Outline

1 Introduction

2 Basic IC fabrication processes

3 Fabrication techniques for MEMS

4 Applications

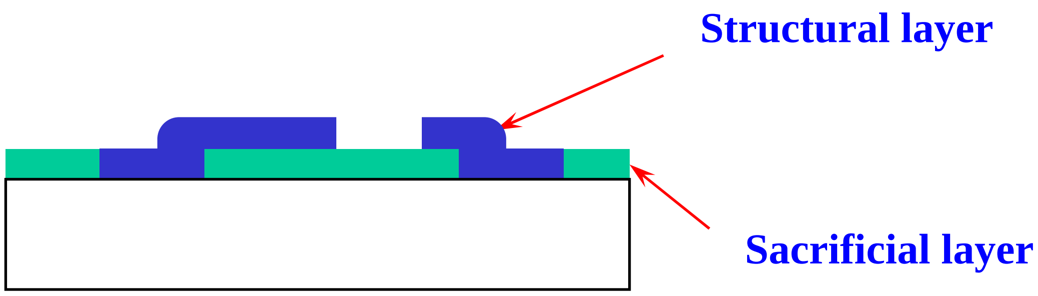
5 Mechanics issues on MEMS

MDL
NTHU

3. Fabrication Techniques for MEMS

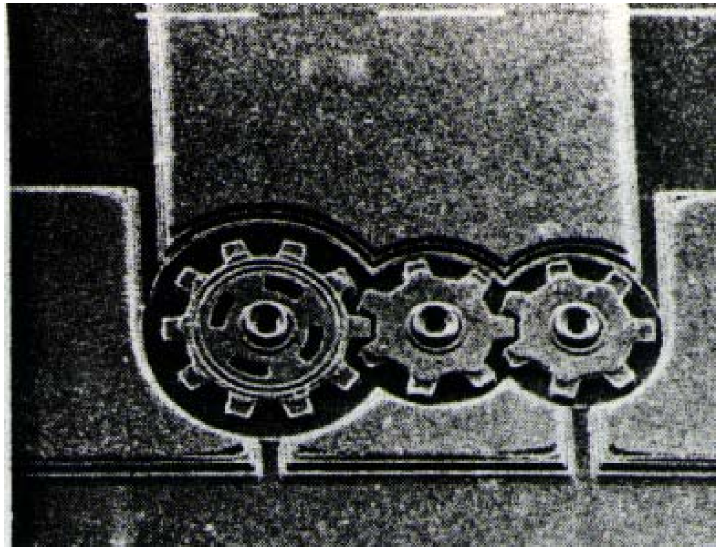
3.2 Surface Micromachining

- Surface micromachining - the technique to construct micromechanical devices on top of the silicon substrate
- The surface micromachined structures are constructed by : (1) structural layer, and (2) sacrificial layer

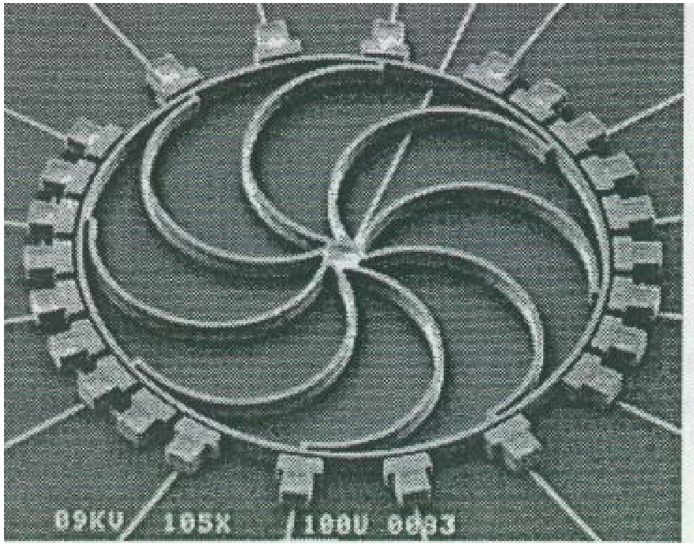


- After the sacrificial layer is removed, the structural layer will be released from the substrate
- Space between each components is limited by the thickness of the sacrificial layer

- The primary advantage of surface micromachining is its capability of fabricating movable micromachined structures with geometries less restricted through the conventional IC process



M. Mehregany, K.J. Gabriel, and W.S.N. Trimmer, IEEE Transactions on ED, 1988.



M.W. Putty and K. Najafi, Proc. of IEEE Solid State Sensor and Actuator Workshop, 1994.

MDL
NTHU

- **In general, all of the materials can be selected as the structural and sacrificial layer, however the most common material for surface micromachining is:**

  + For structural layer - LPCVD polysilicon

  + For sacrificial layer - thermal or LPCVD SiO_2 or LPCVD phosphosilicate (PSG)

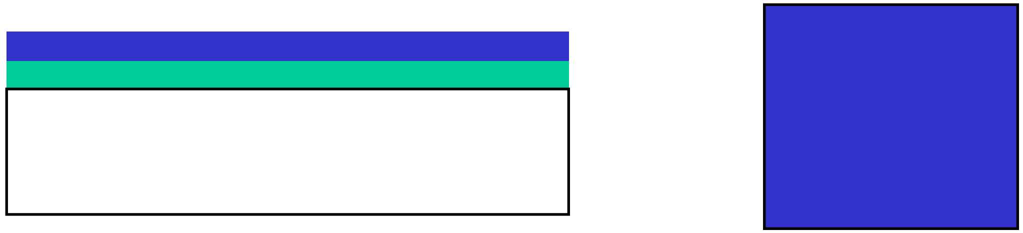
- **The discussion in this section will include**

  + Simple surface structures - constructed by one sacrificial layer and one structural layer

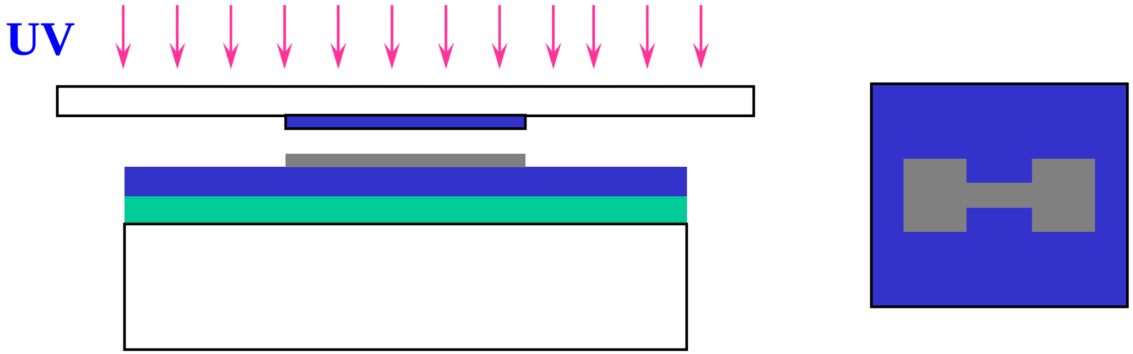
  + Complicated surface structures - constructed by multiple structural layers and multiple sacrificial layers

- **Fabrication processes for single mask structures**

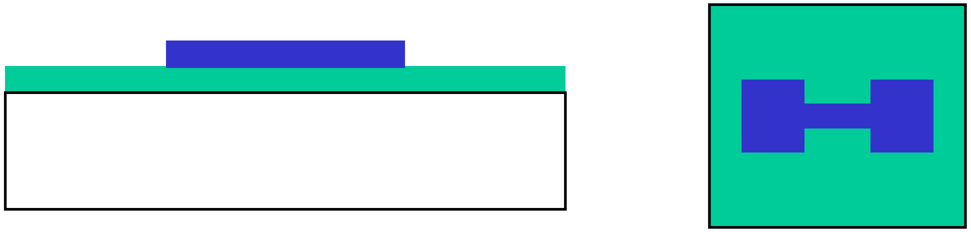
Deposit or grow a sacrificial layer



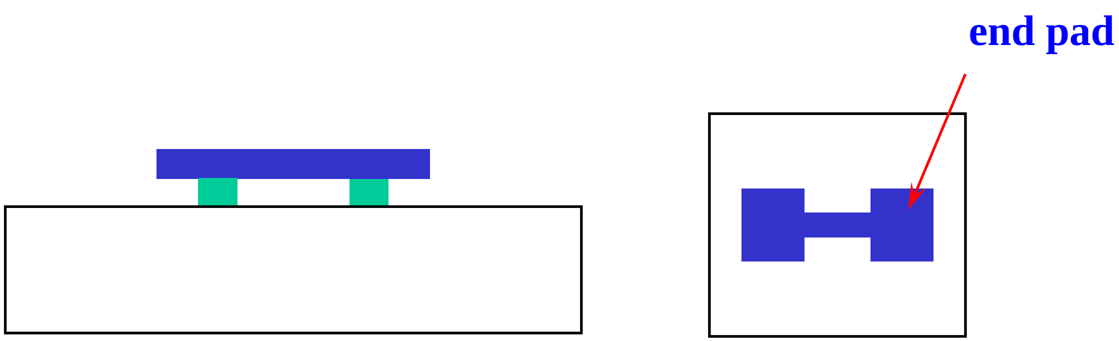
Deposit the structural layer



Spin coat PR and then patterned with mask



Pattern the structural layer

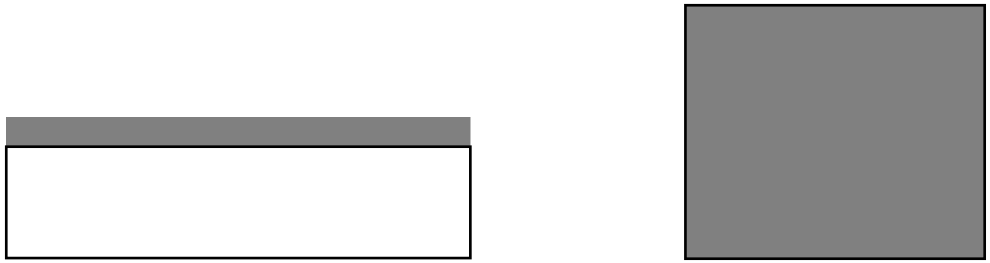


Etch the sacrificial layer

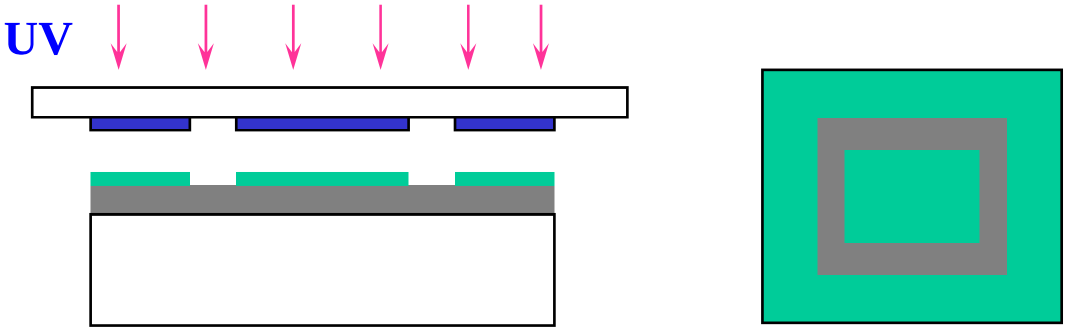
- Since the processes have undercut effect, the end pads have to be big enough to obtain a well support structure

MDL
NTHU

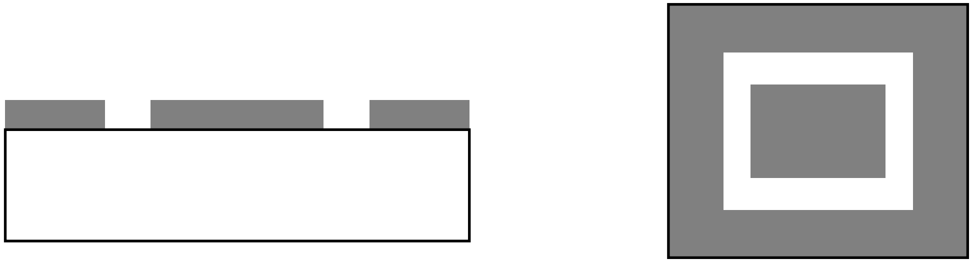
- **Fabrication processes for two masks structures**



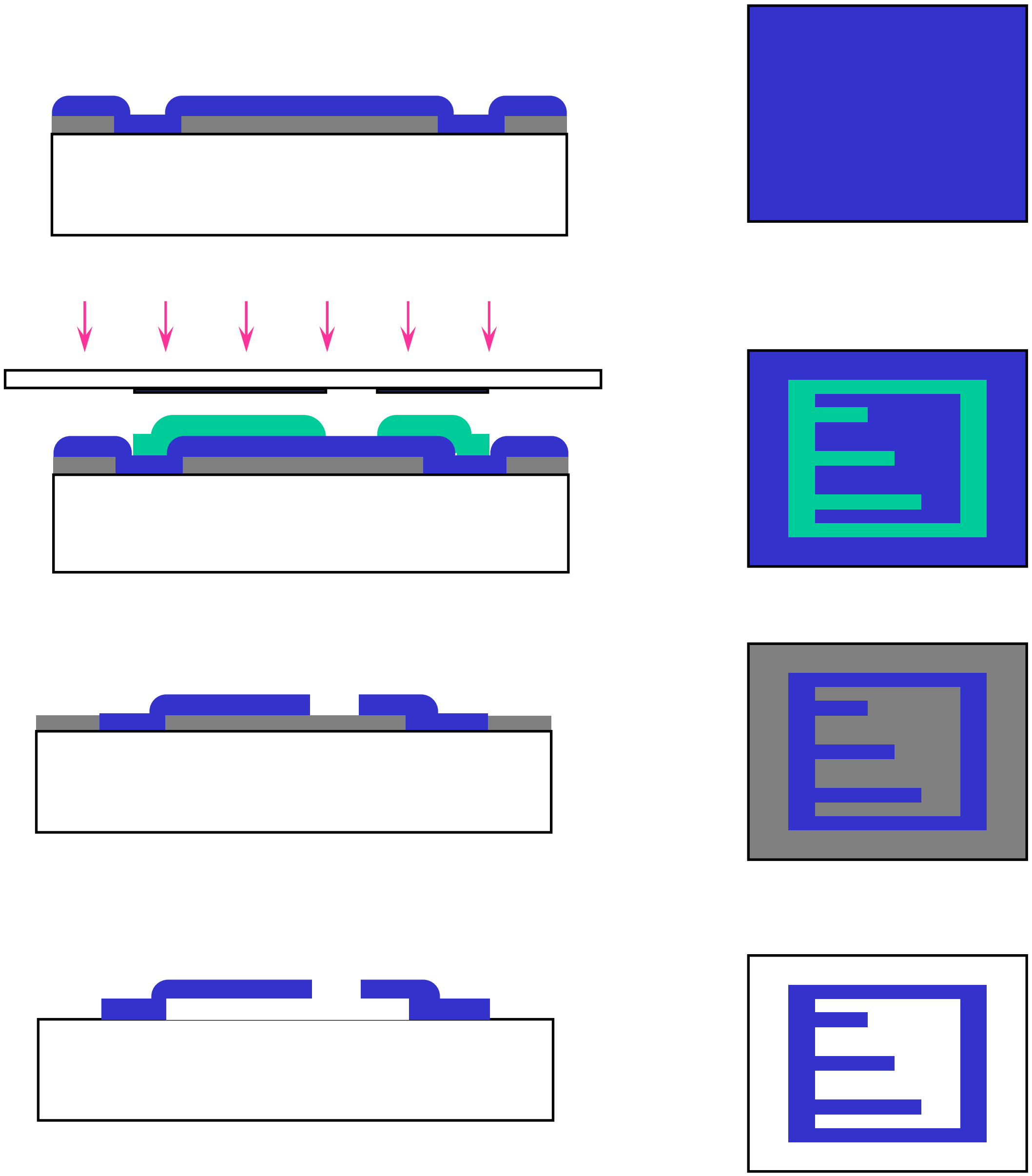
Deposit or grow a sacrificial layer



Spin coat PR and then patterned with 1st mask



Pattern the sacrificial layer



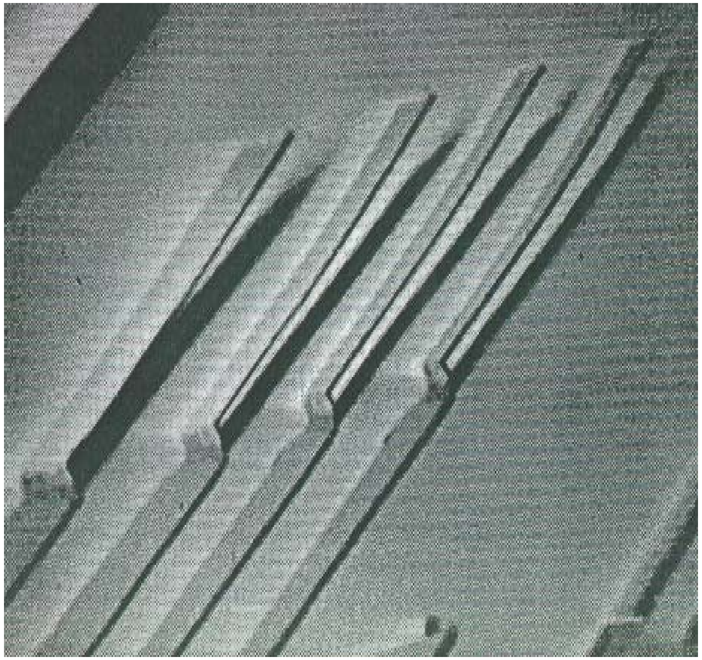
Deposit sturctural layer

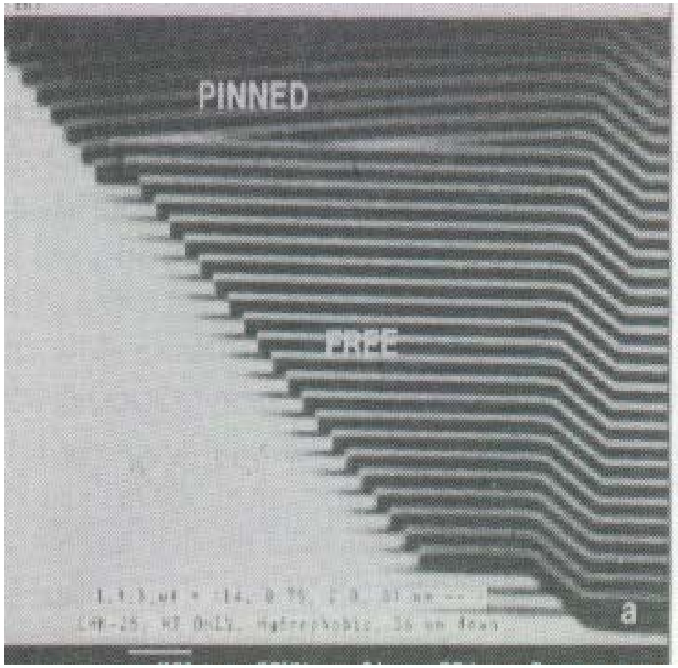
Spin coat PR and pattern PR by 2nd mask

Pattern the sturctural layer

Etch the sacrificial layer

- **Surface micromachined beams**



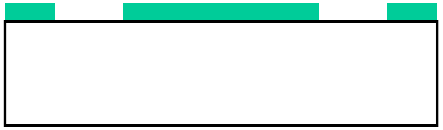


R.T. Howe and R.S. Muller, *J. of Electrochemical Society*, 1983.

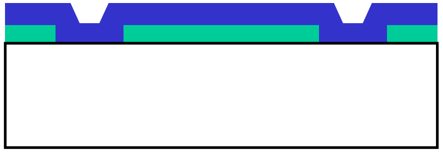
C.H. Mastrangelo and C.H. Hsu, *J. of MEMS*, 1993.

Deposit or grow a sacrificial layer

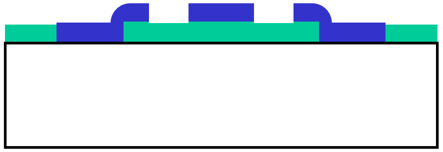
Pattern the sacrificial layer by 1st mask.



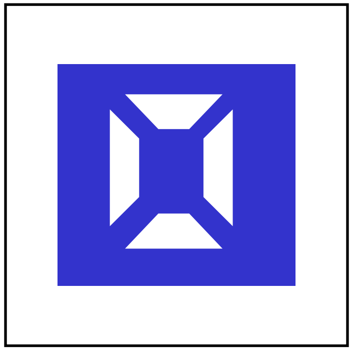
Deposit the structural layer



Pattern the structural layer

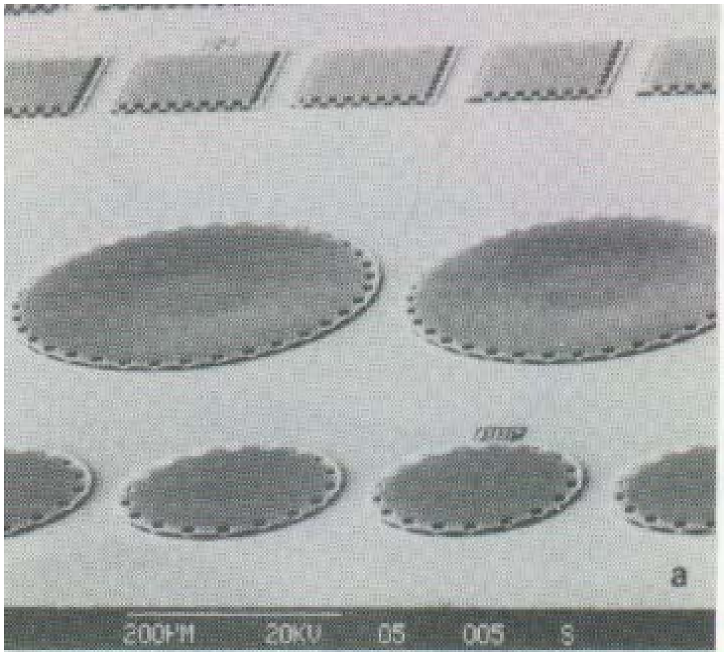


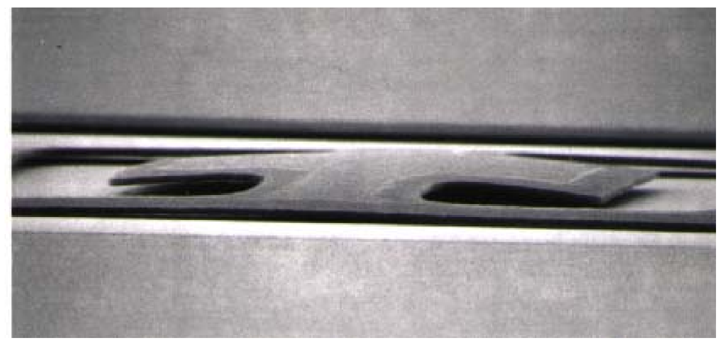
Etch the sacrificial layer



MDL
NTHU

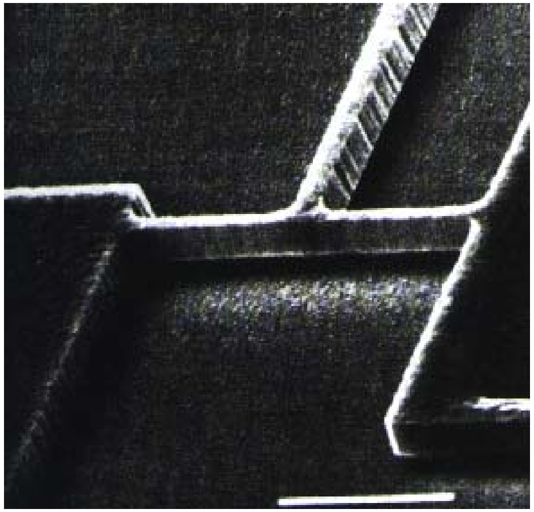
- **Surface micromachined membrane (suspension)**

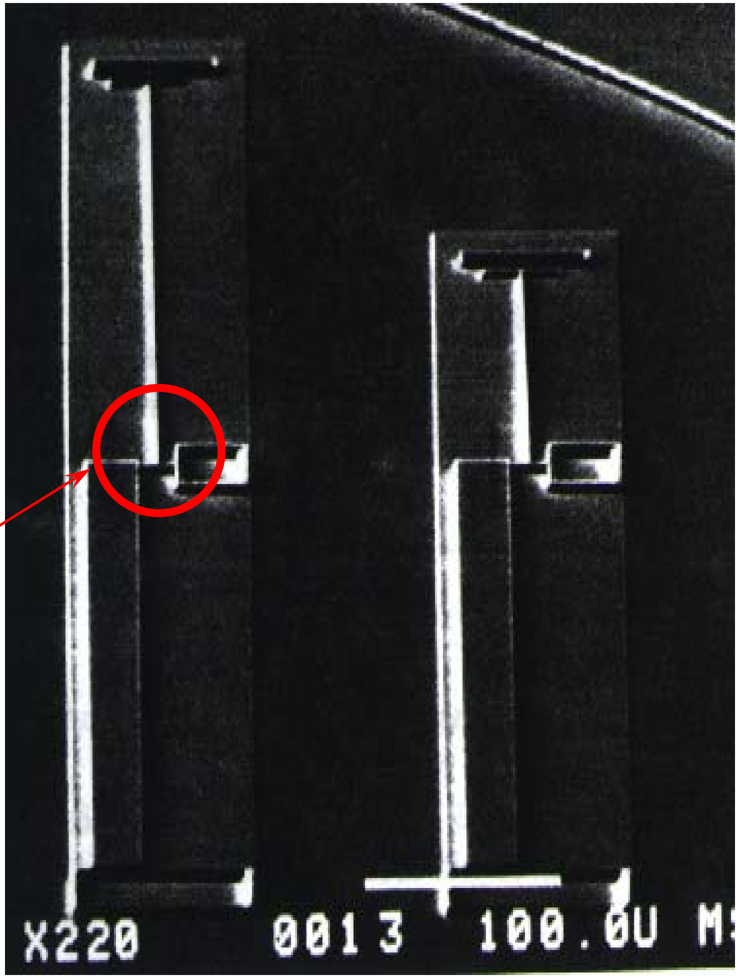




C.H. Mastrangelo and C.H. Hsu, J. of MEMS, 1993.

W. Fang and J.A. Wickert, Data Storage Systems Center Annual Report, 1993.

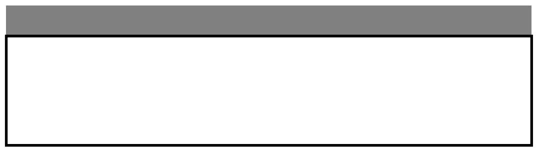




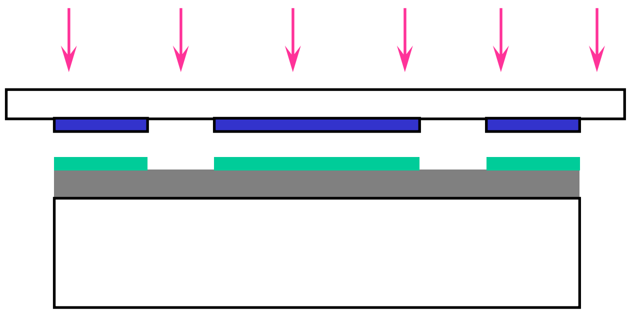
L. Lin, R. Howe, and A.P. Pisano, Proceedings of IEEE Workshop on MEMS, 1993.

MDL
NTHU

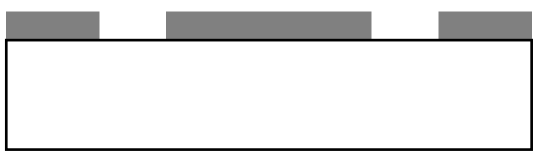
- **Fabrication processes for three masks structures**



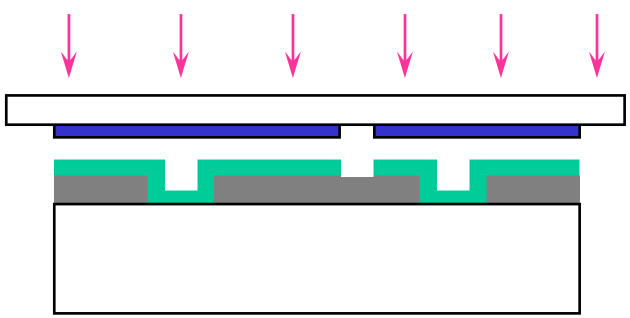
Deposit or grow a sacrificial layer



Spin coat PR and then patterned with 1st mask

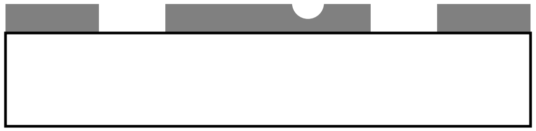


Pattern the sacrificial layer



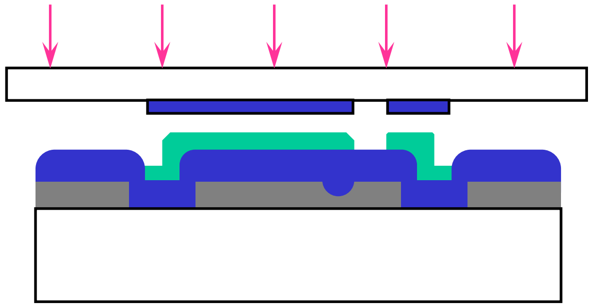
Spin coat PR and then patterned with 2nd mask

MDL
NTHU

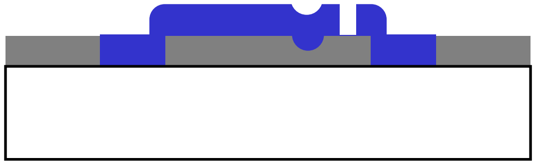


Pattern the sacrificial layer again to define a bushing

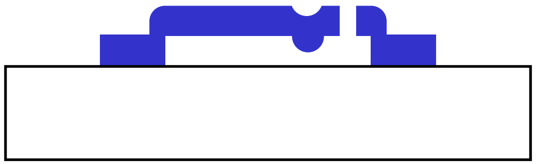
Deposit the structural layer



Spin coat PR nad pattern PR by 3rd mask



Pattern the sturctural layer



Etch the sacrificial layer

MDL
NTHU

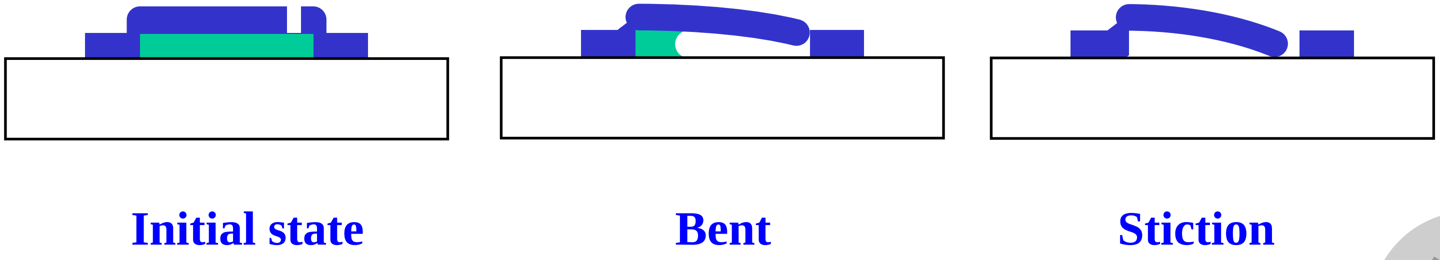
Stiction during drying process

- **Drying process is more critical for surface micromachining since the gap between each layer is only several microns**

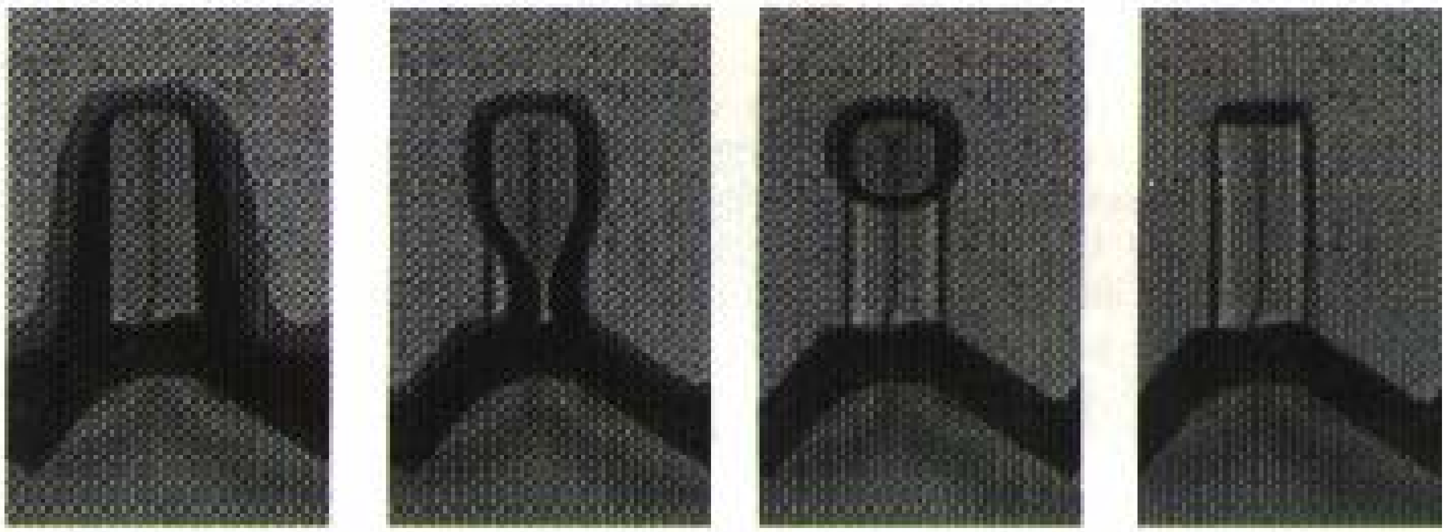
- **The stiction is induced by two mechanisms:**

  + Bent: the structure bent by the surface tension of the solution during drying

  + Stiction: the structure bonded to the substrate due to the chemical reaction between the contact area



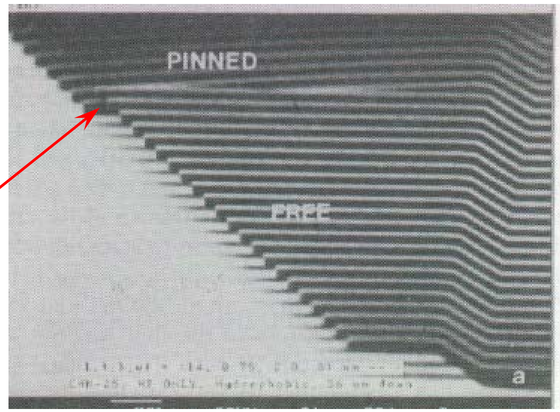
MDL NTHU

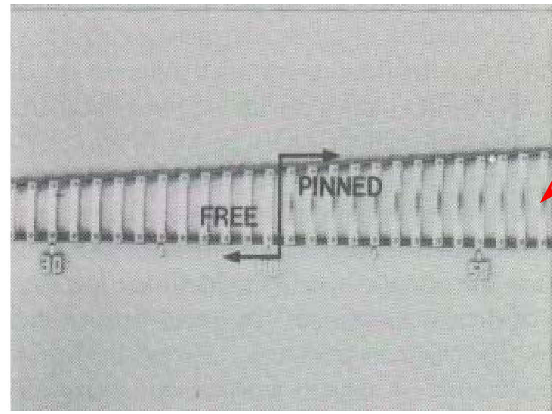


MDL
NTHU

- **Sticking of surface micromachined beams and membrane**

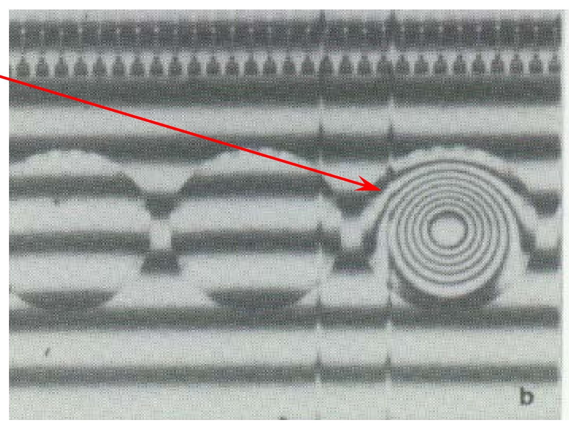
bonded to the substrate

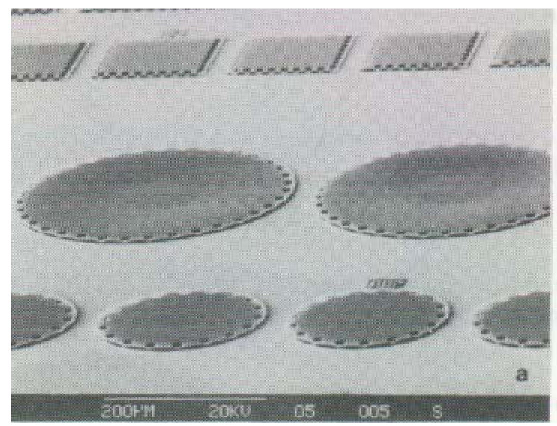




bonded to the substrate

bonded to the substrate





C.H. Mastrangelo and C.H. Hsu, *J. of MEMS*, 1993

MDL
NTHU

- **Many techniques are proposed to reduce the stiction problem**

    + Reduce the contact area

    + Reduce the drying time (use IPA instead of water)

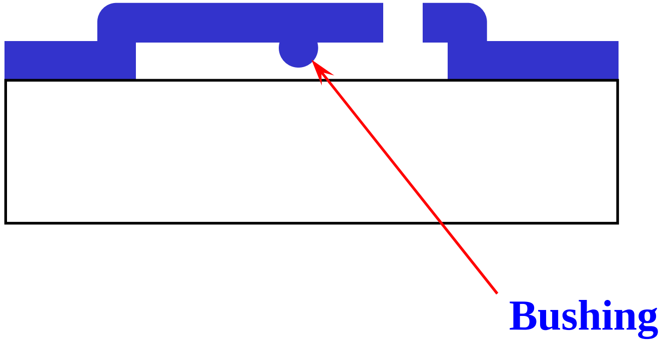
    + Dry or supercritical release

    + Add supporting structures

    + Harmonic excitation

- **Reduce the contact area**

+ Add bushing (or called dimple) to the substrate



+ Surface roughening

- **Dry or supercritical release**

+ Freeze drying method

1. Rinse by DI water after etching

2. Rinse by IPA (isopropyl alcohol)

3. Freeze in t-Butyl alcohol

4. Vaporized in a vacuum chamber

N. Takeshima et.al., Tech. Digest, *Int. Conference on Solid-state sensors and actuators,* 1991

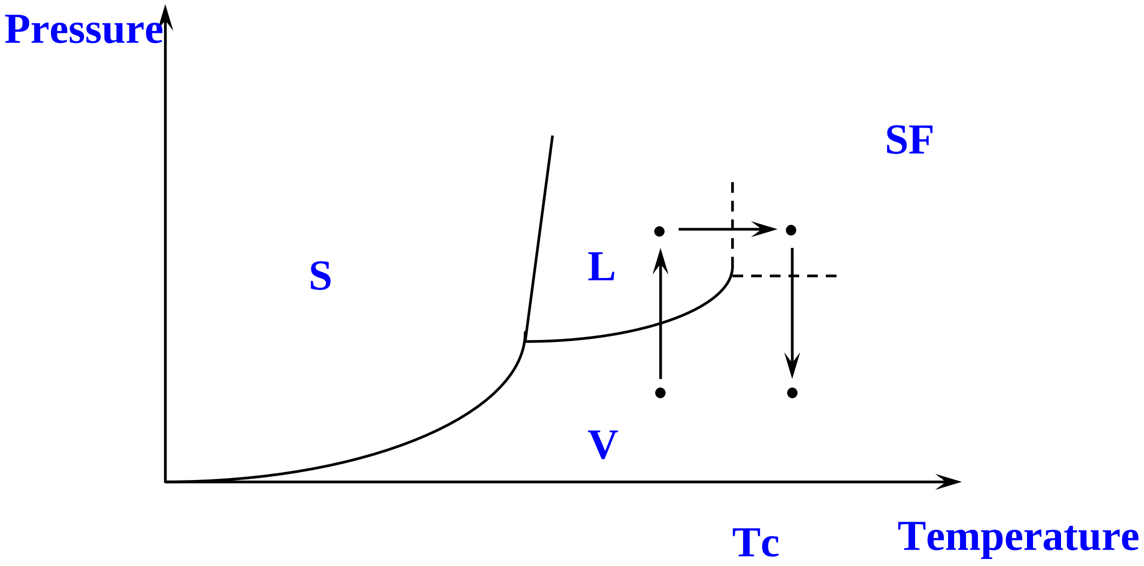
+ Supercritical CO_2 drying method

1. The substrate is initially placed in methanol inside a pressure vessel

2. Replace methanol by liquid CO_2 at 25°C and 1200 psi

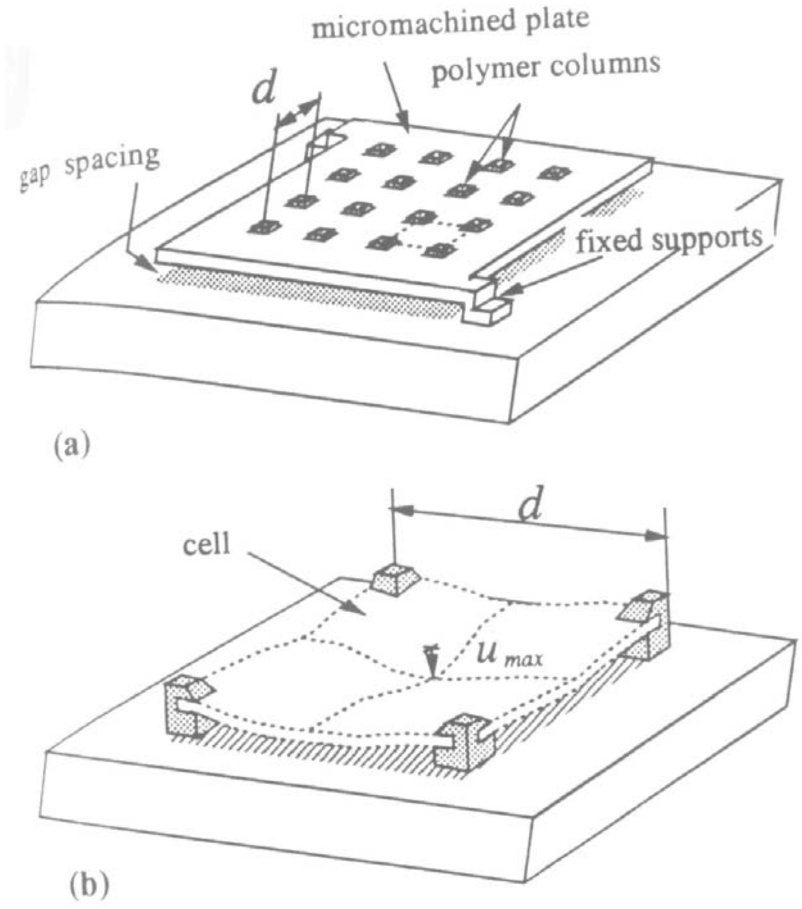
3. Heat liquid CO_2 to supercritical fluid

4. Vent vessel at a constant temperature (above Tc)



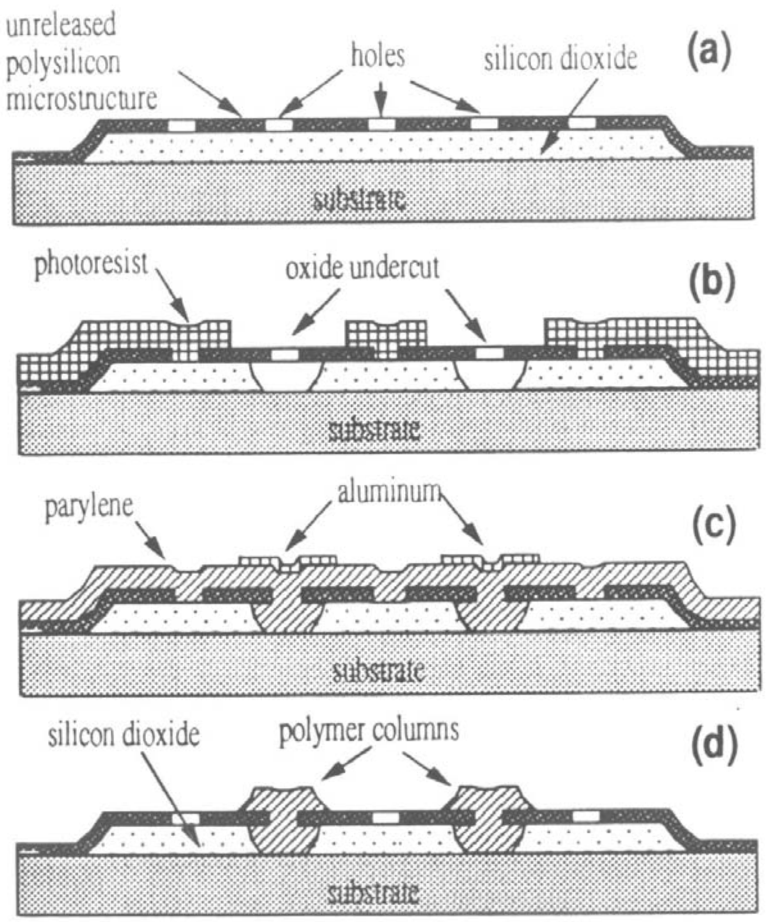
MDL
NTHU

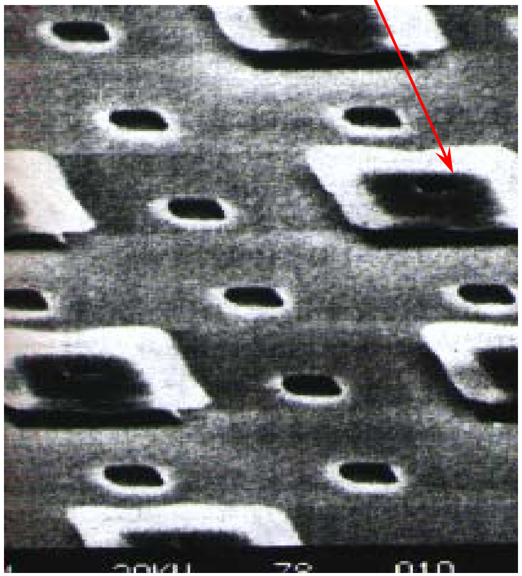
- **Polymer columns - add polymer columns to the surface micromachined structures as extra supports during etching and drying processes**



C.H. Mastrangelo and G.S. Saloka, ***Proceedings IEEE Workshop on MEMS*****, 1993.**

MDL
NTHU



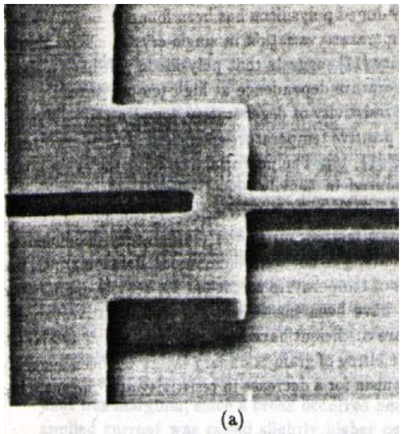


C.H. Mastrangelo and G.S. Saloka, *Proceedings IEEE Workshop on MEMS*, 1993.

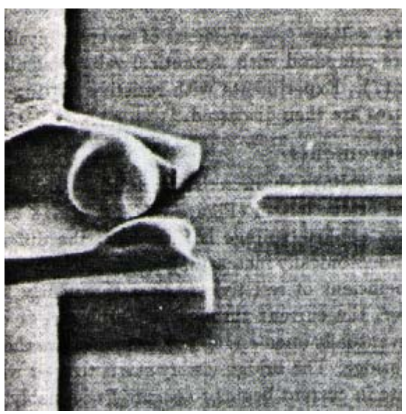
MDL
NTHU

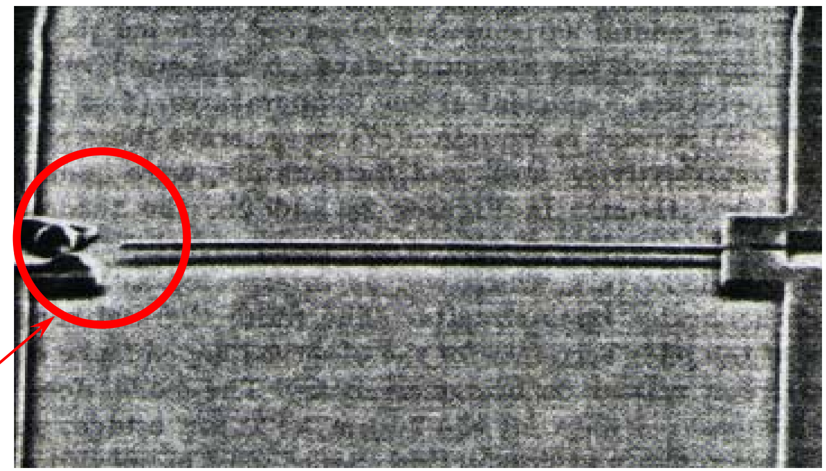
- **Fuses - a very long cantilever beam supported by a structure temporary, and then cut after drying**

Before drying



After drying

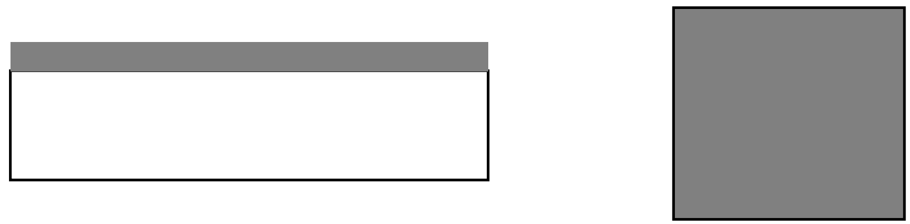




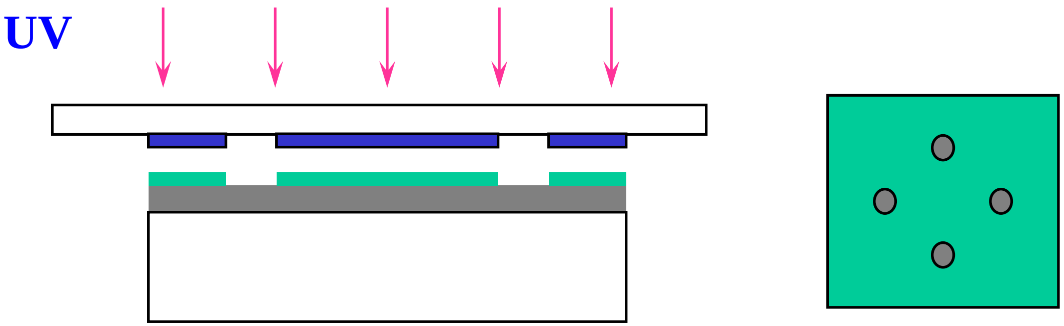
G.K. Fedder and R.T. Howe, *Proceedings IEEE Workshop on MEMS*, 1991.

Complicate surface structure

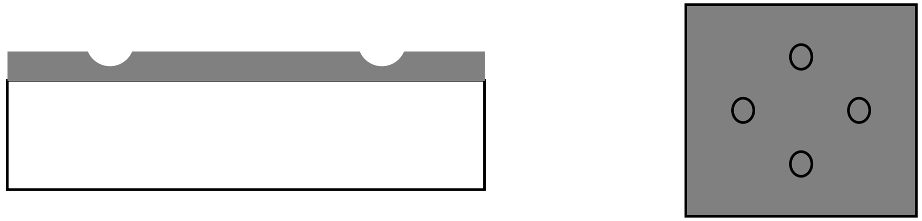
- Fabrication processes for a surface micromachined rotor with bushing



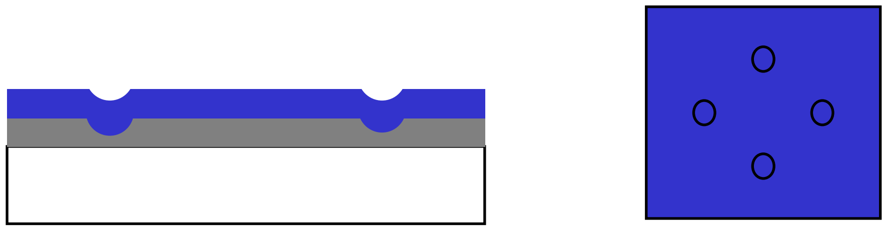
Deposit or grow a sacrificial layer



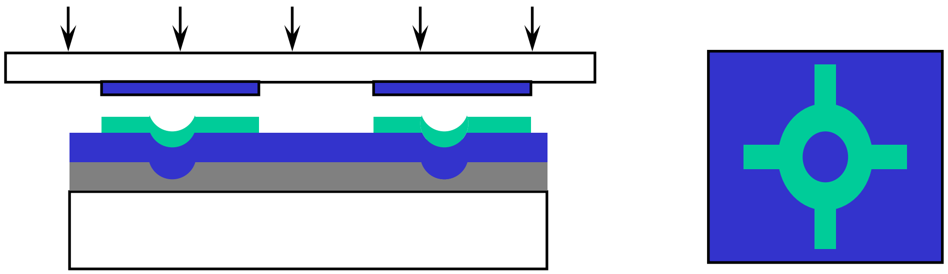
Spin coat PR and then patterned with 1st mask



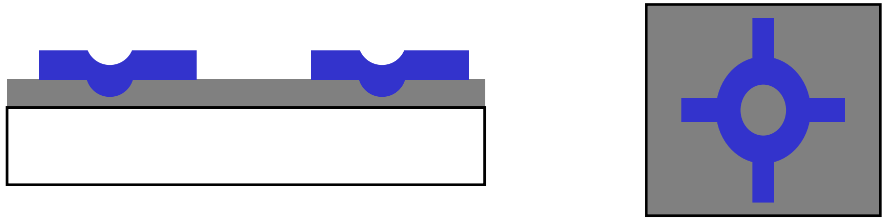
Pattern the 1st sacrificial layer



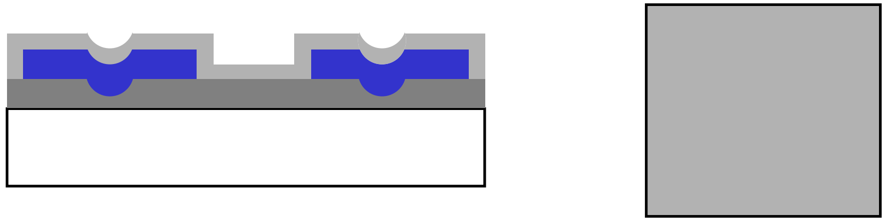
Deposit the 1st structural layer



Spin coat PR and patterned with 2nd mask

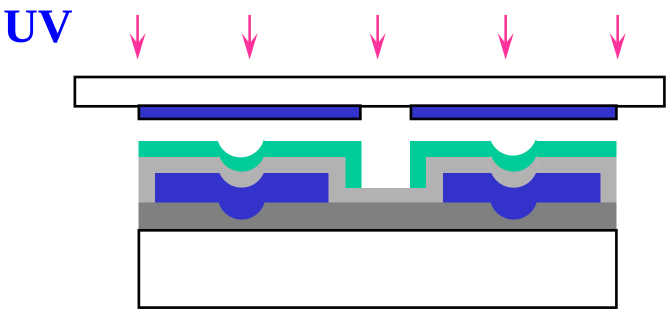


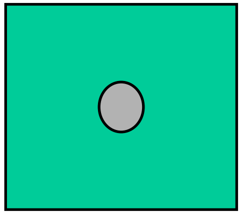
Pattern the 1st sturctural layer



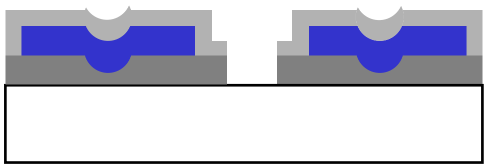
Deposit the 2nd sacrificial layer

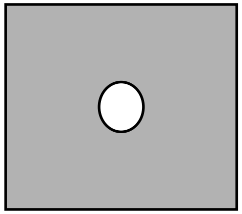
MDL
NTHU



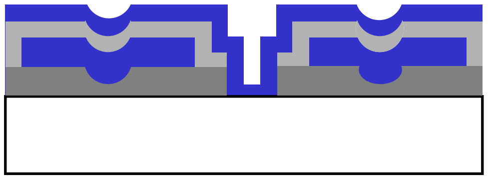


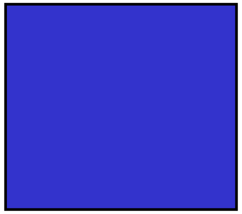
Spin coat PR and then patterned with 3rd mask





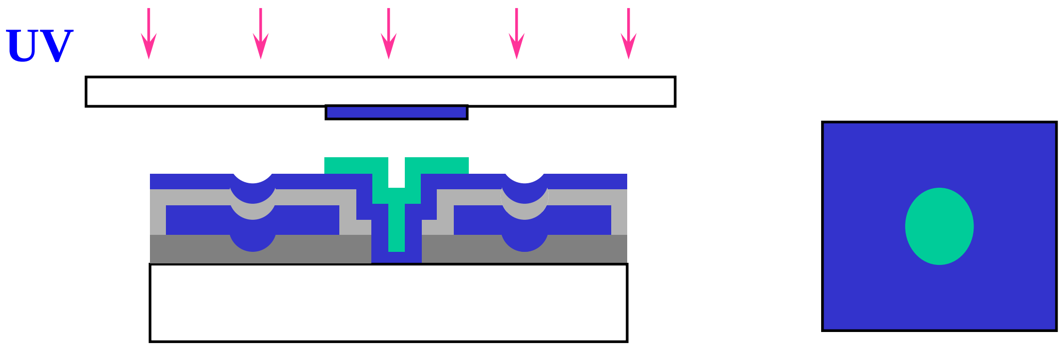
Pattern the 1st and 2nd sacrificial layer



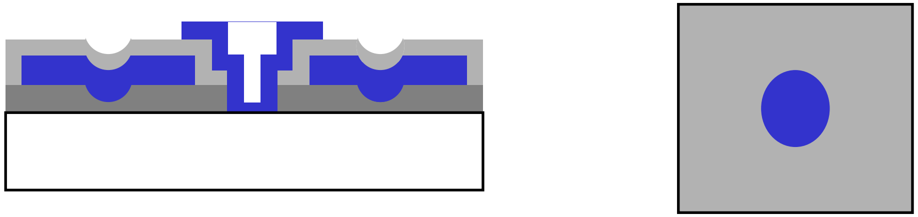


Deposit the 2nd structural layer

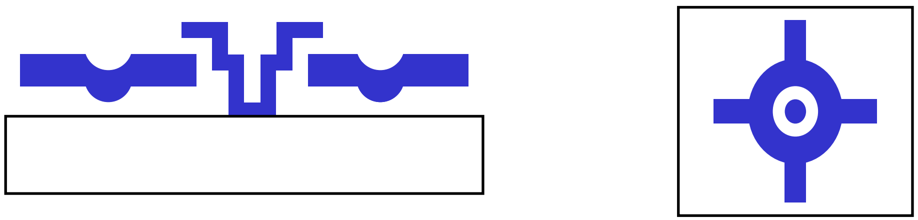
MDL
NTHU



Spin coat PR and then patterned with 4th mask

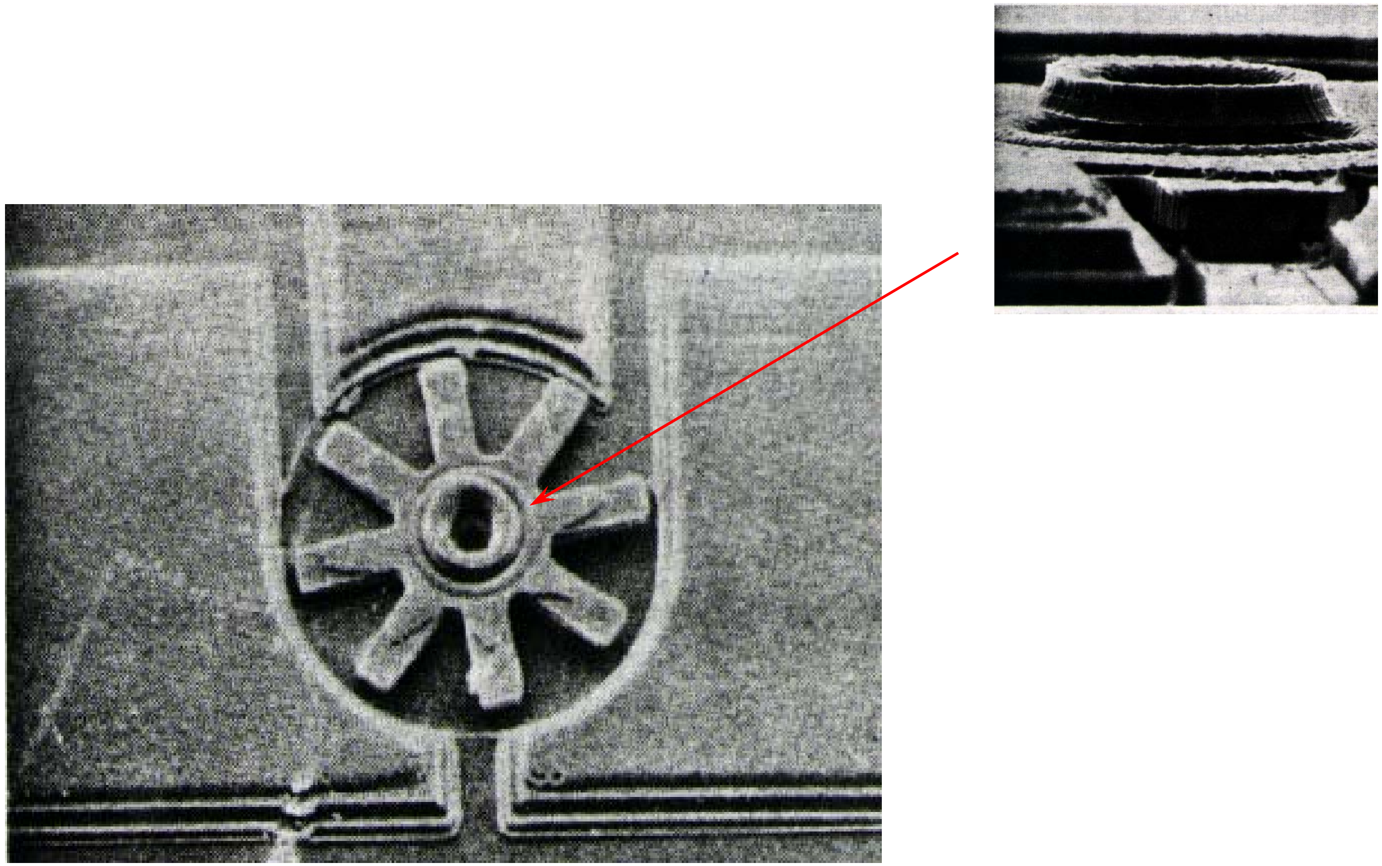


Pattern the 2nd structural layer



Etch the sacrificial layer

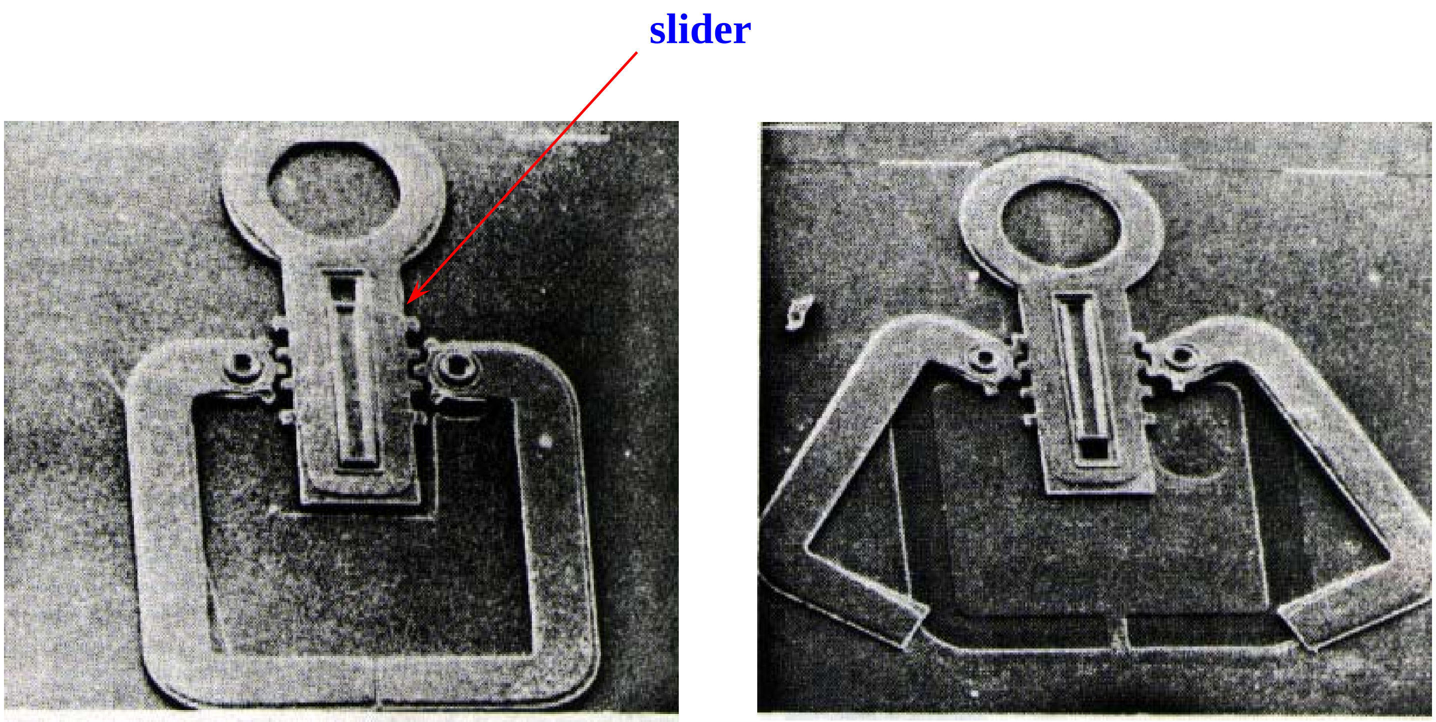
- **Surface micromachined rotor**



M. Mehregany, K.J. Gabriel, and W.S.N. Trimmer, IEEE Transactions on ED, 1988.

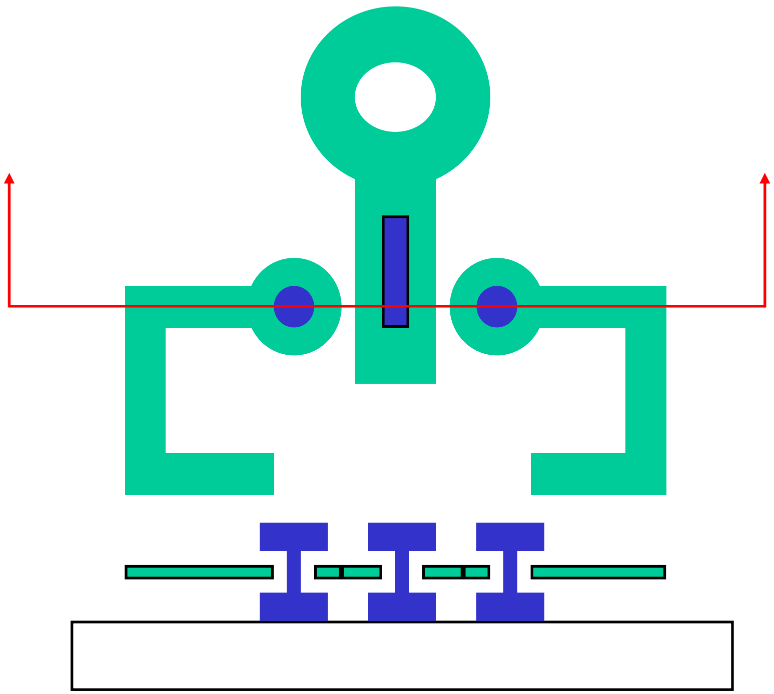
MDL
NTHU

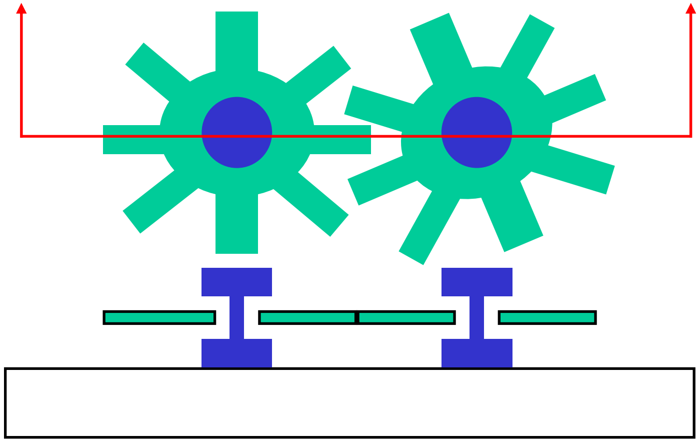
- **Surface micromachined slider driven tweezers**



M. Mehregany, K.J. Gabriel, and W.S.N. Trimmer, *IEEE Transactions on ED*, 1988

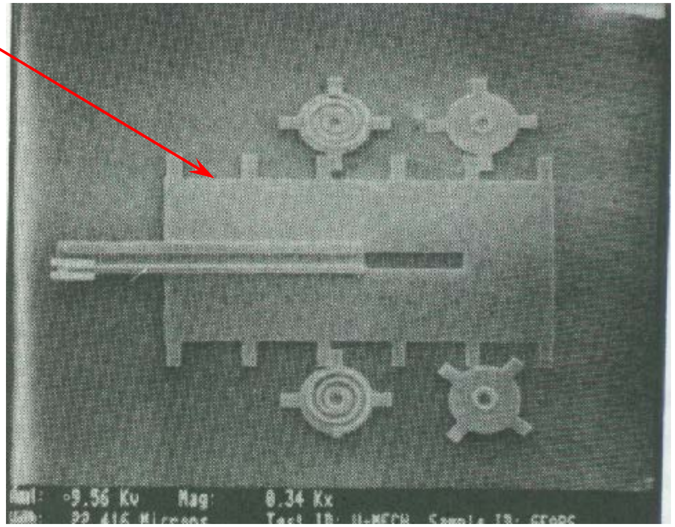
MDL
NTHU



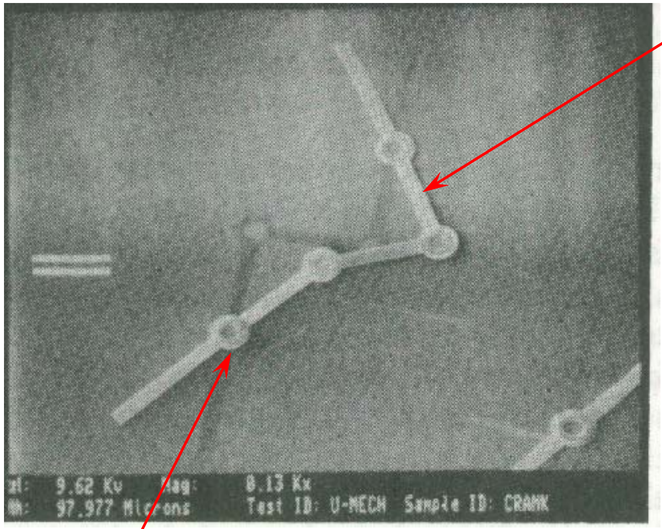


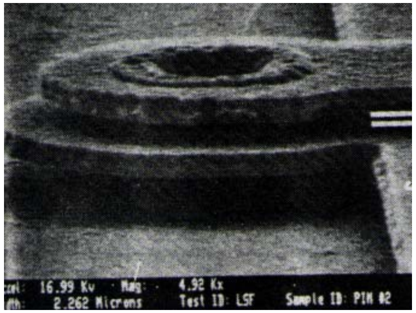
- **Surface micromachined spring, slider, hinge and crank**

slider



crank



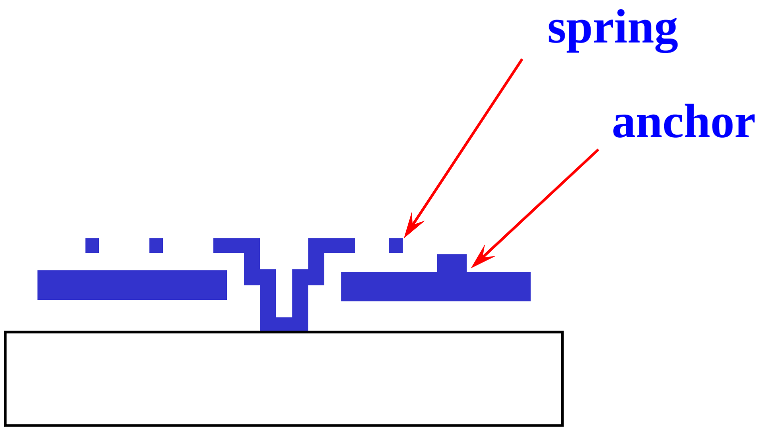


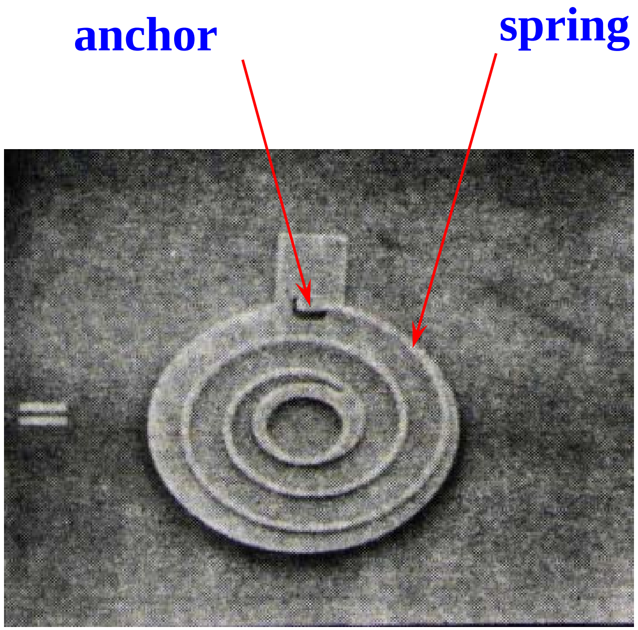
hinge

L.-S. Fan, Y.-C. Tai, and R.S. Muller, IEEE Transaction on ED, 1988.

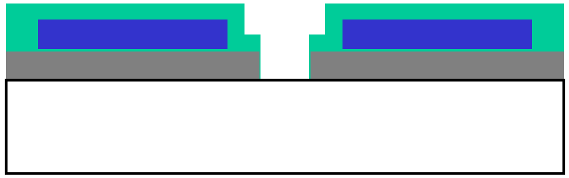
MDL
NTHU

Microspring

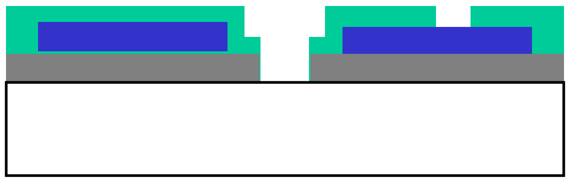




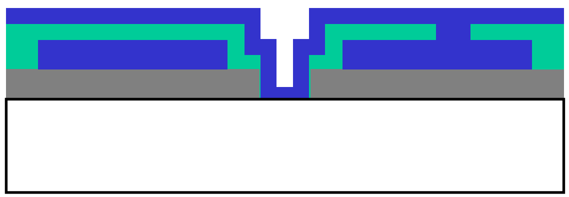
L.-S. Fan, Y.-C. Tai, and R.S. Muller, IEEE Transaction on ED, 1988.



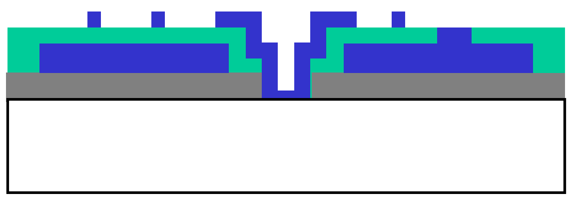
Define the hub



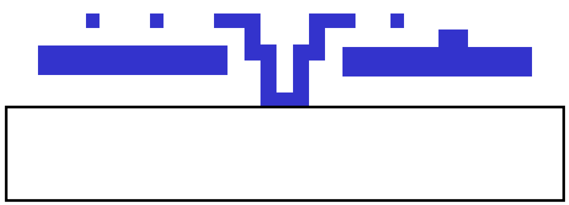
Define the junction of the spring and the rotor



Deposit the 2nd structural layer



Define the spring



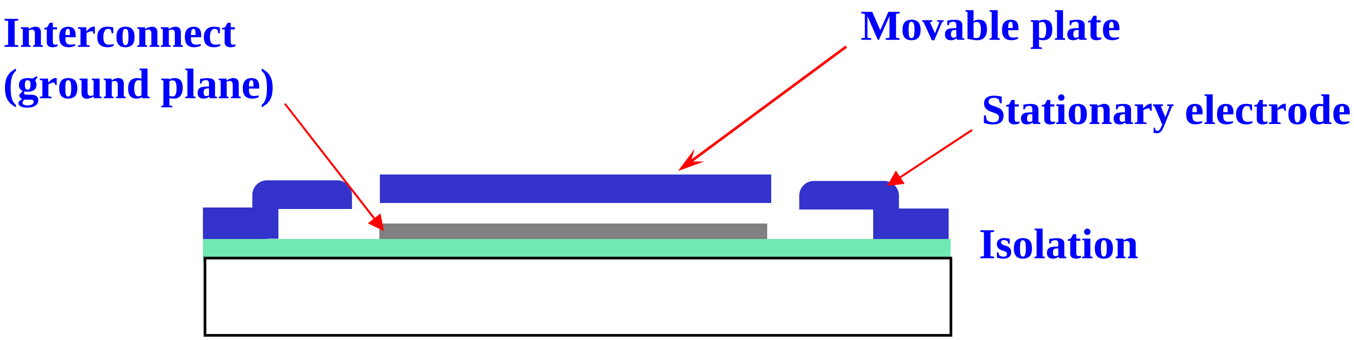
Remove the sacrificial layer

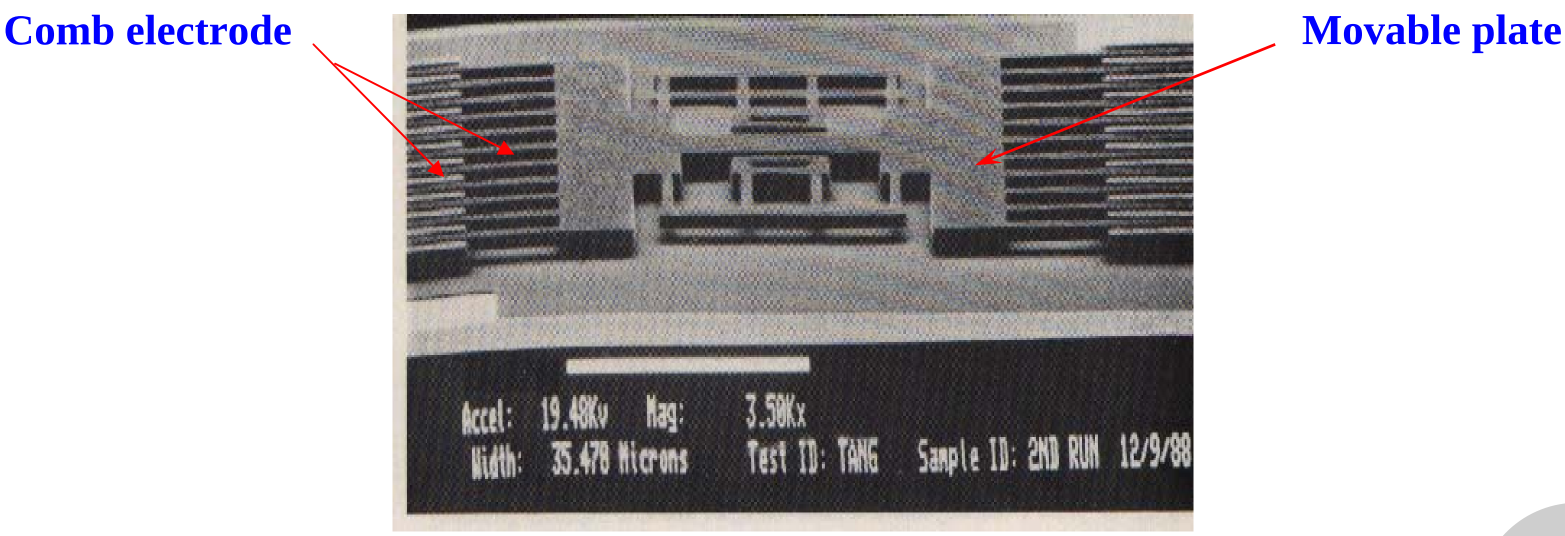
MDL
NTHU

Surface micromachined actuators

MDL
NTHU

Comb-drive actuator

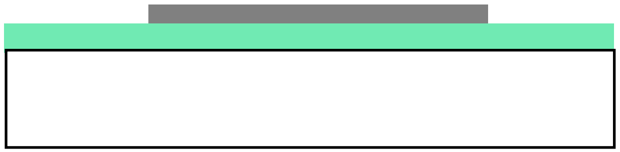




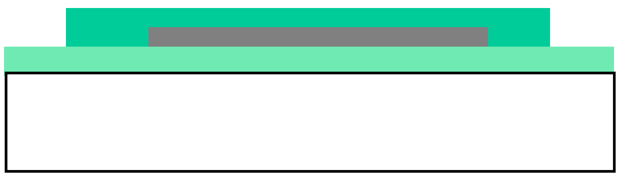
W.C. Tang, T.-C.H. Nguyen, and R.T. Howe, IEEE MEMS Conference, 1989

MDL
NTHU

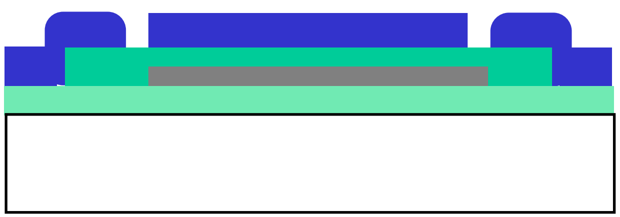
Deposit dielectric films (prevent electrical breakdown)



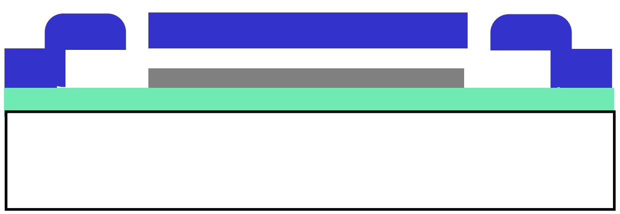
Deposit and pattern 1st poly as interconnect layer



Deposit and pattern 1st PSG as sacrificial layer



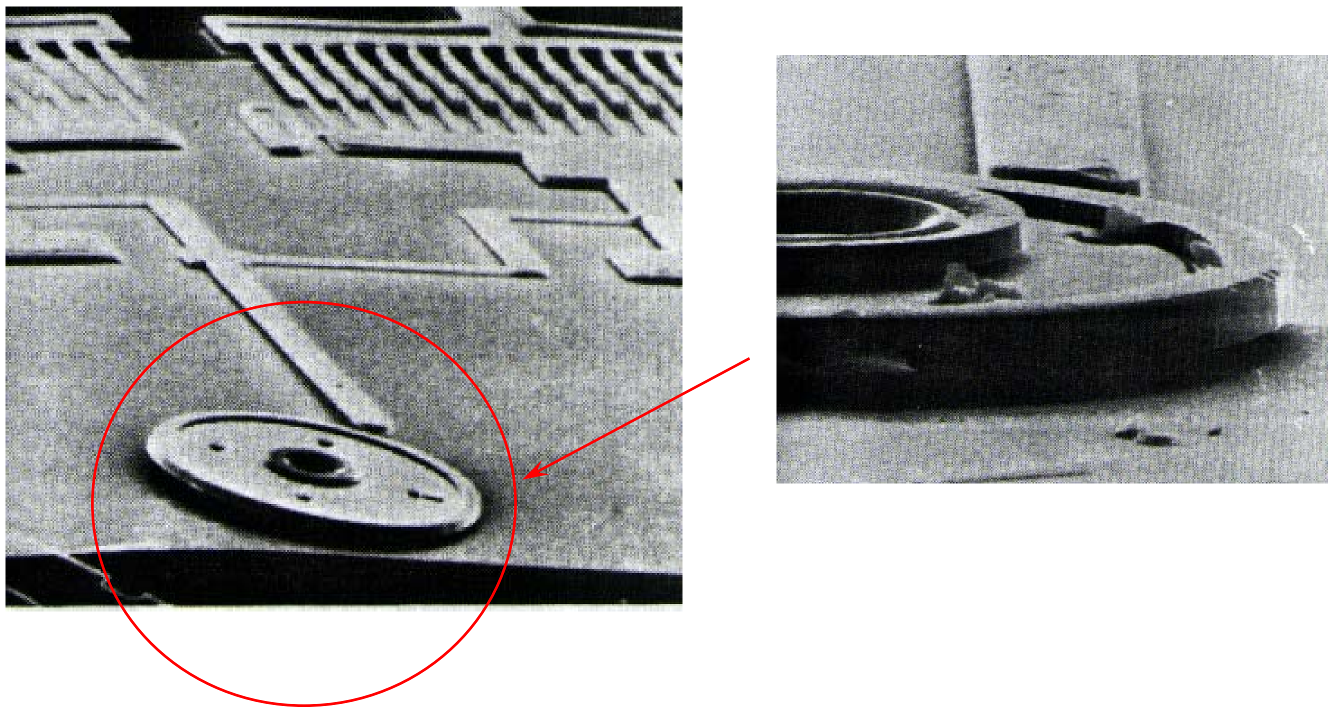
Deposit and pattern 2nd poly as structural layer



Remove the sacrificial layer

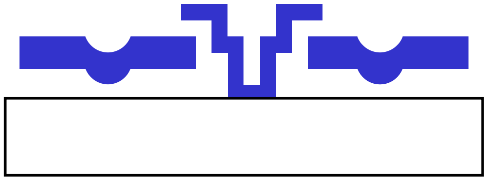
MDL
NTHU

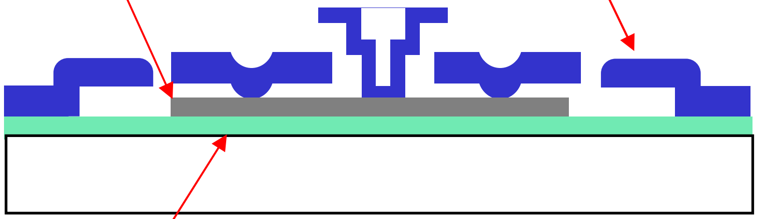
- **Surface micromachined impact vibromotor**

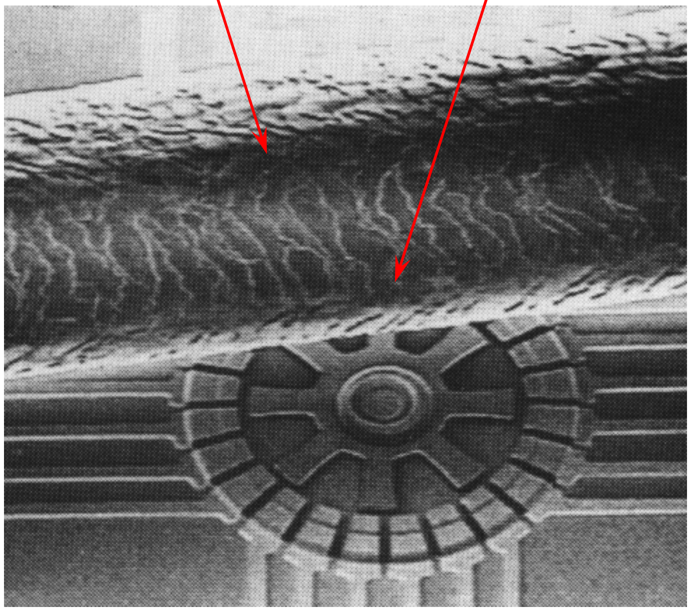


A.P. Lee and A.P. Pisano, J. of MEMS, 1992

Micromotor

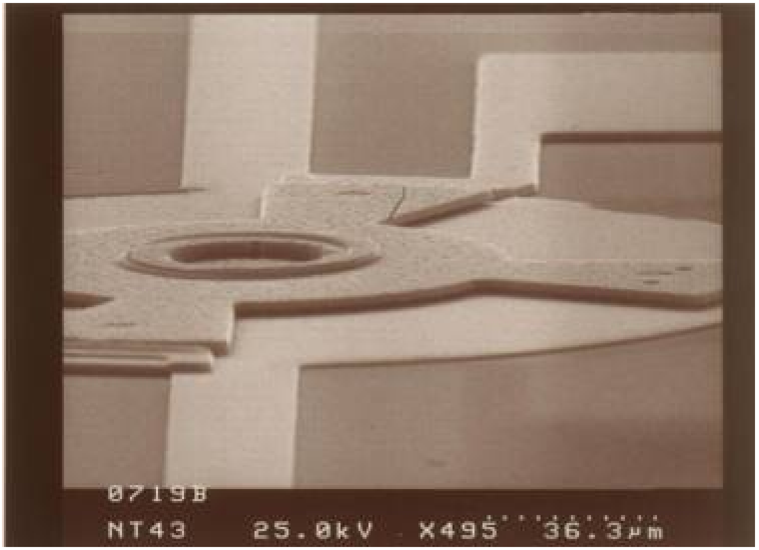


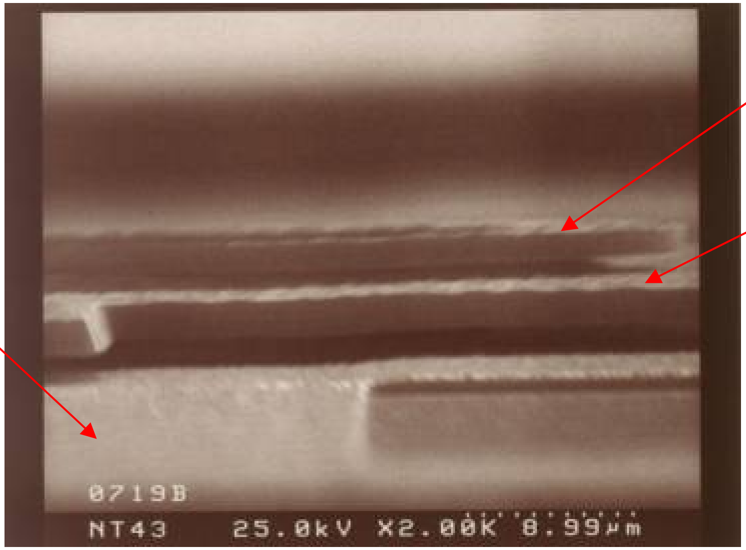




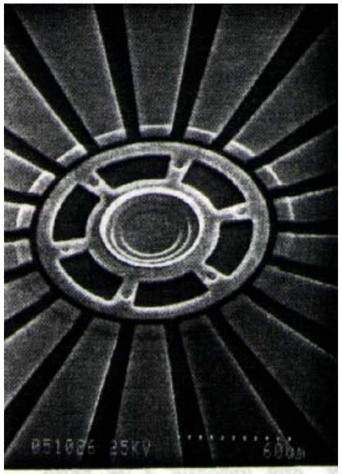
SEM photograph by T. Boot and R.M. White at U.C. Berkeley

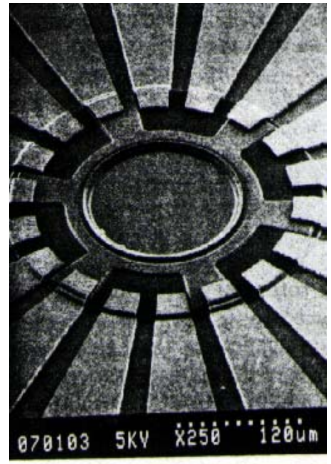
MDL
NTHU

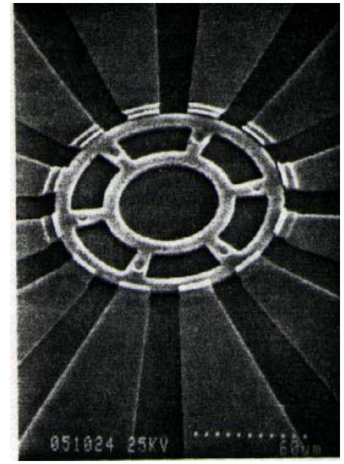

0719B
NT43 25.0kV X495 36.3μm

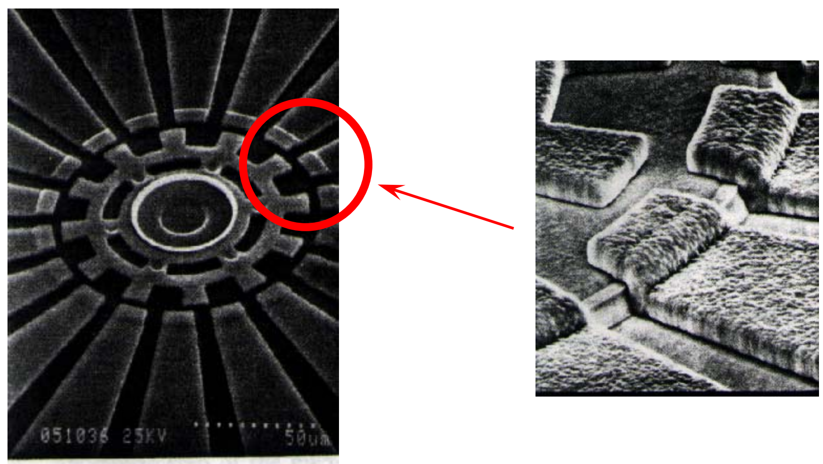

Poly 2
Poly 1
Poly 0
0719B
NT43 25.0kV X2.00K 8.99μm

MDL
NTHU



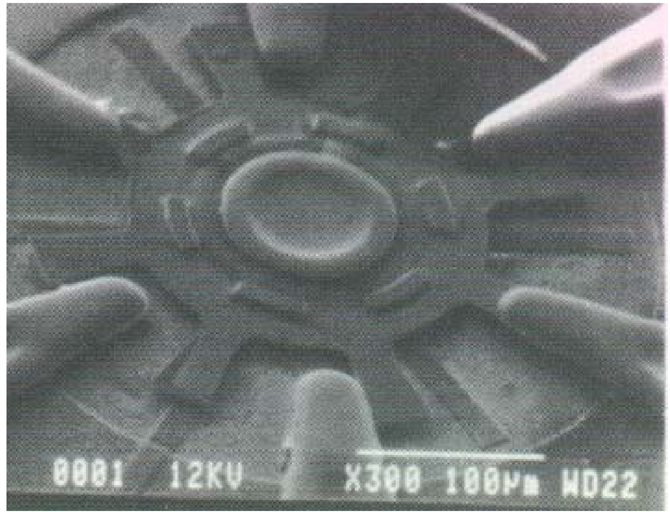




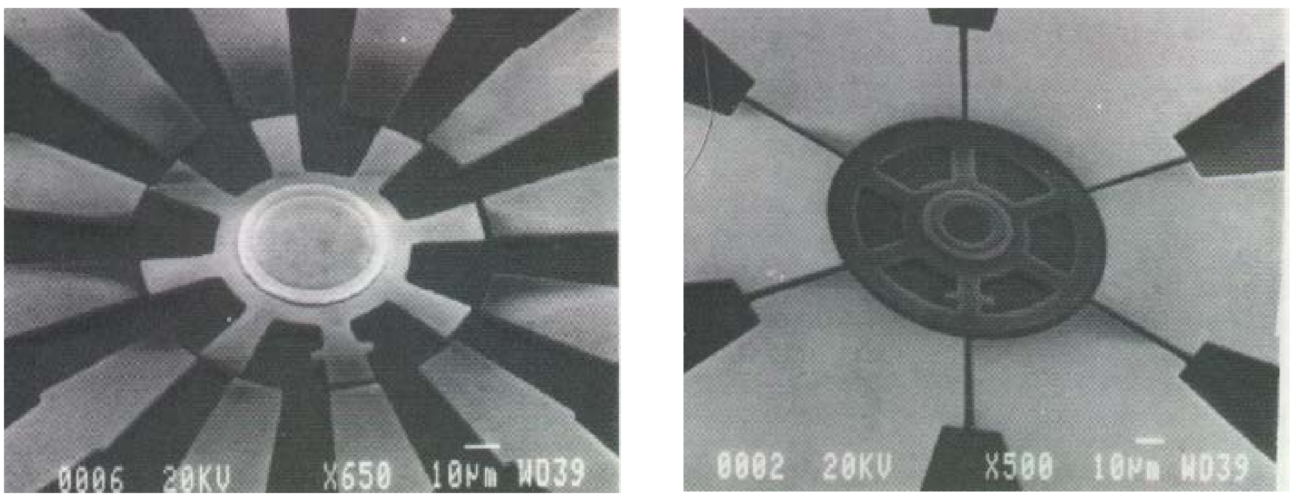


M. Mehregany el al., Sensors and Actuators, 1990

MDL
NTHU

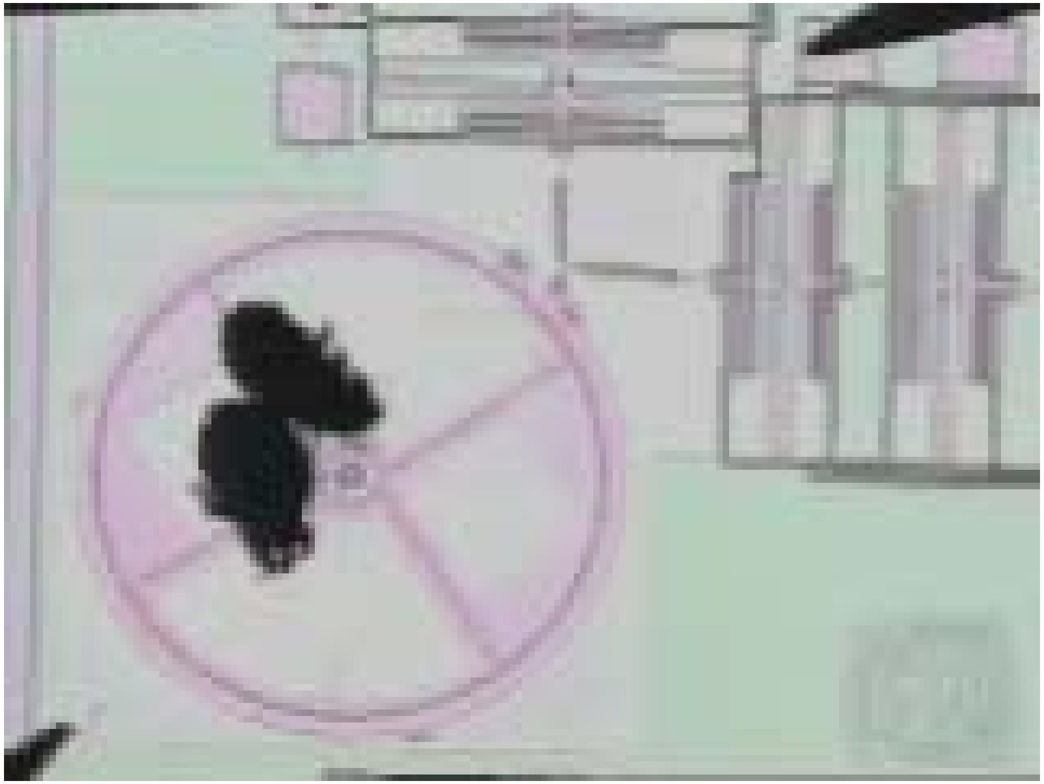


U. Beerschwinger et al., J. of MEMS, 1994



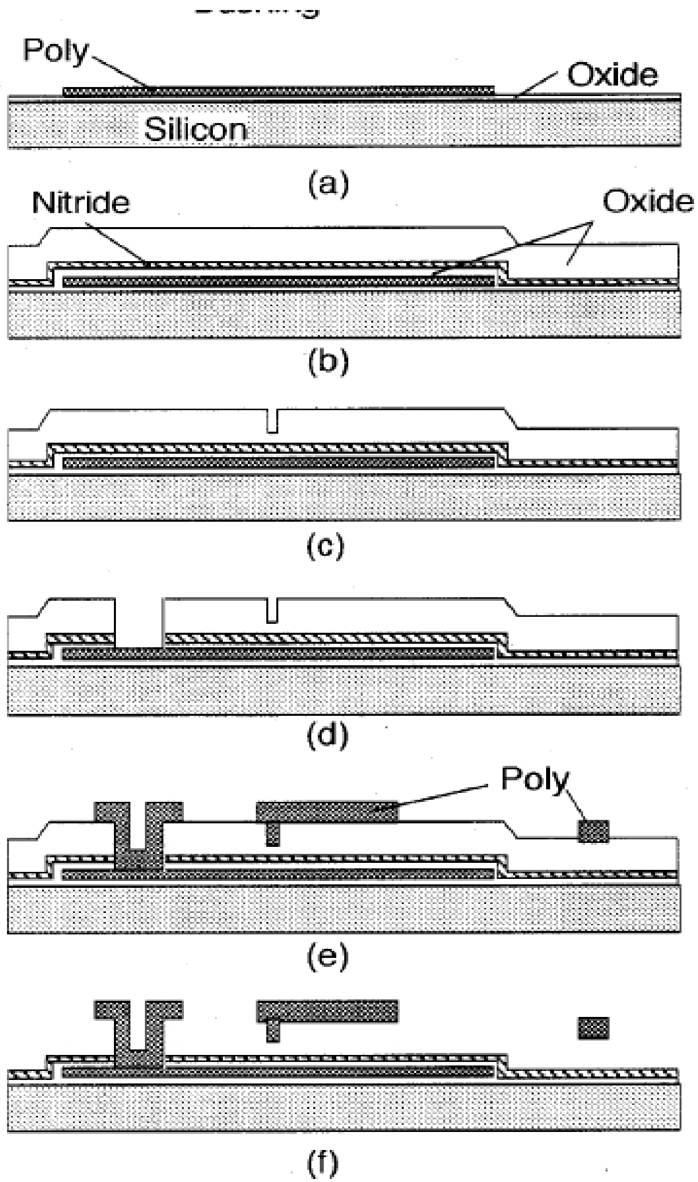
K. Deng, M. Mehregany, and A.S. Dewa, J. of MEMS, 1994

MDL
NTHU



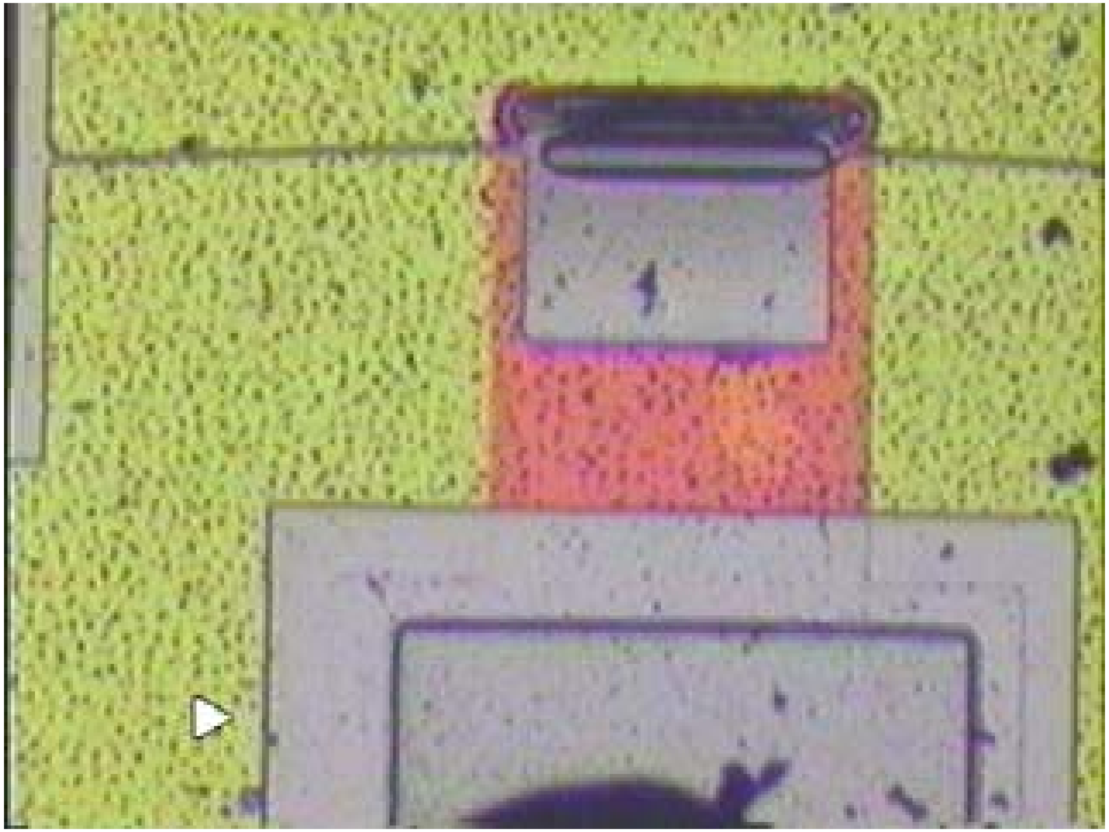
Sandia National Lab, USA

Scratch drive actuator (SDA)

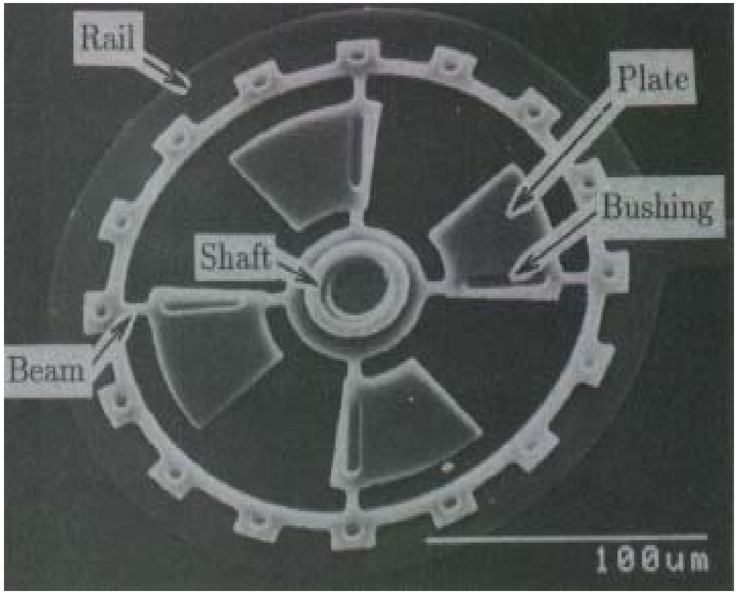


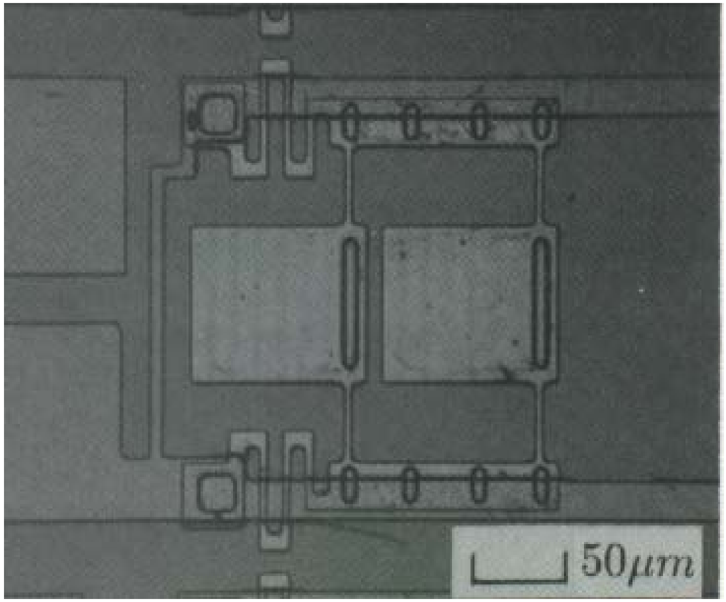
Fukuta, 1997

MDL
NTHU



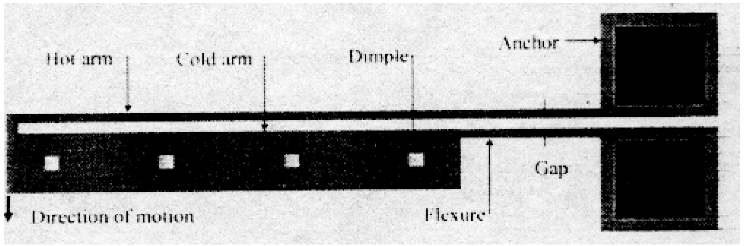
MDL
NTHU



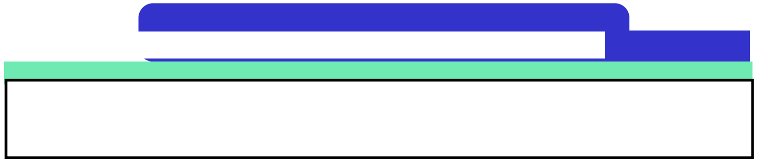


T. Akiyama and K. Shono, J. of MEMS, 1993

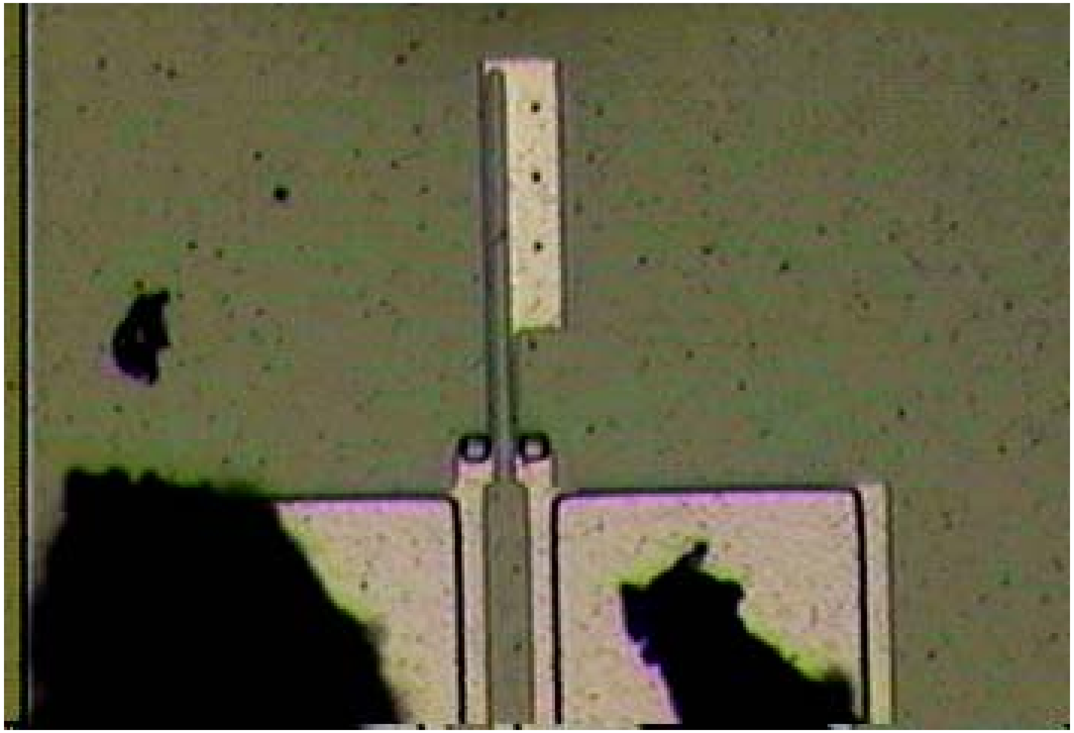
Electrothermal actuator



J.H. Comtois and V.M. Bright, Sensors and Actuators A, 1997

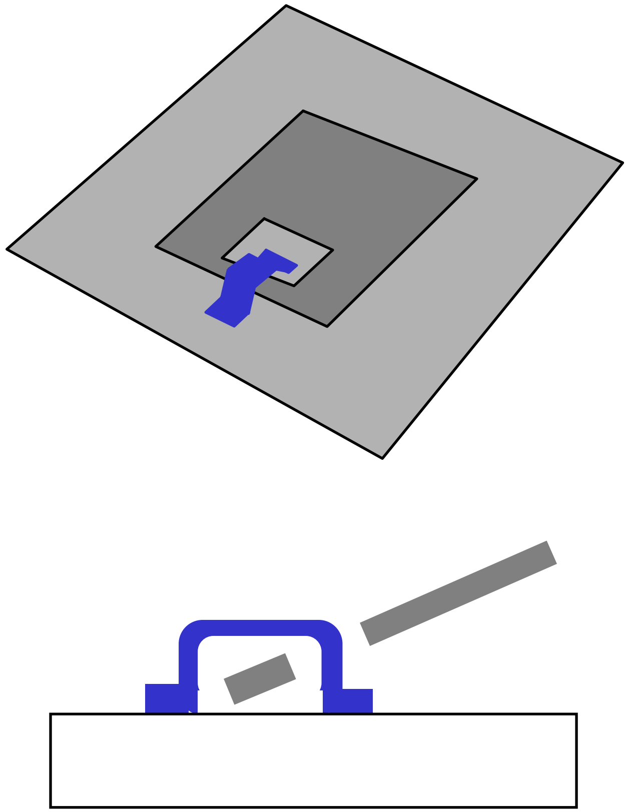


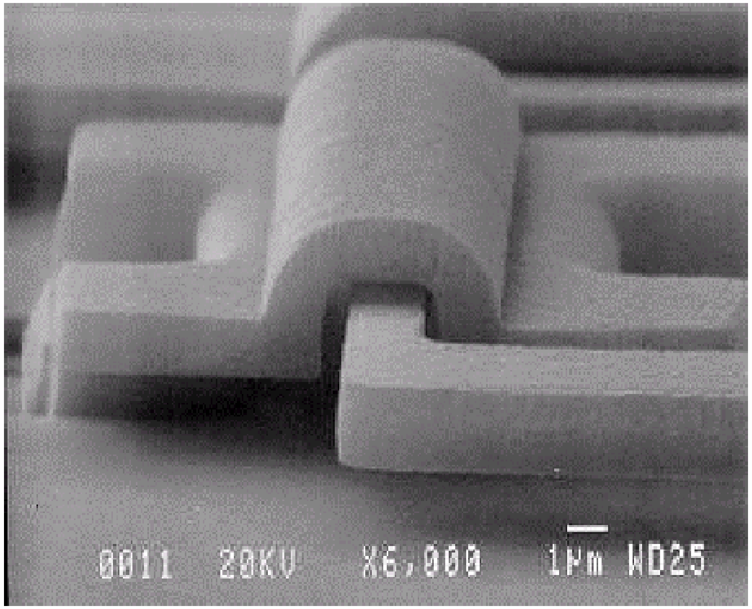
MDL
NTHU



Micro hinge and self assembly

Microhinge (out-of-plane)

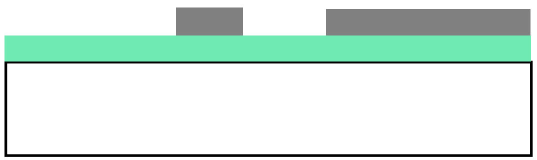




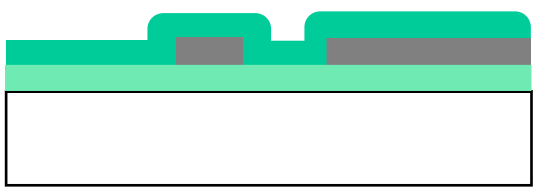
MDL
NTHU

Deposit 1st sacrificial layer

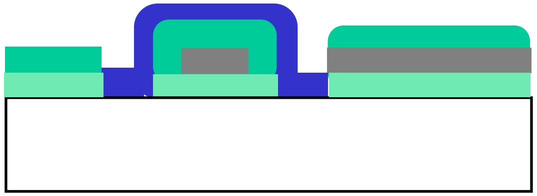
Deposit and Pattern 1st sturctural layer



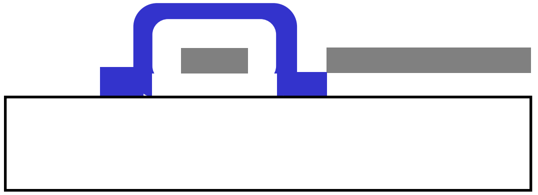
Deposit 2nd sacrificial layer

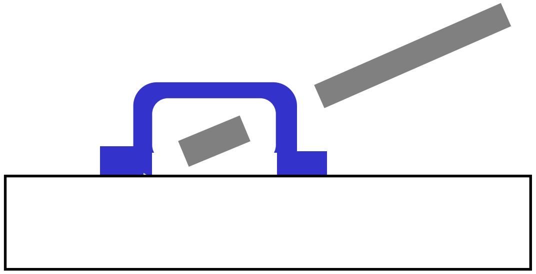


Deposit and Pattern 2nd sturctural layer

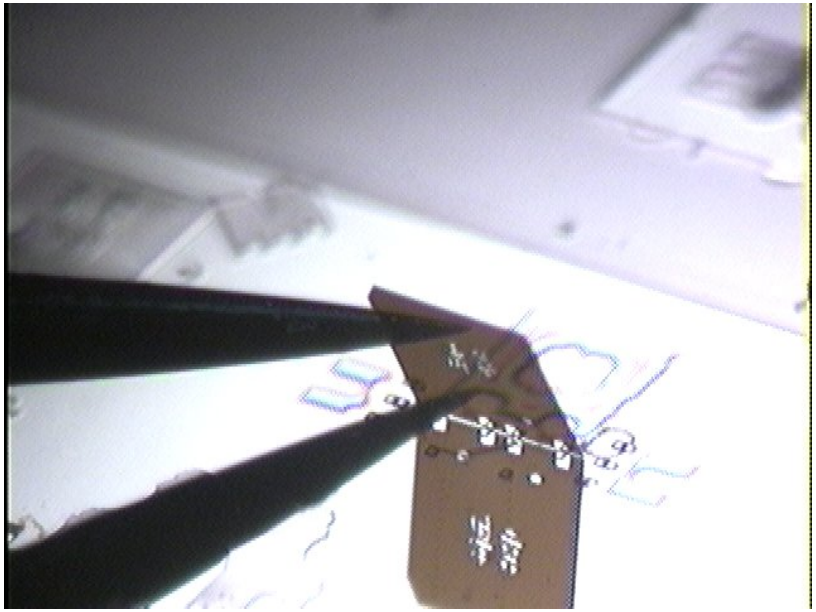


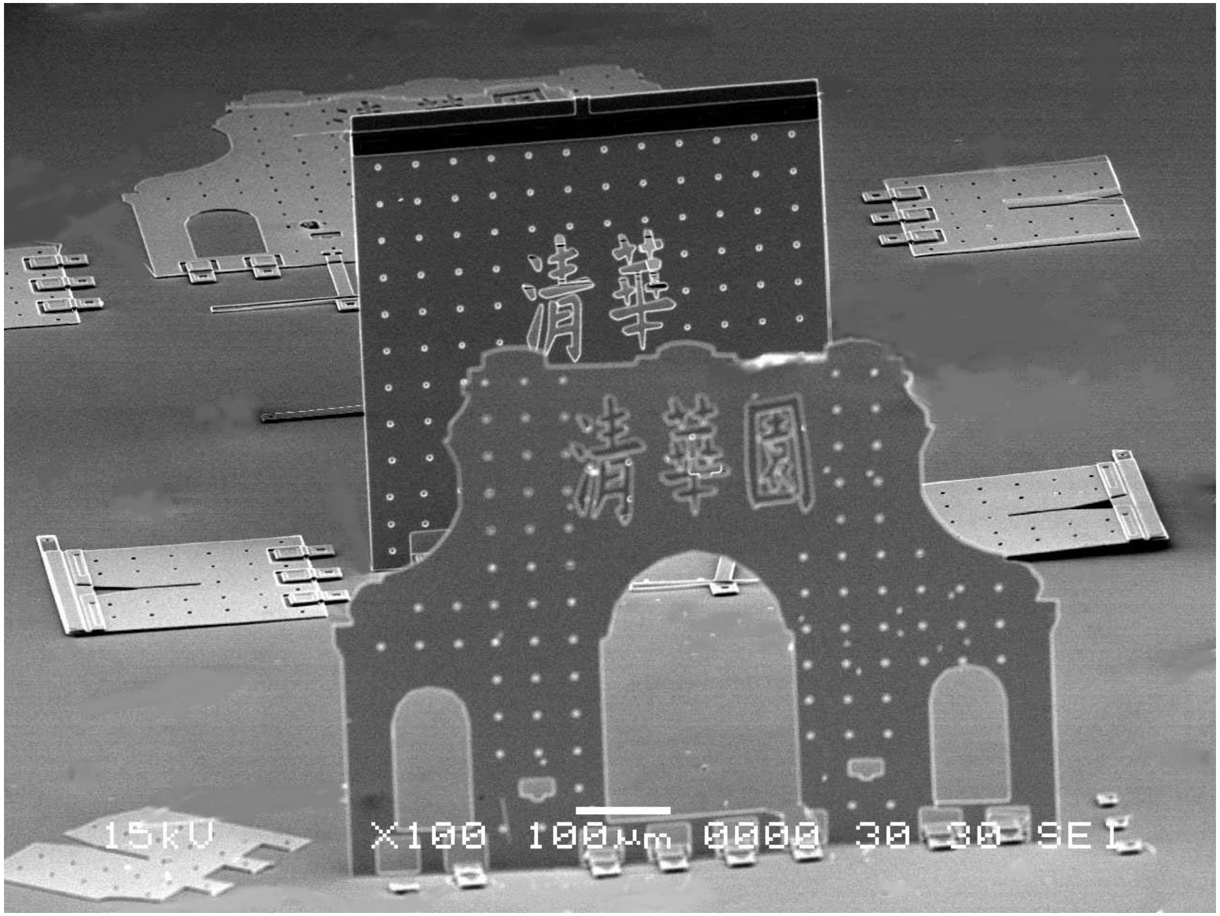
Remove sacrificial layers





MDL
NTHU

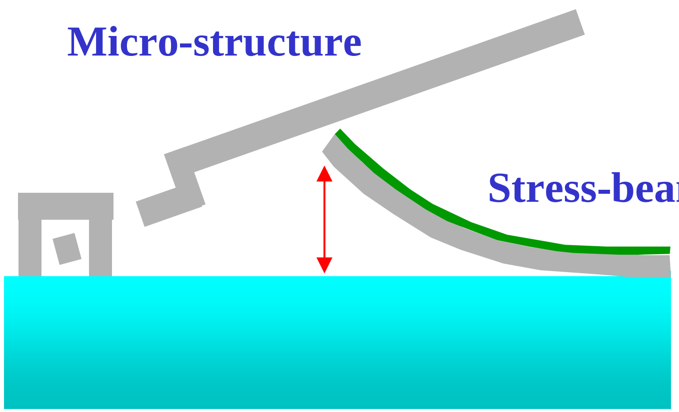


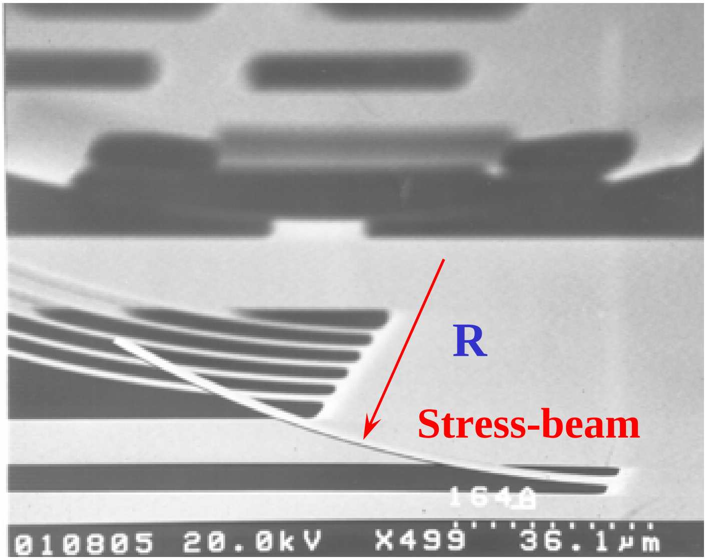


MDL
NTHU

Self assembly

- Employ stress-beam to increase moving space
- Fully integration with process

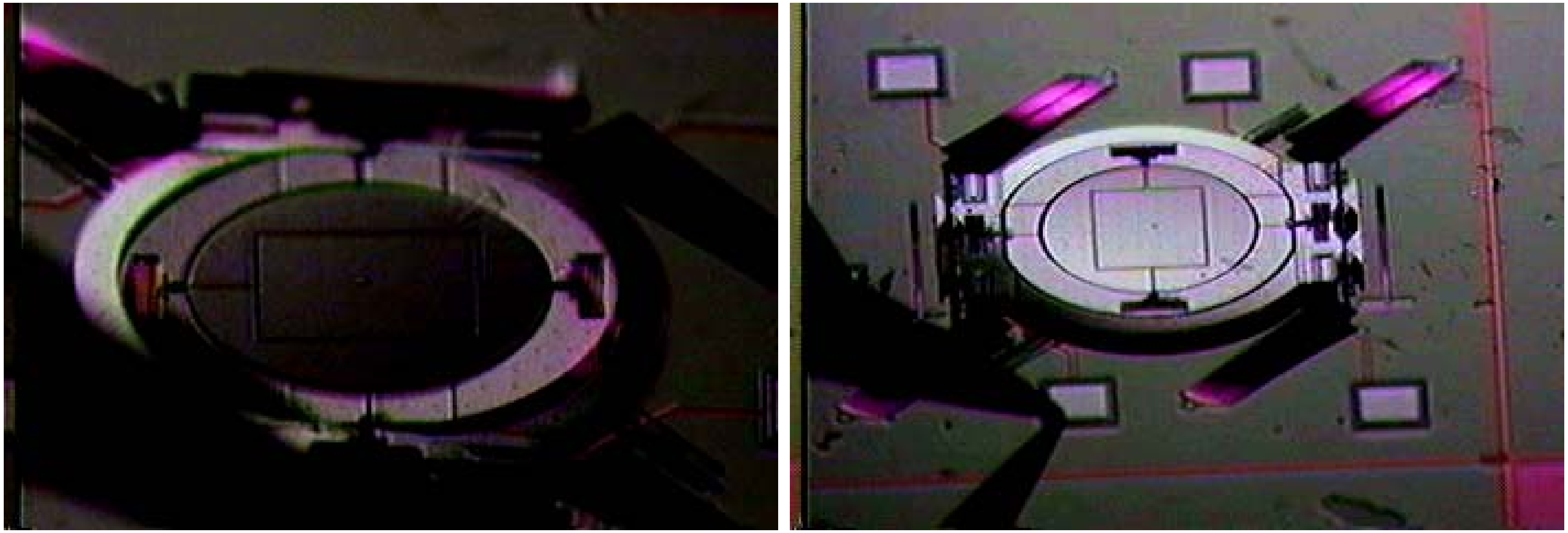




W. Fang, 1995

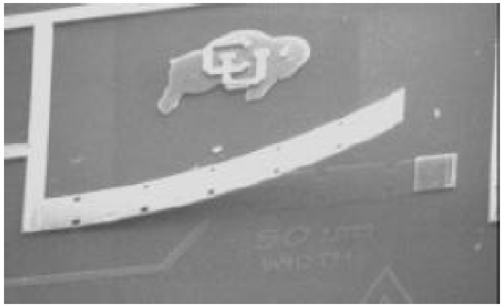
MDL
NTHU

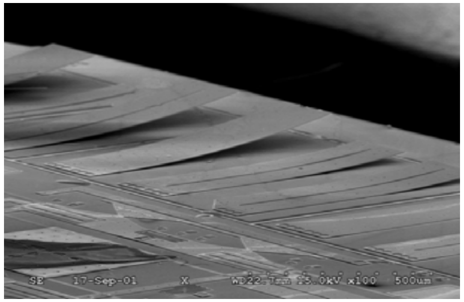
MDL
NTHU

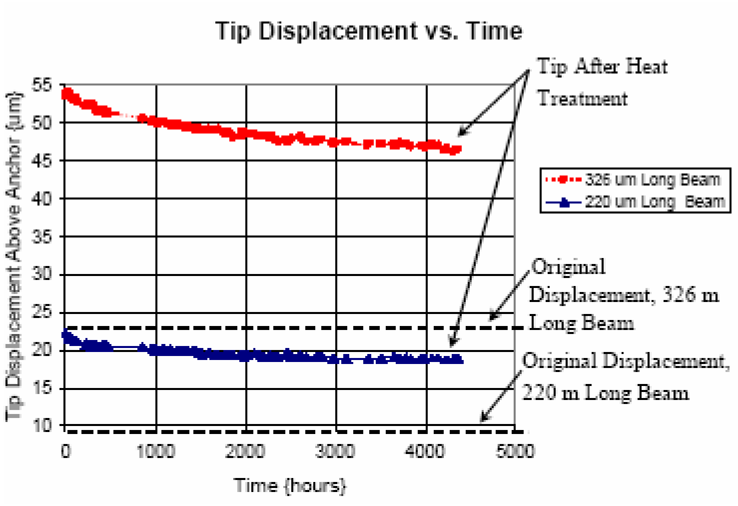


Y.-P. Ho, M. Wu, H.-Y. Lin and W. Fang, *IEEE Optical MEMS '02*, 2002

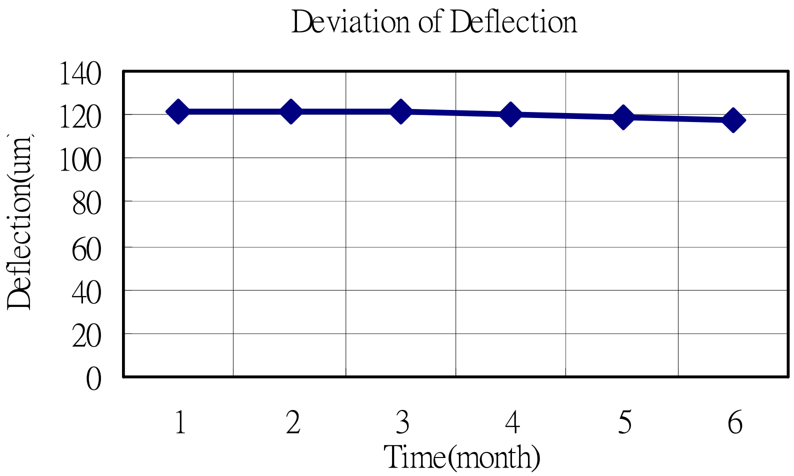
• Reliability issue need to be considered





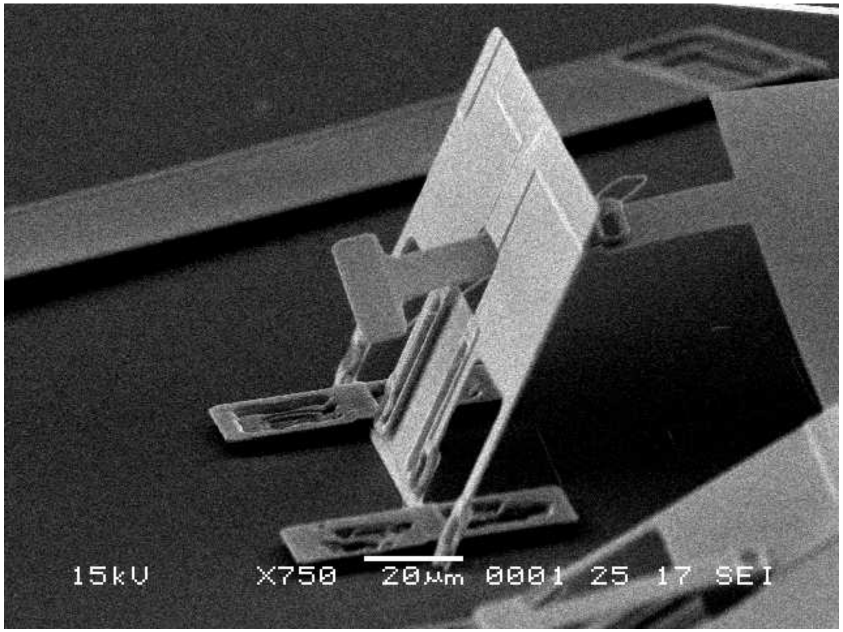


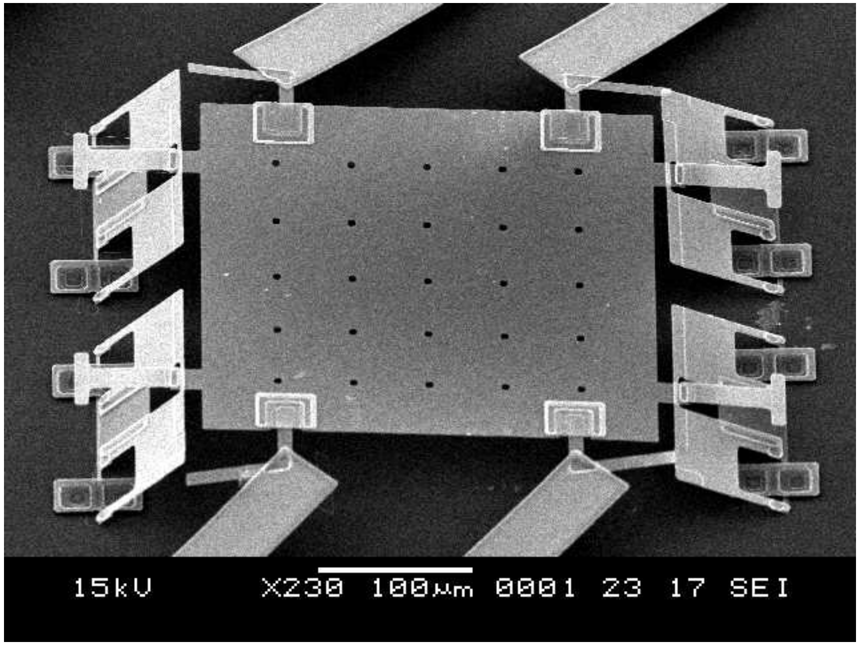
D. C. Miller, 2000



Y.P. Ho, 2002

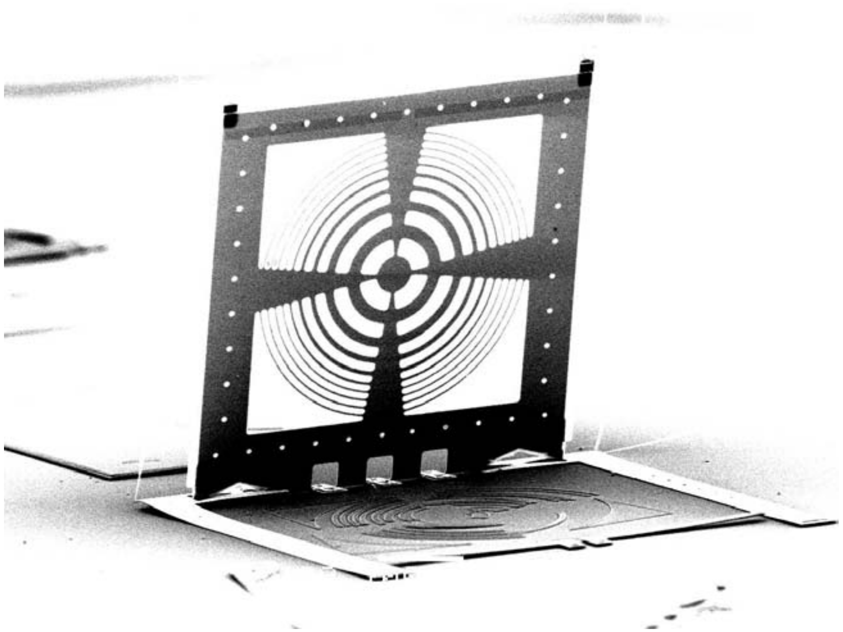
MDL
NTHU

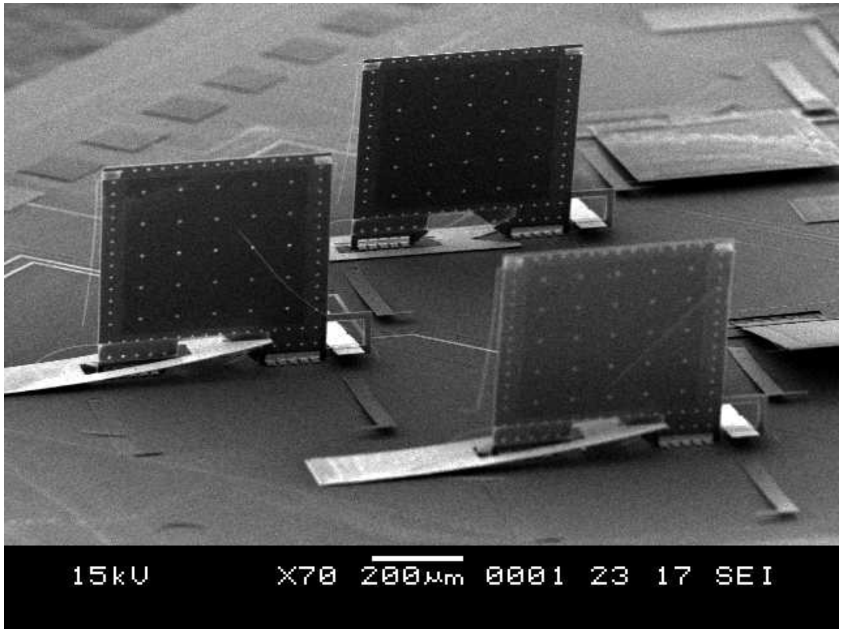




Y.-P. Ho and W. Fang, 2002

MDL
NTHU



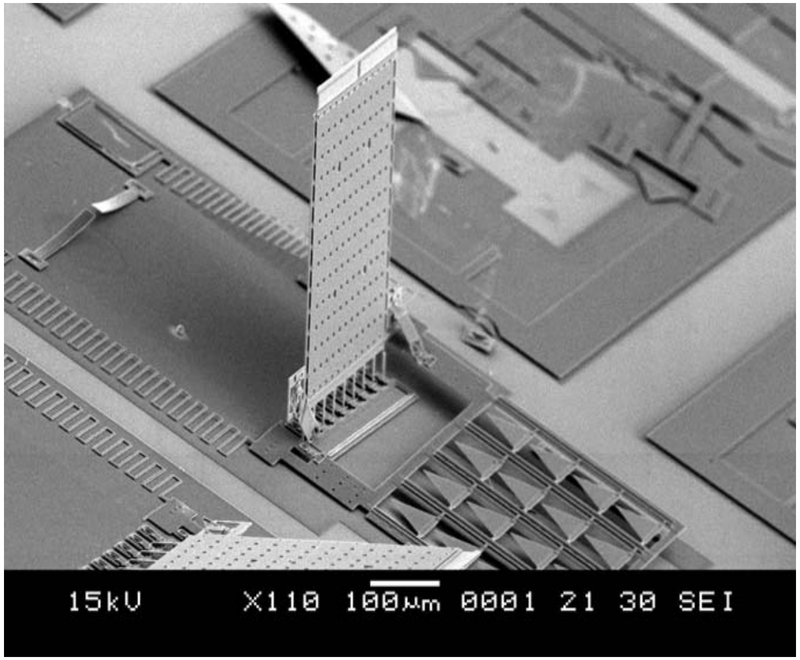


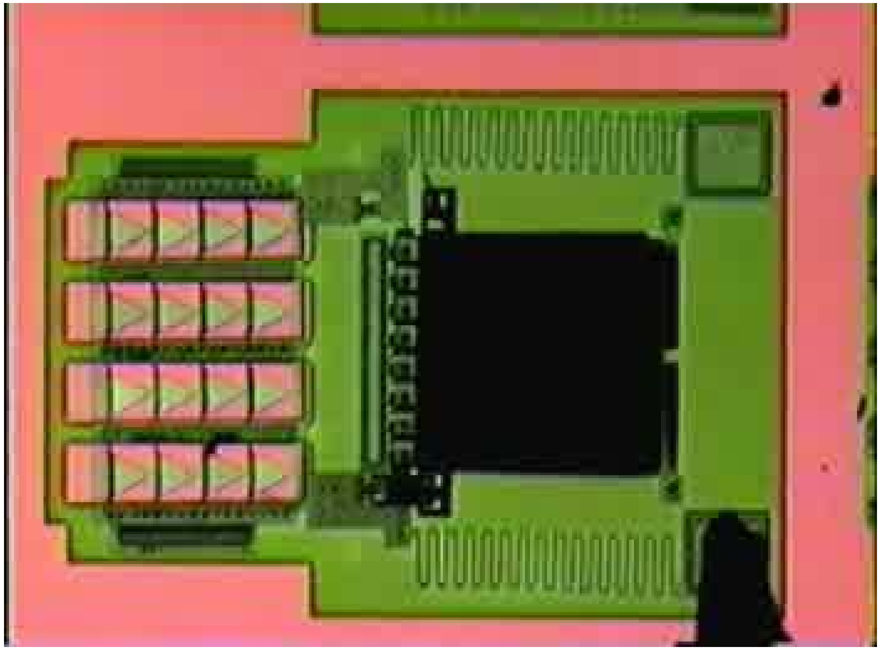
M. Wu and W. Fang, 2002

H.-Y. Lin and W. Fang, 2002

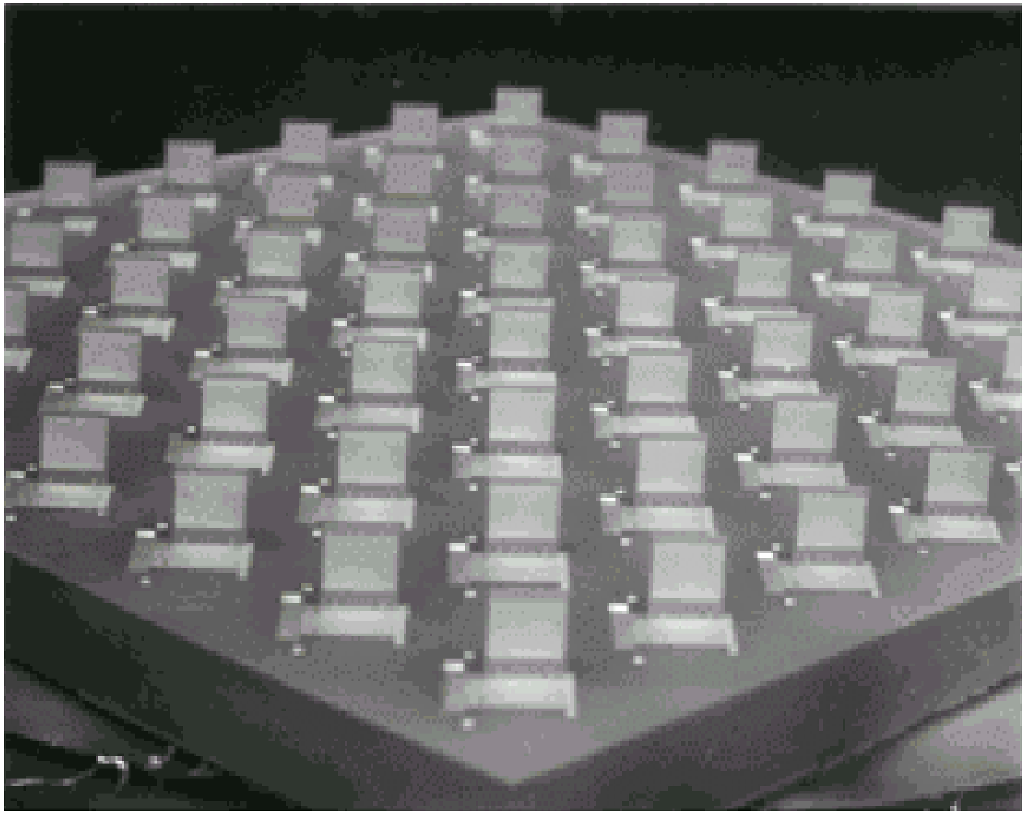
MDL
NTHU

- **Active self-assembly**





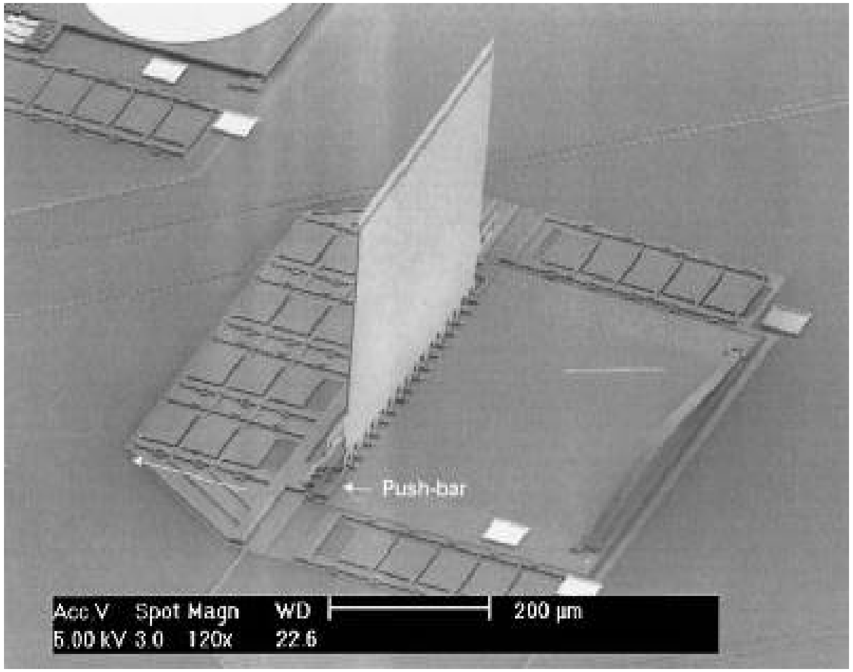
C.-Y. Wu, and W. Fang, 2002



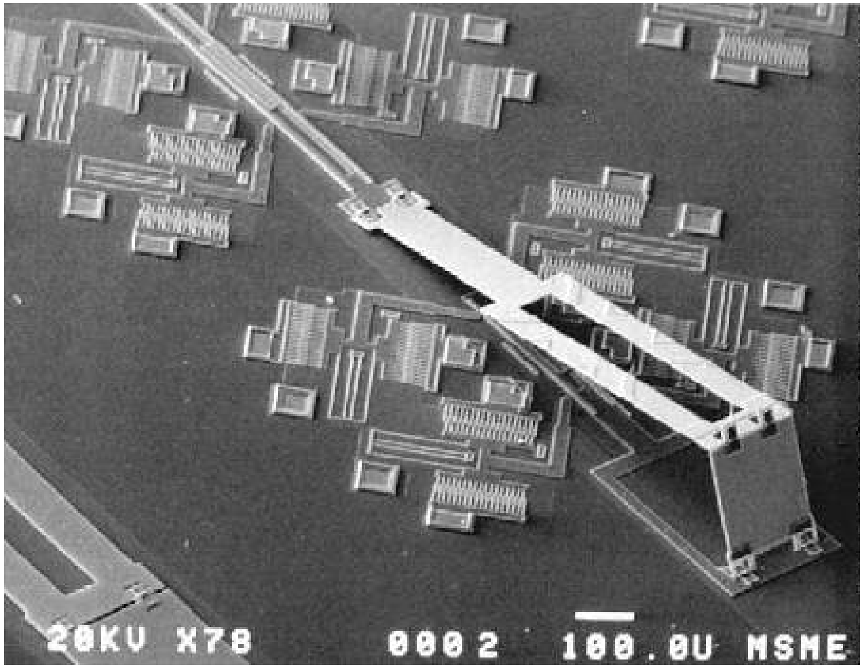
OMM, 1999

MDL
NTHU

Micromachine

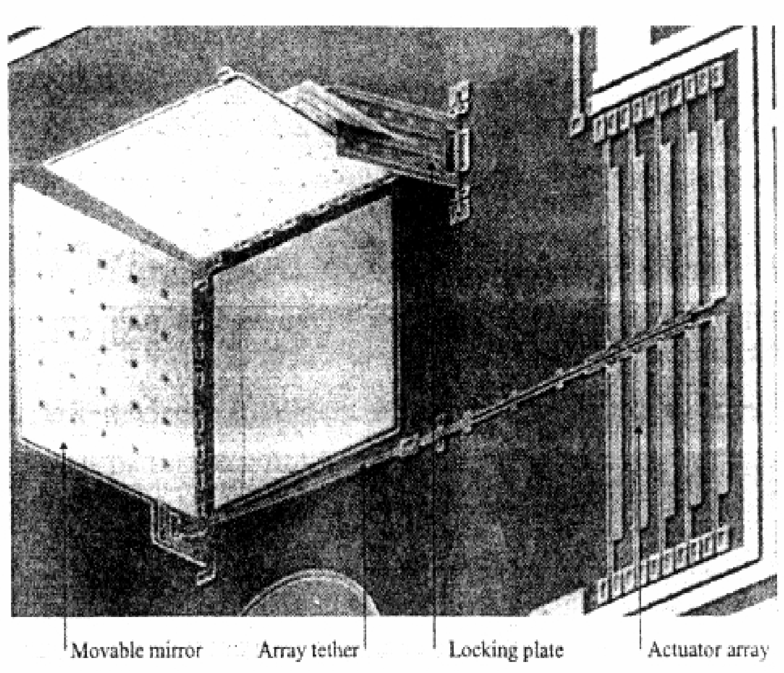


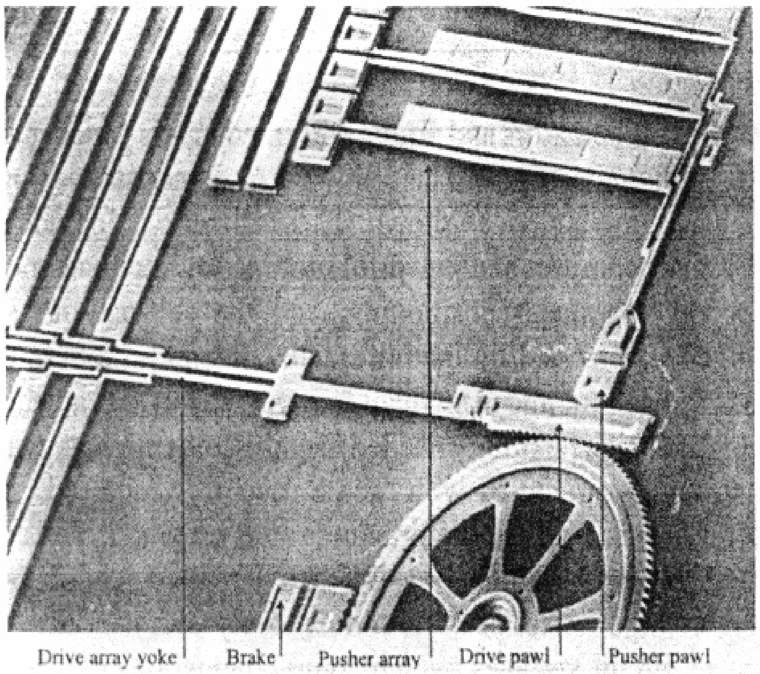
UCLA



UC Berkeley

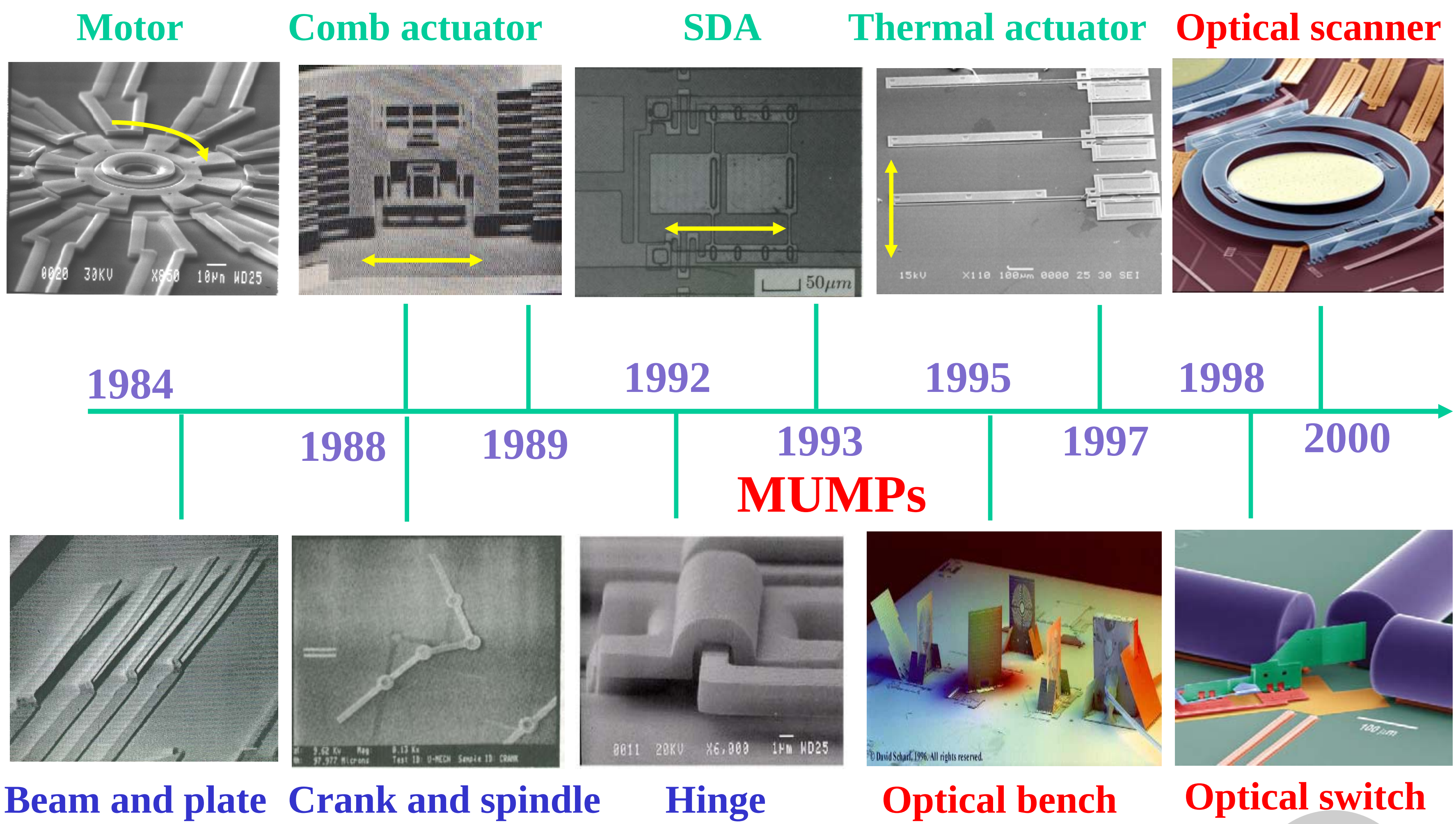
MDL
NTHU





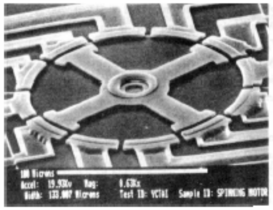
J.H. Comtois and V.M. Bright, Sensors and Actuators A, 1997

MDL
NTHU

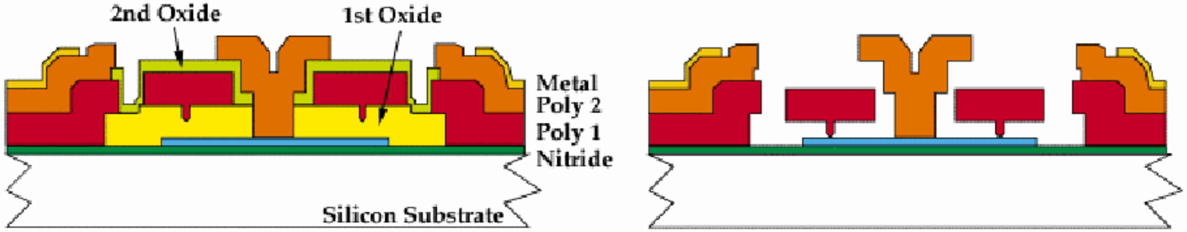


Motor
Comb actuator
SDA
Thermal actuator
Optical scanner
1984
1988
1989
1992
1993
MUMPs
1995
1997
1998
2000
Beam and plate
Crank and spindle
Hinge
Optical bench
Optical switch

Multi-User MEMS Processes (MUMPs)



Y.C.Tai, et al, 1989



Before Release

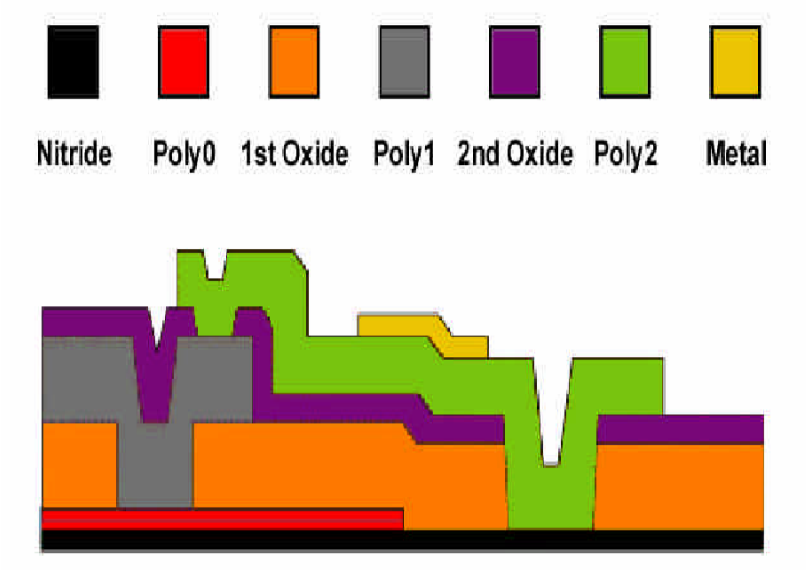
After Release

- 3-layer polysilicon surface-micromachining process
- 2 structural layers: poly-1 and poly-2 (poly-0: electrical contact)
- Sacrificial layers: phosphosilicate glass (PSG)
- 8 photomasks
- Offered by Cronos (acquired by JDS Uniphase in 2000)
- Derived from BSAC's micromotor process

MDL
NTHU

Multi-User-MEMS-Process

- **8 masks**
  - **+ Poly0, Dimple, Anchor1, Poly1, Poly1_Poly2_Via, Poly2, Anchor2, Metal**
  - **+ Hole1, Hole2, Hole-metal…**



- **7 layers total**
  - **+ Nitride—Poly0 —PSG1 — Poly1—PSG2—Poly2—Metal**

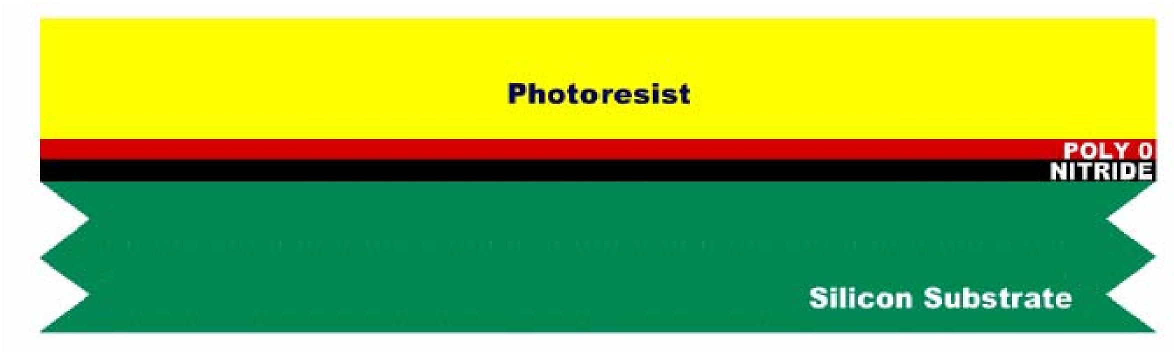
  2 released polysilicon layers

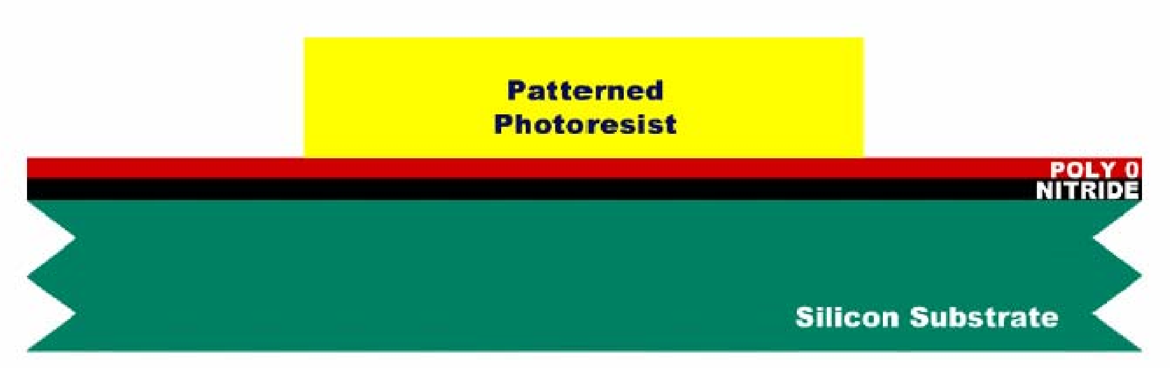
  2 PSG sacrificial layers

  1 metal layer

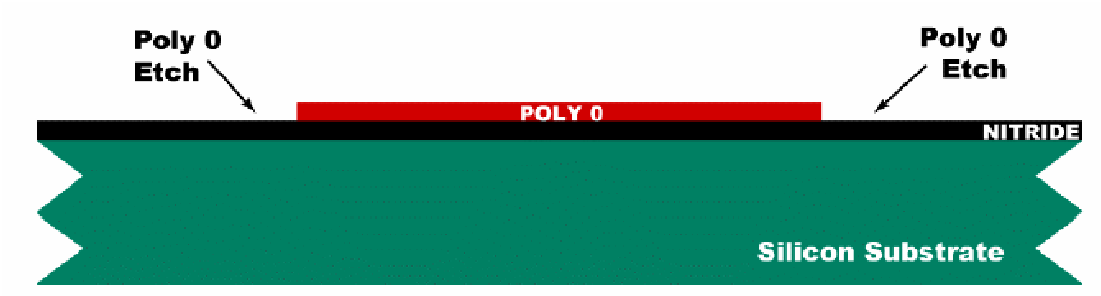
MDL
NTHU

MUMPs process
(MCNC - CRONOS - JDS-Uniphase)





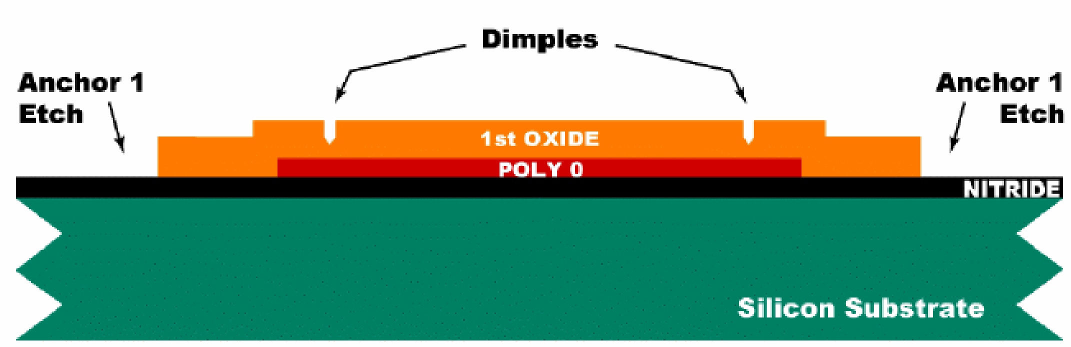
MDL
NTHU

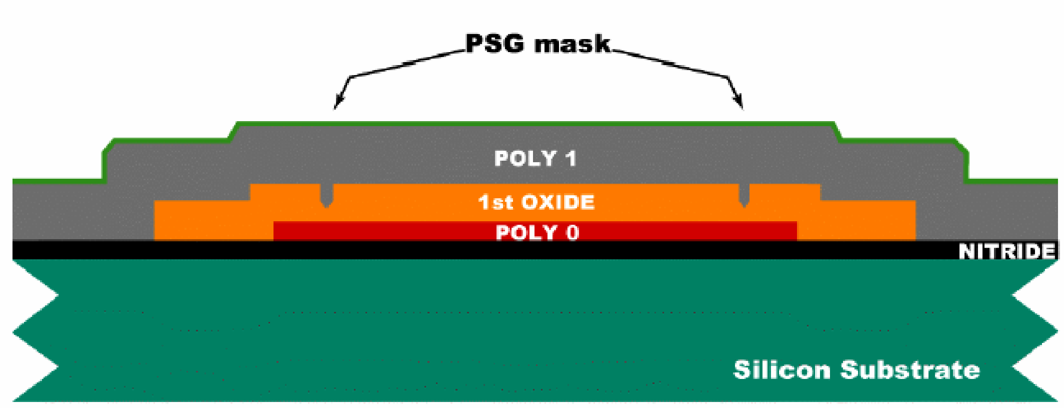

Poly 0
Etch
Poly 0
Etch
POLY 0
NITRIDE
Silicon Substrate

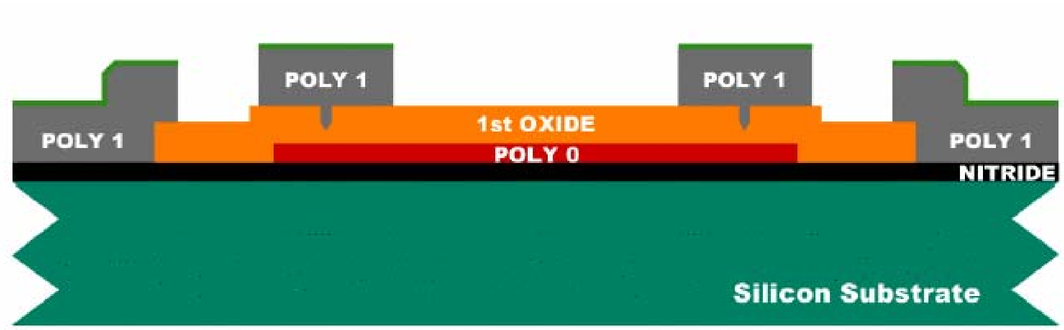

1st OXIDE
POLY 0
NITRIDE
Silicon Substrate


1st OXIDE
POLY 0
NITRIDE
Silicon Substrate

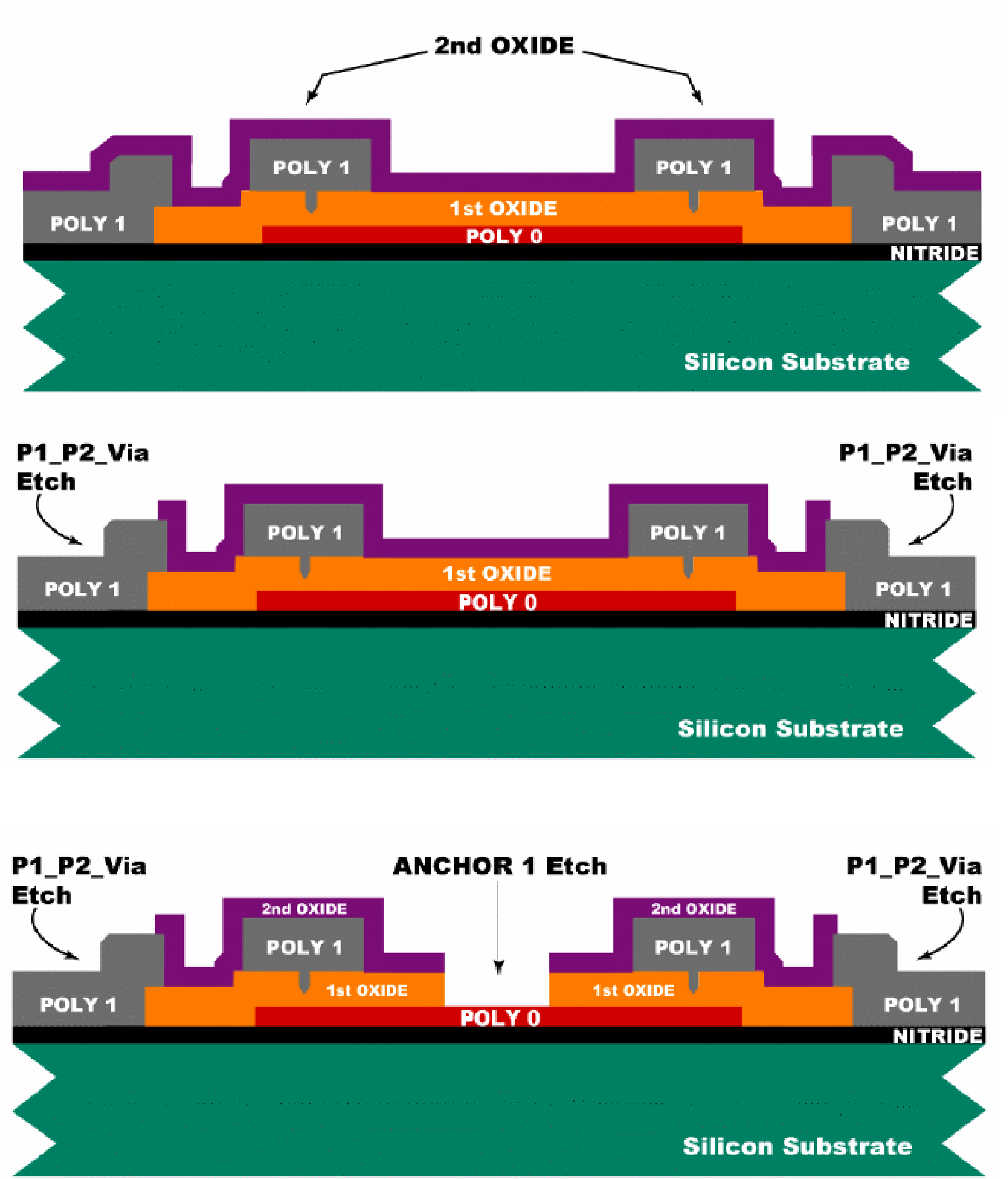
MDL
NTHU


Dimples
Anchor 1
Etch
Anchor 1
Etch
1st OXIDE
POLY 0
NITRIDE
Silicon Substrate

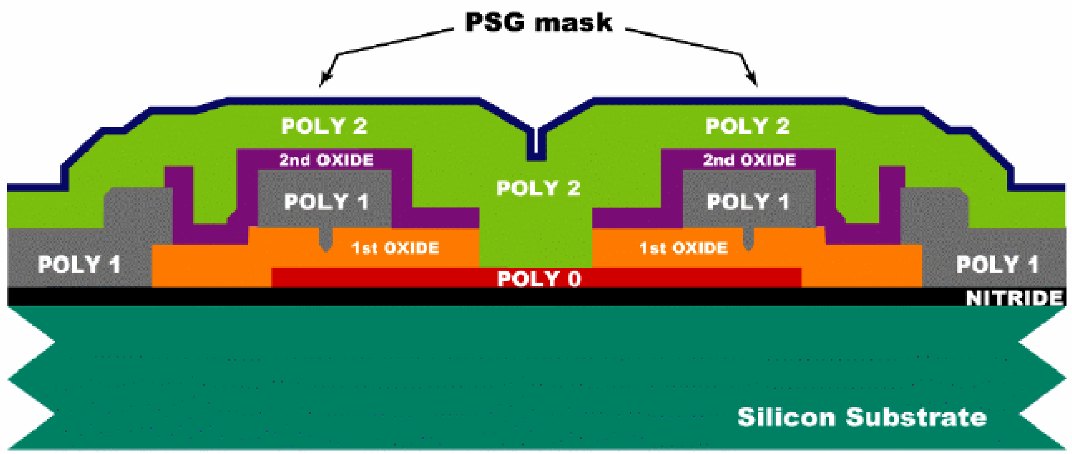

PSG mask
POLY 1
1st OXIDE
POLY 0
NITRIDE
Silicon Substrate

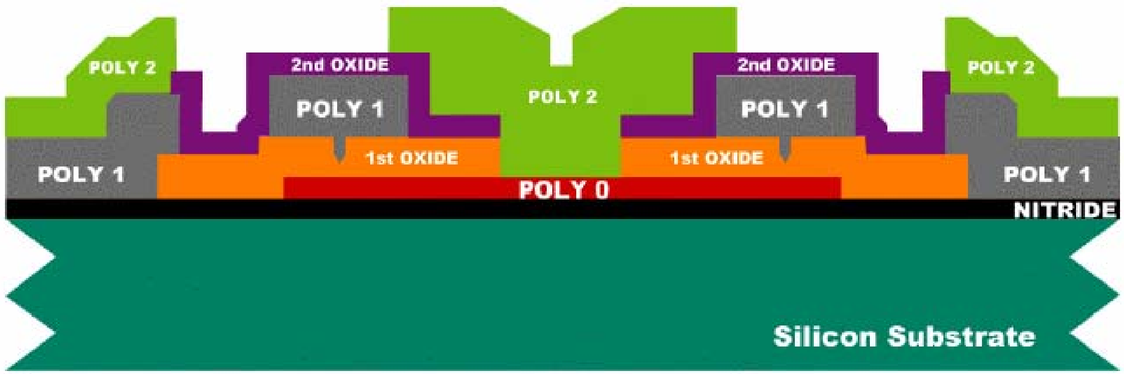

POLY 1
POLY 1
POLY 1
1st OXIDE
POLY 0
POLY 1
NITRIDE
Silicon Substrate

MDL
NTHU

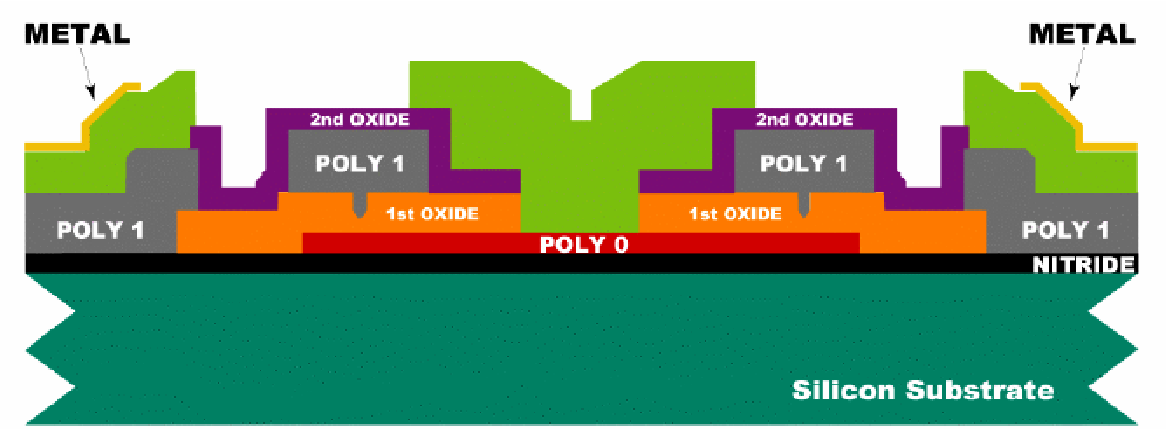

2nd OXIDE
POLY 1
POLY 1
1st OXIDE
POLY 1
POLY 0
POLY 1
NITRIDE
Silicon Substrate
P1_P2_Via Etch
P1_P2_Via Etch
POLY 1
POLY 1
1st OXIDE
POLY 1
POLY 0
POLY 1
NITRIDE
Silicon Substrate
P1_P2_Via Etch
ANCHOR 1 Etch
P1_P2_Via Etch
2nd OXIDE
2nd OXIDE
POLY 1
POLY 1
1st OXIDE
1st OXIDE
POLY 1
POLY 0
POLY 1
NITRIDE
Silicon Substrate

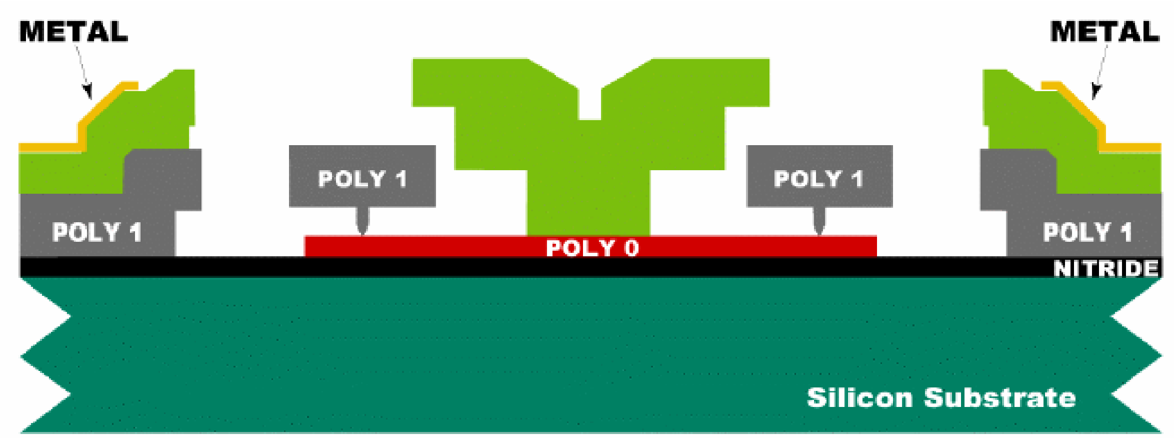
MDL NTHU


PSG mask
POLY 2
POLY 2
2nd OXIDE
2nd OXIDE
POLY 2
POLY 1
POLY 1
1st OXIDE
1st OXIDE
POLY 1
POLY 1
POLY 0
NITRIDE
Silicon Substrate


2nd OXIDE
2nd OXIDE
POLY 2
POLY 2
POLY 2
POLY 1
POLY 1
1st OXIDE
1st OXIDE
POLY 1
POLY 1
POLY 0
NITRIDE
Silicon Substrate

MDL
NTHU


METAL
METAL
2nd OXIDE
2nd OXIDE
POLY 1
POLY 1
1st OXIDE
1st OXIDE
POLY 1
POLY 1
POLY 0
NITRIDE
Silicon Substrate

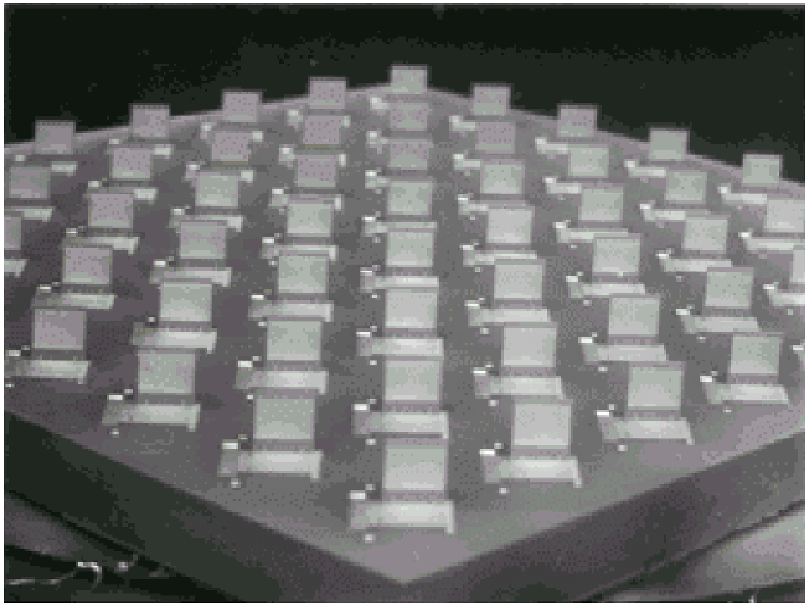

METAL
METAL
POLY 1
POLY 1
POLY 1
POLY 1
POLY 0
NITRIDE
Silicon Substrate

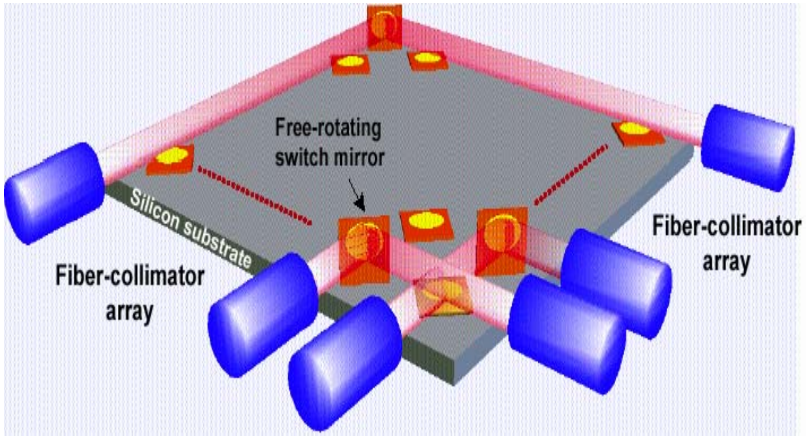
MDL
NTHU

Applications

MDL
NTHU

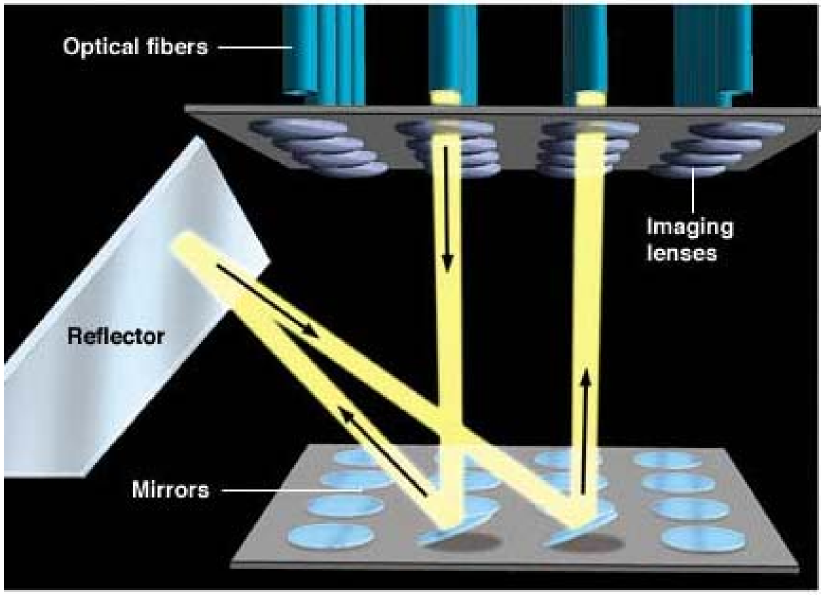
- 2D optical switch by OMM

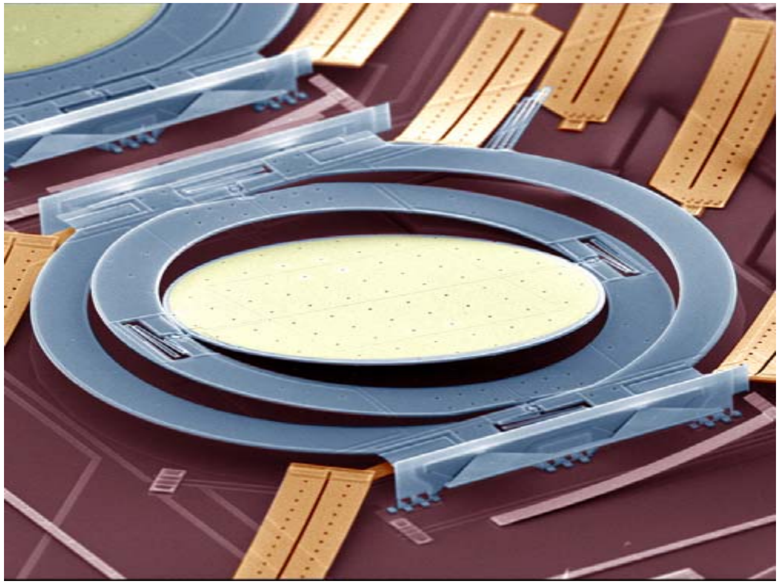




OMM

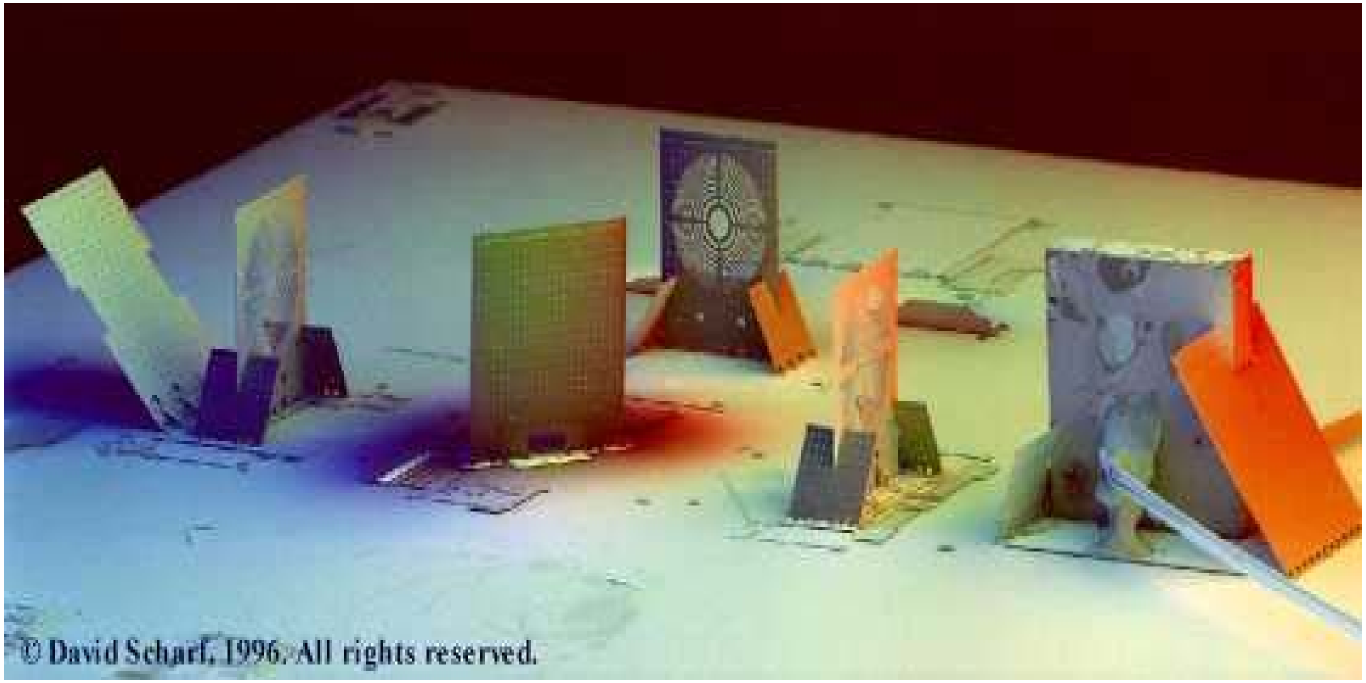
- 3D optical switch





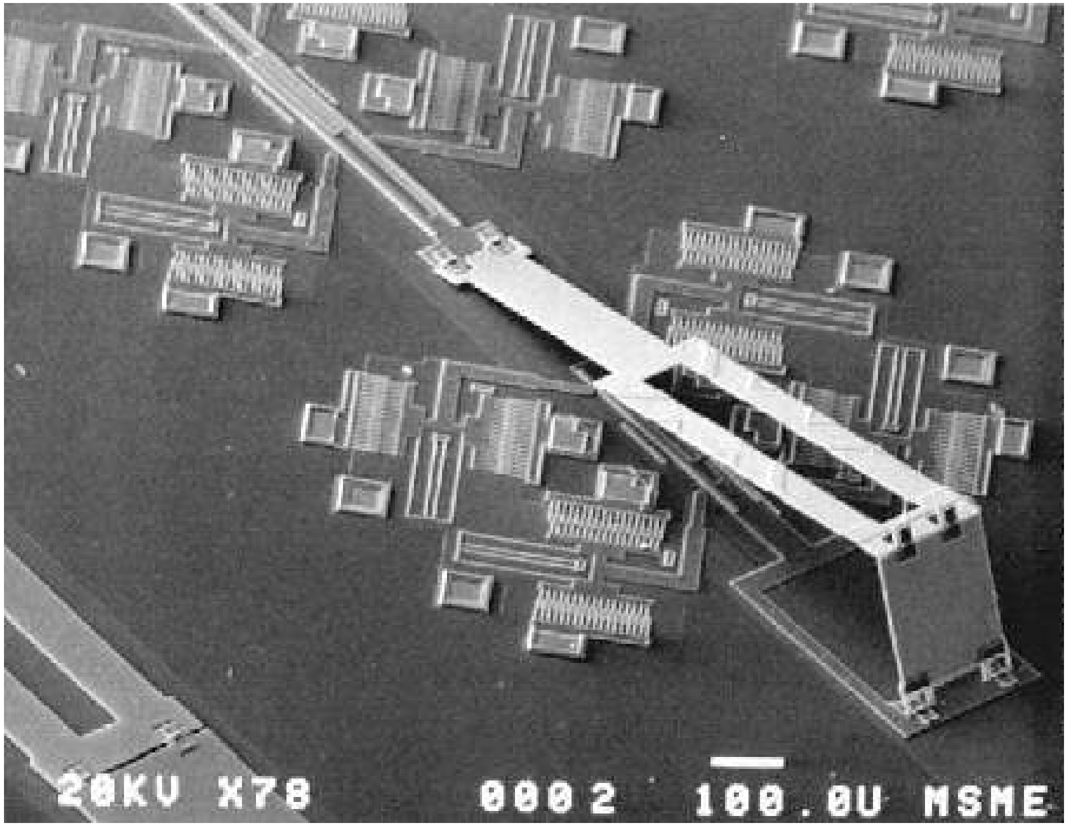
Lucent

- **Free space optical bench**



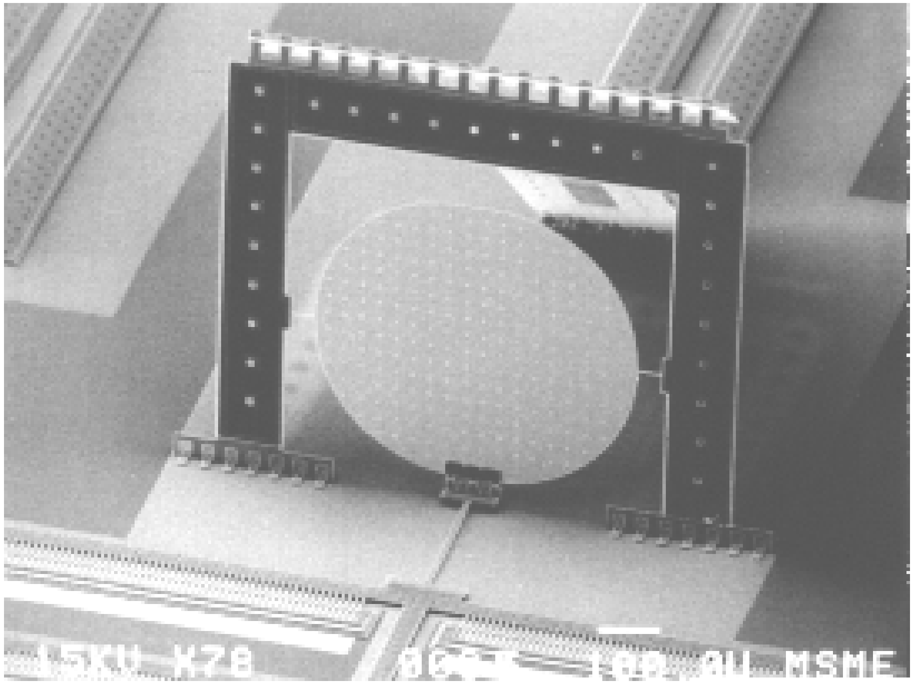
L.-Y. Lin and M. C. Wu, UCLA, 1995

- **Optical scanner for display or barcode reader**



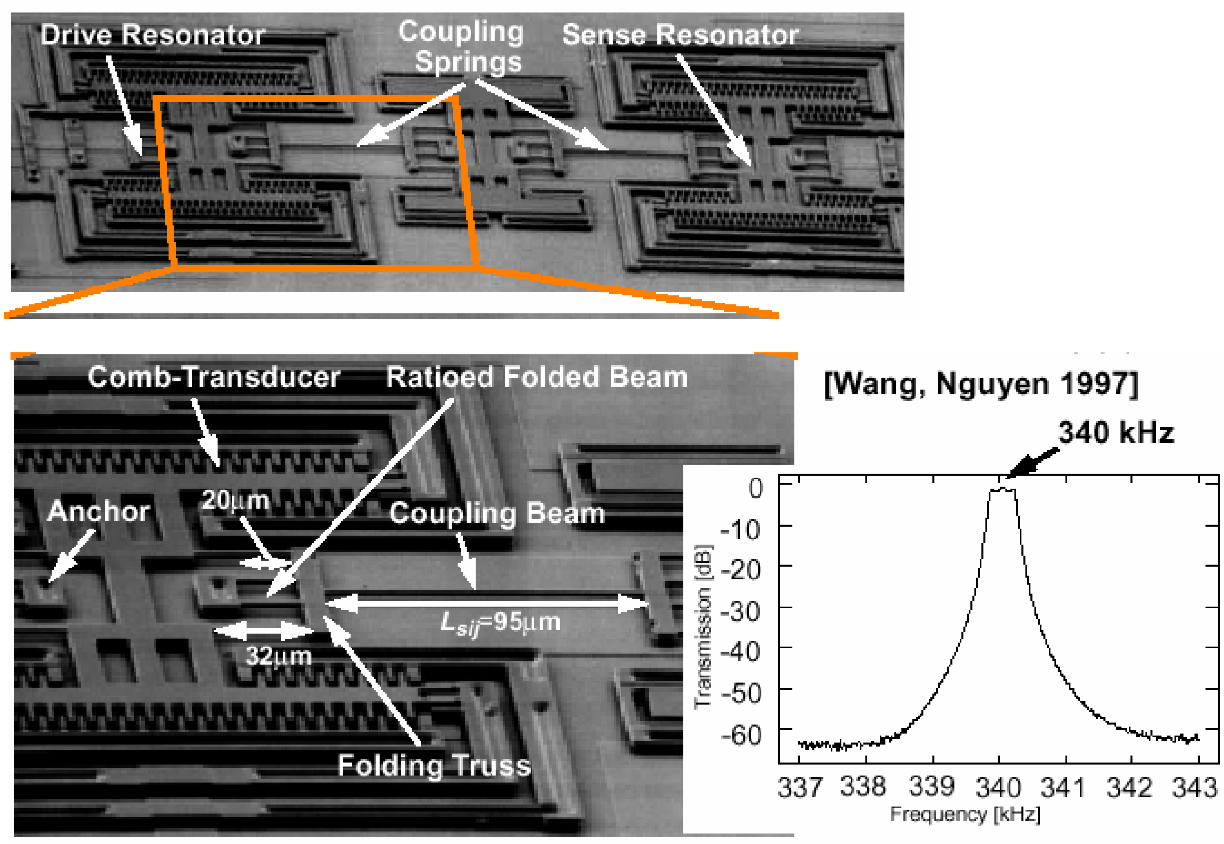
UC Berkeley

- **Optical scanner**



MDL
NTHU

- **Low frequency bandpass filter**

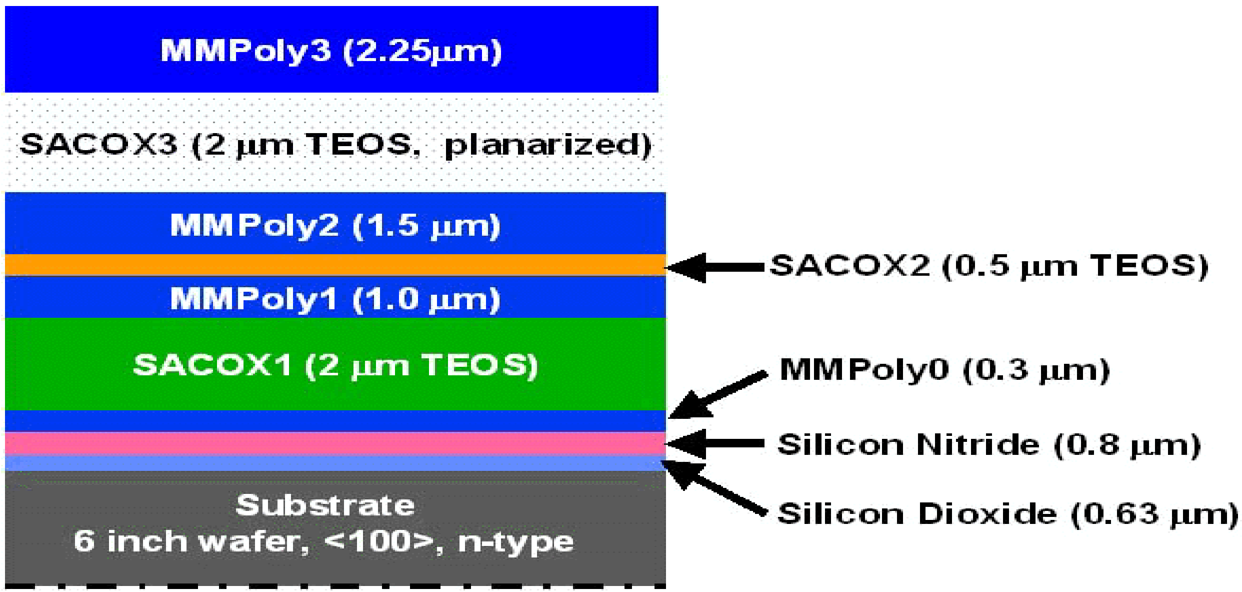


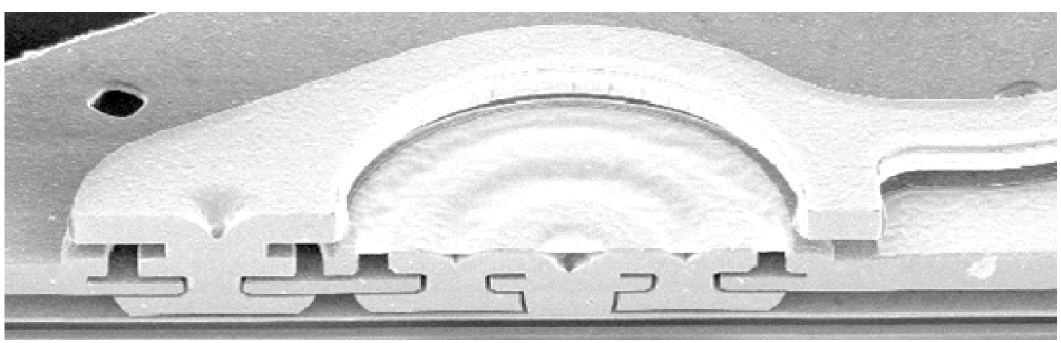
Wang and Nguyen, 1997

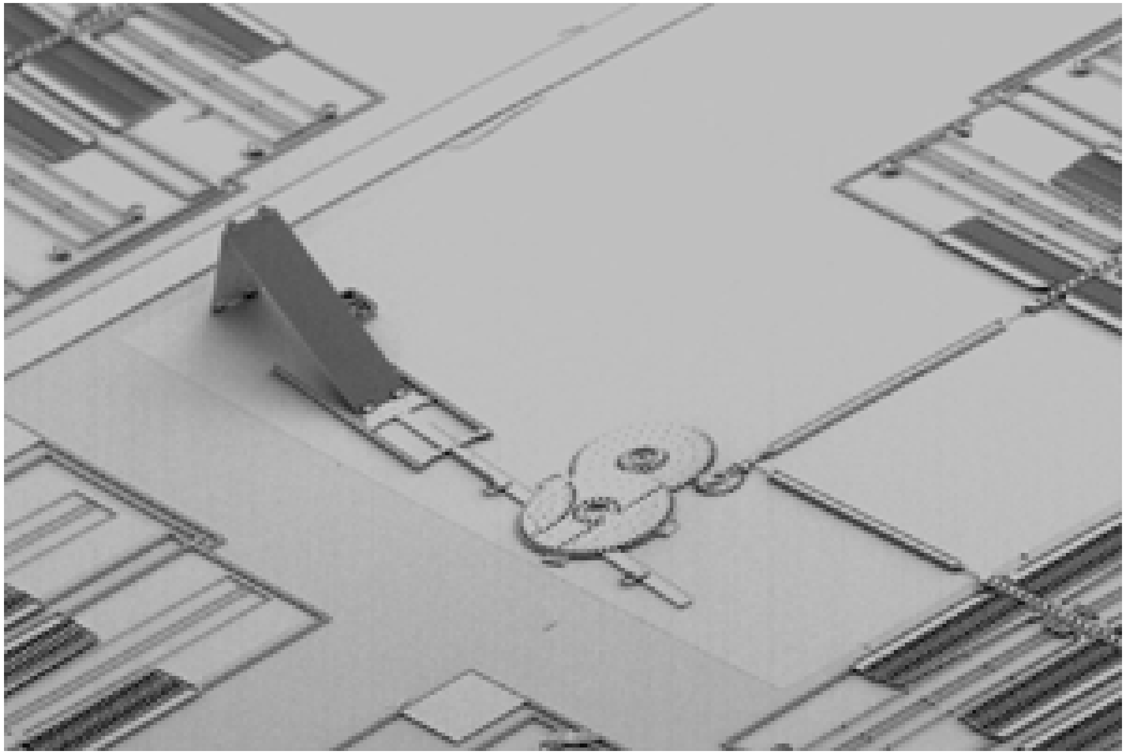
MDL
NTHU

Other surface processes platform

Summit process
(Sandia National Lab)

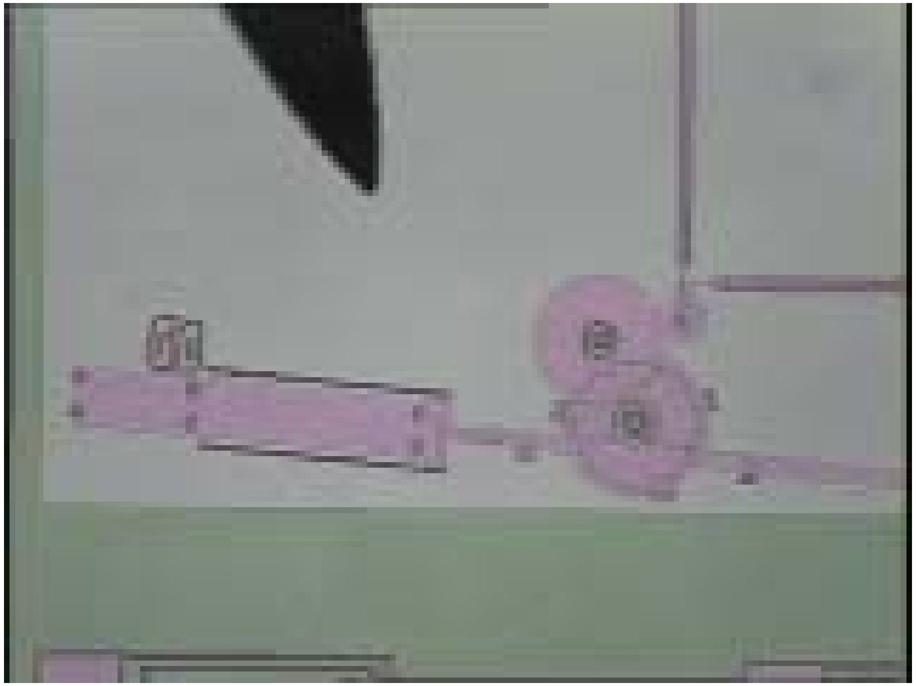






Sandia National Lab, USA

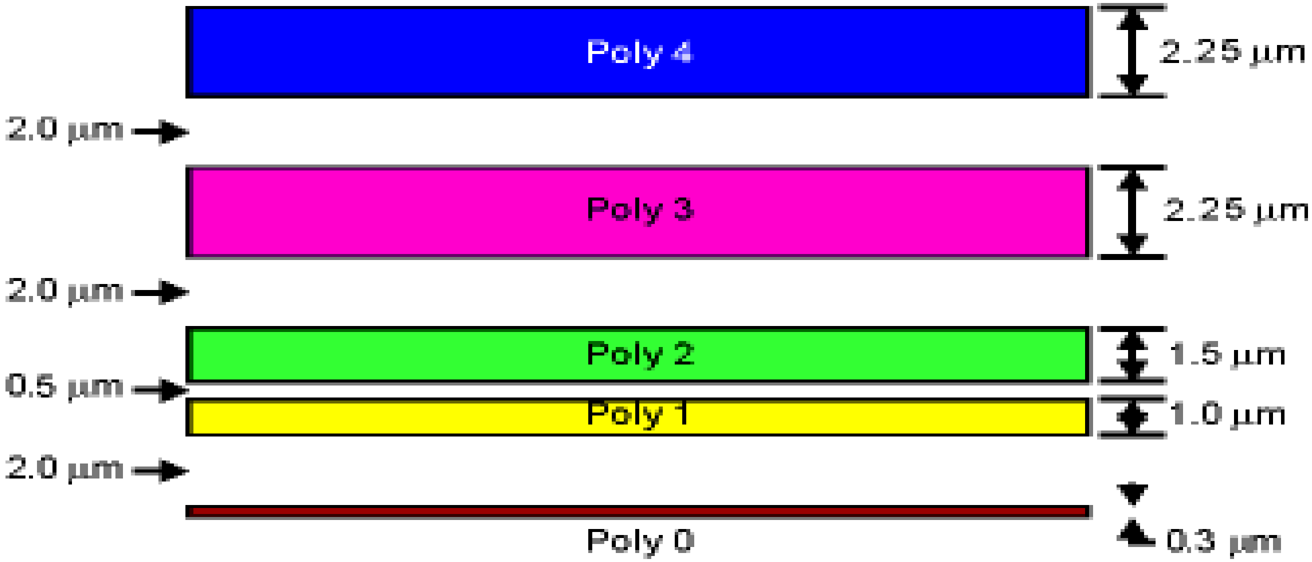
MDL
NTHU

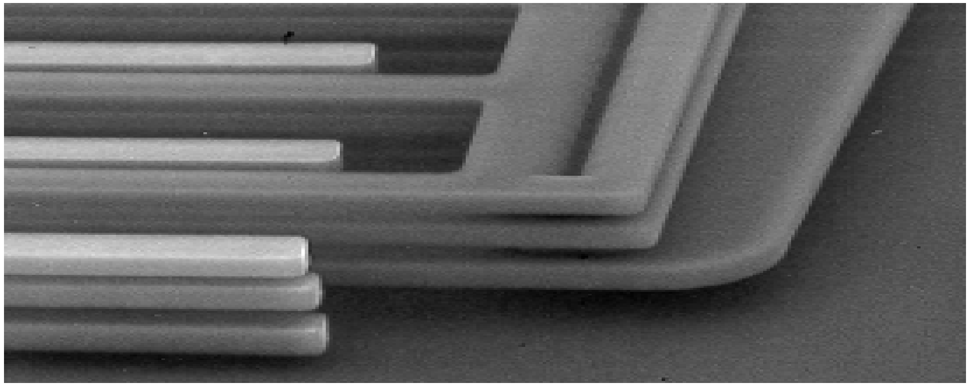


Sandia National Lab, USA

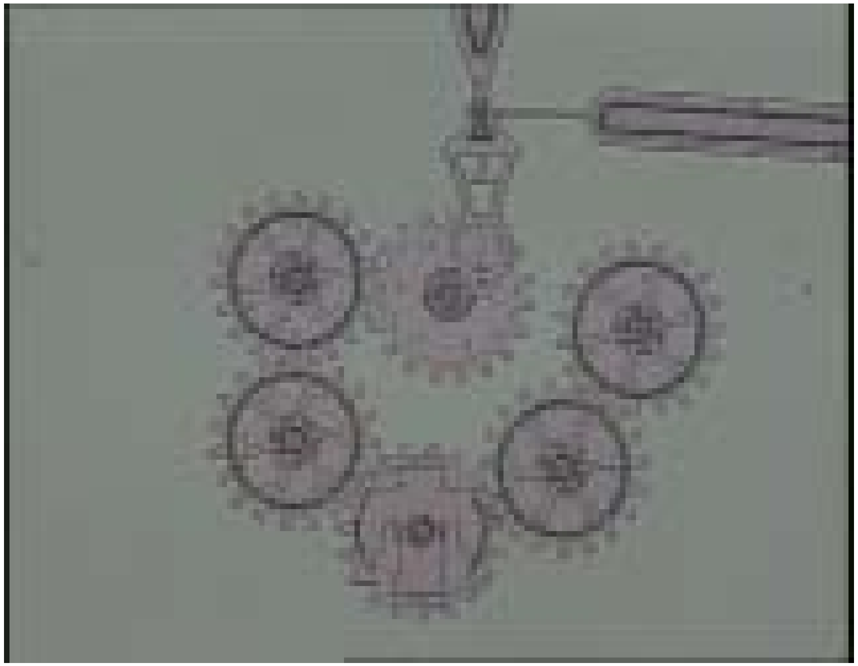
MDL
NTHU

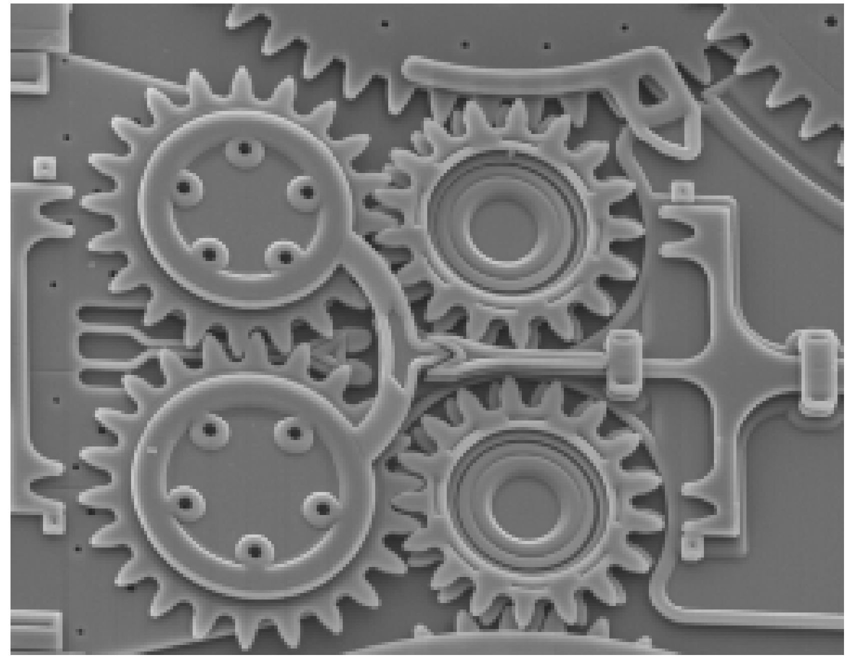
Summit V process
(Sandia National Lab)





MDL
NTHU





MDL
NTHU

Thin film materials

- The thin film materials for surface micromachining can be characterized as (1) materials for structural layer, and (2) materials for sacrificial layer
- Several important issues need to be considered in selecting the proper thin film materials for structural and sacrificial layers

+ Conformal coverage

+ Selectivity to etchants

+ Process compatibility

+ Mechanical property

+ Residual stresses

+ Compatible with the standard IC process

LPCVD Polysilicon

- Reaction of silane at 500 to 700 °C and 300-500 mTorr to generate silicon

$$SiH_4 \longrightarrow Si + 2H_2$$

+ Amorphous silicon for T < 580 ^{o}C

+ Polysilicon for T > 580 ^{o}C

+ Crystal structure of the amorphous silicon can transfer to polysilicon by high temperature annealing

- Young's modulus vary from 140 GPa to 210 GPa (Al is 70 GPa, steel is 210 GPa)

- Comformal coverage

MDL
NTHU

LPCVD Oxides

- Reaction of silane and oxygen at 450 °C and 300-500 mT to generate oxide

$$SiH_4 + O_2 \longrightarrow SiO_2 + 2H_2$$

+ Low temperature oxide (LTO) - LPCVD undoped oxide

+ Phosphosilicate glass (PSG) - LPCVD phosphorous doped oxide

+ Borosilicate glass (BSG) - LPCVD boron doped oxide

- Selectivity to polysilicon is very high (for example, selectivity of polysilicon/LTO is ~ 10^5)

- Comformal coverage

- Film is under compressive residual stress

MDL
NTHU

LPCVD Nitrides

- Reaction of dichlorosilane and ammonia at 700-900 °C and 300-500 mT to generate silicon nitride

$$3SiCl_2H_2 + 4NH_3 \longrightarrow Si_3N_4 + 6HCl + 6H_2$$

- Comformal coverage

- Film is under large tensile residual stress

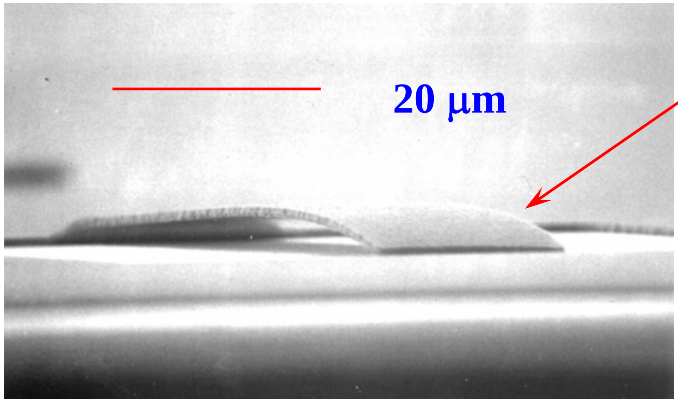
- The residual stress can be reduced by changing the composition of Si_3N_4 to Si_xN_y (silicon rich, x:y ~ 1:1.1)

MDL
NTHU

Residual stresses

- In general, the structures is under a uniform residual stress and a gradient residual stress
- The residual stresses of the deposited films will lead cracking (by tensile residual stress) and delamination (by both tension and compression) to the deposited films
- In addition, the mechanical structures will be deformed by the residual stresses

+ The Ti film is deposited by sputtering



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

Limitation of the structure design

- Stiffness and patterning of the structure layers are two major concerns during design

- Spin coat the PR is difficult for a surface with large variation of its height

- The structure is easy to have large deformation under capillary force or residual stress if its stiffness is small (for example, a cantilever beam with small beam thickness or large beam length)

Basic features	Bulk micromachining	Surface micromachining
Mask number	≥ 1	≥ 2
Motion	Out-of-plane	In-plane
Approach to construct complicated structures	Bonding and etch stop layer	Layer construction
Design of the structures	limited	Flexible
Materials	Si or doped - Si SiO_2	Polysilicon silicon nitride
Applications		
Fluidic system	yes	
Accelerometer	yes	yes
Pressure transducer	yes	yes
Actuator: angular		yes
Actuator: linear		yes
Actuator: out-of-plane	yes	

MDL
NTHU