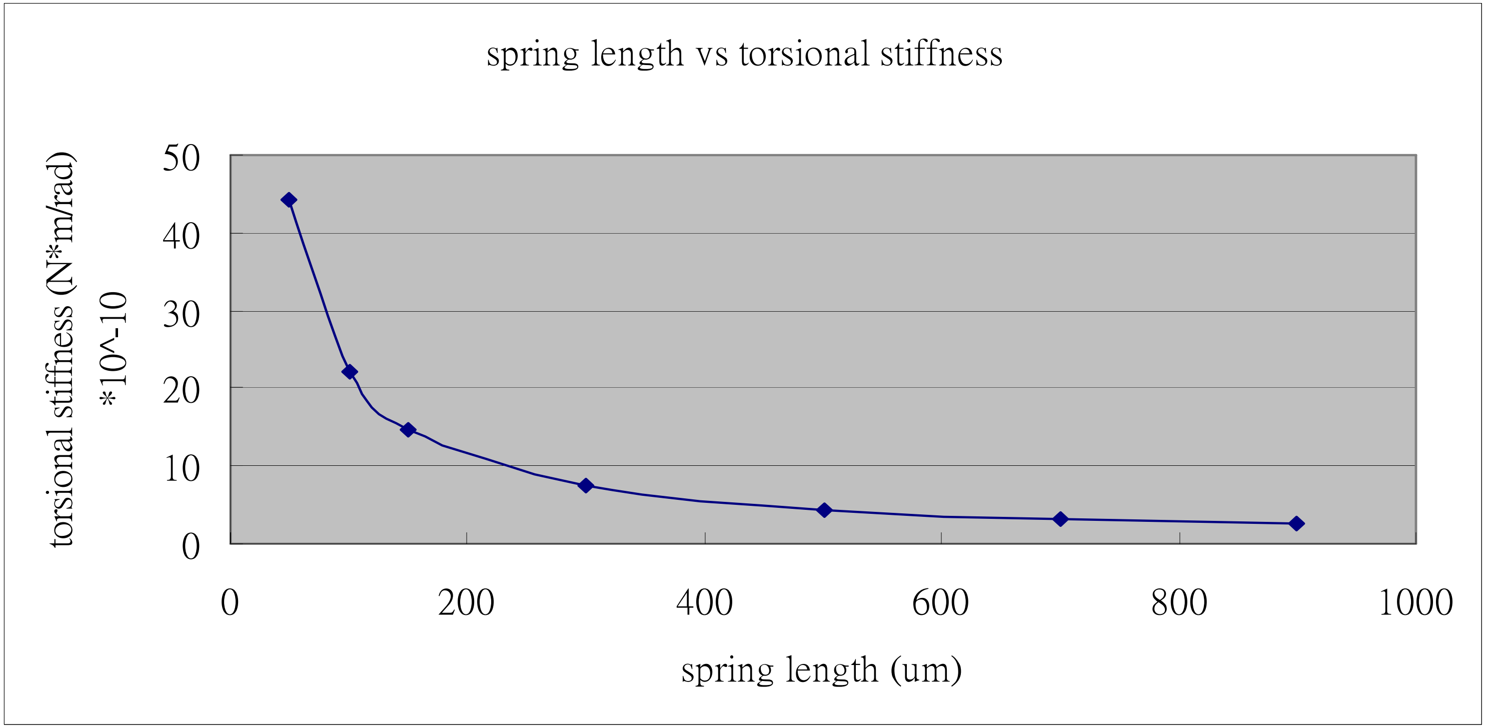
- Micro “free-free” beam
  - + The location of suspension
  - + Torsional Stiffness vs resonant frequency & mode



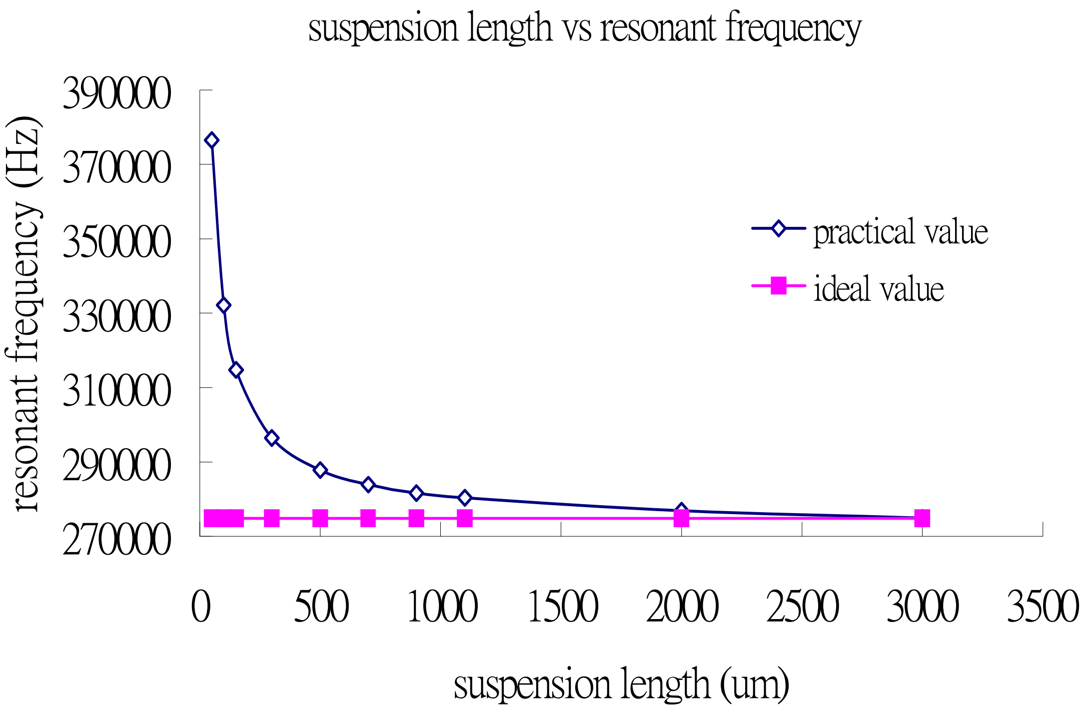
$$E = 0.9465\frac{\rho A L^4 f_F^2}{bh^3}T_1$$



- **Torsional stiffness vs suspension length**

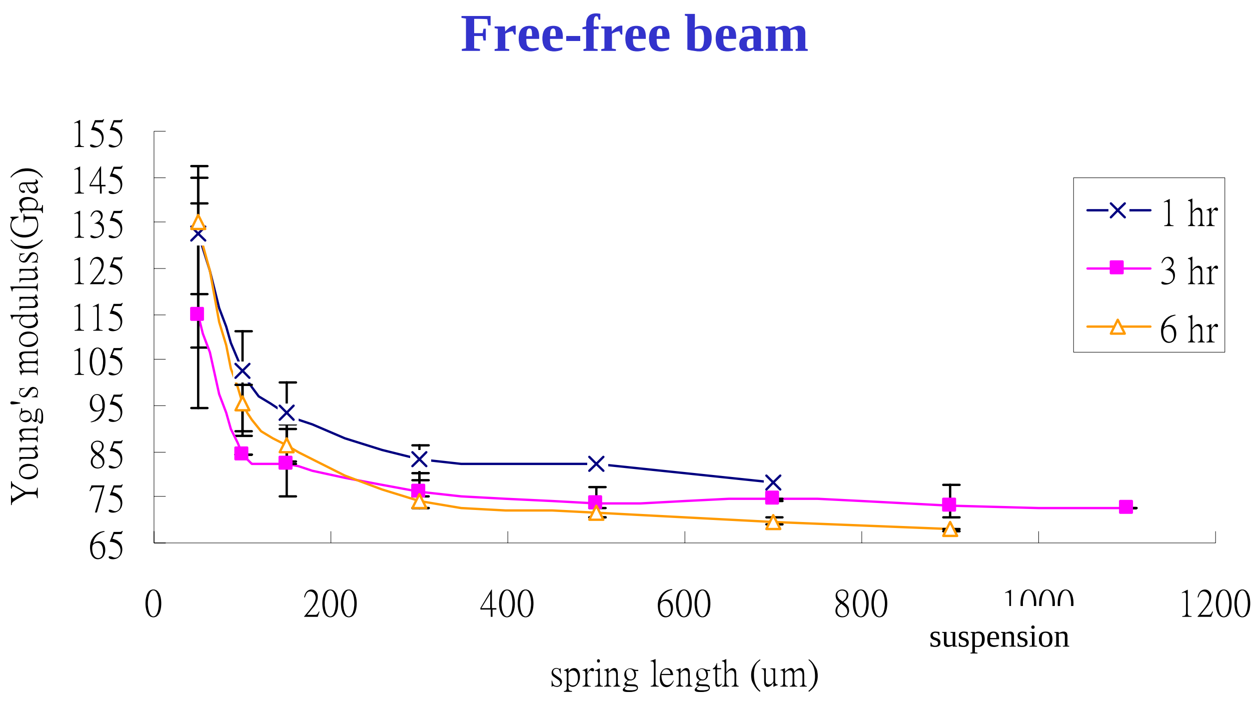


- **Simulation of the natural frequency vs suspension length**



4.7 % error when torsional spring length is 500 μm

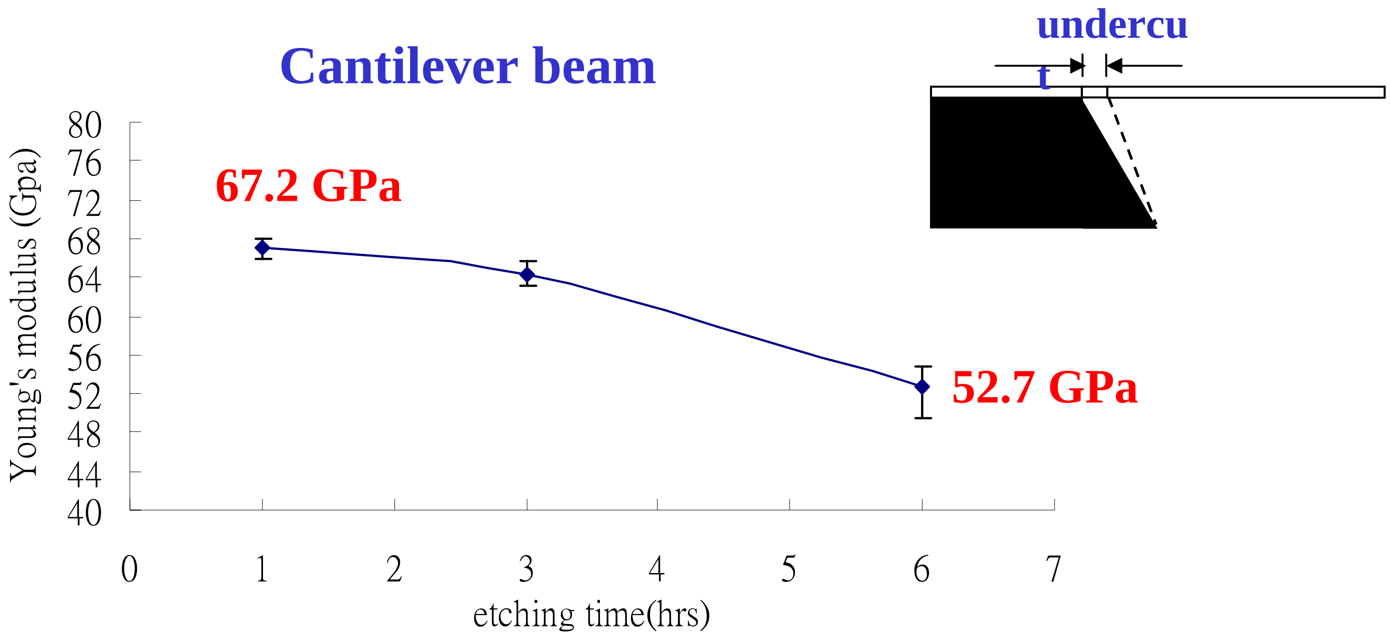
- **Measurement of 0.84 µm thermal oxide – Young's modulus**



E = 67.9 GPa (for 900 µm suspension with 6 hrs etching time)

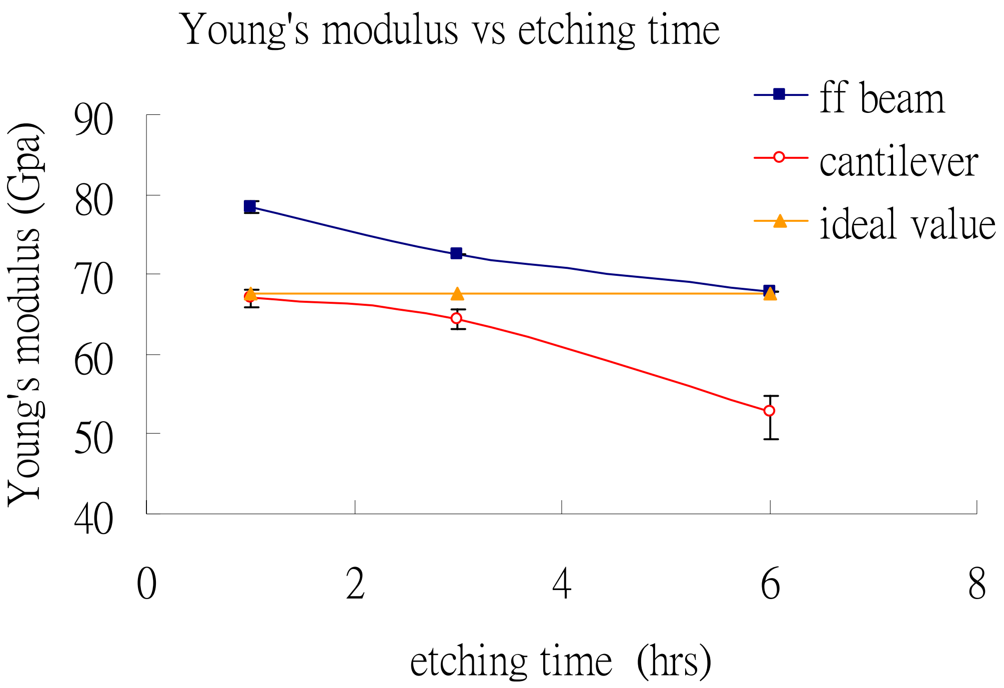
MDL
NTHU

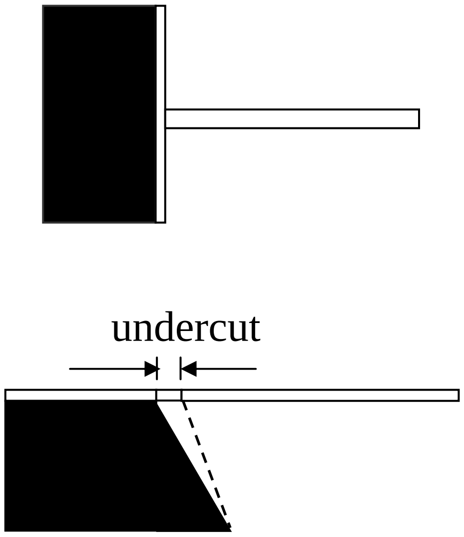
- # Measurement of 0.84 μm thermal oxide – Young's modulus


Cantilever beam

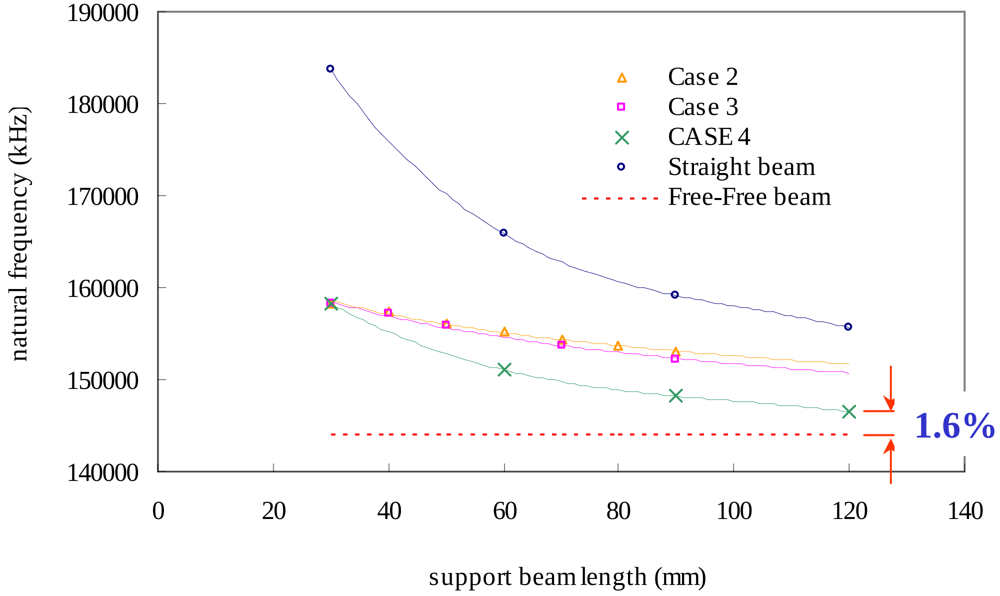
After 6 hours etching, cantilever has 21.5% deviation from ideal

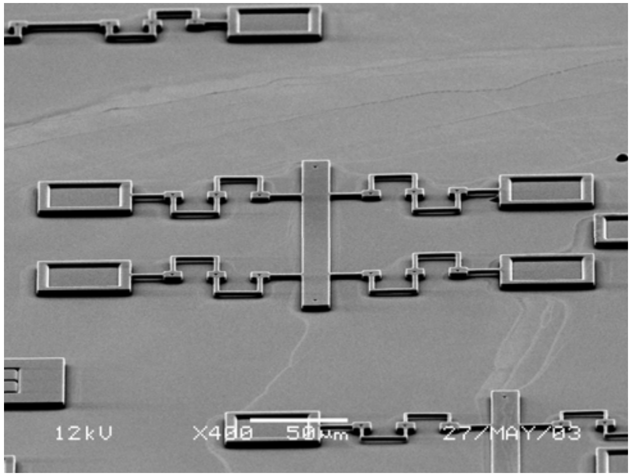
- **For shorter etching time - Cantilever is a better test key**
- **For longer etching time - Free-free beam is a better test key**



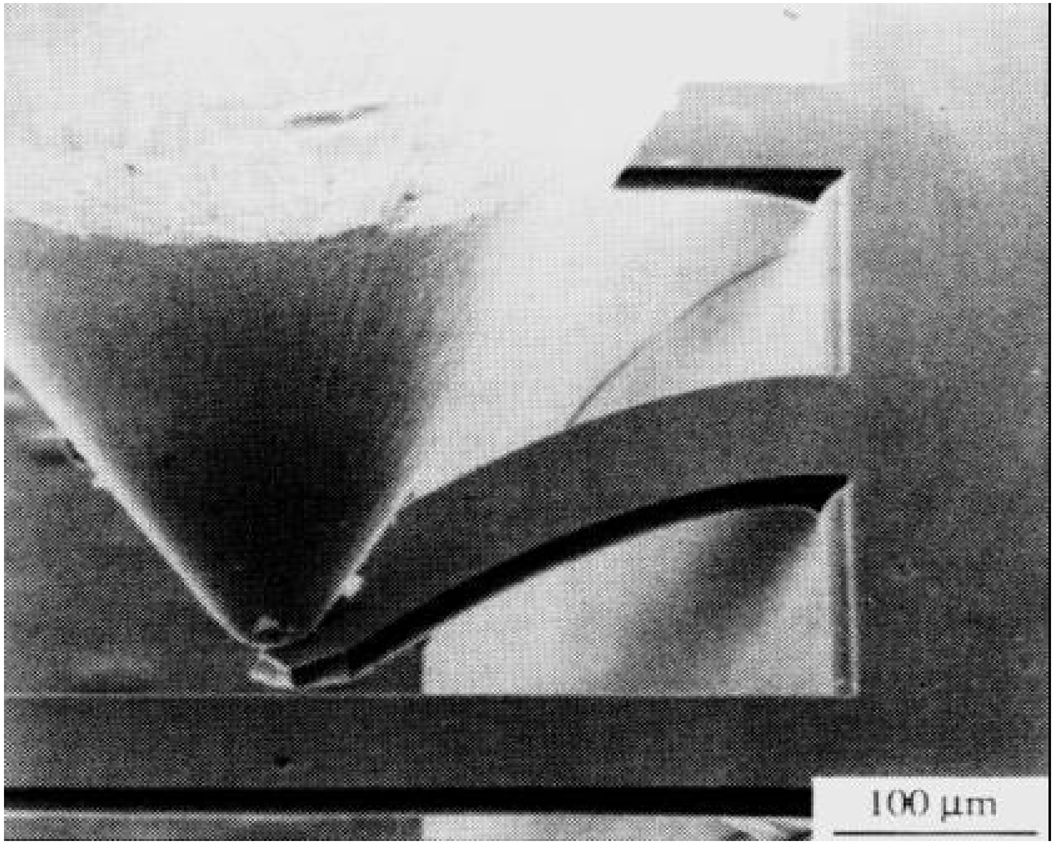


- **For surface micromachined beam, the free-free beam can prevent the boundary imperfection due to step**



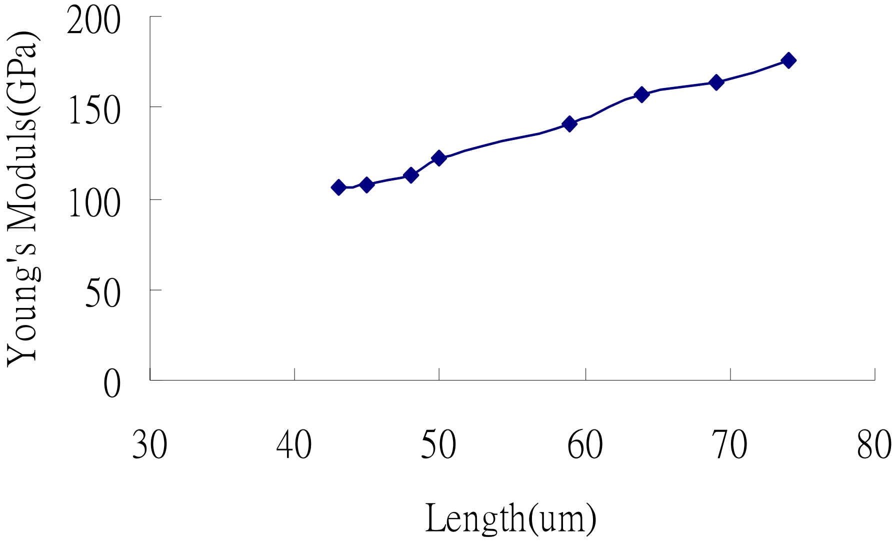


Improvement of Indentation Test



J.-A. Schweitz, 1992

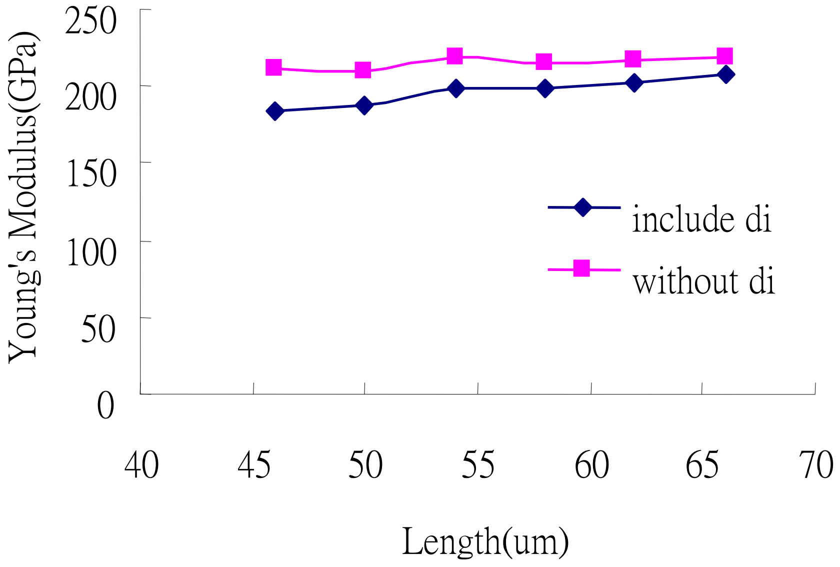
- **Variation of the Young's modulus with beam length**

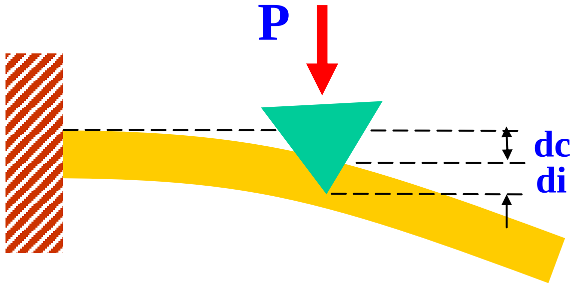


Length	E(loading)
74	175.18
69	163.70
64	156.44
59	140.33
50	121.90
48	113.32
45	107.58
43	105.88

- # The indentation effect – Nickel film

length	E1(include di)	E2(remove di)
66	207.14	218.40
62	203.05	216.24
58	199.36	215.09
54	198.75	218.49
50	187.55	210.11
46	182.93	211.36





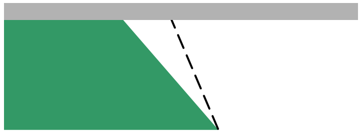
$$K = \frac{P}{dc+di}$$

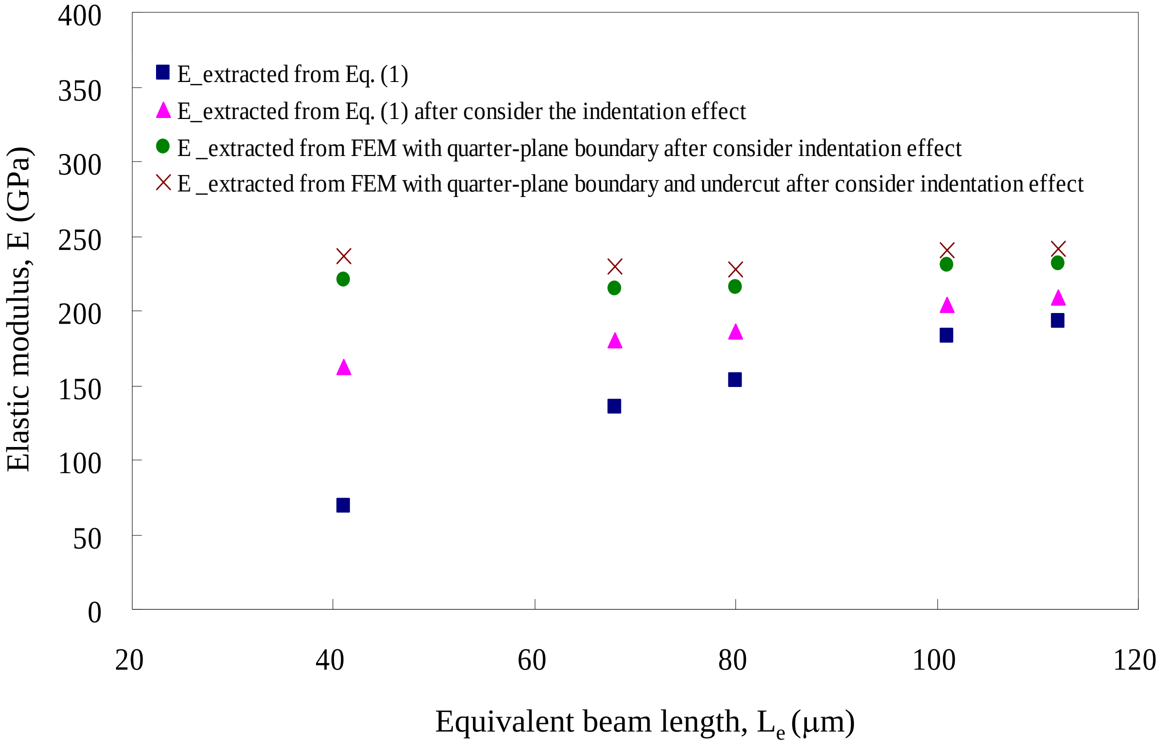
The boundary effect – Nickel film

- **Conventional BC**

- **MEMS BC**

- **BC undercut**





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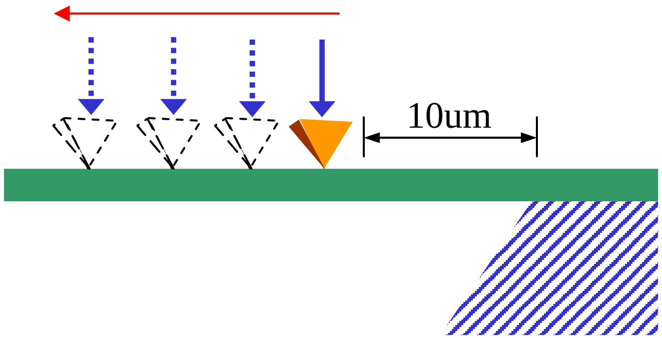
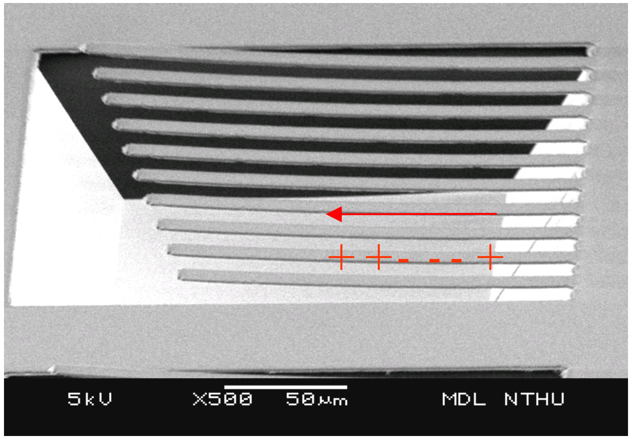
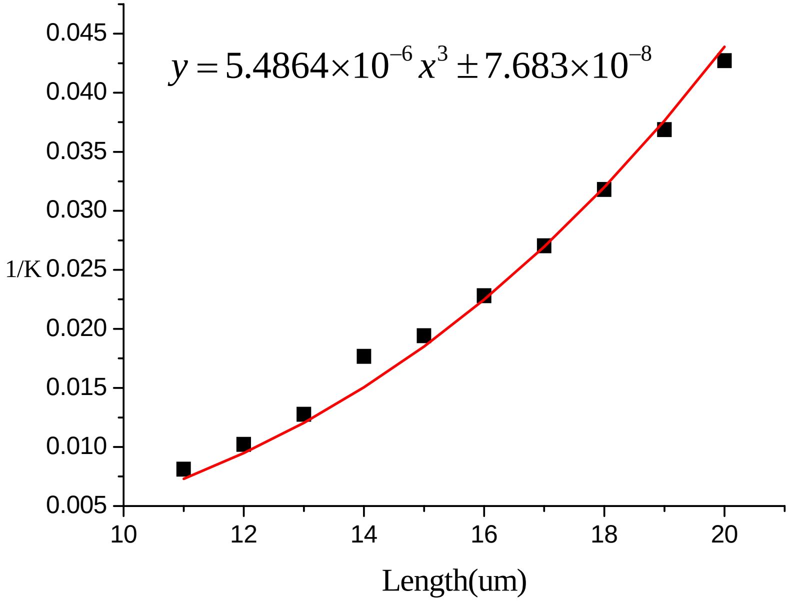
- # The elastic modulus of SiO_2 film

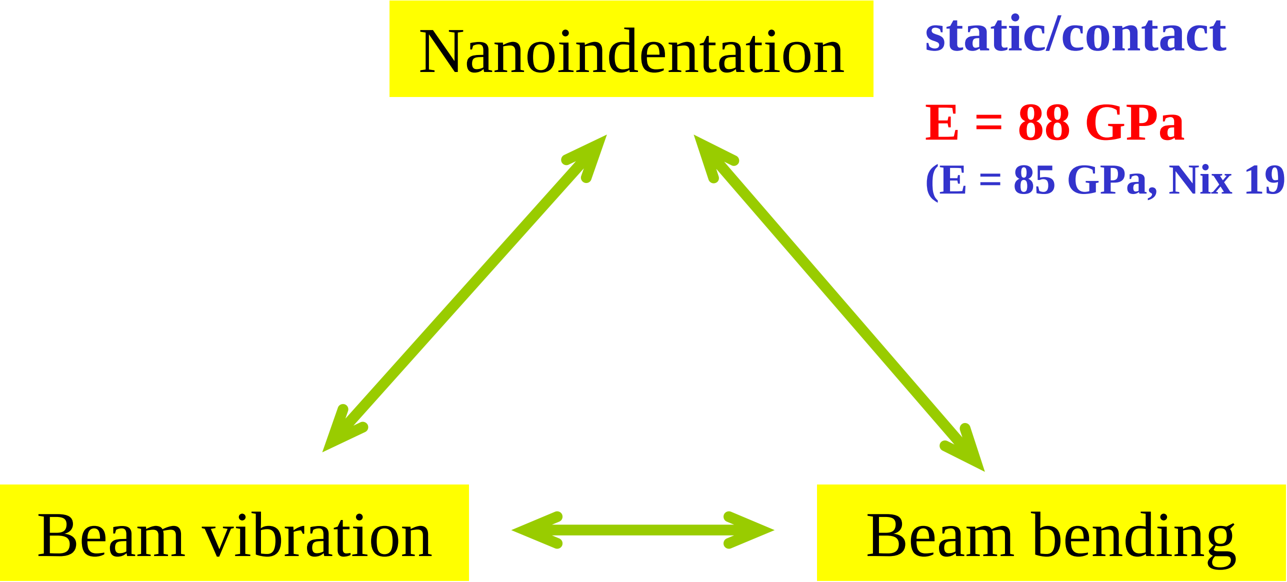






+ **E : 71.5 GPa (67.3 ~ 75.9 GPa)**

- **Elastic modulus of SiO_2 film from different approaches**



Nanoindentation

local

static/contact

E = 88 GPa

(E = 85 GPa, Nix 1988)

Beam vibration

global

dynamic/non-contact

E = 68 GPa

(E = 57~70 GPa)

Beam bending

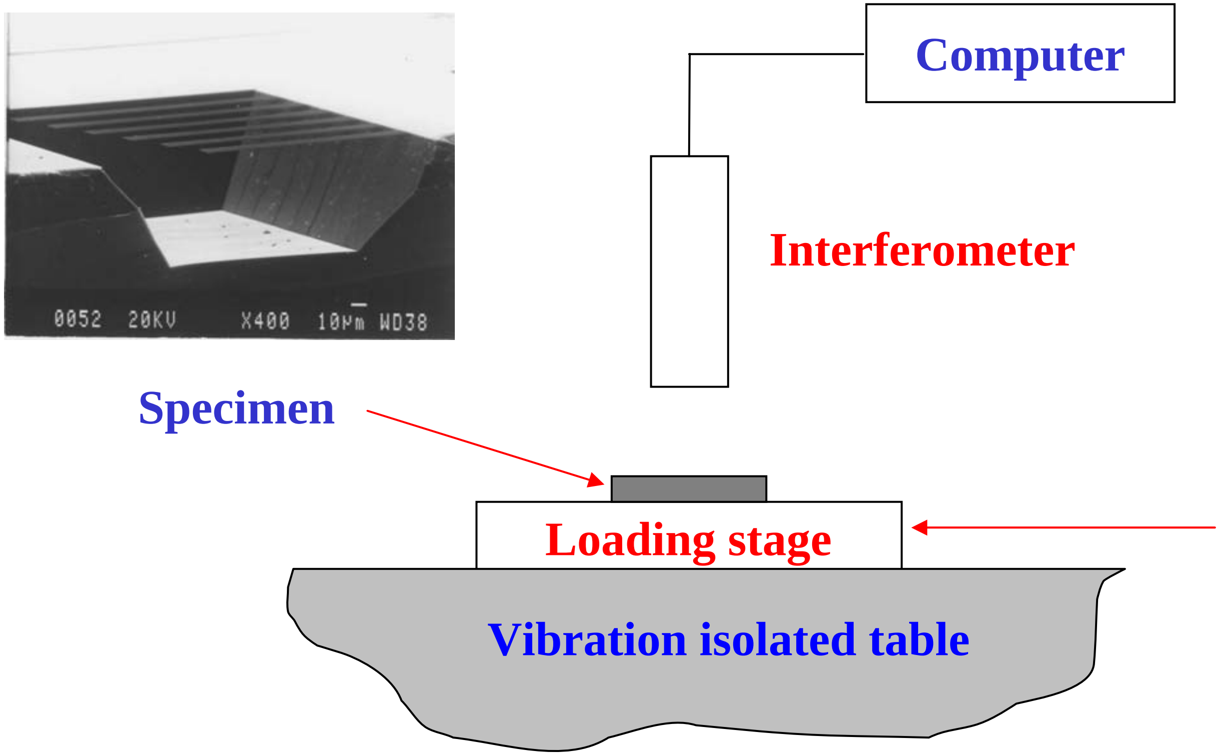
global

static/contact

E = 72 GPa

Residual stresses of thin film

Static Testing Platform



Computer

Interferometer

Specimen

Loading stage

Vibration isolated table

Residual stresses

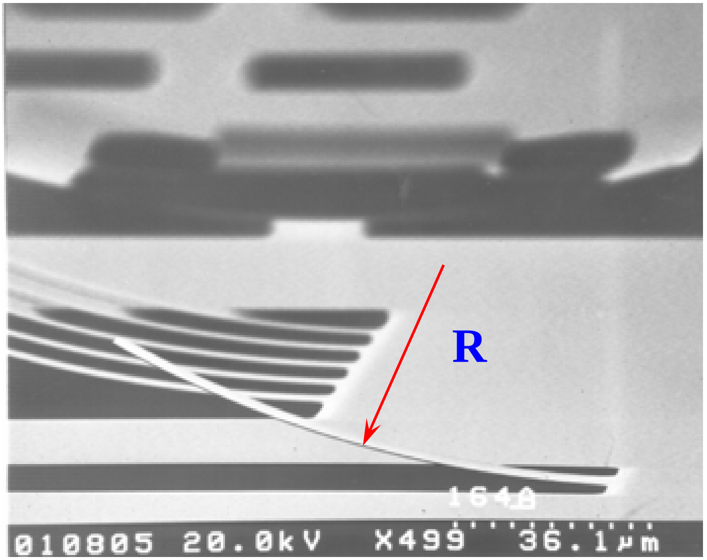
Heating stage

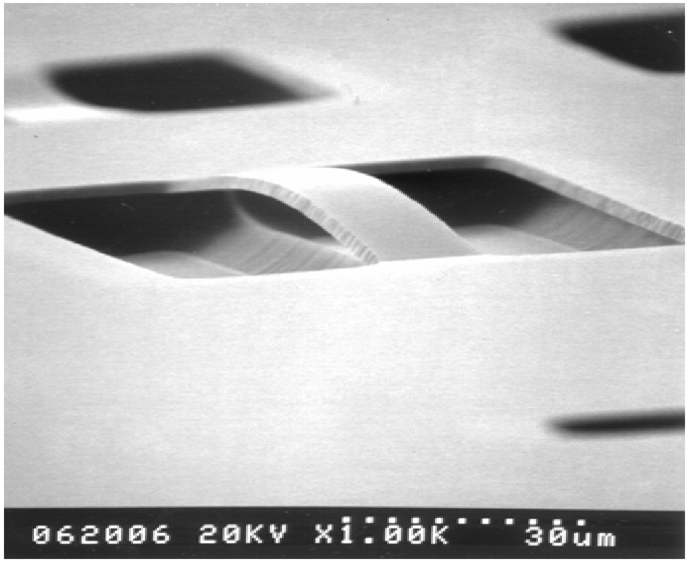
Electromagnetic stage

Pressure source

Indenter

Residual stress

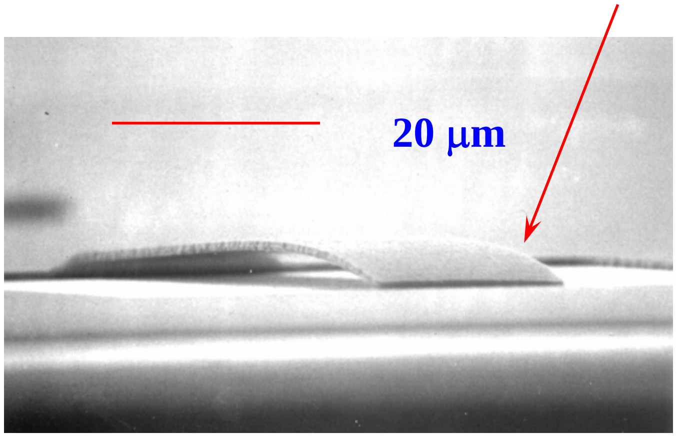


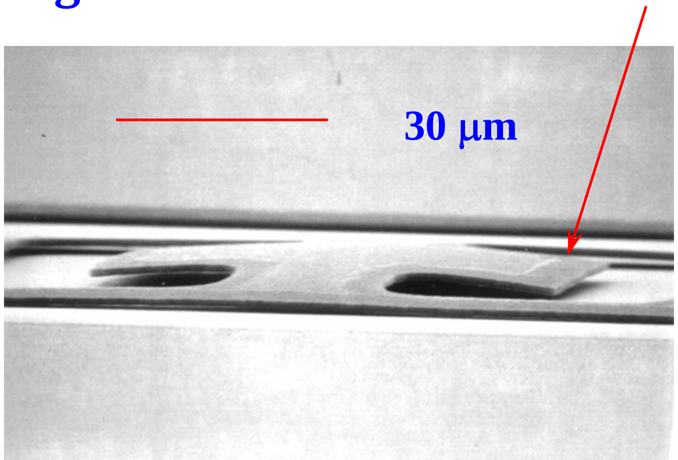


W. Fang, and J.A. Wickert, *J. of Micromechanics and Microeng.*, 1994
W. Fang, and J.A. Wickert, *J. of Micromechanics and Microeng.*, 1995
W. Fang, and J.A. Wickert, *J. of Micromechanics and Microeng.*, 1996

- **Surface micromachined Ti cantilever beam and gimbal suspension**

+ The Ti film is deposited by sputtering

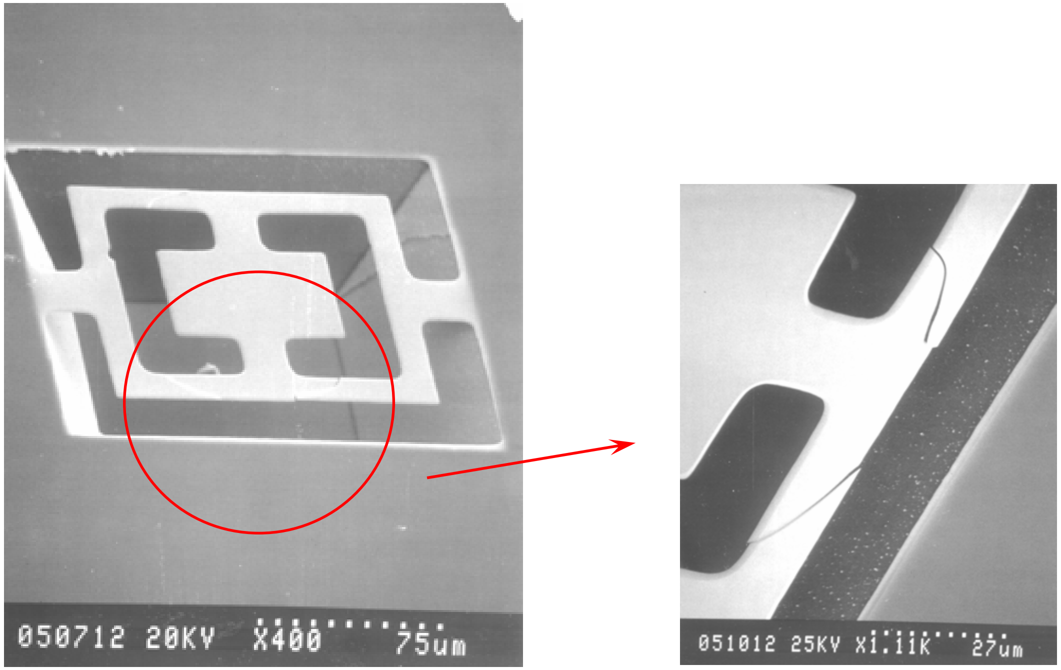




W. Fang and J.A. Wickert, J. of Micromech. and Microeng., 1996

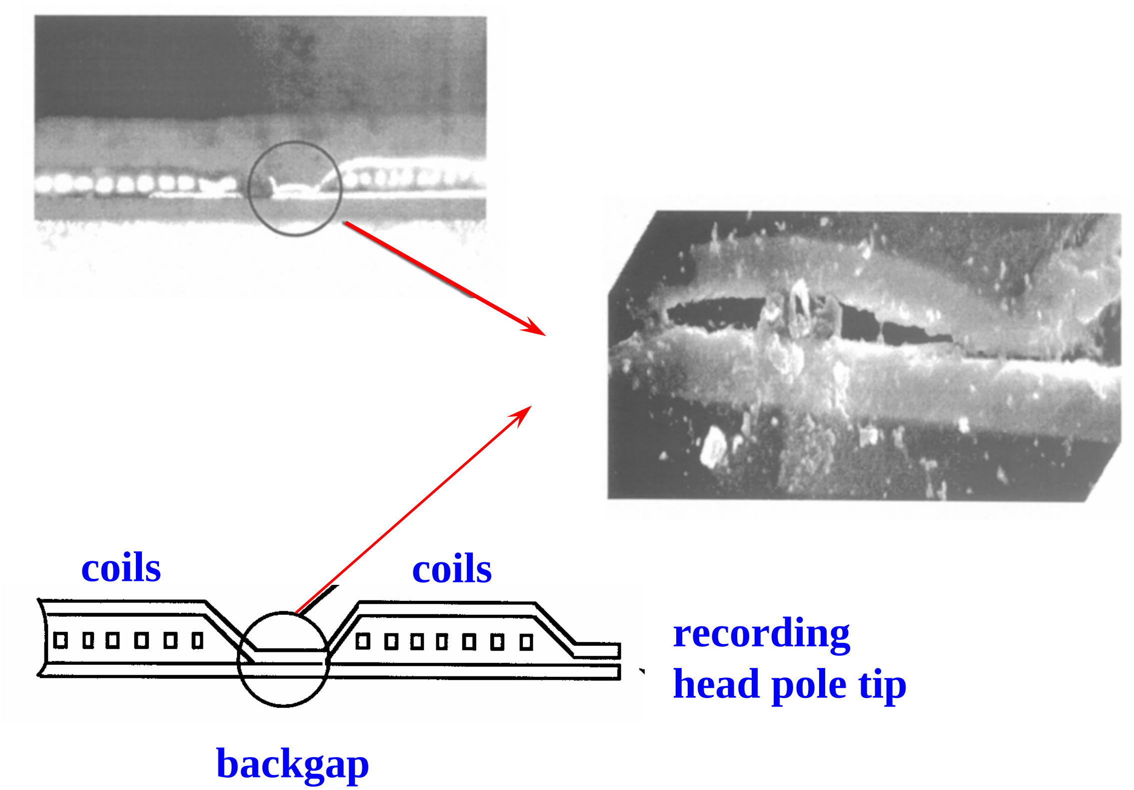
- **Crack of a bulk micromachined *SiO_2* suspension**

  + **The *SiO_2* film is grown thermally**



**W. Fang, DSSC annual report,
Carnegie Mellon University, 1993**

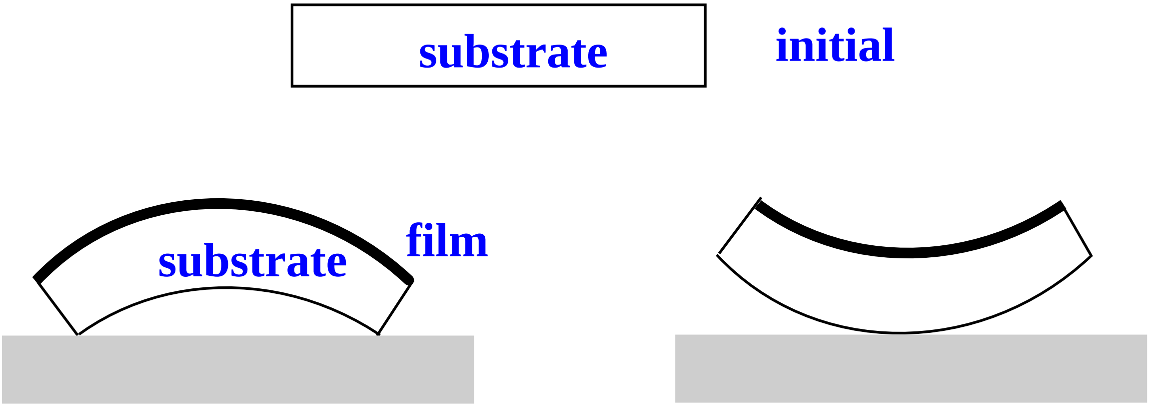
- **Buckling of the sputtered FeAlN layer in a thin film recording head by residual stress**



S. Wang and M. Kryder, personal contact, 1993

Wafer curvature technique

- The most common technique to determine thin film residual stresses is measuring wafer curvature



substrate

initial

film

substrate

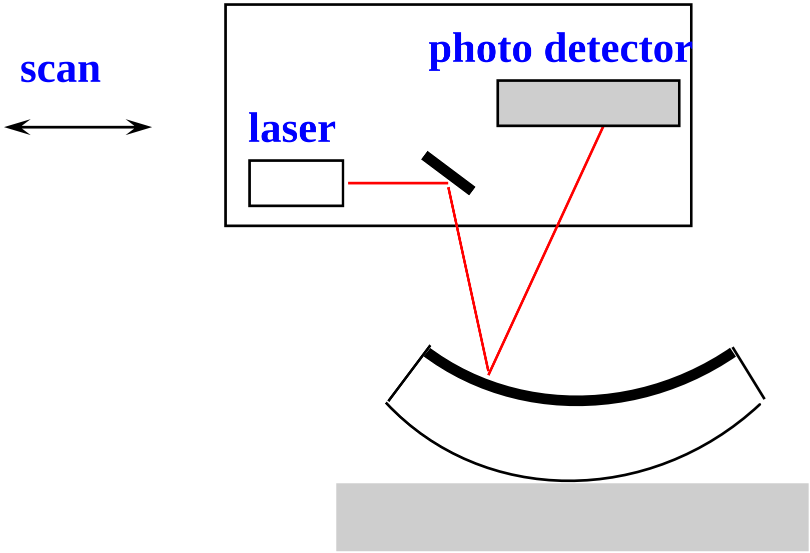
film is under compression

film is under tension

- The radius of curvature is varied with the magnitude of residual stresses

- **Stoney's equation**

$$\sigma = \frac{Eh^2}{6Rt(1-\upsilon)}$$



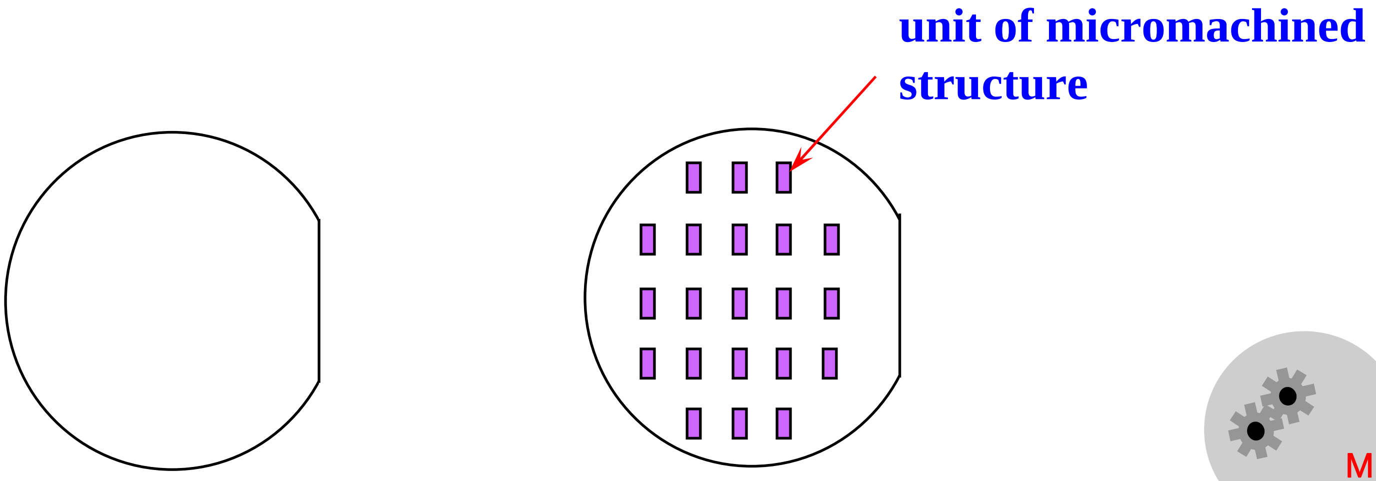
***E/(1-υ)*: the biaxial elastic modulus of the substrate**

***h,t*: the thickness of the film (*t*) and substrate (*h*)**

***R*: the measured radius of curvature**

σ: the average film stress

- The **disadvantages** of the wafer curvature technique are
  - \+ Not sensitivie
  - \+ Average stress of the whole wafer
- Stress measurement using micromachined structures
  - \+ Same dimensional scale as thin film - sensitive
  - \+ Local measurement instead of global measurement

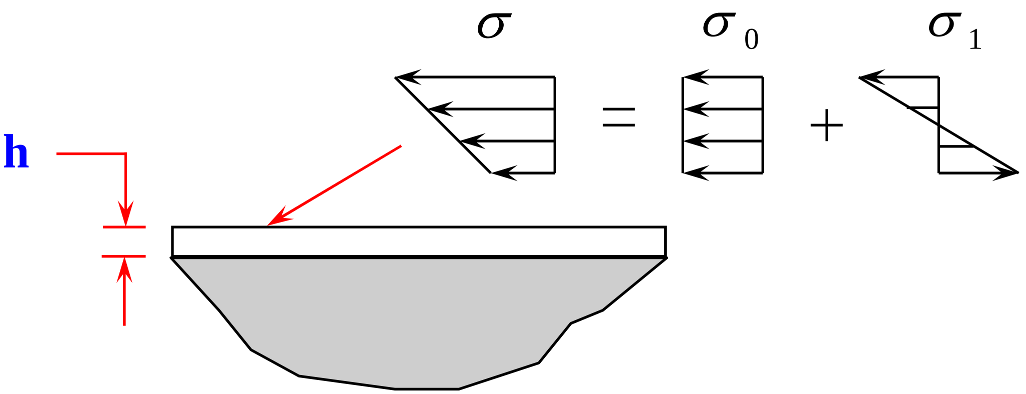

unit of micromachined structure

- Residual stress can be represented as a polynominal
- For the first approximation, the residual stresses containing (1) mean, and (2) gradient components

$$\sigma = \sum_{k=0}^{\infty} \sigma_k \left(\frac{y}{h}\right)^k \approx \sigma_0 + \sigma_1 \left(\frac{y}{h}\right)$$

mean residual stress

gradient residual stress



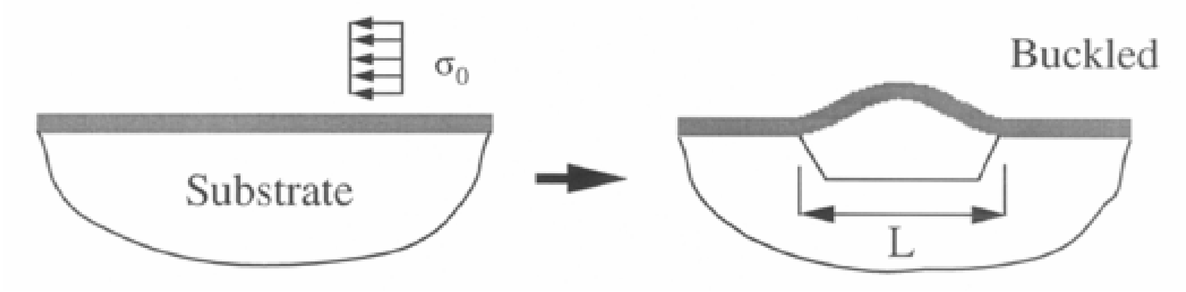
- **Compression σ_0**
- **Tension σ_0**
- **Gradient σ_1**

Bulk Micromachined Test Structures

Critical Buckling Beam Method

Guckel, Randazzo, and Burns, *J. of Applied Physics,* 1985

- Fabricate micromachined beams out of the thin film material for which the residual stress is desired



- Idealization: critical beam length

L < L_{cr} unbuckled
L > L_{cr} buckled

where $$L_{cr} = 2\pi\sqrt{\frac{EI}{\sigma_0 A}}$$

- **Key processes of this technique**

  + Fabrication of micromachined beams with different length

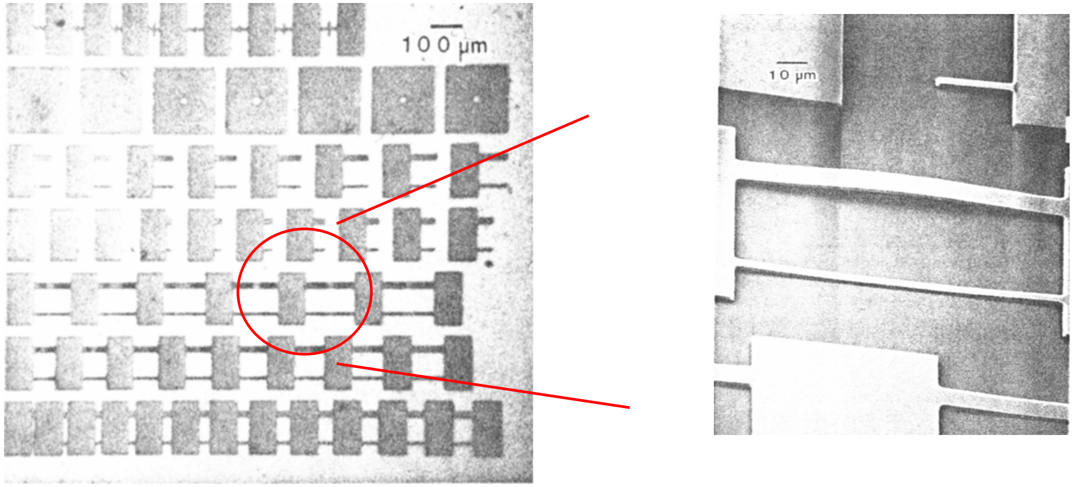
  + Use optical microscope to find the critical buckling beam length L_{cr}

  + The residual stress is determined from L_{cr}

- **Disadvantages**

  + L_{cr} is determined subjectively

  + Need very accurate beam thickness to prevent error of residual stress

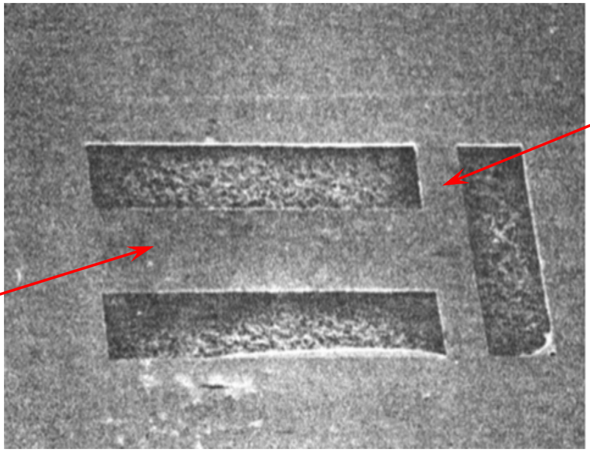


T-shape Plate Method

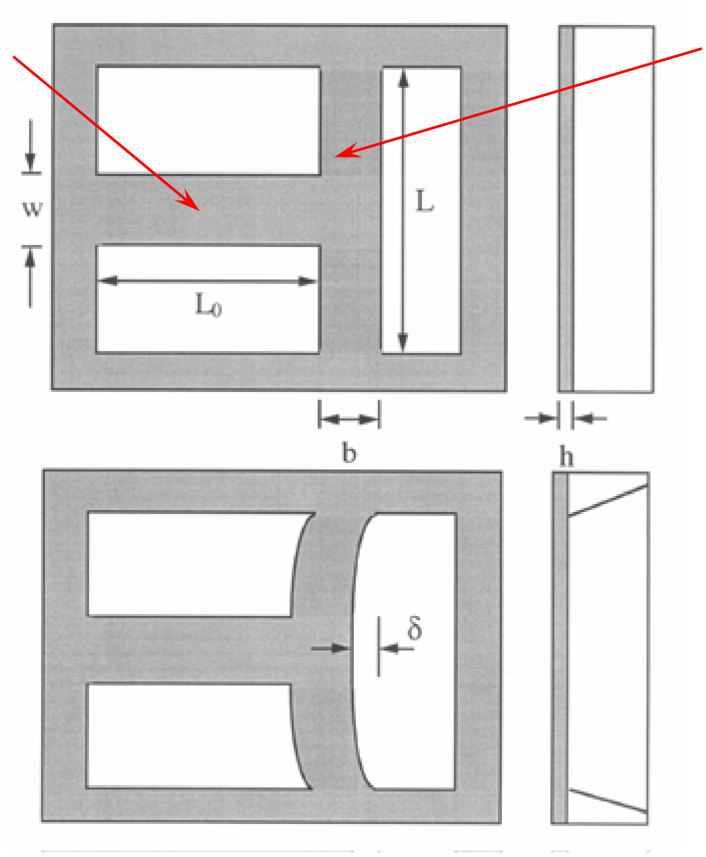
M. Mehregany, R.T. Howe, and S.D. Senturia, J. of Applied Physics, 1987

- **In general, tensile residual stress will not lead an out of plane deformation to the micromachined structures**

- **T-shape structure is designed to give a significant deflection, δ, under the relief of tensile residual stress**

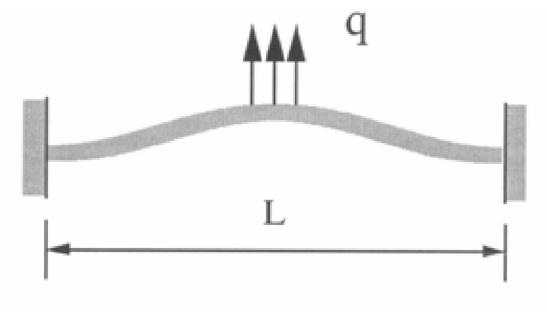


- **Configuration of the T-shape diagnostic structure before and after the relief of tensile residual stress**



Loading beam

Test beam



Test beam

- **Disadvantages of this technique**

  - **+ Large structure is required to provide a measurable deflection amplitude for the optical microscope**

  - **+ The initial tension of the test beam has been ignored**

  - **+ Boundary condition of the test beam**

  - **+ The loading beam also gives a constraint to the deflection of at the contact region**

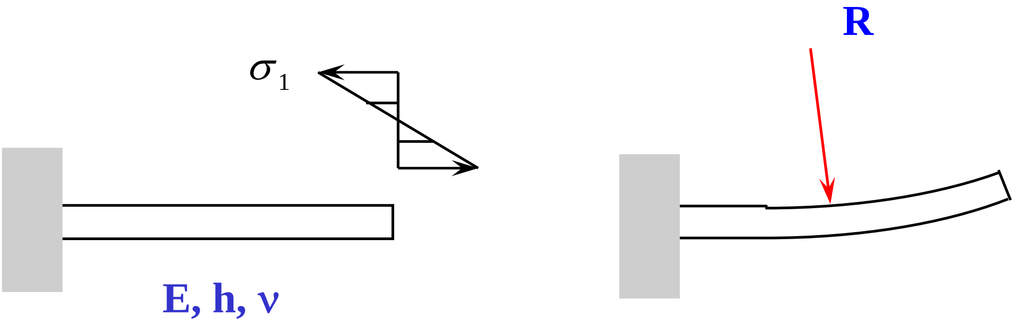
- **Comment: a simple structure can (1) reduce the error arrived from modeling, and (2) simplify the analytical model**

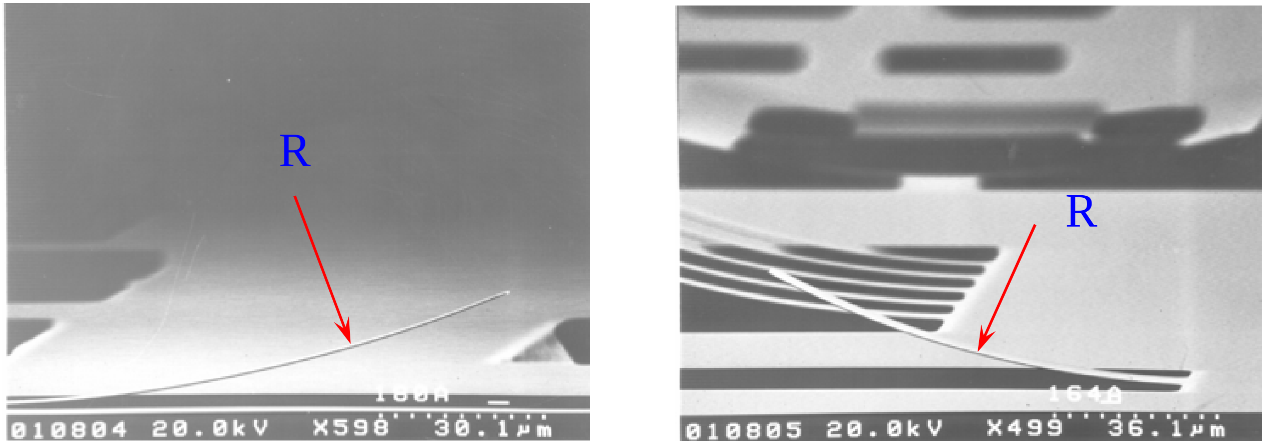
Cantilever Beam Method

- The relief of a **gradient residual stress σ_1** will lead to a **bending moment** applying on the thin film cantilever

- The gradient residual stress can be determined by the **radius of curvature R** of the bent cantilever beam

$$\sigma_1 = \frac{Eh}{2R}$$



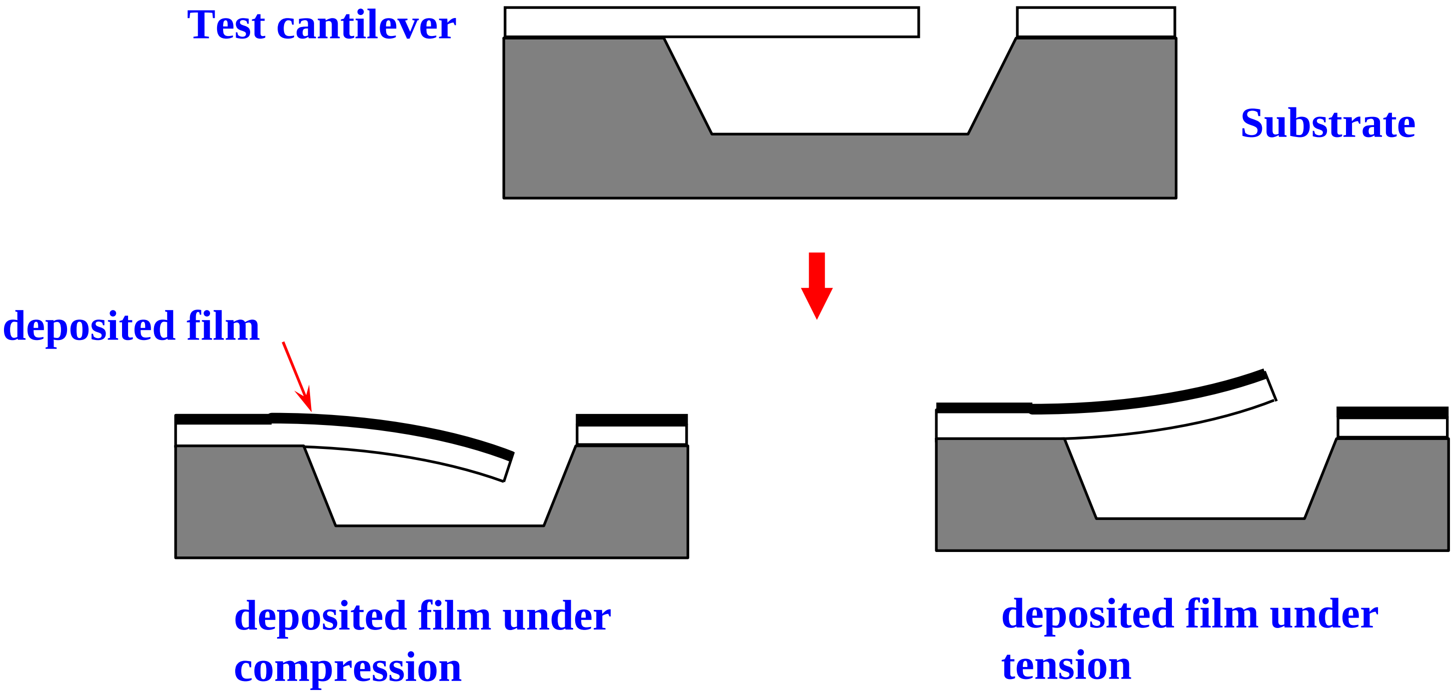


Y.-L. Chen, J.-S. Shie, and W. Fang, 1997

Bilayer beam technique

W. Fang and J.A. Wickert, J. of Micromech. and Microeng.,1995

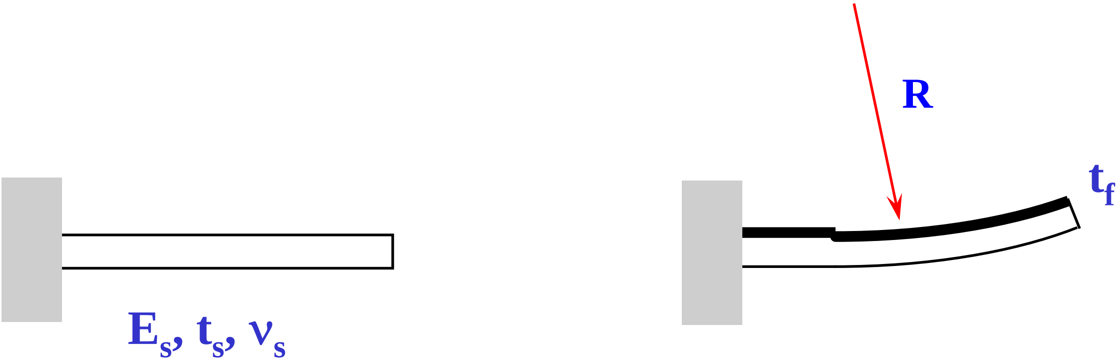
- **Deposit the film on top of a test cantilever to form a bilayer beam, therefore the residual stress of the film can be measured by the deflection of the bilayer cantilever**



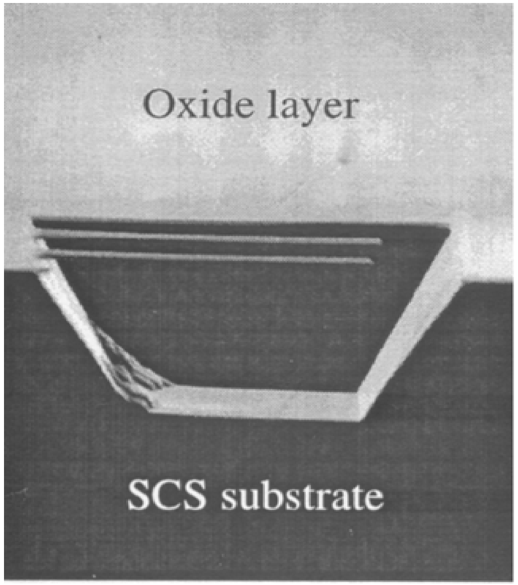
- **Stoney equation**

$$\sigma_0 = \frac{E_s (t_s)^2}{6 R t_f (1 - \nu_s)}$$

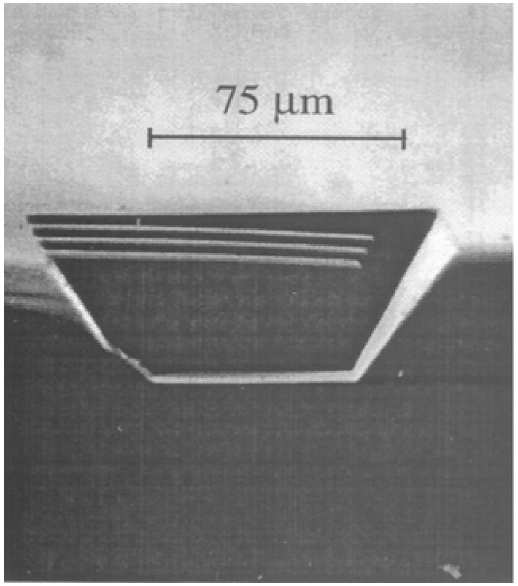
measured



- **Bilayer beam technique can be applied to measure residual stress of thin films whose thickness are too small to fabricate micromachined structures**



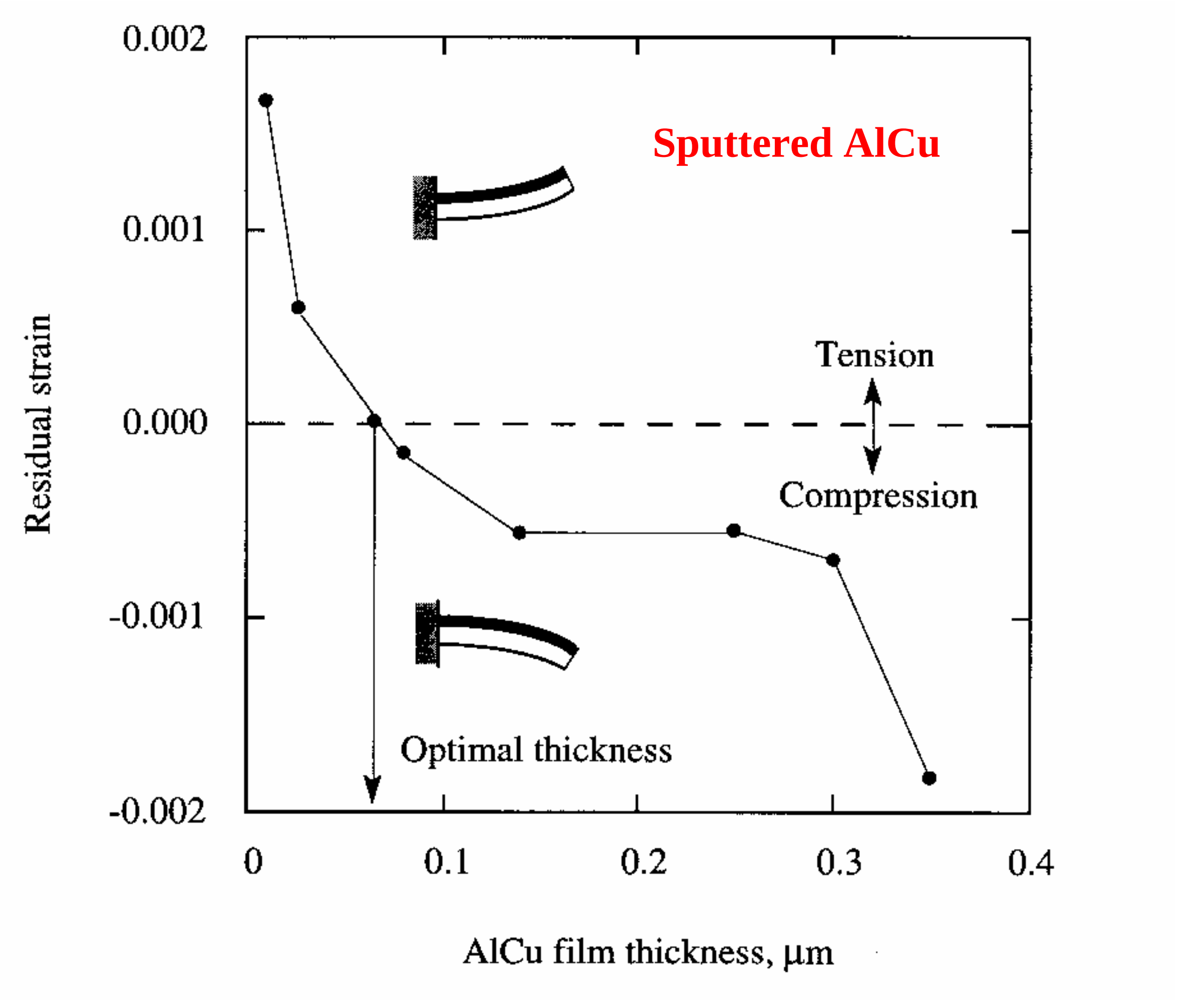
SiO_2 test cantilever



Test cantilever deposited with a 15 nm thick *DLC* film

W. Fang and J.A. Wickert, *J. of Micromechanics and Microengineering*, 1995

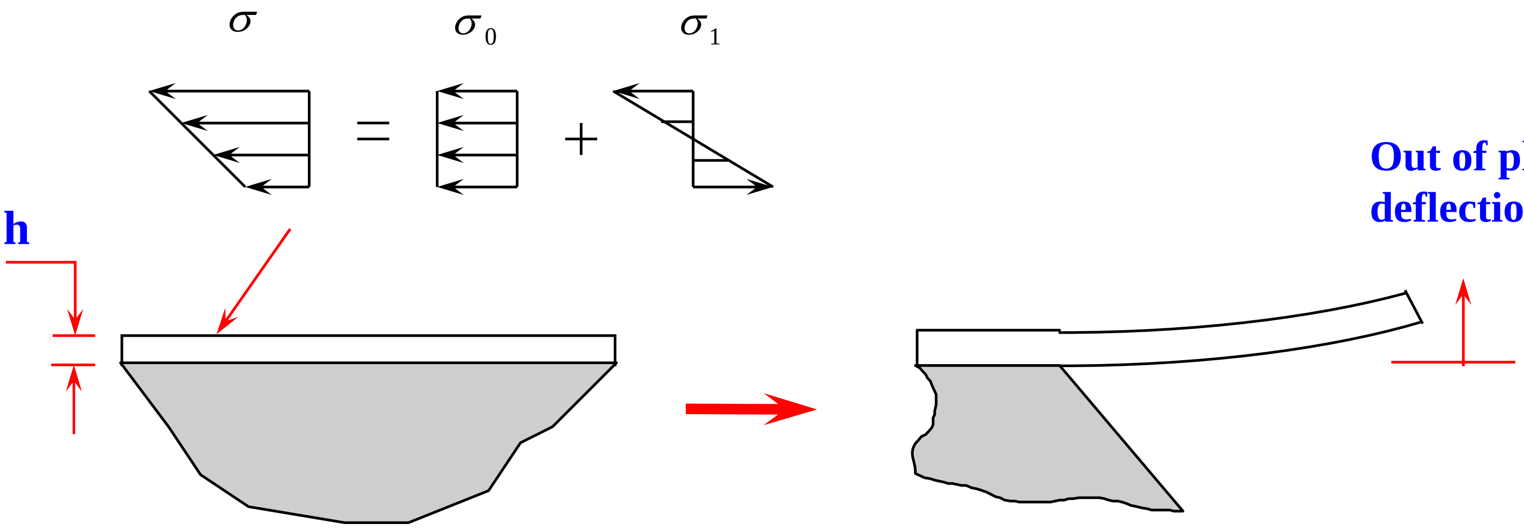
- **Variation of the residual strain with the thickness of *AlCu* film**



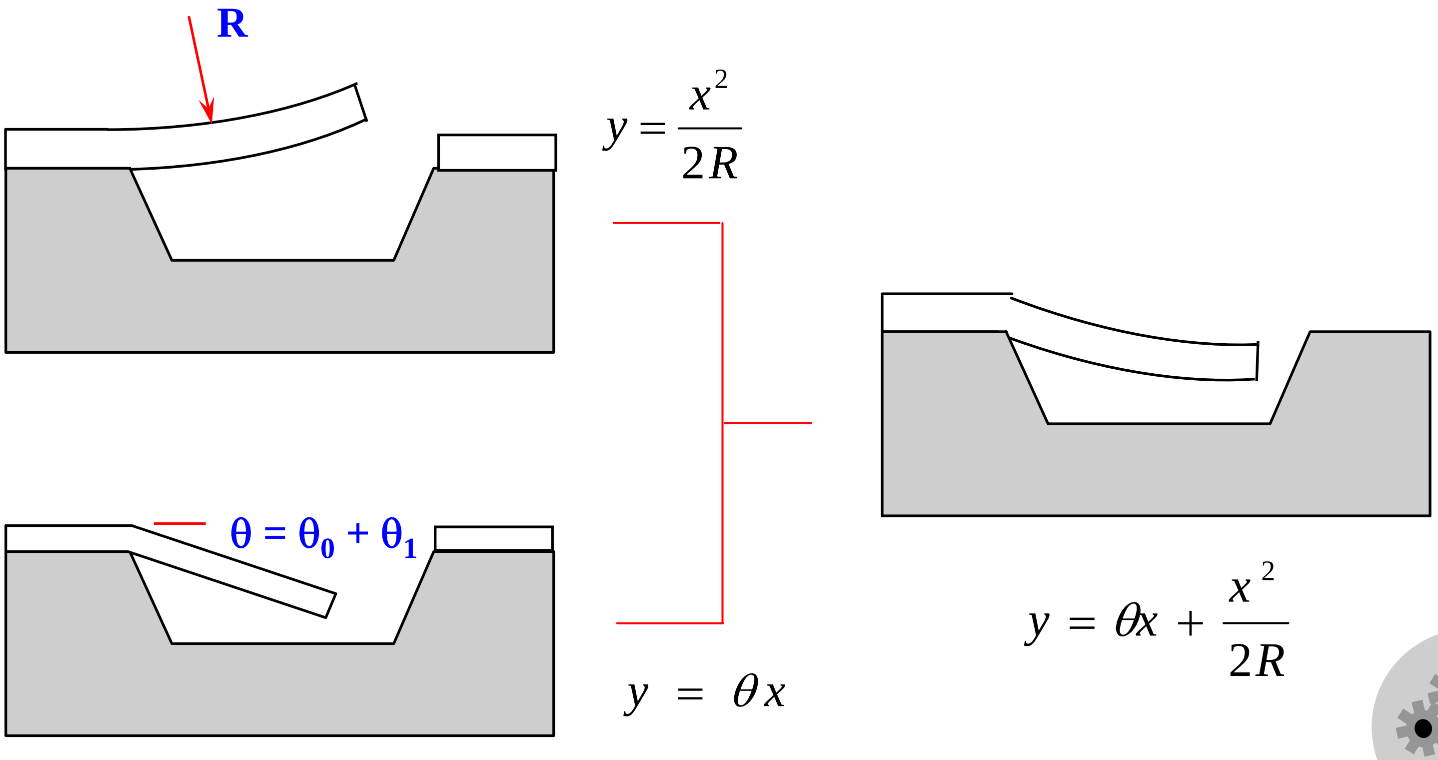
Boundary rotation method

W. Fang and J.A. Wickert, J. of Micromechanics and Microengineering, 1996

- The mean and gradient residual stresses are determined simultaneously by an out of plane deformed cantilever beam



- In short, the beam will be deflected with curvature by σ_1, and slope by σ_1 and σ_0
- The total deflection profile is, $y = \theta x + \dfrac{x^2}{2R}$

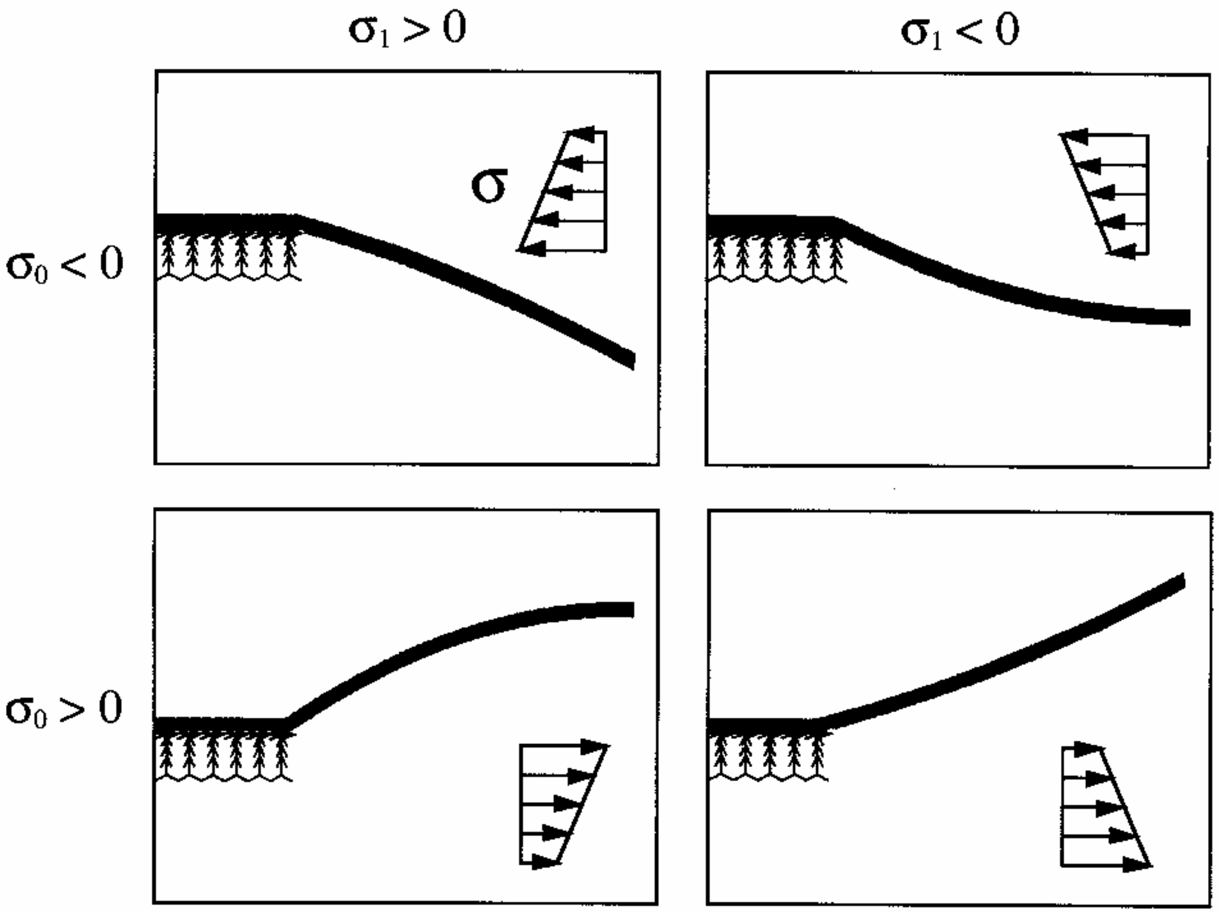


$$y = \frac{x^2}{2R}$$

$$y = \theta x$$

$$y = \theta x + \frac{x^2}{2R}$$

- **Deformation profile for the four possible stress states**



Fang and Wickert, J. of Micromechanics and Microengineering, 1996

- **FEM analysis**

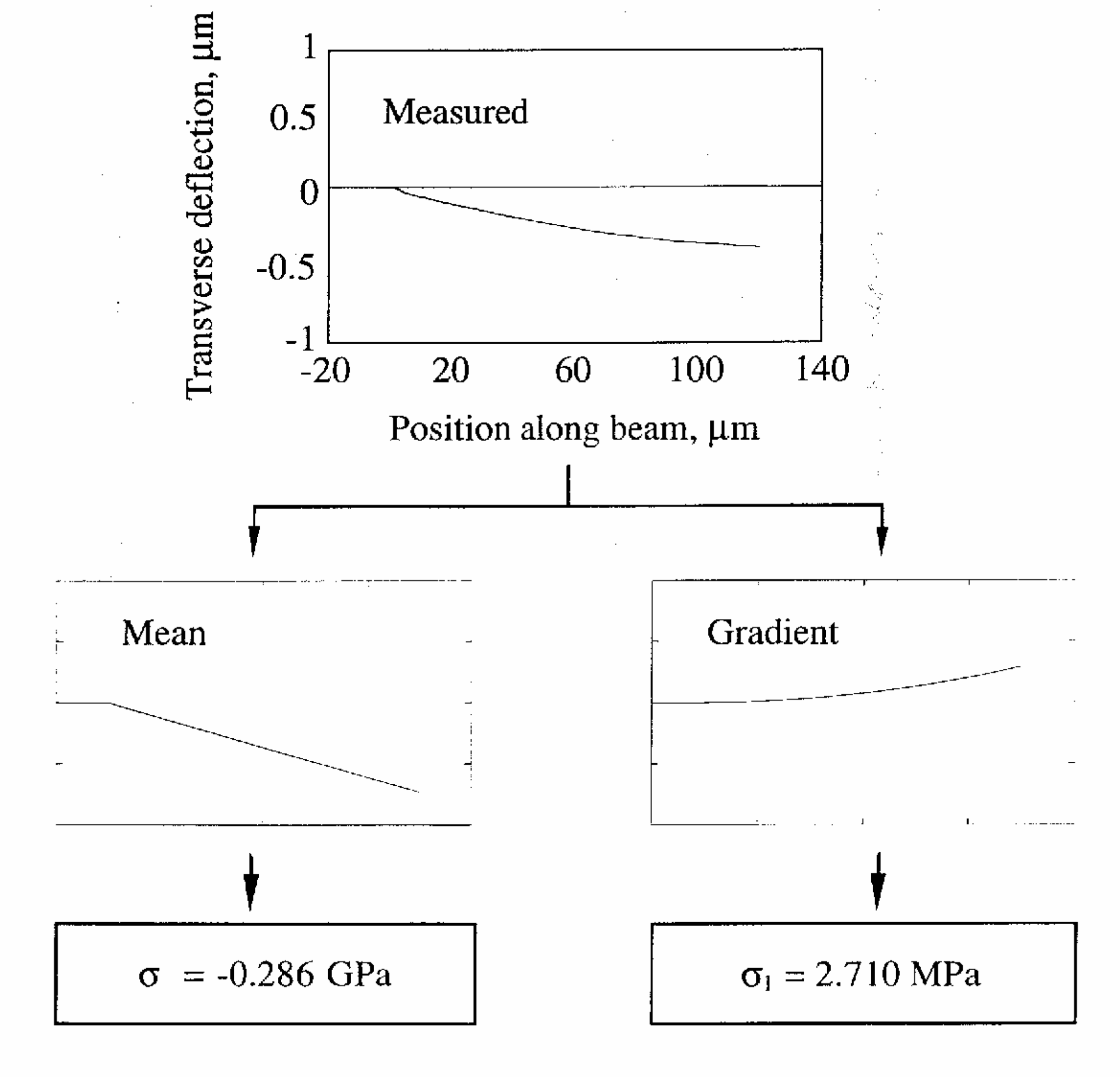
+ The angular deflection due to the mean residual stress

$$\theta_0 = \frac{\sigma_0}{E}(1.33 + 0.45\nu)(-0.014h + 1.022)$$

+ The angular deflection due to the gradient residual stress

$$\theta_1 = \frac{\sigma_1}{E}(0.0086h^2 - 0.047h + 0.81)$$

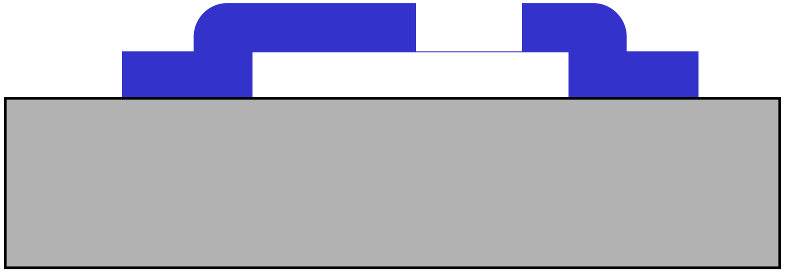
- **Application : 1 μm thick thermal silicon dioxide beam**



$\sigma = -0.286$ GPa

$\sigma_1 = 2.710$ MPa

Surface Micromachined Test Structures



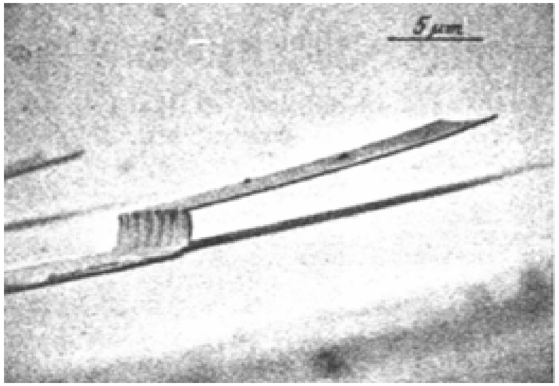
Surface Micromachined Cantilever

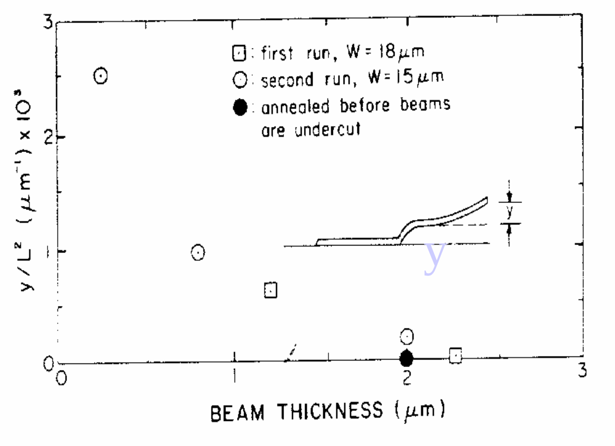
R.T. Howe and R.S. Muller, J. Electrochem. Soc., 1983

- **The relation between tip deflection *y* and the bending moment *M* arrived by the gradient residual stress is**

$$y = 6ML^2/(Eh^3)$$

+ This equation is the same as the equation $\sigma = Eh/(2R)$





Micro Vernier Technique

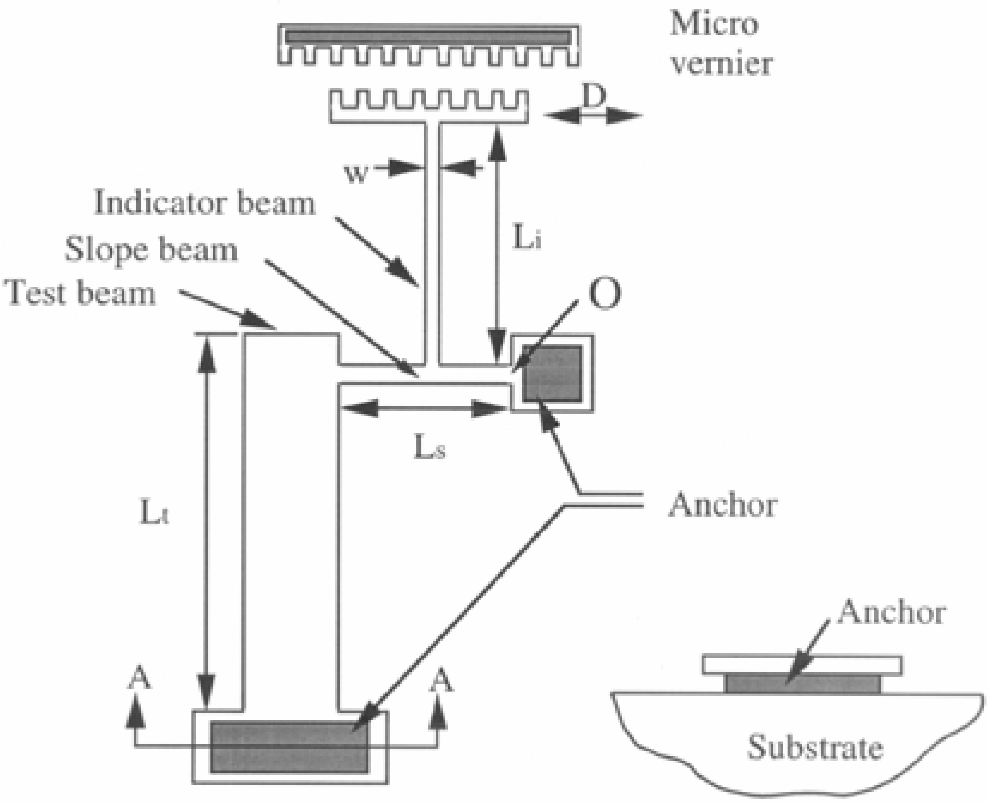
L. Lin, et.al., *Proc. of the 6th IEEE MEMS Workshop*, 1993

- Configuration of the micro vernier structure (in-plane deformation magnification mechanism)

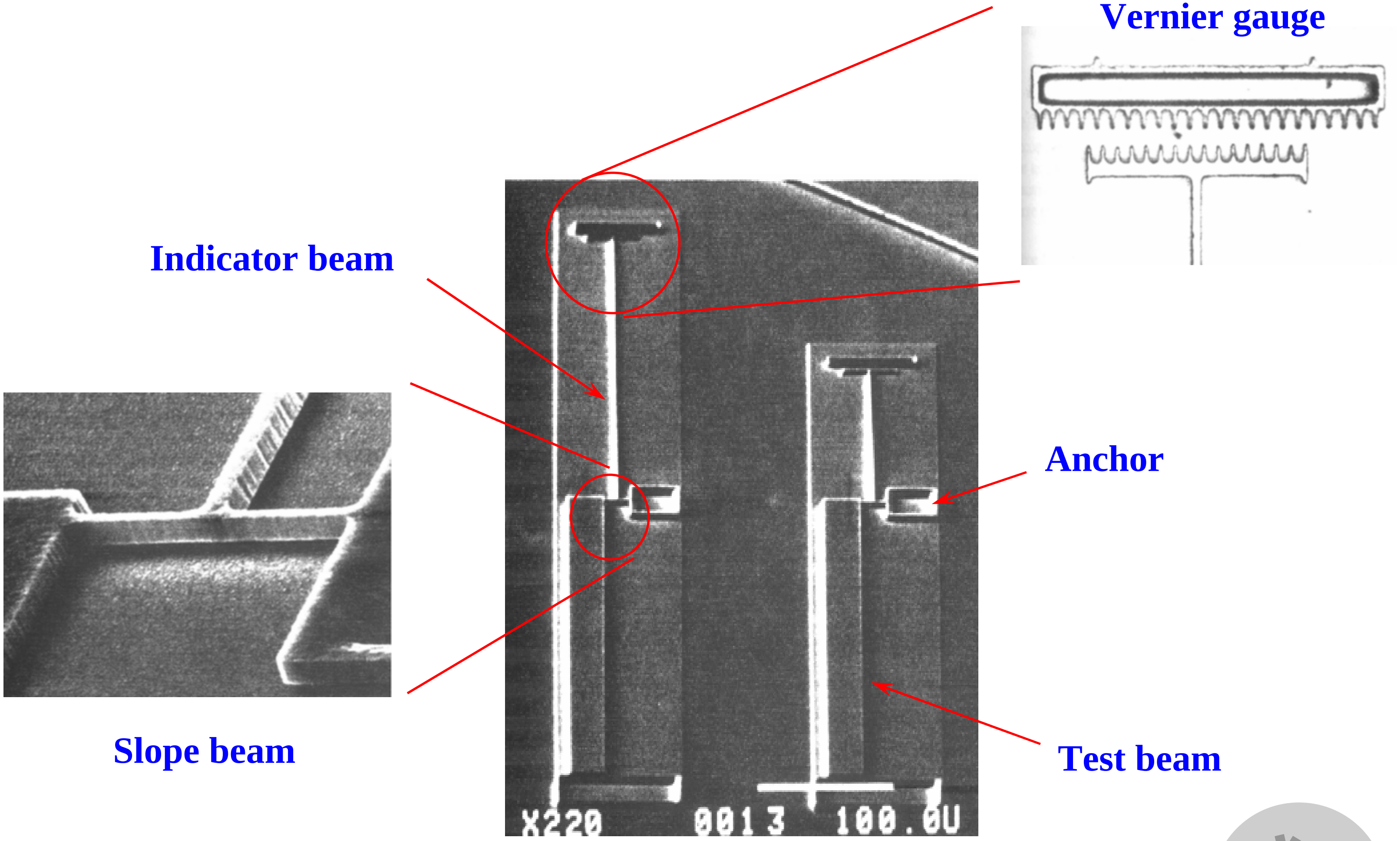
+ The test beam length will be changed when the residual stress is relief

+ Thus, the slope beam will rotate about point O

+ The indicator beam will also rotate



- **SEM photo of the micro vernier**



Vernier gauge

Indicator beam

Anchor

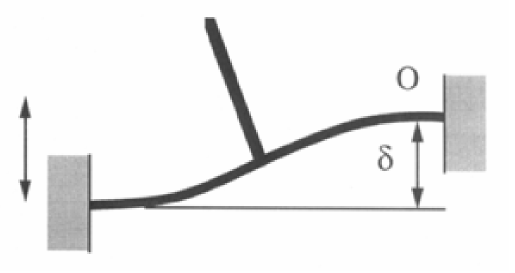
Slope beam

Test beam

- The deflection angle at the center of the slope beam is

$$\theta = \frac{3\delta}{2L_s}\frac{(1-d^2)}{(1-d^3)} \qquad (1)$$

$$\text{where, } d = \frac{w}{L_s}$$



displacement of the test beam

- The displacement measured by the vernier is

$$e = L_i\theta \qquad (2)$$

- Since the residual strain is the ratio of d and Lt, the residual strain can also be rewritten as an equation with measurable parameters

Measured

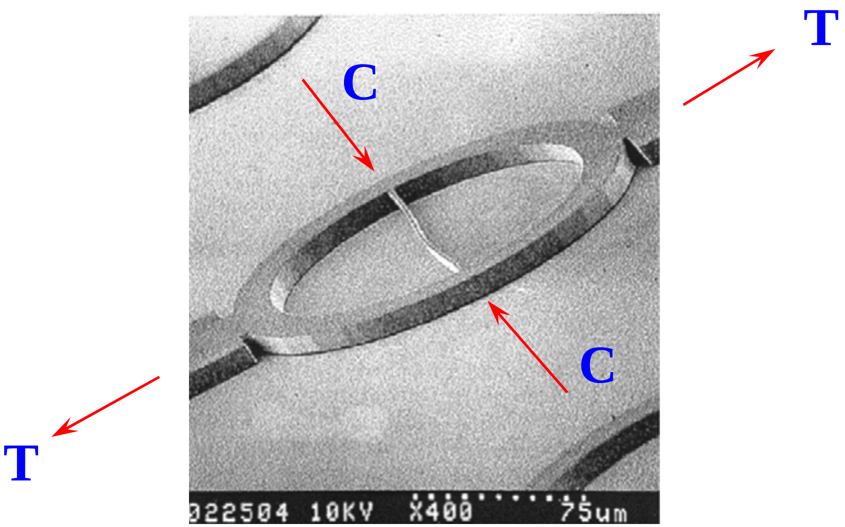
$$\varepsilon = \frac{\delta}{L_t} = \frac{2L_s e}{3L_i L_t}\frac{(1-d^2)}{(1-d^3)}$$

- **Many design issues need to be considered**
  - **Large structure is necessary to provide a large deflection amplitude which can be measured easily by optical microscope**
  - **The residual stress of the slope beam**
  - **The stiffness of the slope beam**
  - **Buckling of the test and slope beam**
  - **The application of this technique is limited to the thin film which used to fabricate surface micromachined structures**

Ring Structure

H. Guckel, et.al., J. of Micromechanics and Microengineering, 1992.

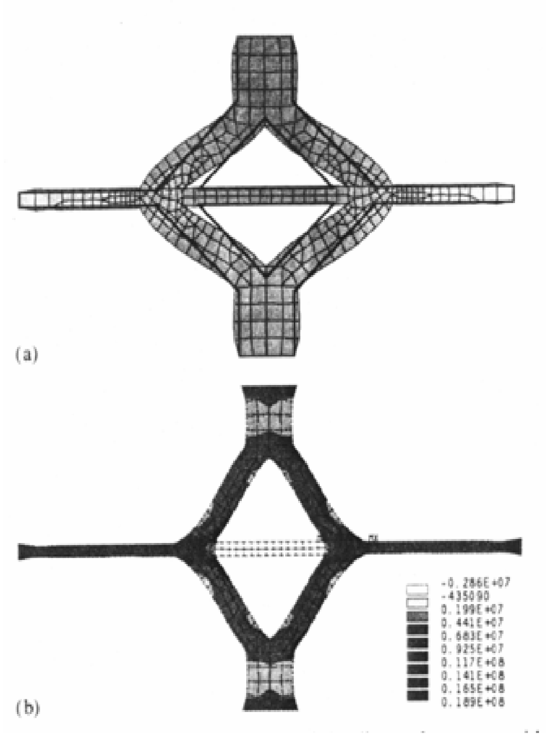
- Diagnostic structures of greater complexity are designed to measure tensile residual stress
- When the film is under tension, the ring structure will applied a compression on the thin beam inside the ring to cause the beam buckle

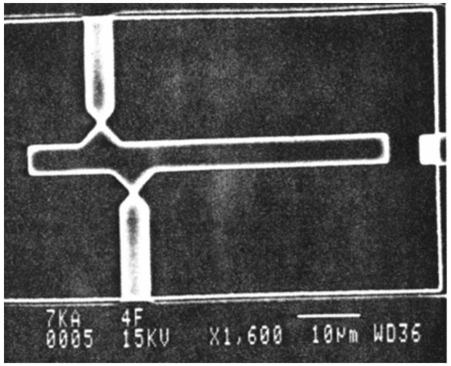


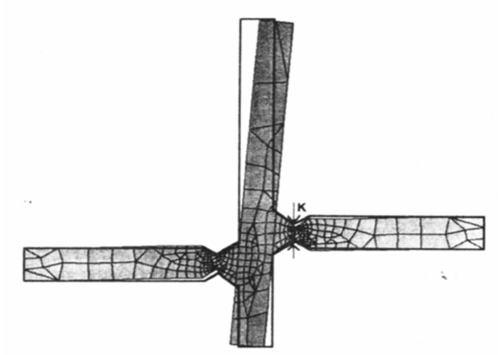
Other Surface Structures

B.P. van Drieenhuizen, et.al., Sensors and Actuators, 1993.

- Micromachined complicated diagnostic structures



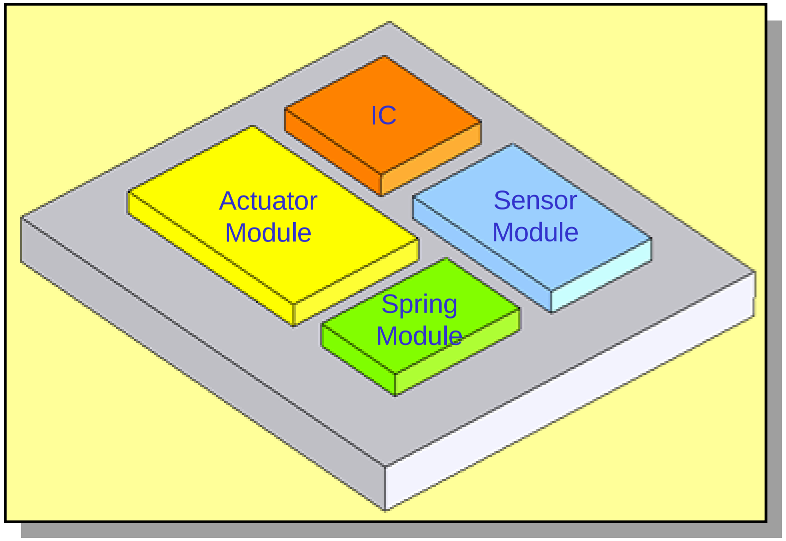




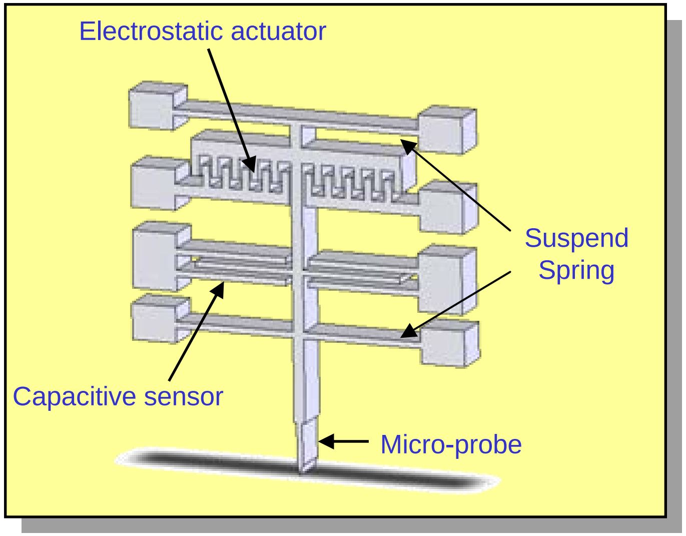
On-chip Micro Instrument

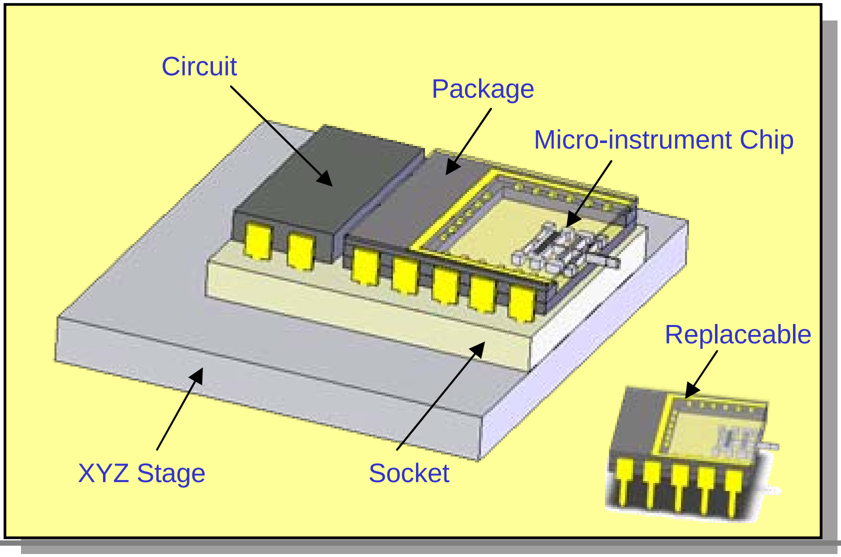
Concept

- **Option requirement for end users**



- **Micro-instrument Chip**





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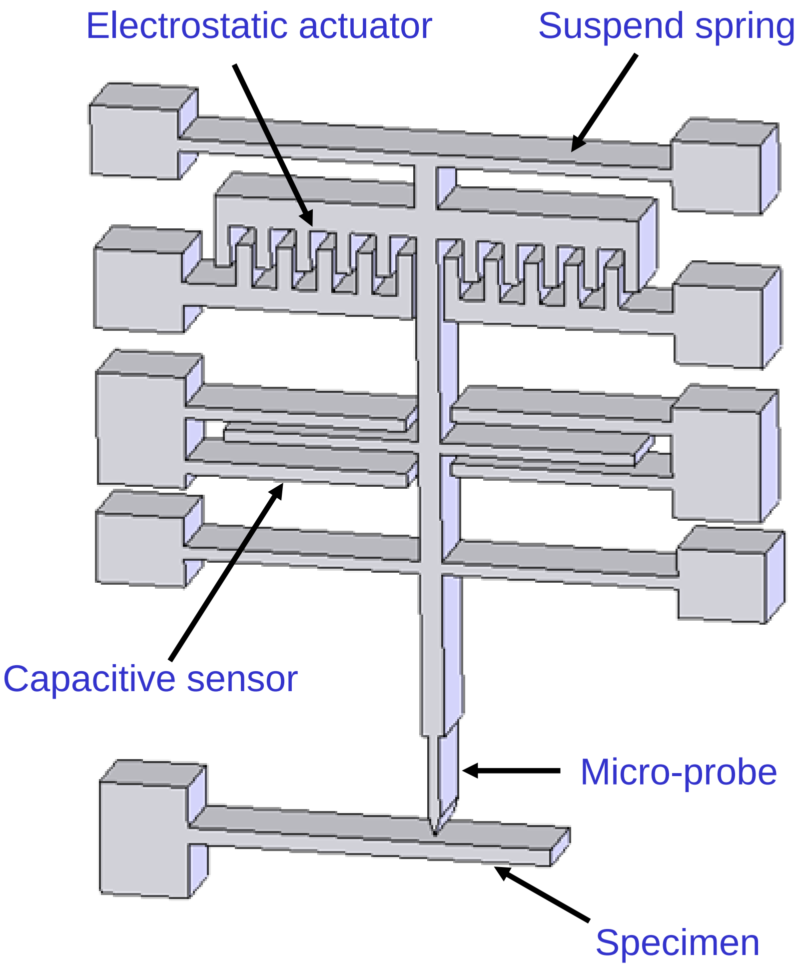
Design Issues



- Force on Specimen

$$F_s = F_a - K_y \cdot y$$

Actuator force | Stiffness of spring | Displacement sensing

- Suspended Spring
  - Linear spring, and stiffness ratio is enough
- Electrostatic Actuator
  - Constant force
- Capacitive Sensor
  - Linearity, min. initial capacitance, resolution

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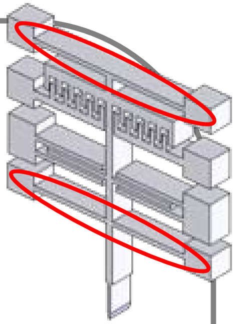
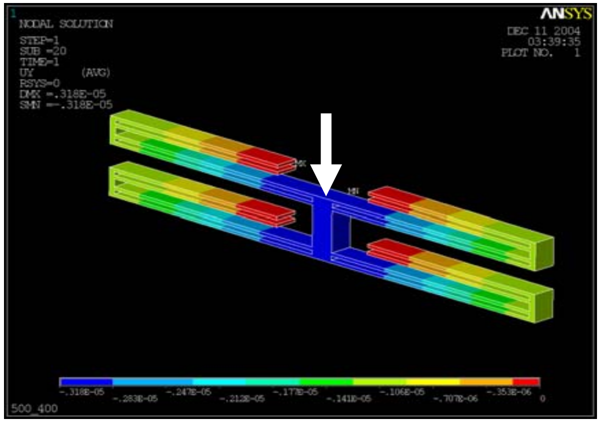
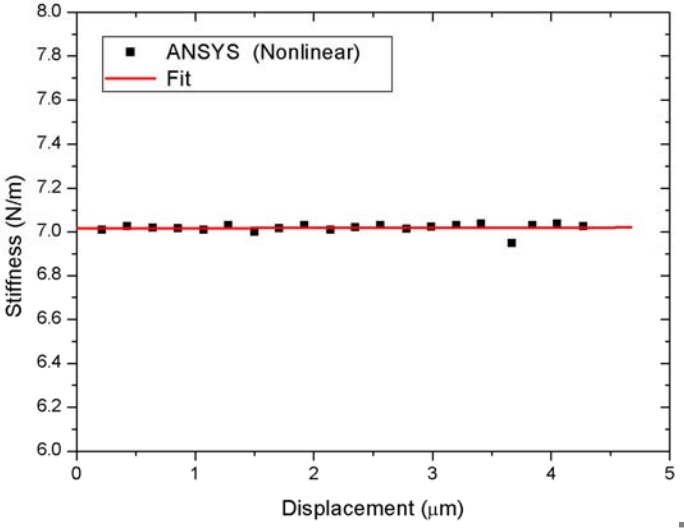
Support Spring

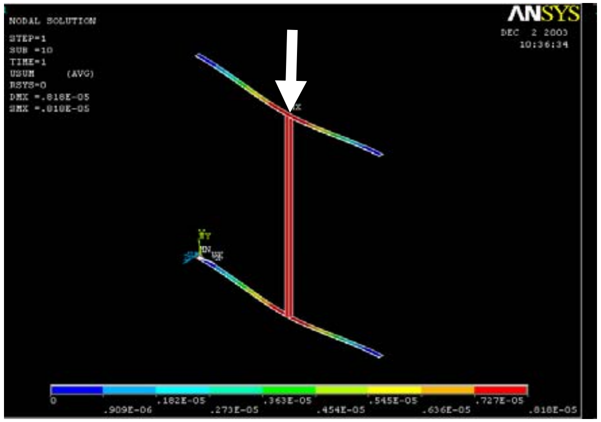


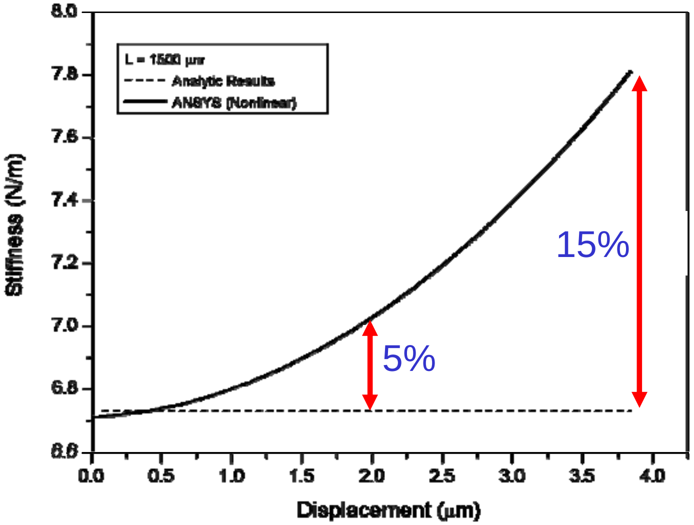
- Folded beam



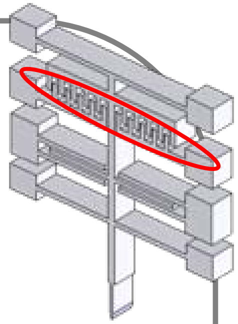


- Clamped beam



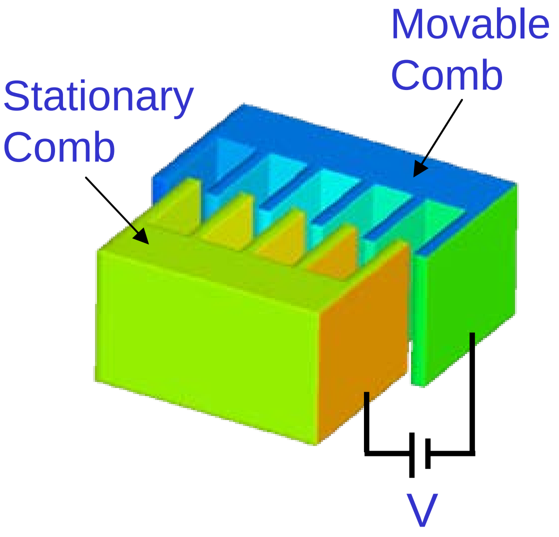


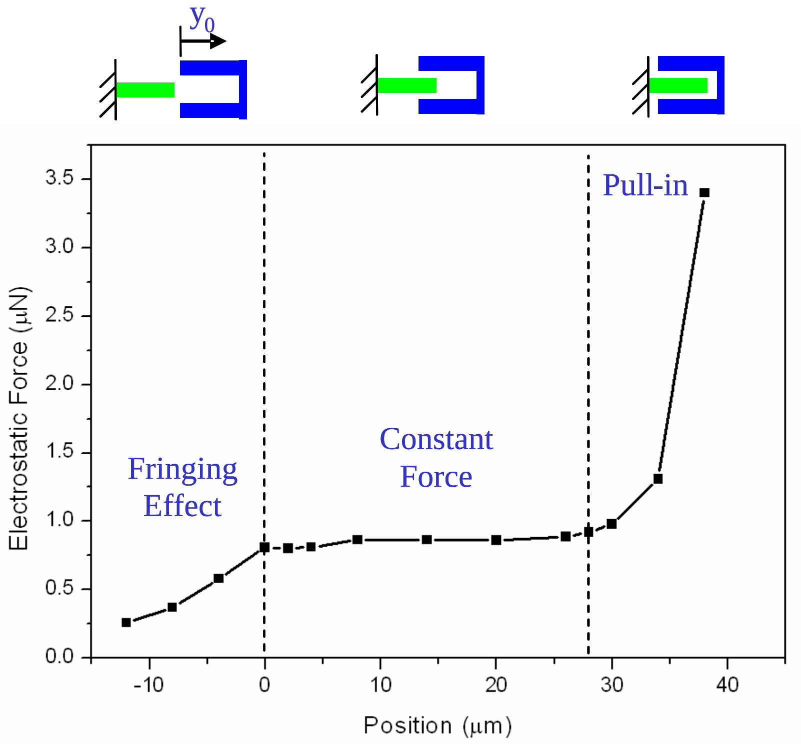
Comb Actuator



- Analytic Analysis
- Numerical Analysis
  - Commercial software Coventorware

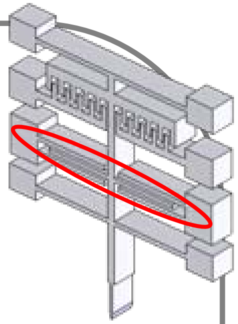
$$F_a = N\frac{\varepsilon t}{g}V^2$$





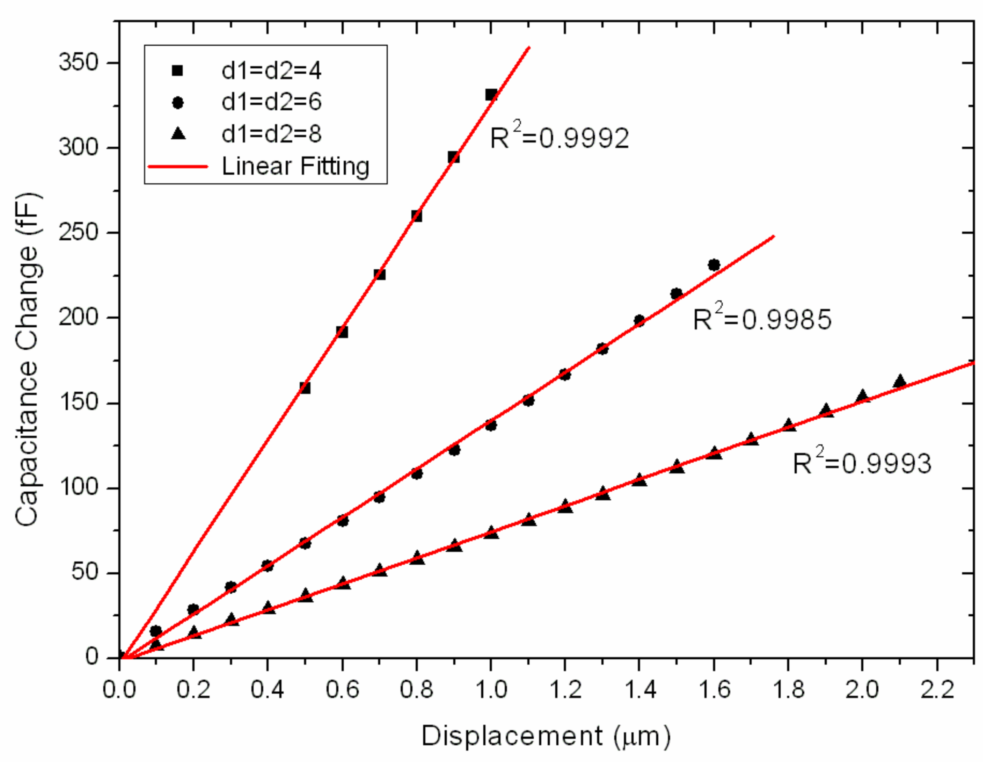
N	5
Voltage	50 (V)
Ideal Force	0.78 (μN)
Simulation Force	0.86 (μN)
Operation range	0-28 μm

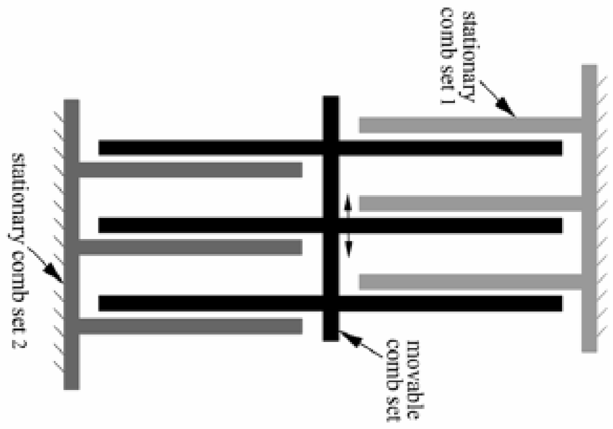
Capacitive Sensor



- Analytic Analysis
- Numerical Analysis

$$\Delta C = C_0 \frac{d \cdot \Delta d}{d^2 - \Delta d^2}$$





$$\Delta d \rightarrow \Delta C \rightarrow \Delta V$$

Coventorware

MS3110

Process Flow

- Microfabrication Processes
  - Micro-instrument

DRIE mask

device wafer

Oxide

handle wafer

1. Pattern DRIE mask

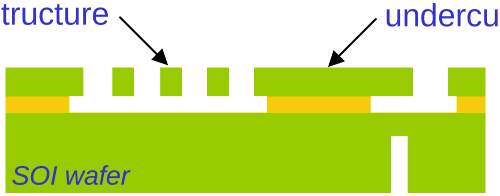
2. Pattern dicing mask

3. DRIE etching

4. Dicing (200μm)

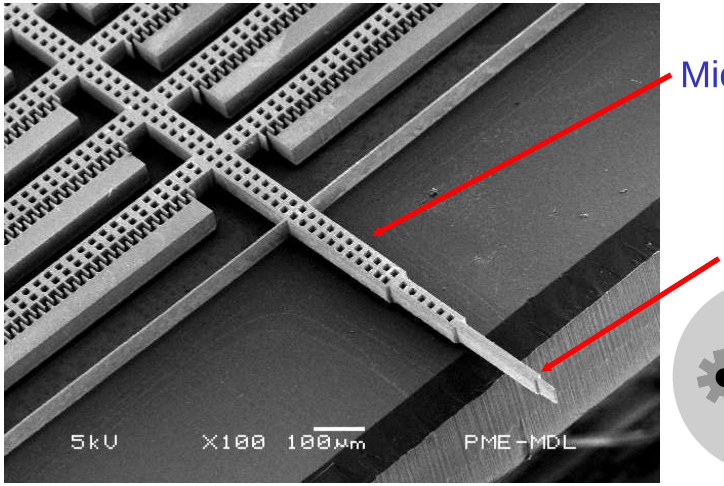
Released structure

Anchor with undercutting



5. HF releasing

6. The probe freely hangs in air



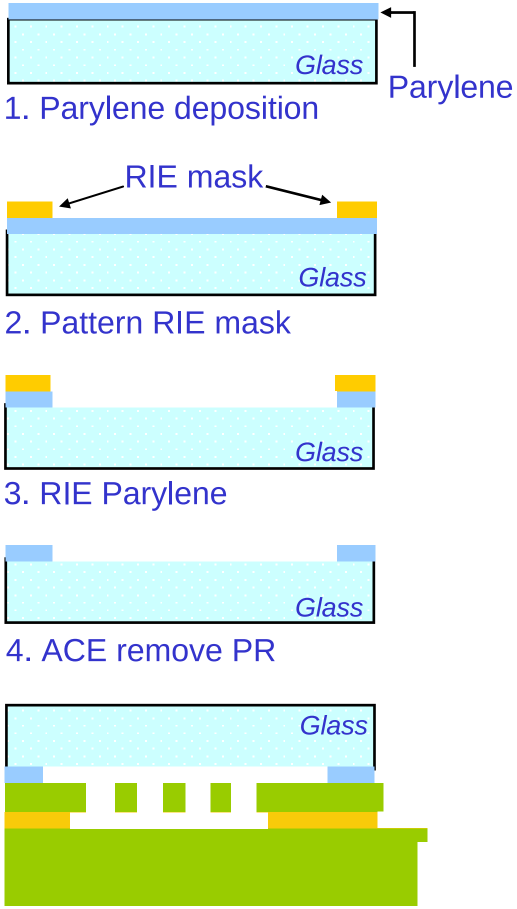
Micro-instrument

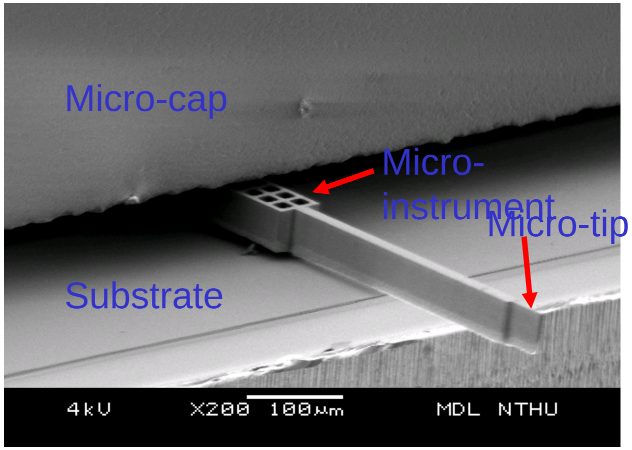
Micro-tip

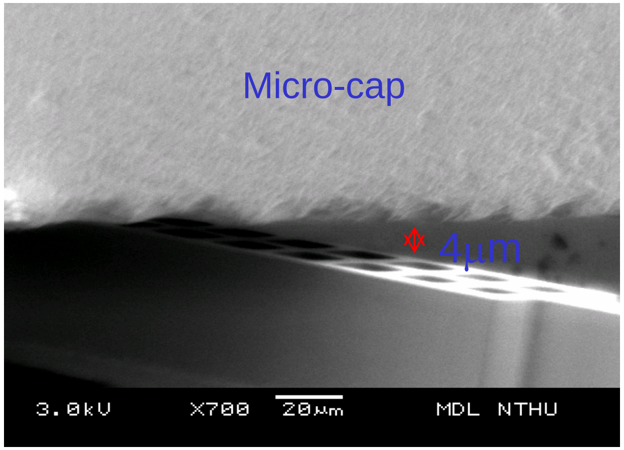
MDL
NTHU

Process Flow

- Microfabrication Processes
  - Micro-cap







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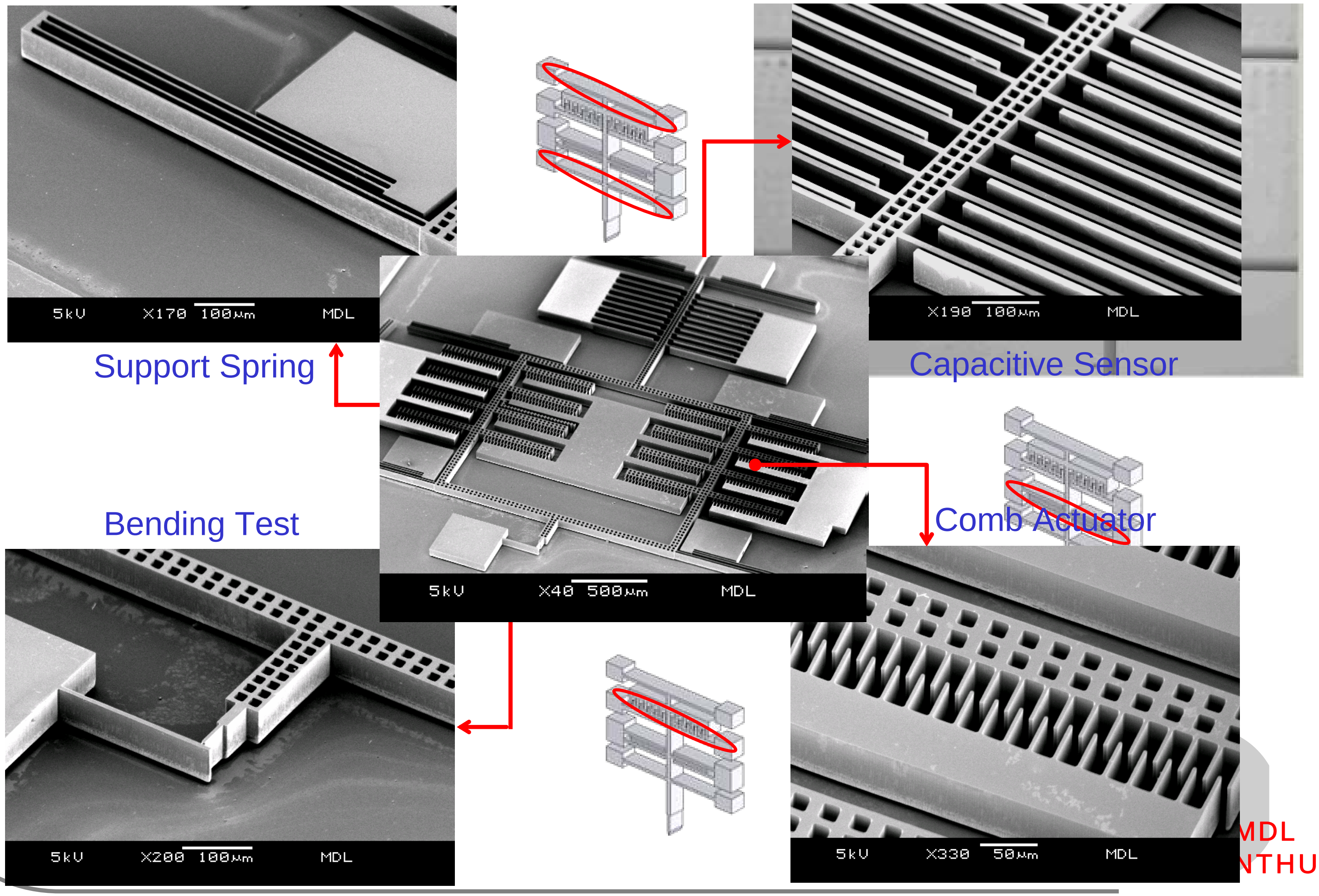
Fabrication Results



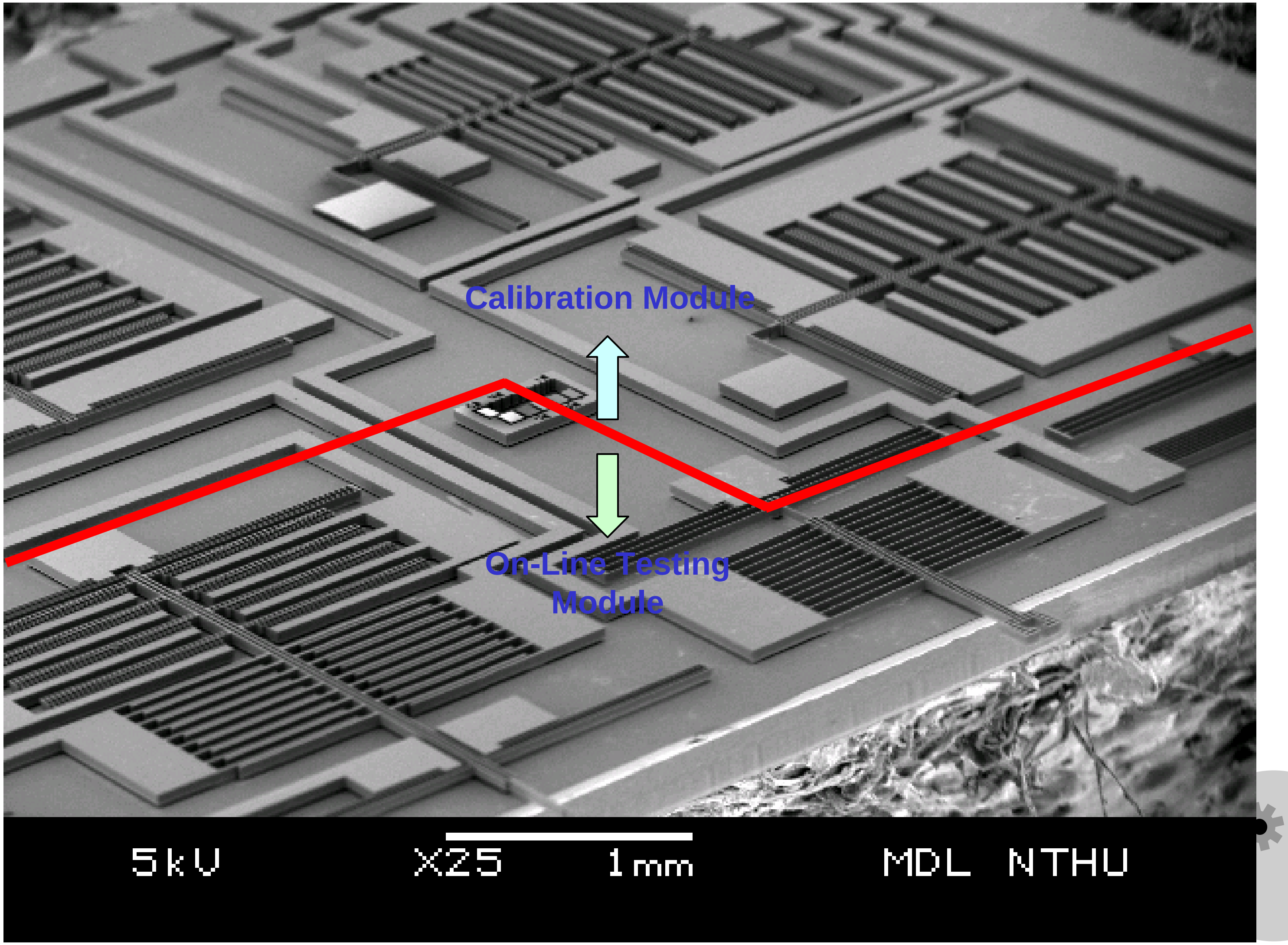
Support Spring

Capacitive Sensor

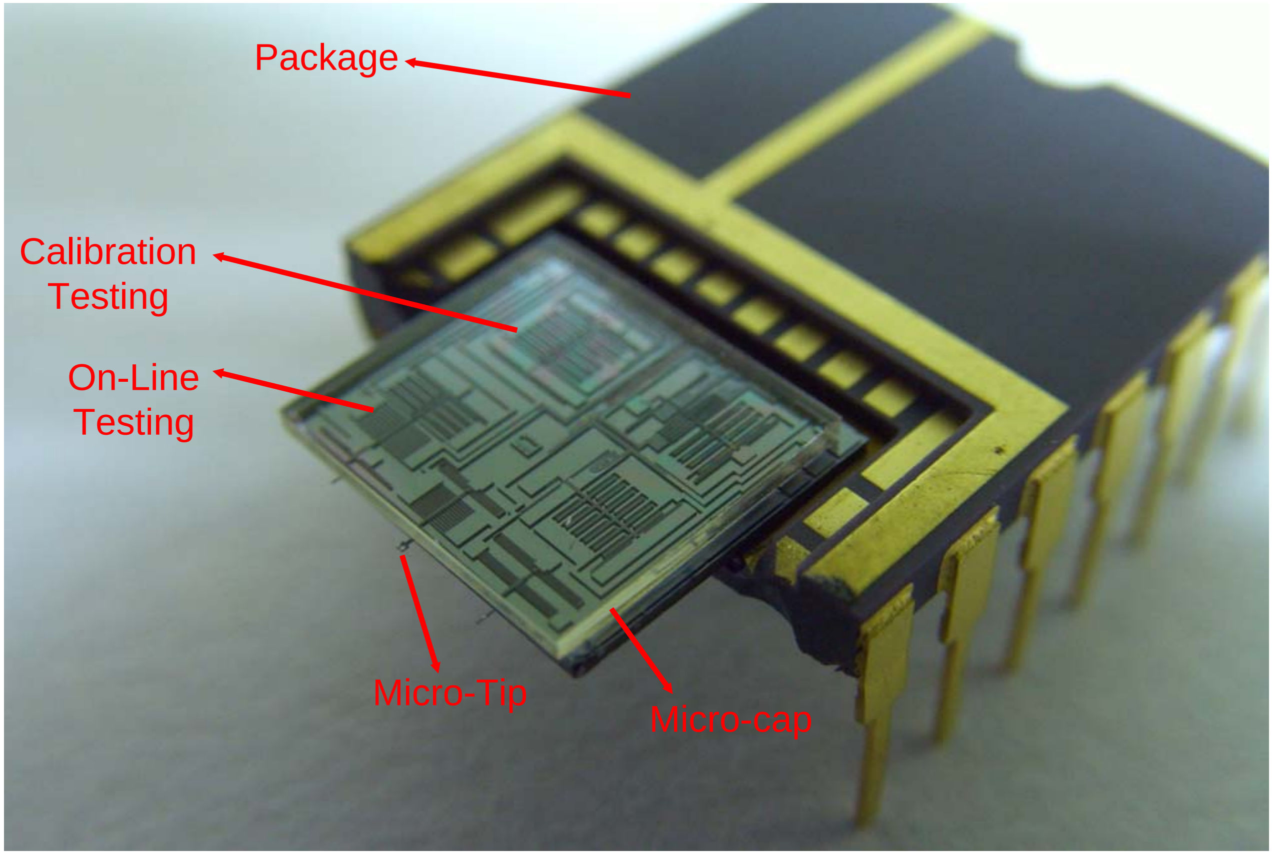
Bending Test

Comb Actuator

Fabrication Results

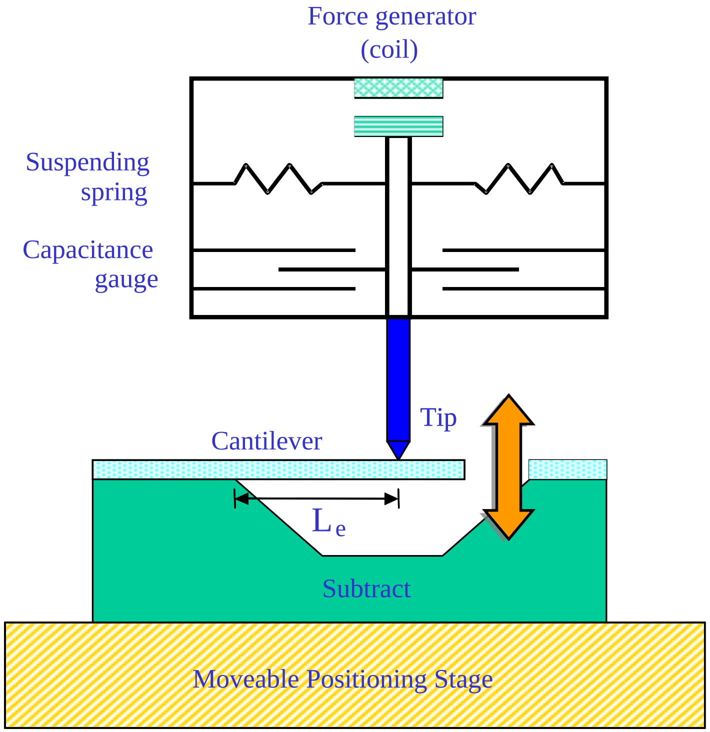


Package

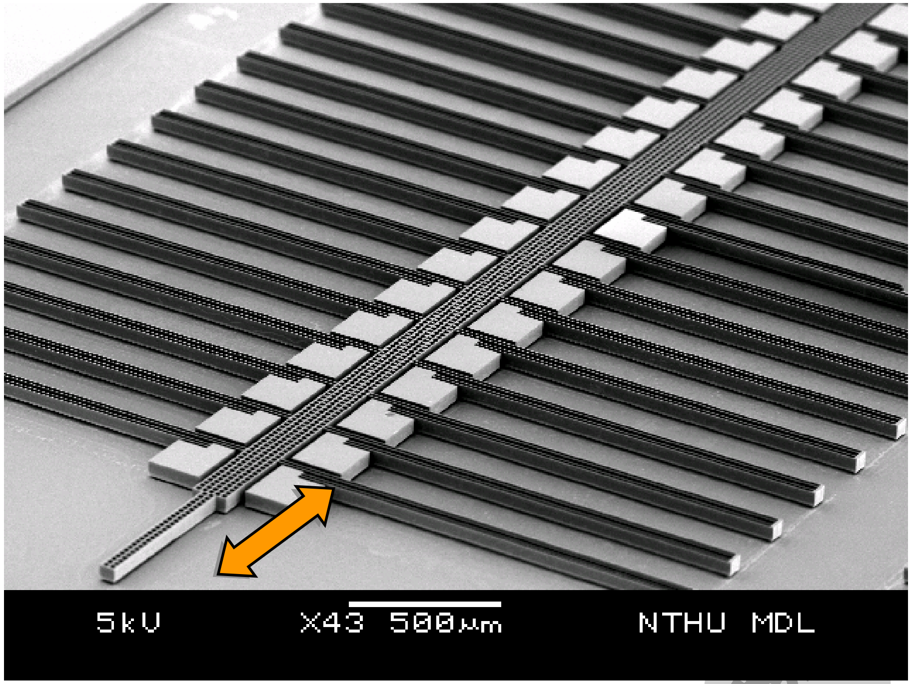

Package
Calibration Testing
On-Line Testing
Micro-Tip
Micro-cap

Stiffness Calibration

- The out-of-plane stiffness of cantilever can be measured by nanoindenter.
- How to measure in-plane stiffness of folded beam ?



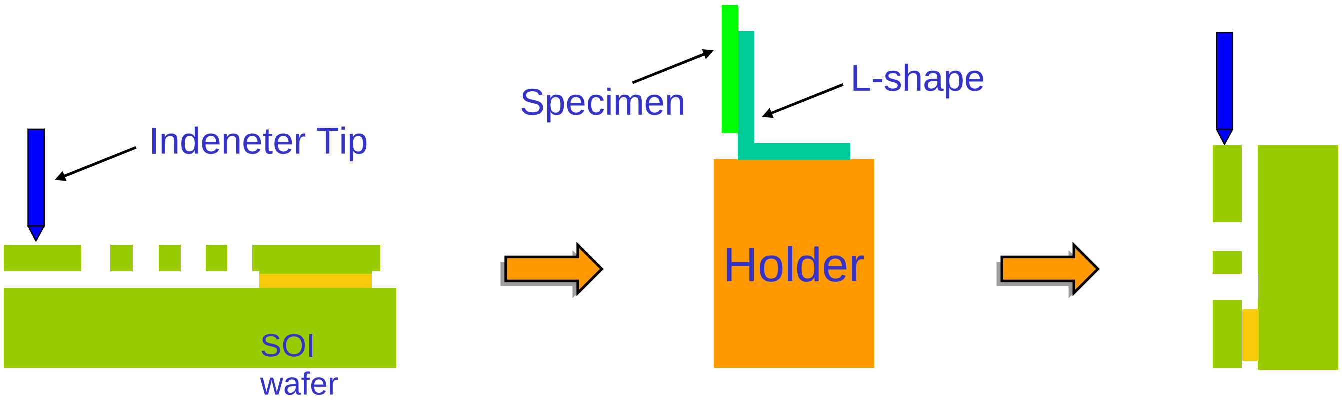
Out-of-plane motion

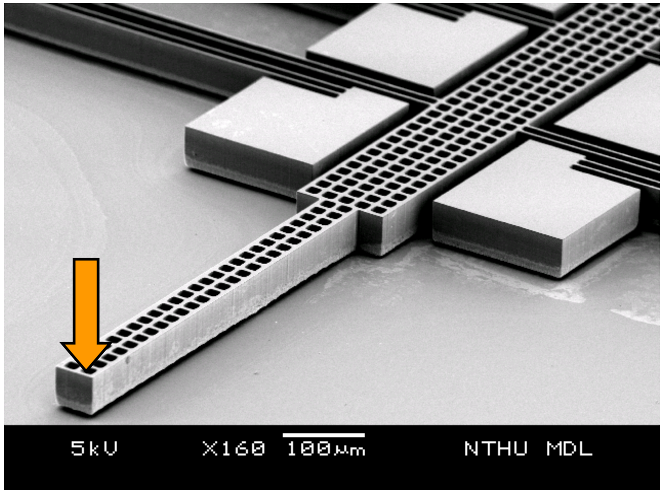


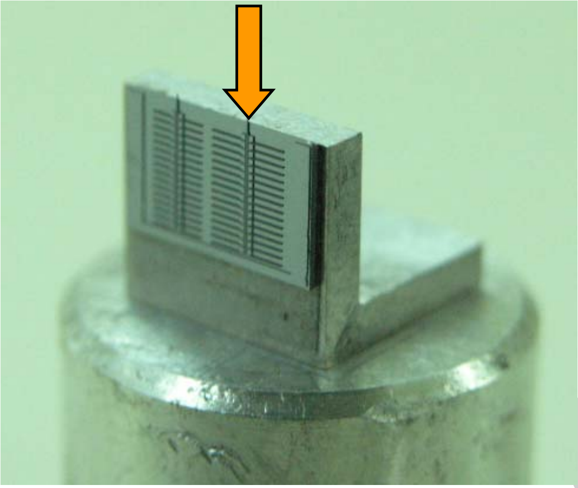
In plane motion

Stiffness Calibration

- Set-up photograph
- Transfer in-plane motion into out-of-plane motion using L-shape holder.

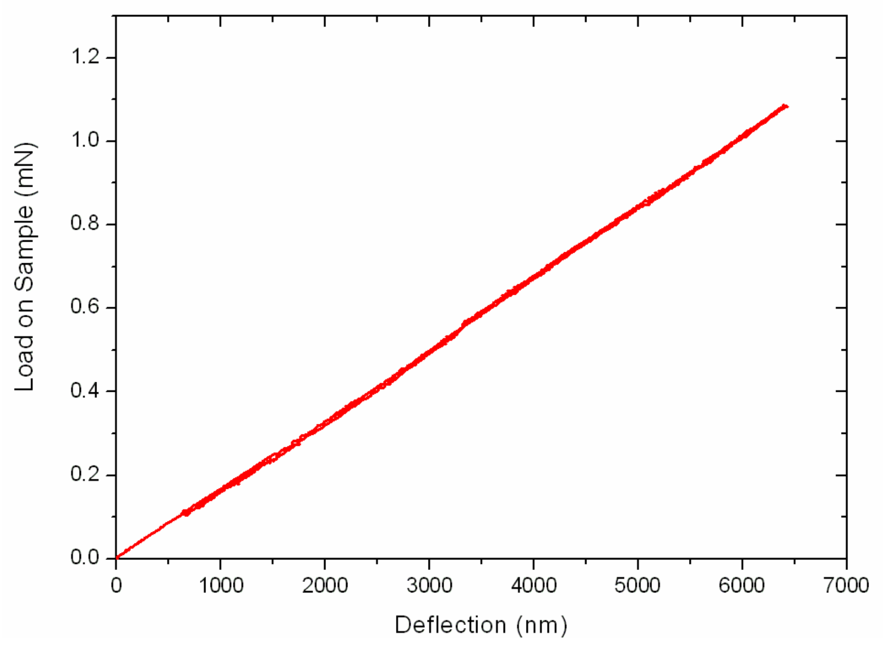


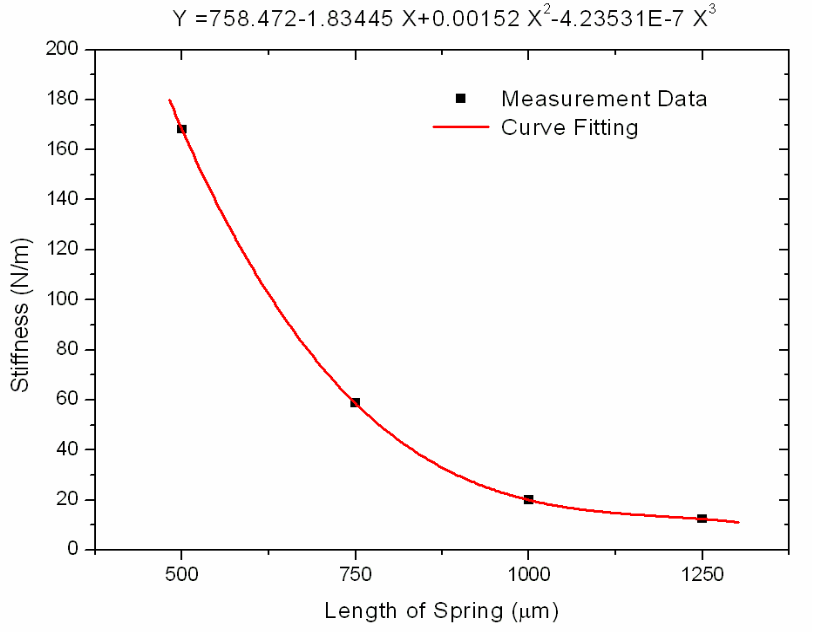




Stiffness Calibration

- Typical load-deflection relationship for 500 μm of folded beam
- Stiffness：168 N/m





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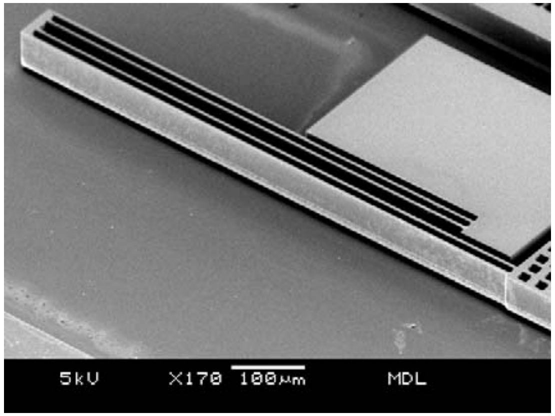
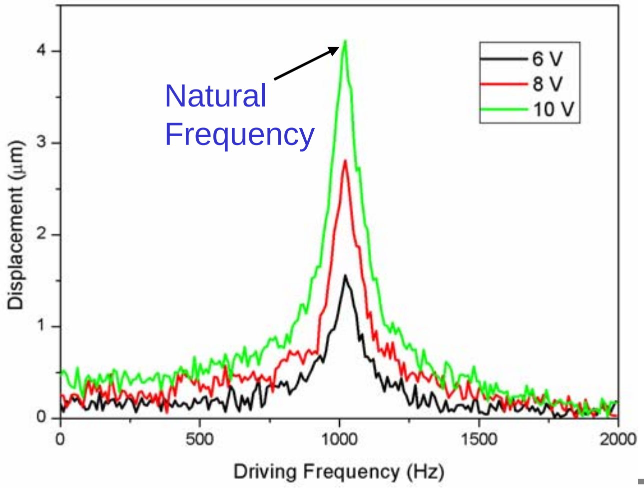
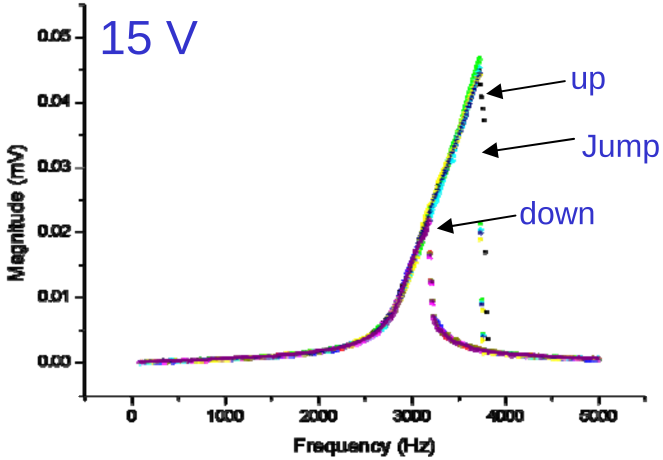
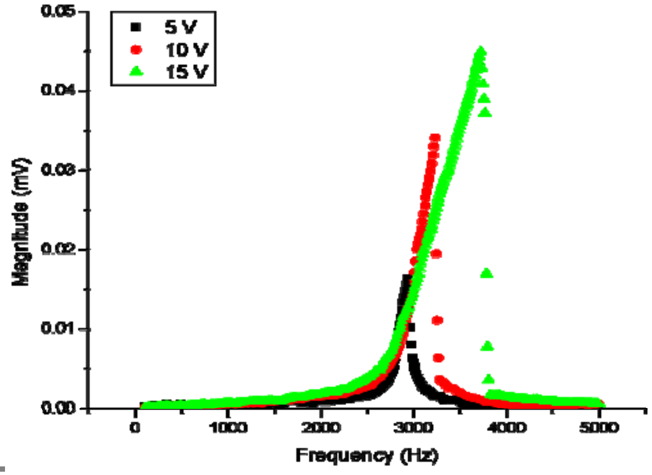
Dynamic Response

- Dynamic Measurement - Frequency Response
  - Folded beam
  - Clamped beam - Jump phenomenon







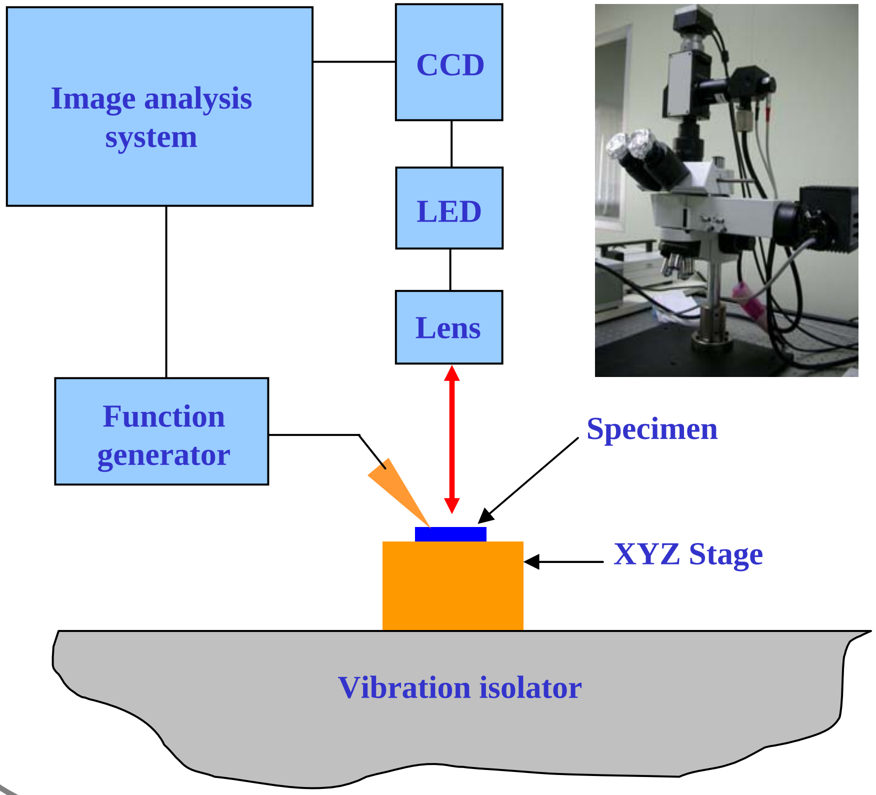


Force Calibration

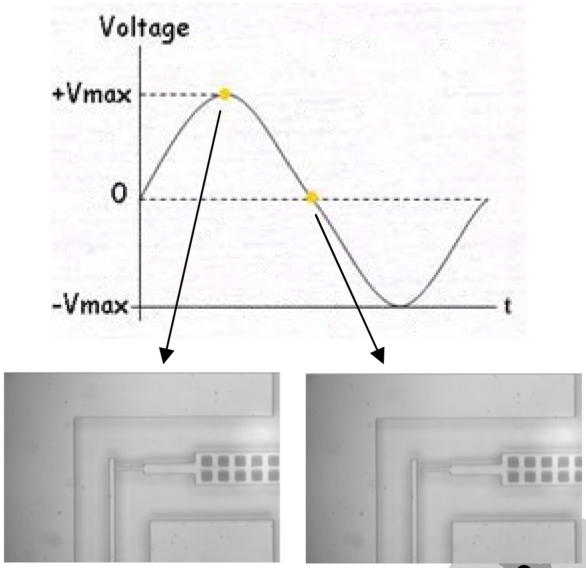
- Experimental setup

  by MMA(MEMS Motion Analyzer)

  - In-plane motion is measured



- Specifications
  - Measured by image capture
  - Frequency range：1 Hz～10MHz
  - In-plane motion resolution：20nm



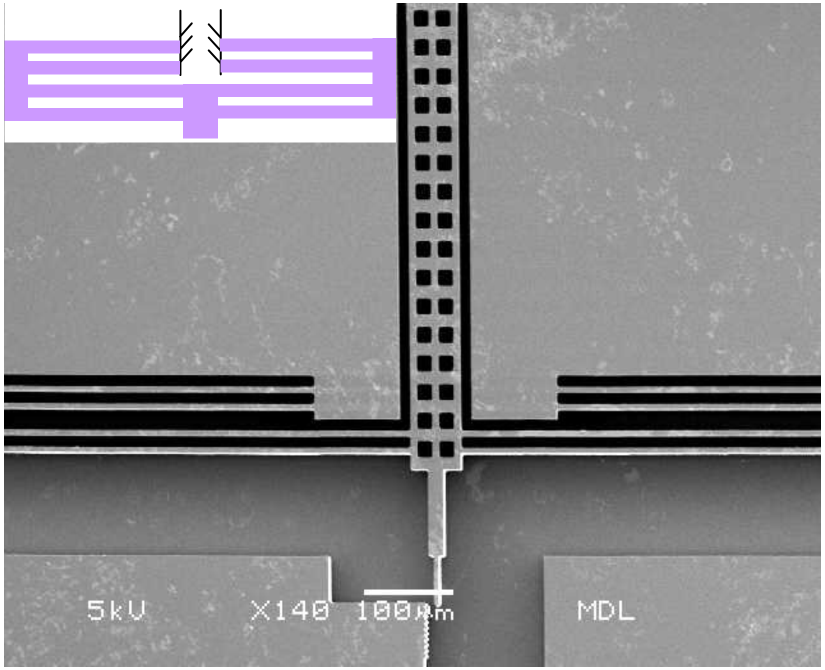
Force Calibration

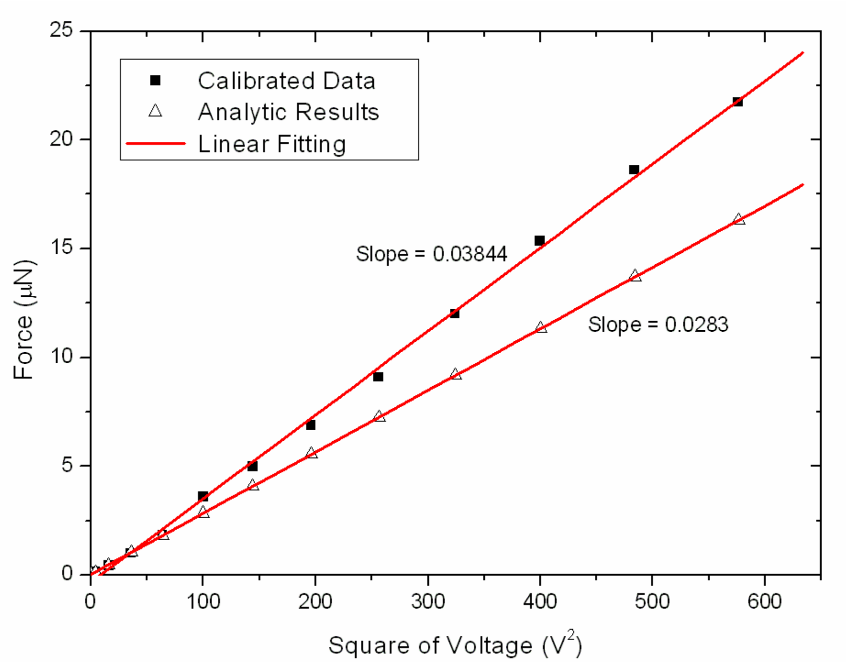
- 1 Hz frequency simulate static load-deflection relationship

- Folded beam

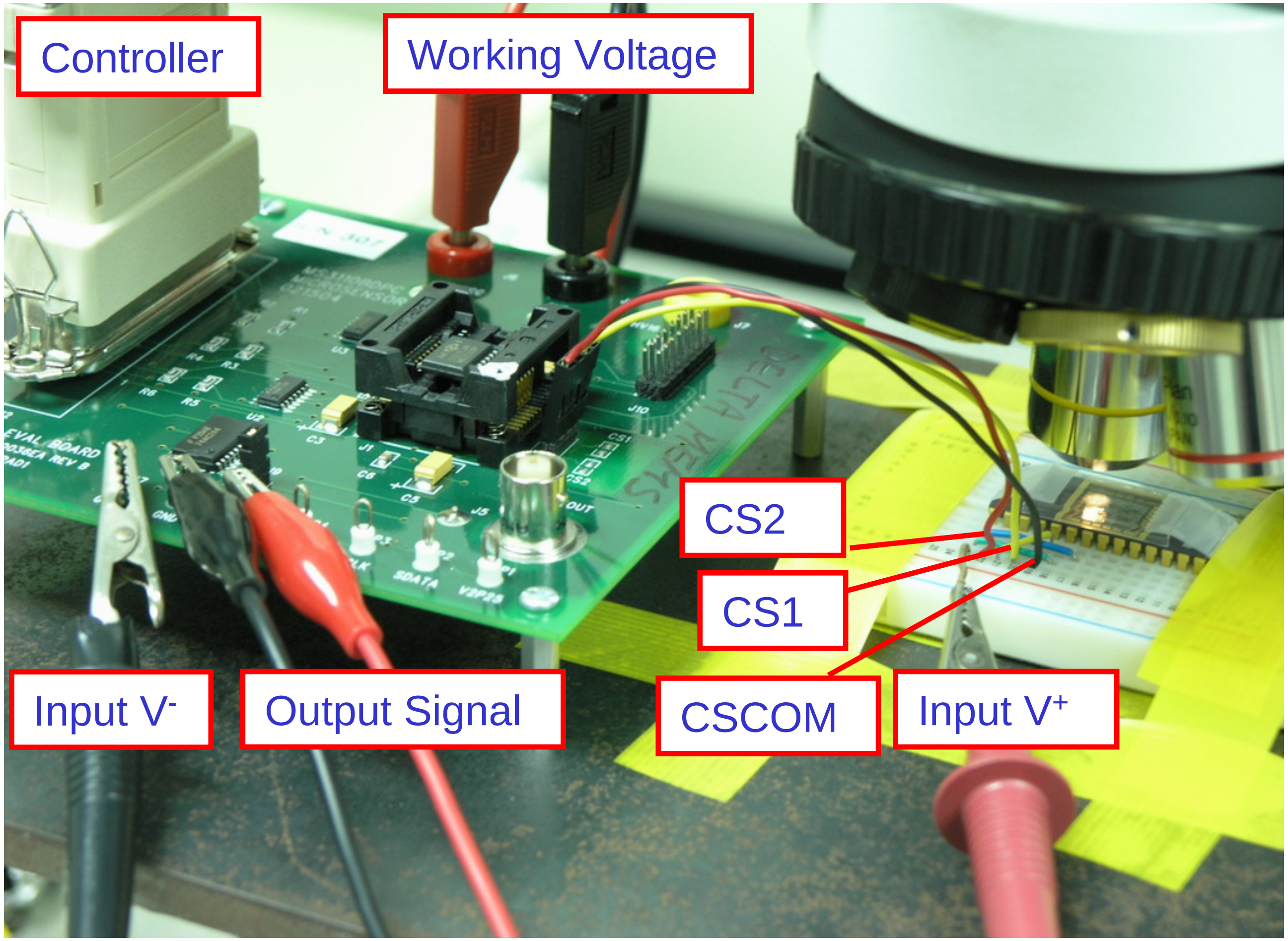
$$F_a = N\frac{\varepsilon t}{g}\boxed{V^2} = K_y \cdot \boxed{y} \longrightarrow$$

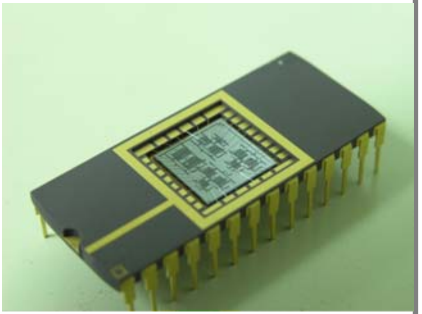
MMA Measurement

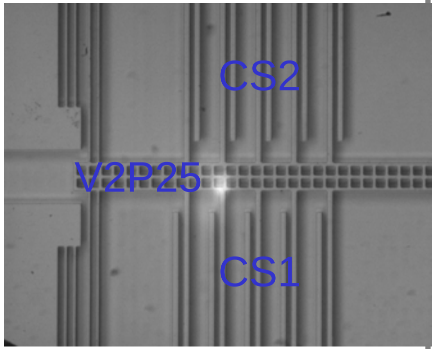




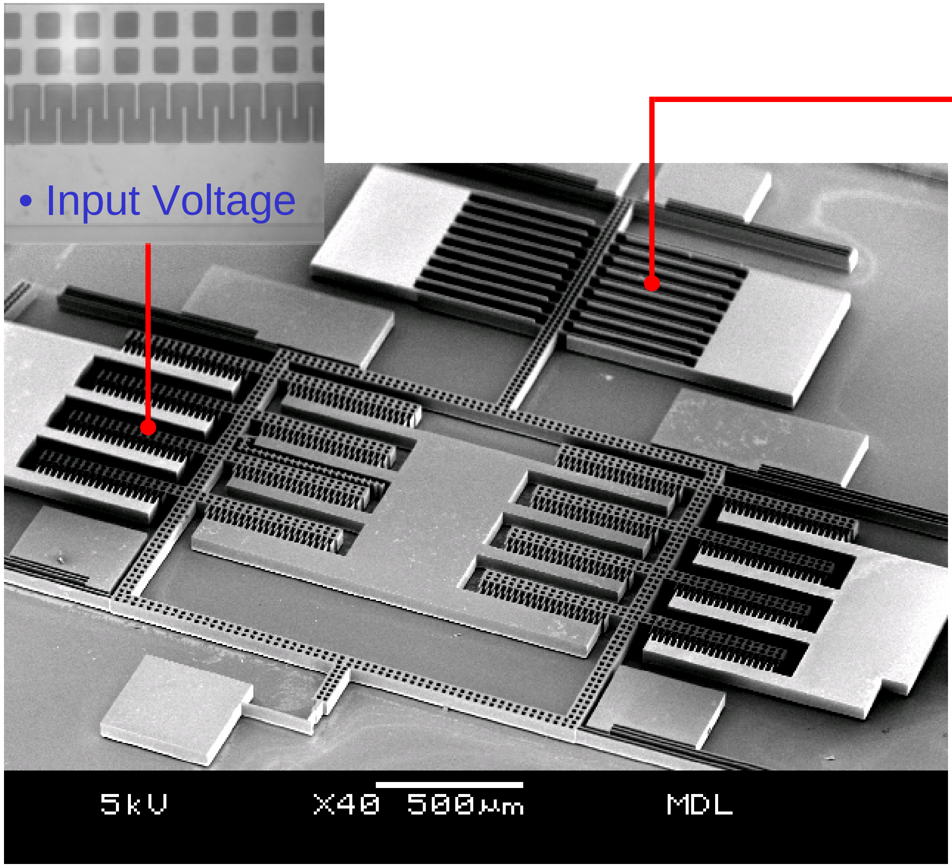
Electrical Output



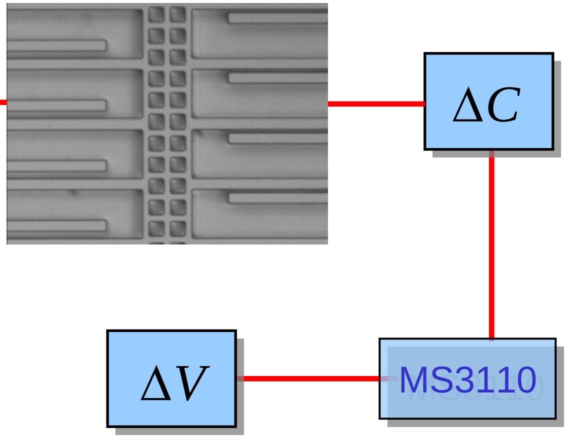


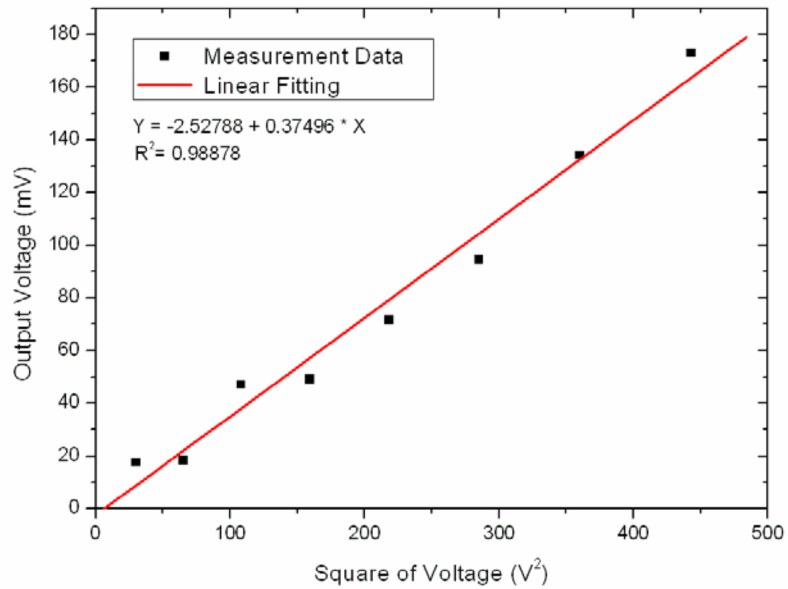


Electrical Output



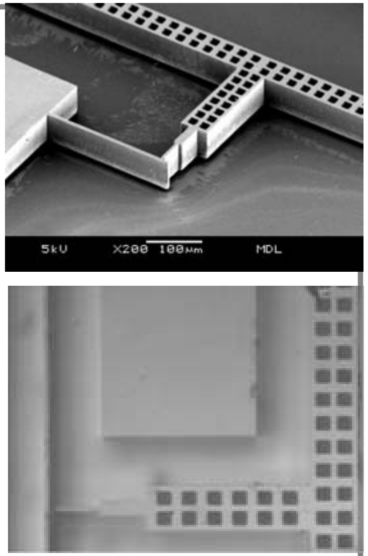
- Input Voltage

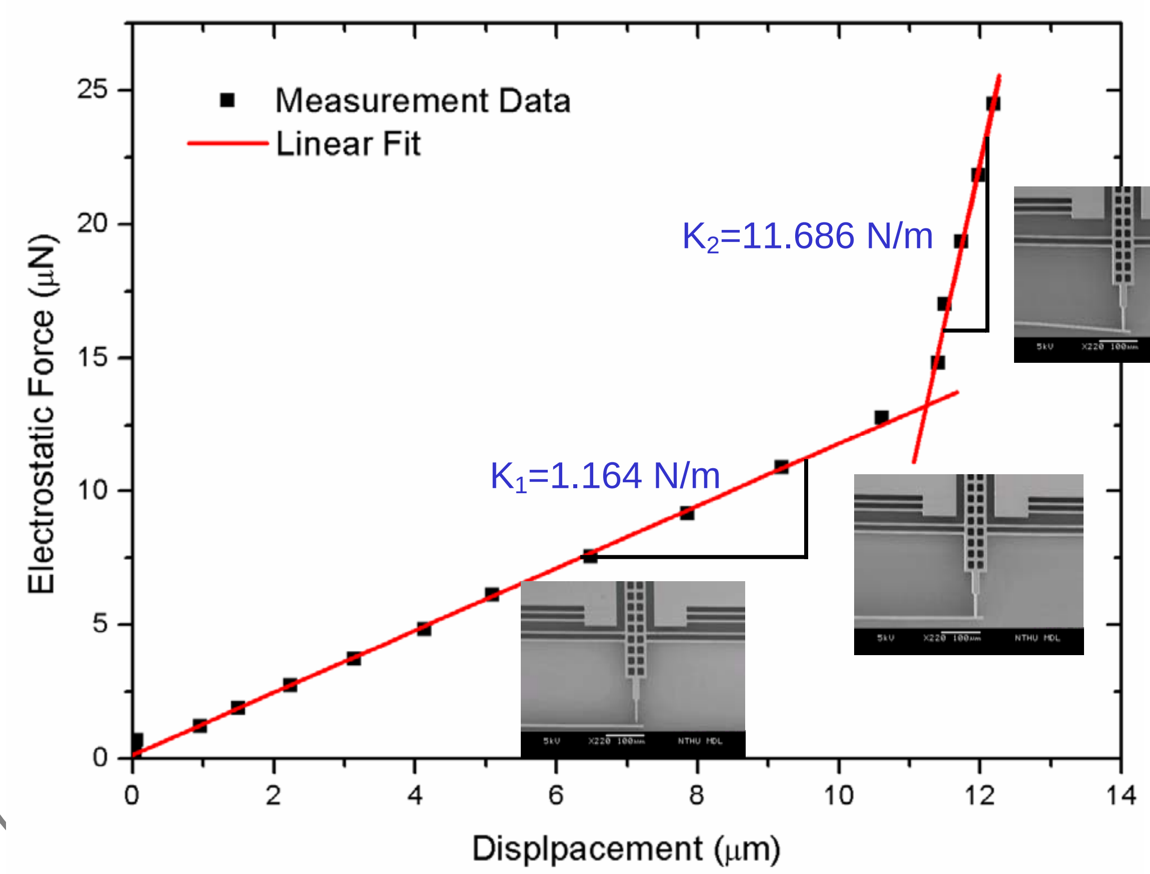


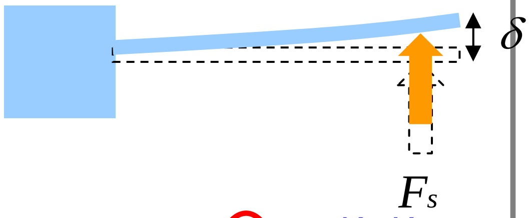


Applications

- Extract Young's Modulus
- There exist a error deviation on bending test using the micro-instrument and textbook about 4.8 %.





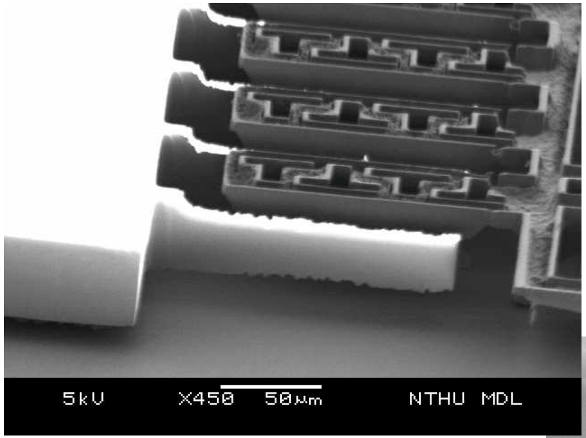


K₂-K₁

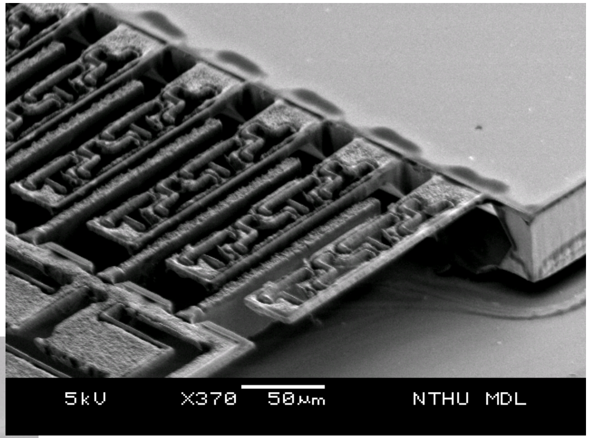
$$E_s = \frac{4l^3}{hb^3} \cdot \frac{F_s}{\delta}$$

E = 173 GPa

Other Available Instrument

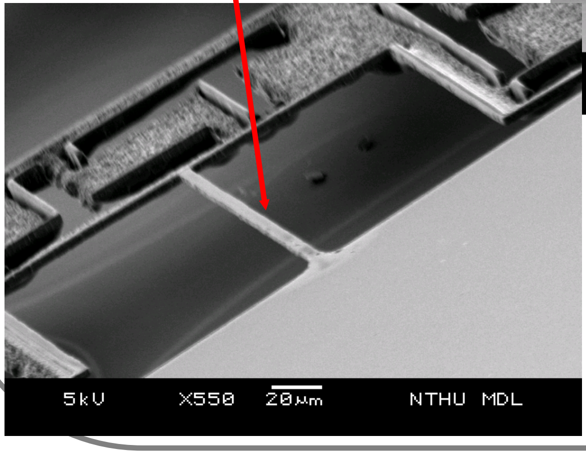


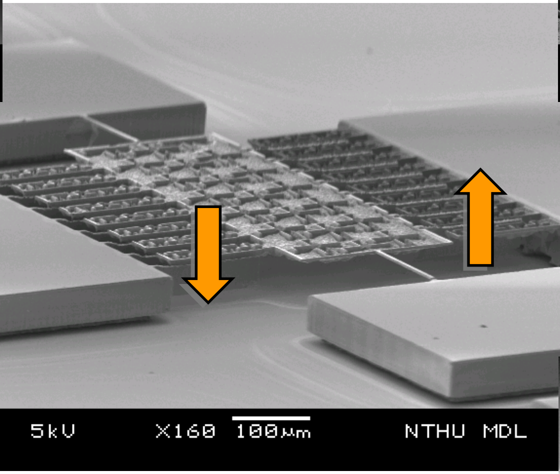
Vertical Comb
(downward actuation)



Vertical Comb
(upward actuation)

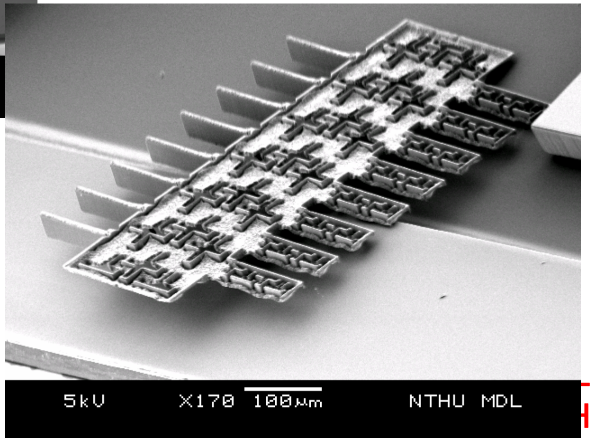
Torsion Specimen



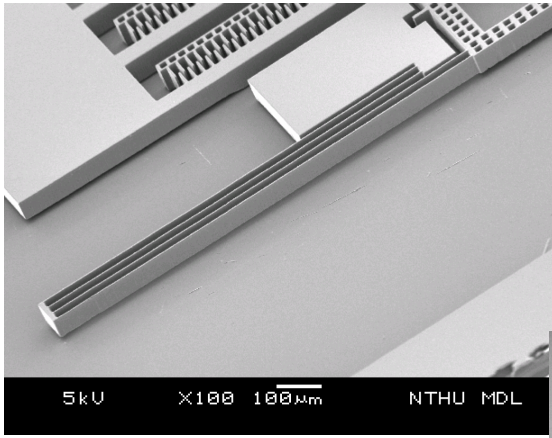


Pure Torsion Testing

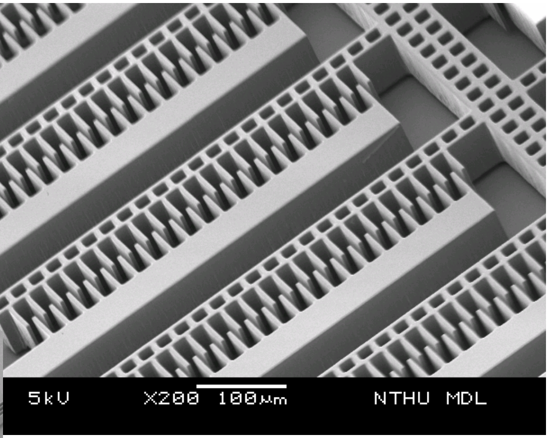
Rein-force Structure



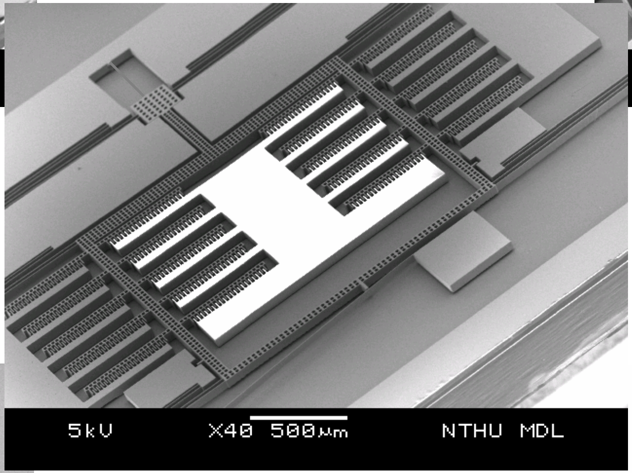
Other Available Instrument



Support Spring

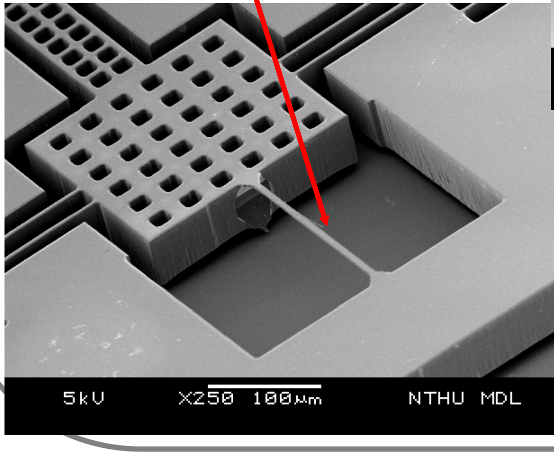


Comb Actuator

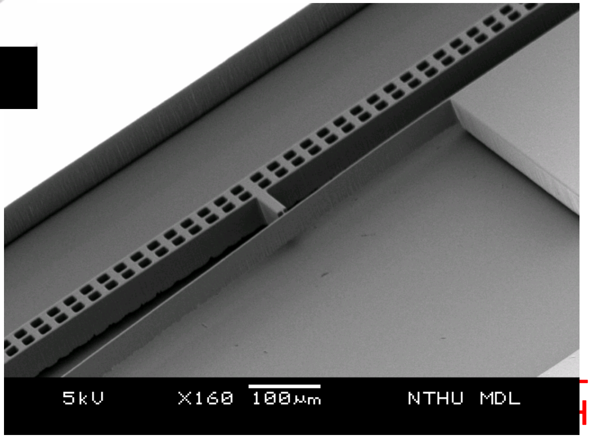


Tensile Testing

Tensile Specimen

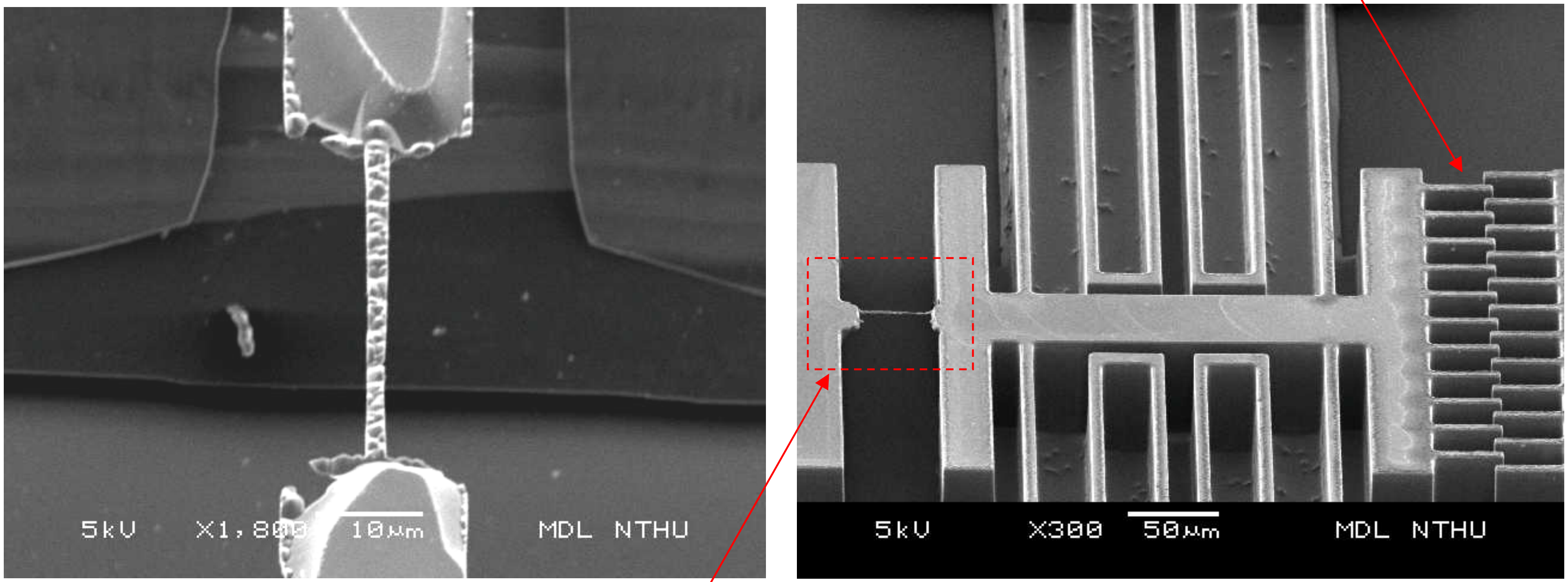


Motion Amplification



Integration of N/MEMS

- Nano structure testing



MEMS actuator

Nano structure/sample holder

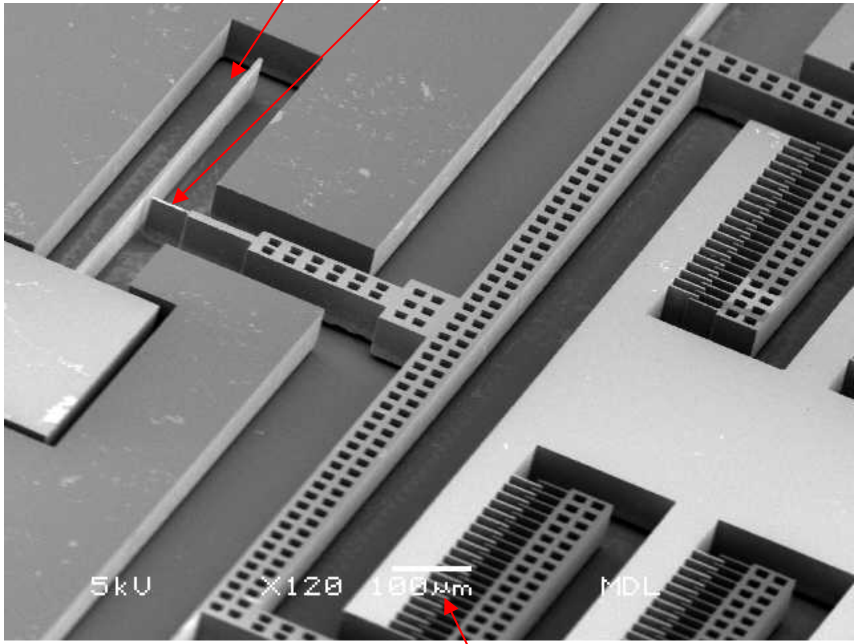
H.-Y. Chu, and W. Fang, *IEEE MEMS'04*, the Netherlands, 2004

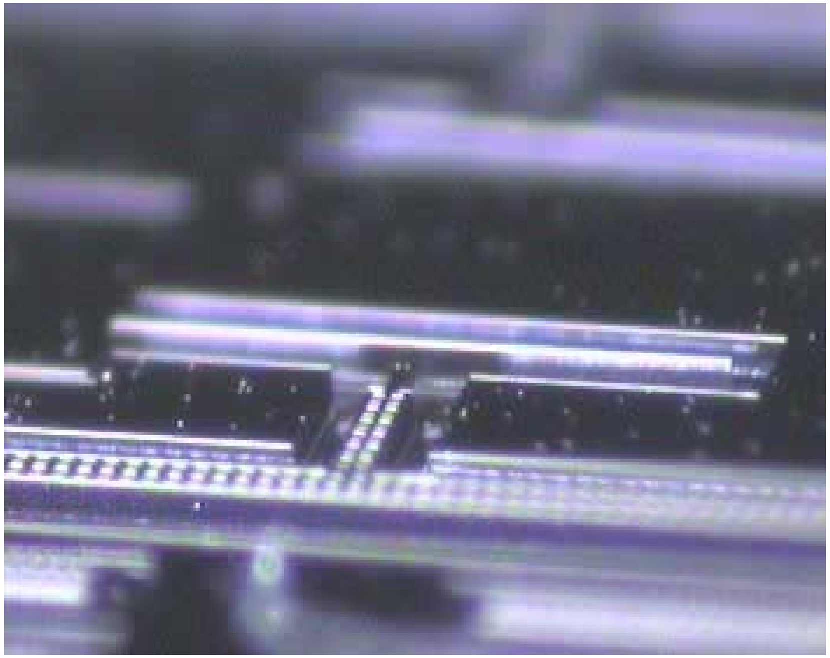
Integration of N/MEMS

- Nano structure testing

Nano/micro test specimen

Micro probe



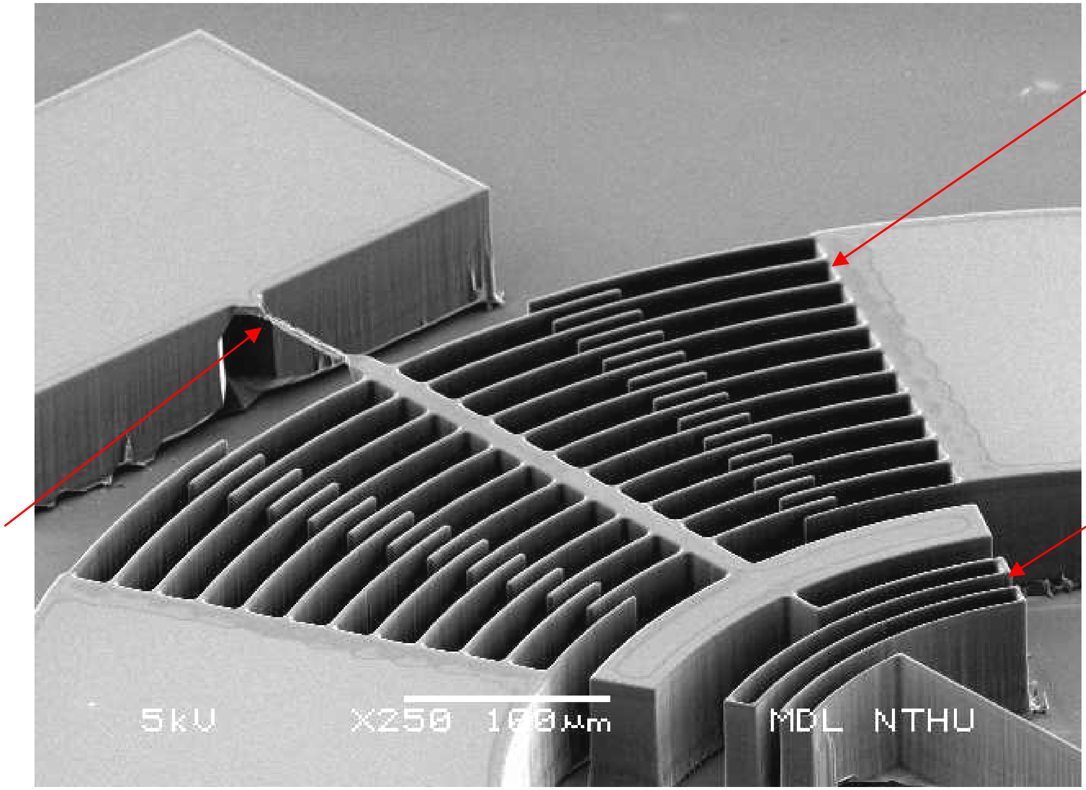


MEMS linear actuator

C. Chang, H.-Y. Chu, and W. Fang, 2004

Integration of N/MEMS

- Nano structure testing



MEMS actuator

MEMS spring

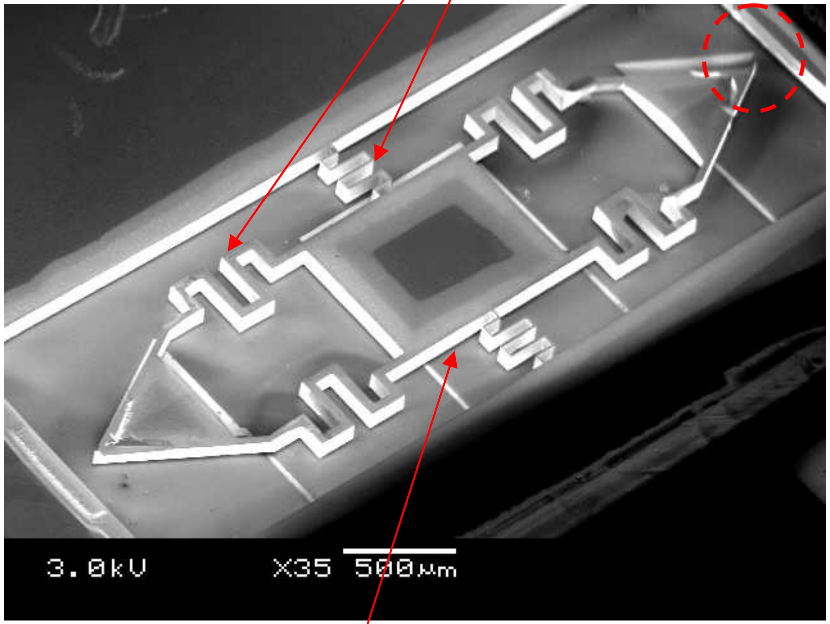
Nano structure /Sample holder

H.-Y. Chu, and W. Fang, *IEEE MEMS'04*, the Netherlands, 2004

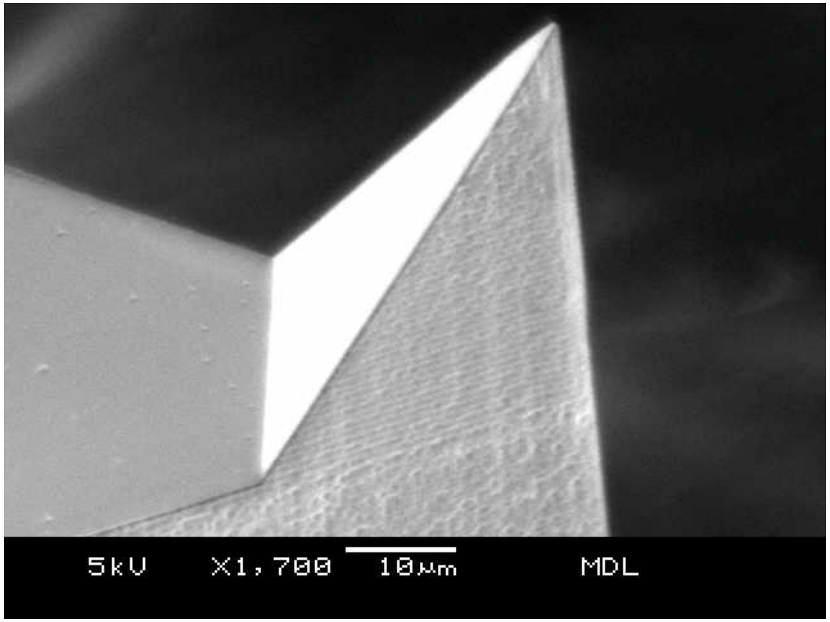
Integration of N/MEMS

- **Nano structure testing**

Spring



Electrostatic actuator



B. Chang, H.-Y. Chu, and W. Fang, 2004

Conclusions

- On-chip micro-instrument for thin film and micro-structures testing.
- Standard testing platform for micro/nano structures