The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

World Year of PHYSICS 2005

SMR.1670 - 13

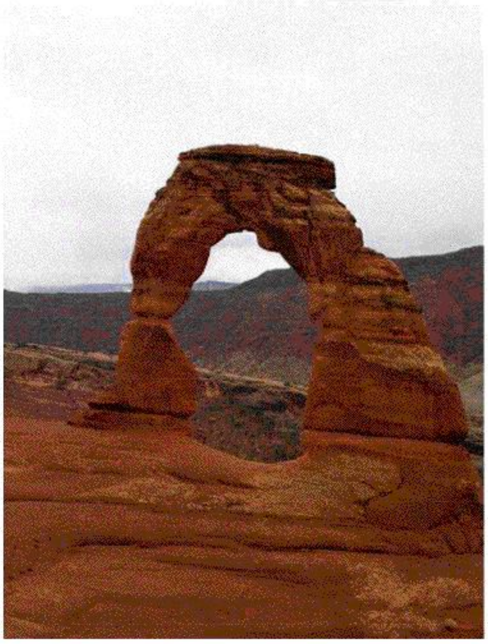
INTRODUCTION TO MICROFLUIDICS

8 - 26 August 2005

Surface Micromachining

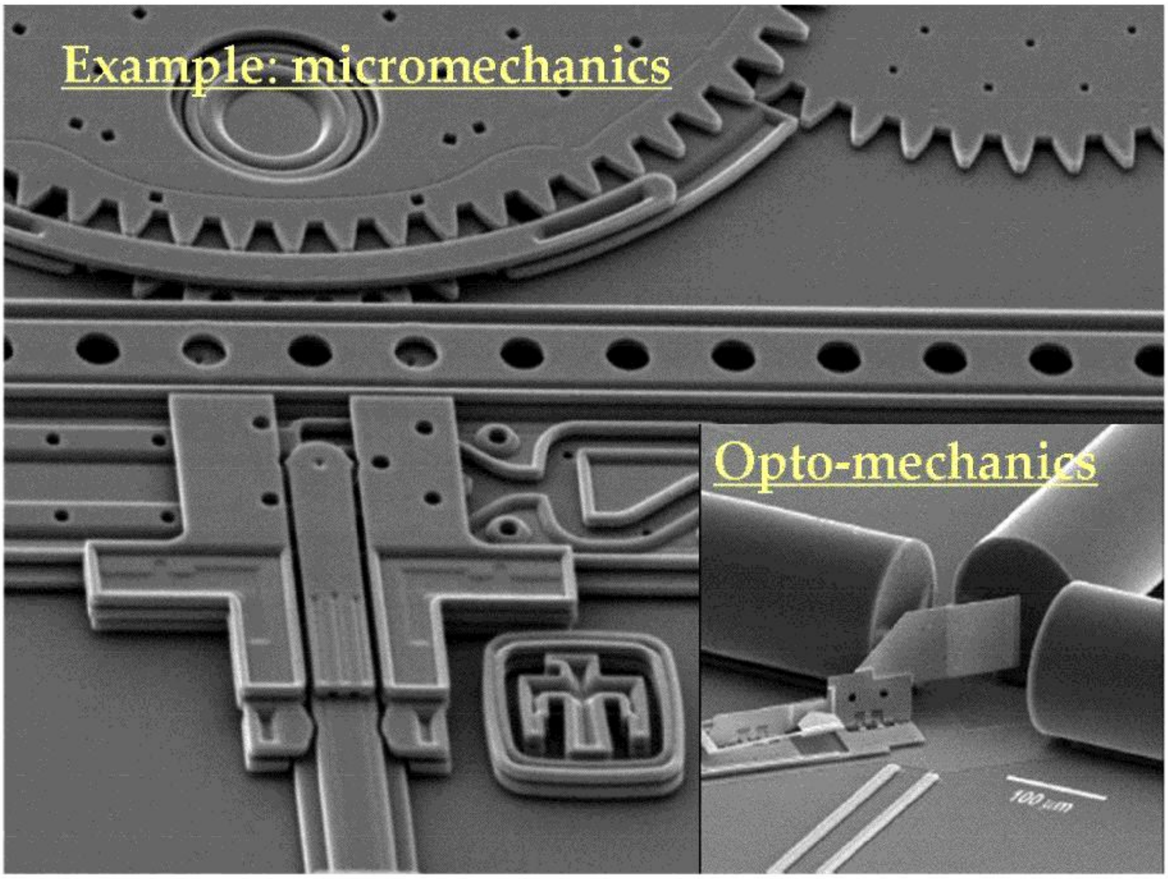
H. Gardeniers
University of Twente, Enschede, The Netherlands

Surface micromachining

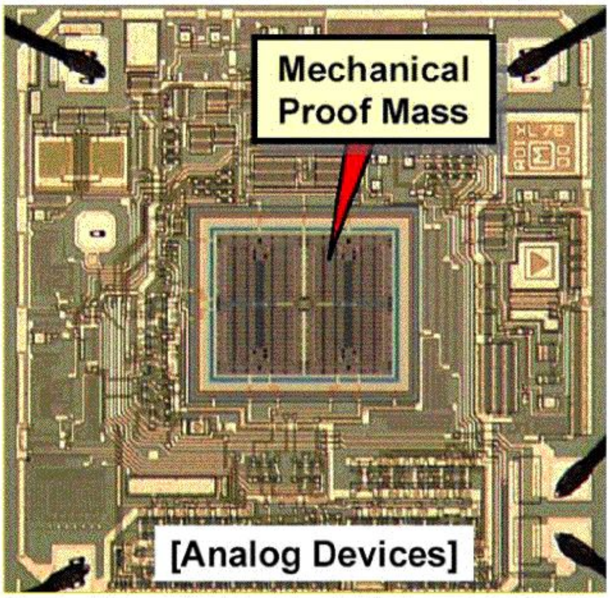


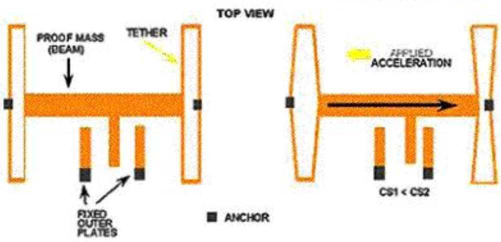
Han Gardeniers
MESA+ Institute for Nanotechnology
University of Twente

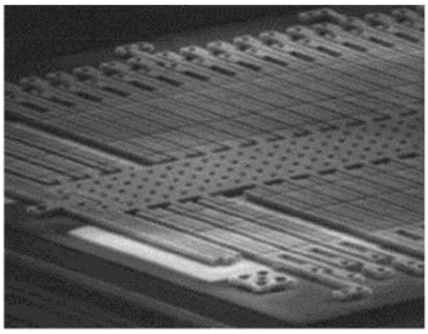
Summer School in Microfluidics
ICTP, Trieste, Italy



Fully-integrated accelerometer (AD)







working principle: http://ccrma.stanford.edu/CCRMA/Courses/252/sensors/node9.html
AD accelerometers: http://www.analog.com/Analog_Root/static/library/techArticles/mems/sensor971/

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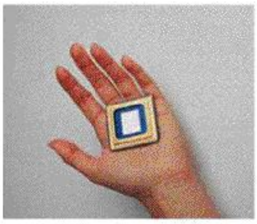
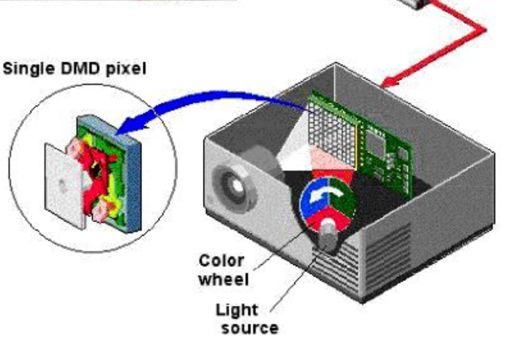
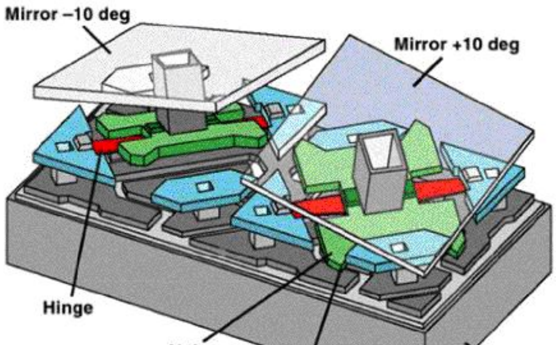
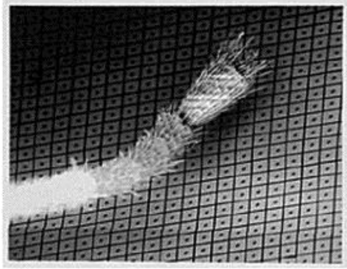
Digital Micromirror Devices (TI)









see demo at: http://www.dlp.com/Default.asp?bhcp=1

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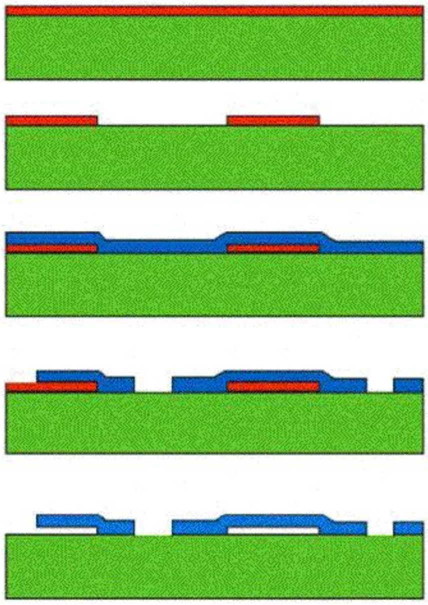
Surface micromachining: basic scheme



deposition of sacrificial layer

patterning of sacrificial layer

deposition of structural layer

patterning of structural layer

release etch

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Thin Film Deposition

Vacuum conditions and formation of monolayers

Degree of vacuum	Pressure (Torr)	Gas density (molecules m^{-3})	Mean free path (m)	time / ML (s)
Atmospheric	760	2×10^{25}	7×10^{-8}	10^{-9}
Low	1	3×10^{22}	5×10^{-5}	10^{-6}
Medium	10^{-3}	3×10^{19}	5×10^{-2}	10^{-3}
High	10^{-6}	3×10^{16}	50	1
UltraHigh	10^{-10}	3×10^{12}	5×10^{5}	10^{4}

$$t = 3.2 \times 10^{-6} / P$$

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Physical Vapour deposition (PVD)

- Evaporation (resistive, e-beam)
- Sputtering (plasma)
- Electroplating (or electroless dep.): thick films

Thin: up to a few micron

Thick: up to a few mm

Limiting factors: deposition rates, internal stress

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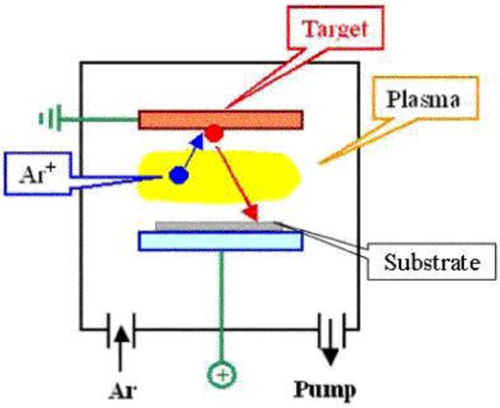
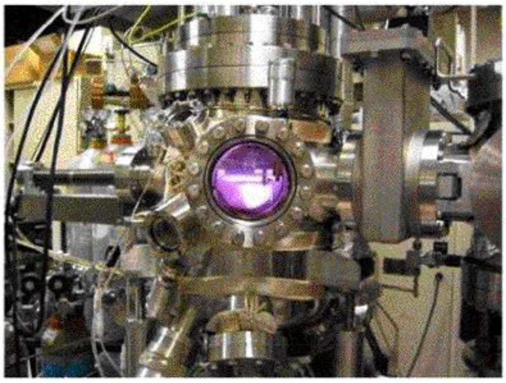
Thin film: sputtering

Vacuum chamber with argon gas

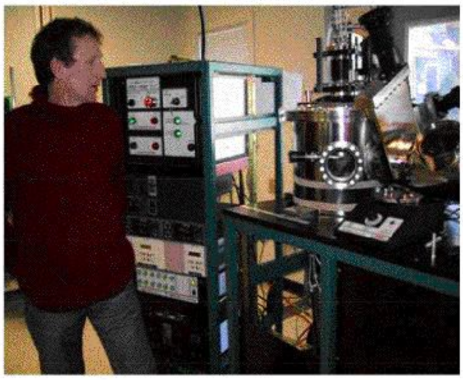


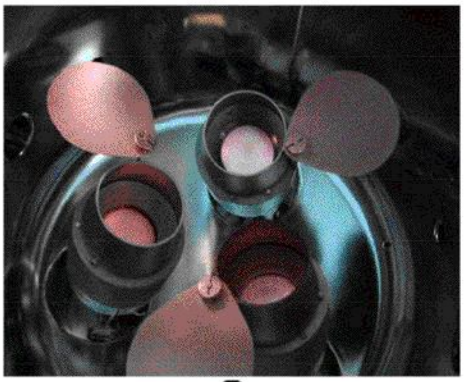
Simple

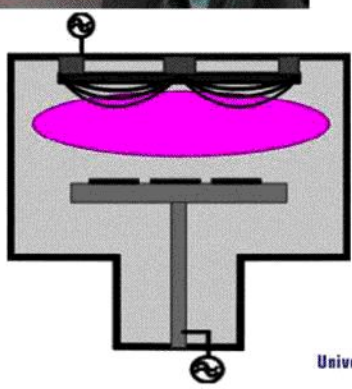
Not so simple



Sputtering with "guns"

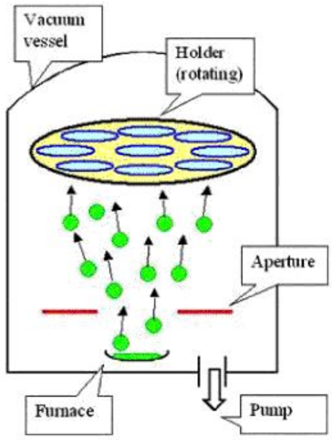


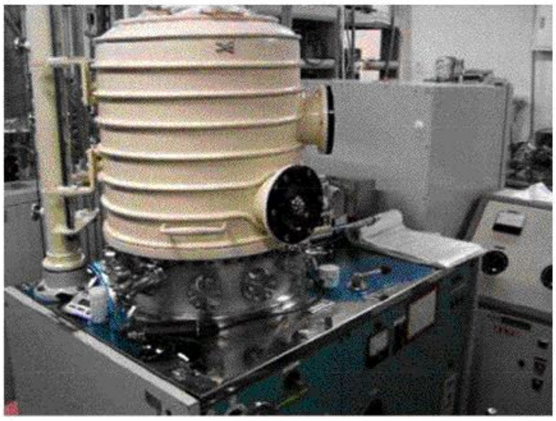




Thin film: evaporation

Vacuum chamber
Used for metals like Al and Cr





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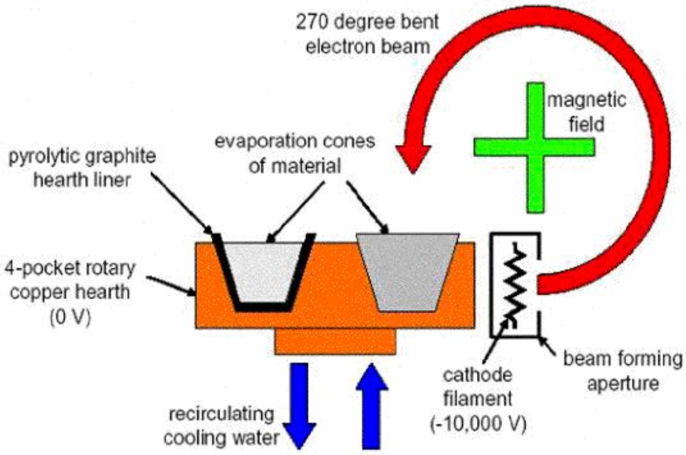
Electron Beam Heated Evaporation Source



source: http://www.engr.washington.edu/~cam/PROCESSES/NEWtutorial.html

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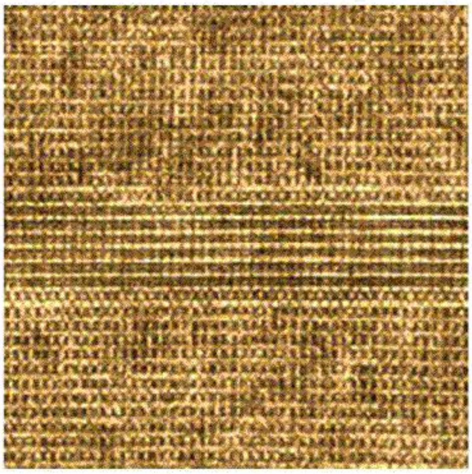
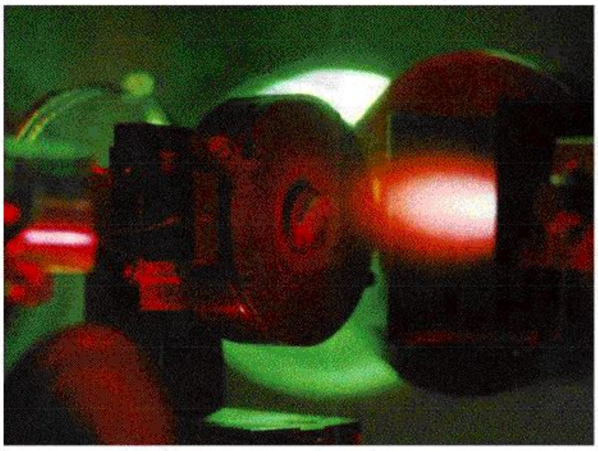
Nm-thick multilayers: e.g. PLD





Pulsed Laser Deposition

Chemical vapor deposition (CVD)

- APCVD -Atmospheric Pressure
- LPCVD -Low Pressure
- PECVD -Plasma Enhanced

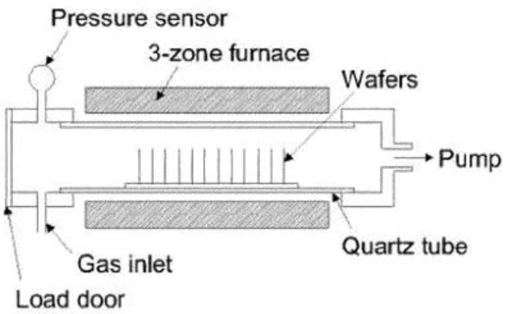
- Different method means different
  - chemical, physical, electrical, mechanical properties
  - deposition rate and uniformity, thermal budget

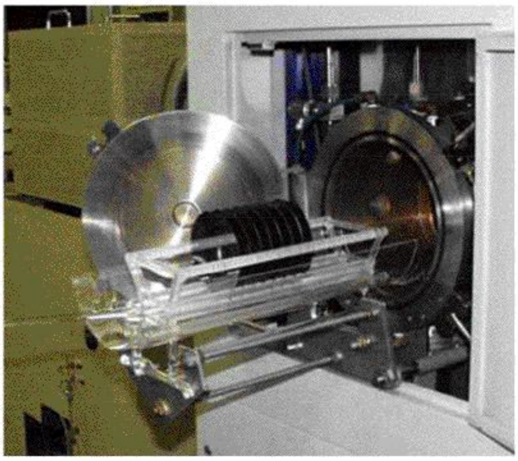
- materials:
  - oxides, nitrides, poly or amorphous silicon, doped silicate glasses, metals, polymers

LPCVD SiO_2

Deposition of silicon dioxide from TEOS in vacuum furnace at 650-750 °C:

$Si(OC_2H_5)_4 \rightarrow SiO_2$ + gaseos products





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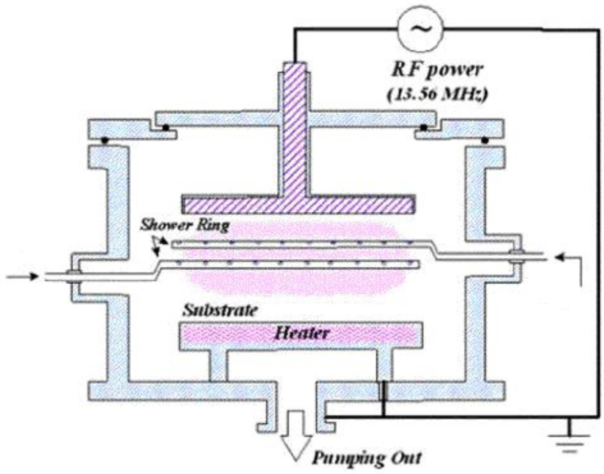
PECVD SiO_2

Deposition of silicon dioxide in plasma reactor at 250-400 °C:

$SiH_4 + 2\ N_2O \rightarrow SiO_2$ + gaseos products



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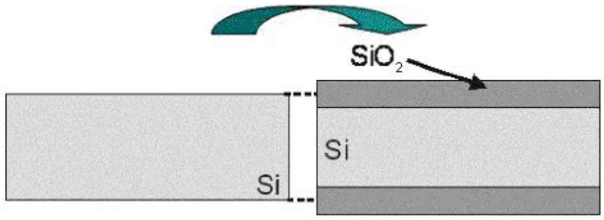
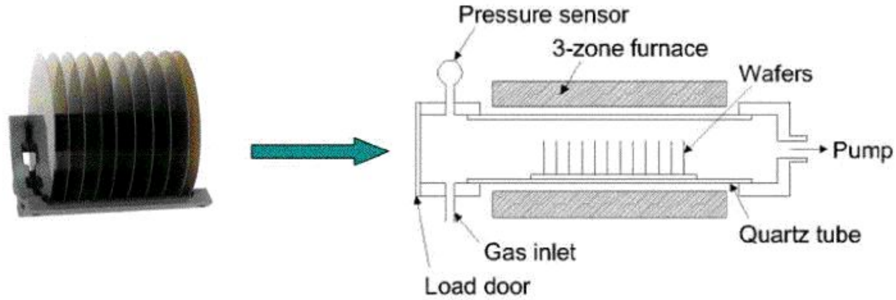
Thermal oxidation of silicon

Oxide formation on silicon in furnace at 900-1200 °C:

$Si + O_2 \rightarrow SiO_2$ ("dry" oxidation)

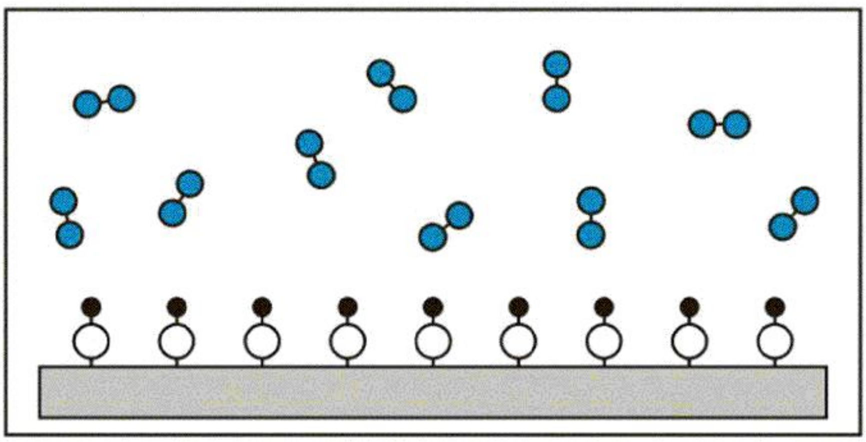
$Si + H_2O \rightarrow SiO_2 + H_2$





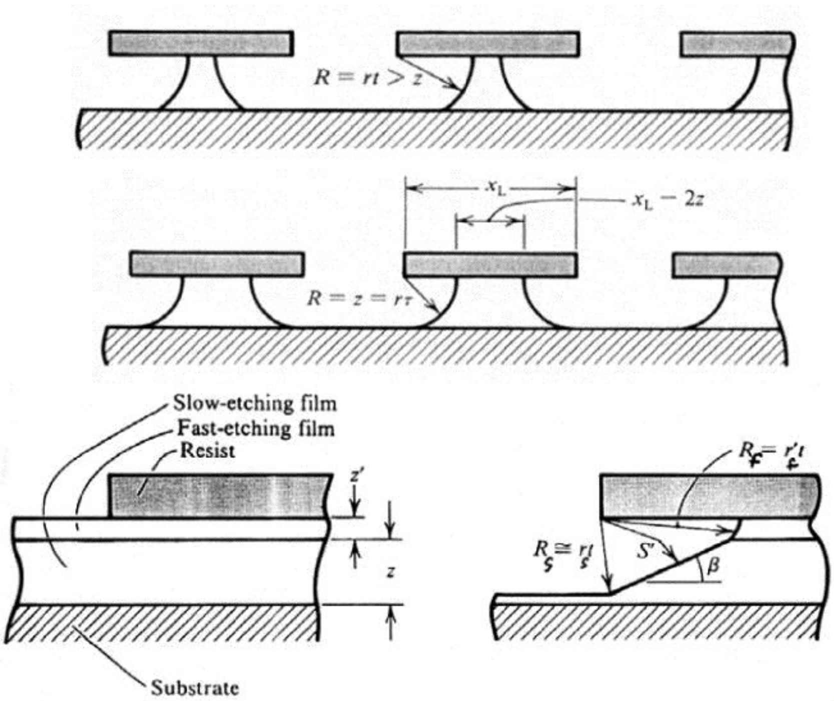
Atomic layer CVD: layer by layer

Termination and re-activation
Multiple species

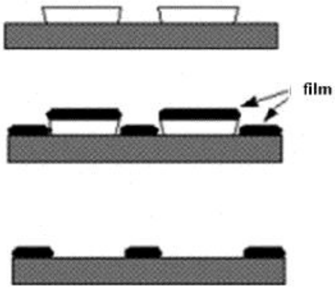


Methods
to make a pattern
in a thin film

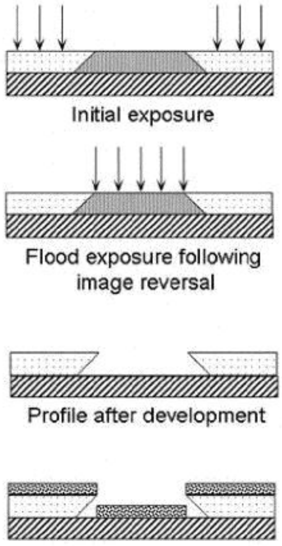
Etching of thin films through mask layer



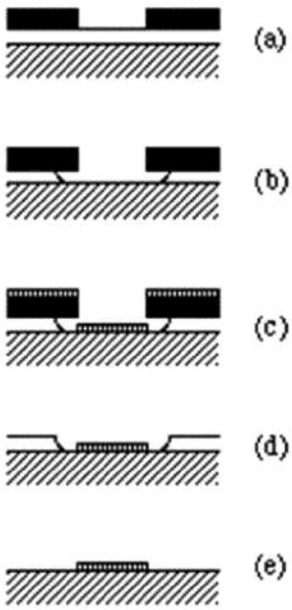
Lift-off photolithography



basic lift-off process



lift-off with
image reversal resist



assisted lift-off

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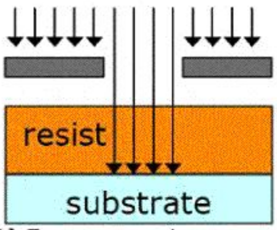
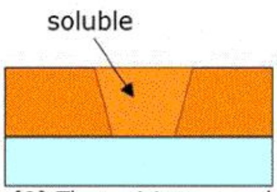
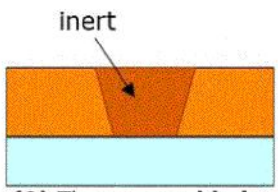
Intermezzo: image reversal resist



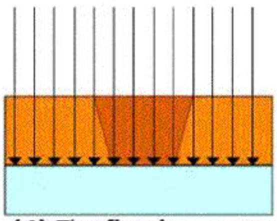
(1) Exposure using an inverted mask (the exposed areas finally remain)



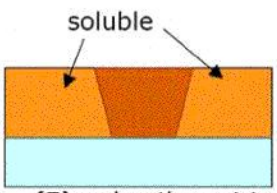
→ **(2)** The resist now would behave like an exposed positive resist.



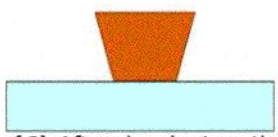
→ **(3)** The **reversal bake** cross-links the exposed area, while the unexposed area remains photo-active



→ **(4)** The **flood exposure** (without mask) ...



→... **(5)** makes the resists, which was not exposed in the first step, soluble in developer



→ **(6)** After developing, the areas exposed in the first step now remain

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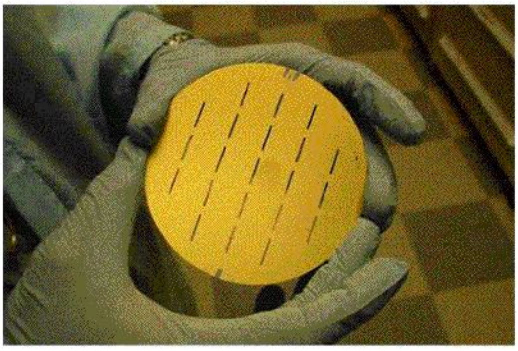
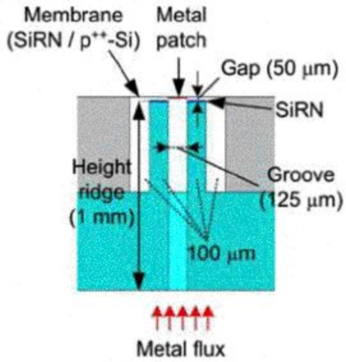
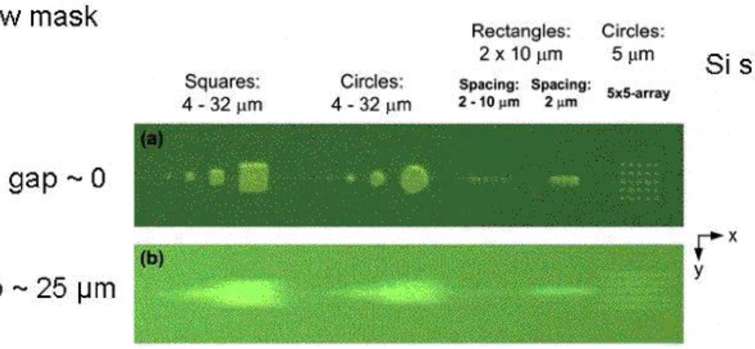
Shadow mask thin film deposition



metal shadow mask



Si shadow mask



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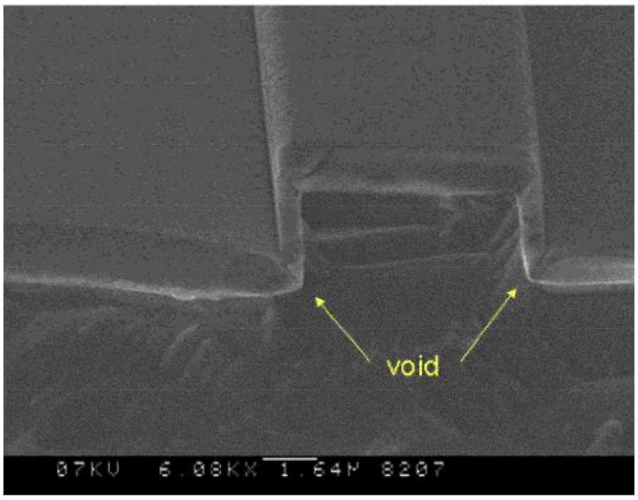
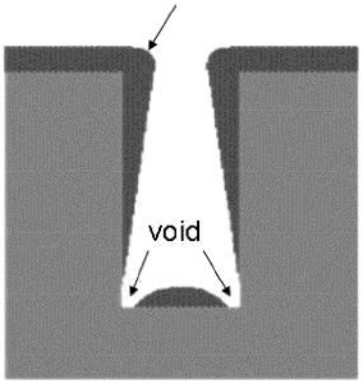
Thin film step coverage

Step coverage depends on deposition mechanism

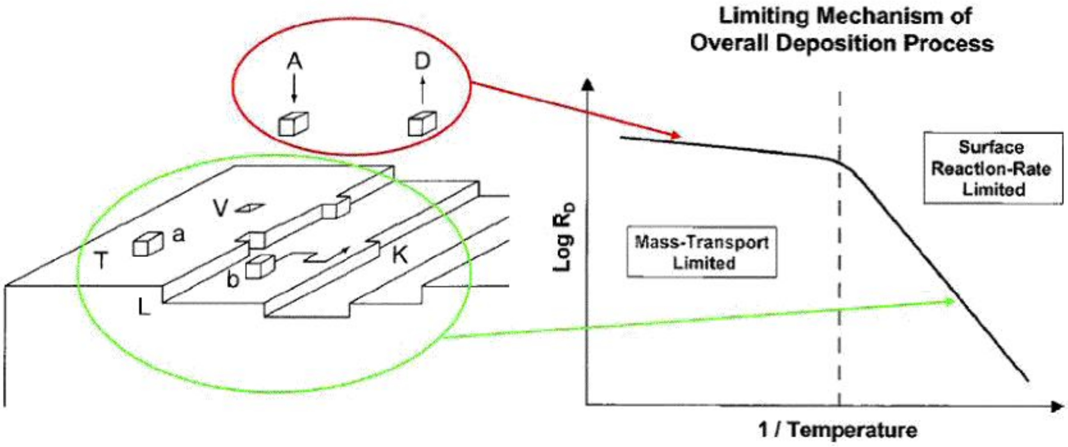


PECVD SiON layer on silicon ridge
(deposition governed by diffusion)

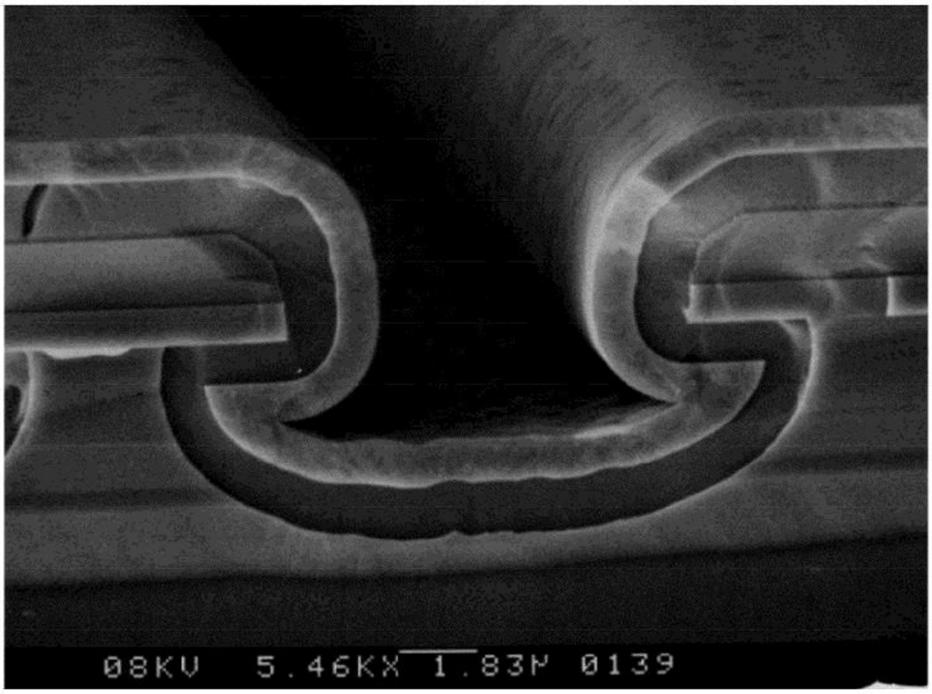


Typical profile for PVD
(directional deposition)

General deposition mechanisms



Perfect step coverage with LPCVD



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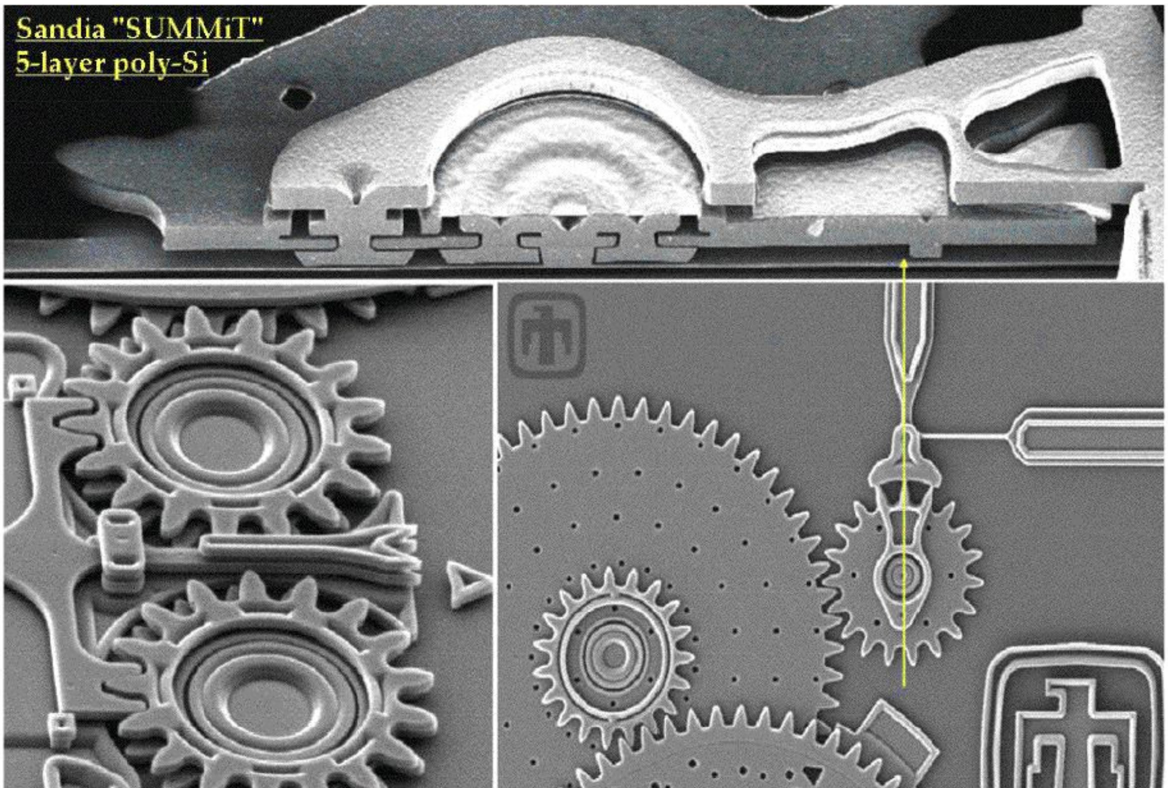
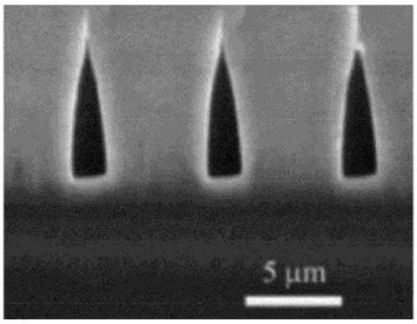
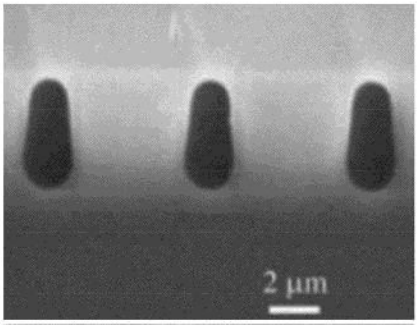
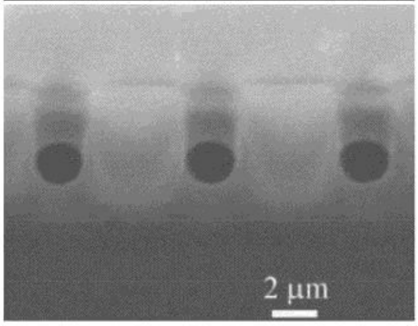


Overhang used for microchannels







Void formation in a 6-µm-thick BPSG layer deposited over template ridges with *h* 6.4µm, *w* 4µm and *d* 3µm: a. as deposited, b. and c. annealed at 1050 °C for 4 and 12 hrs, resp.

Callender e.a. J. Mater. Res.20, 759-764 (2005)

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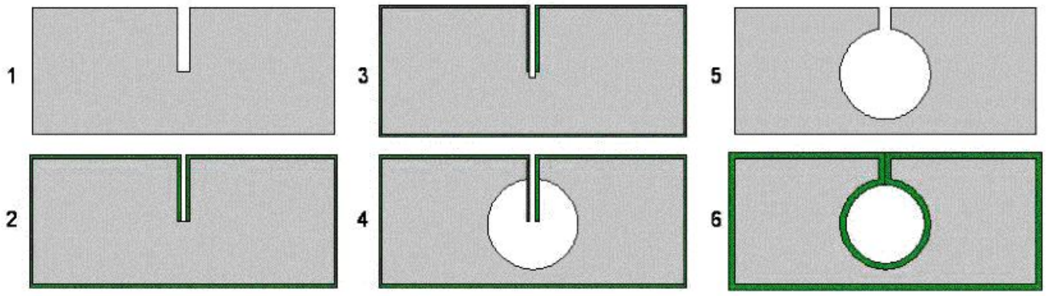
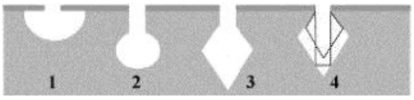
Combination of microfabrication methods:

Buried microchannels

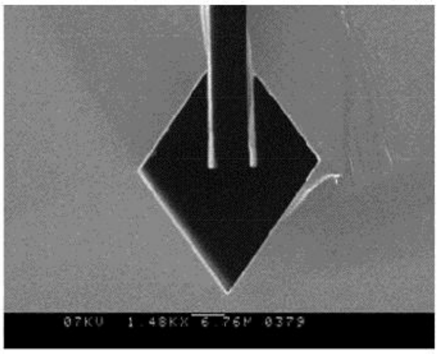
Burried channel process





Different profiles of buried channels

M.J. de Boer et al. J. MEMS 9, 2000, pp. 94-102



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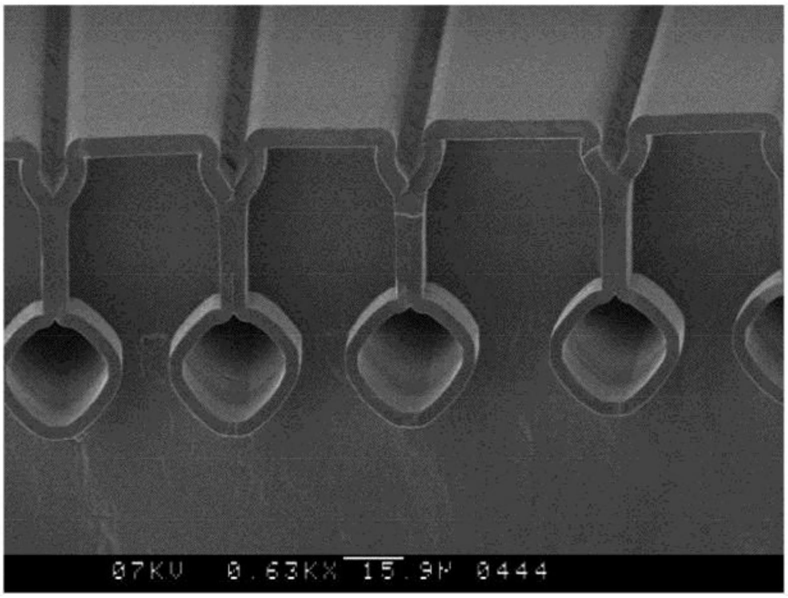
Silicon nitride tubes



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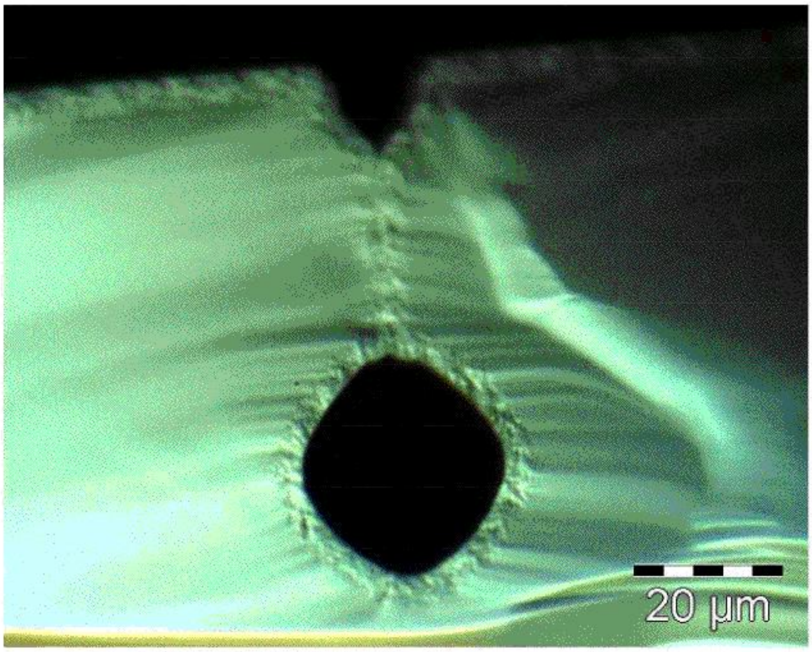
Polysilicon microchannels (opt. microsc.)



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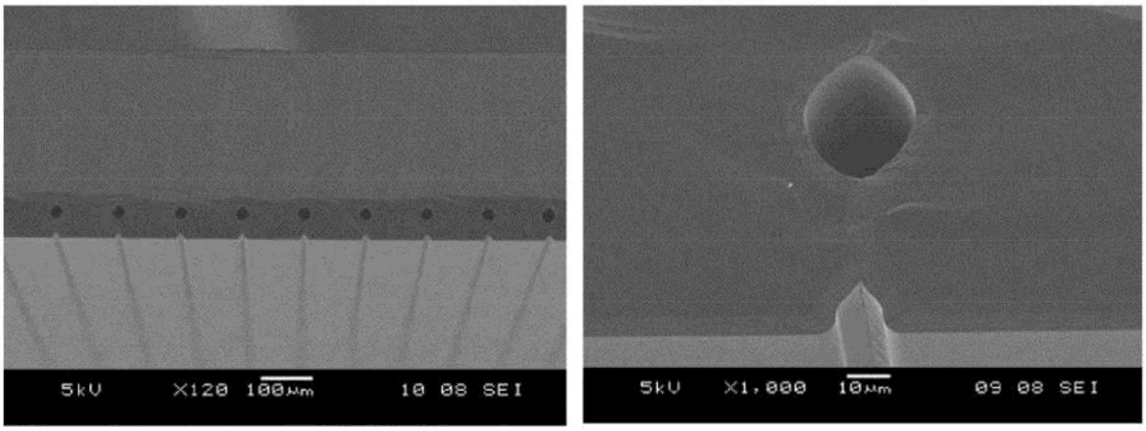
Polysilicon microchannels (SEM)



Inner diameter channel: 27 - 30 microns

Center of channel positioned 54 microns below the wafer surface

Poly-Si layer thickness: 3.4-3.6 microns inside channel, 4.9-5.1 microns on top surface

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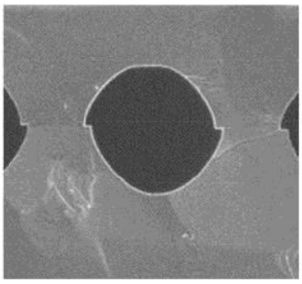
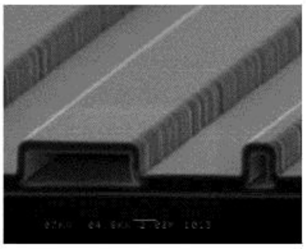
Microchannel for gas chromatography



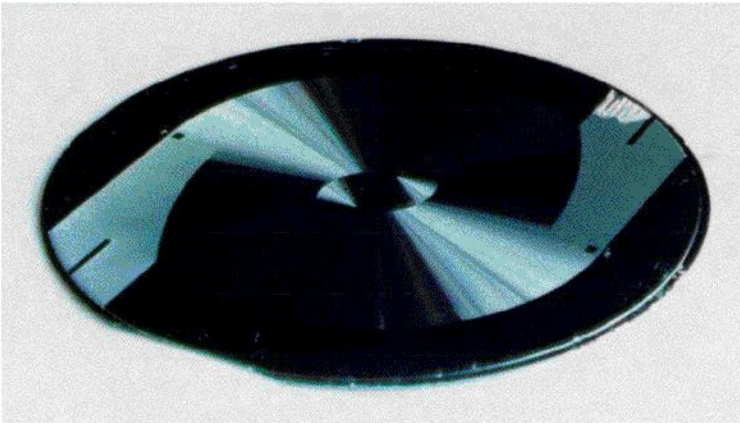
bonded wafer pair

problem: misalignment



surface micromachined

problem: non-circular, only low pressure



buried microchannel: circular cross-section, smooth walls

problem: SiN stress leads to wafer curvature

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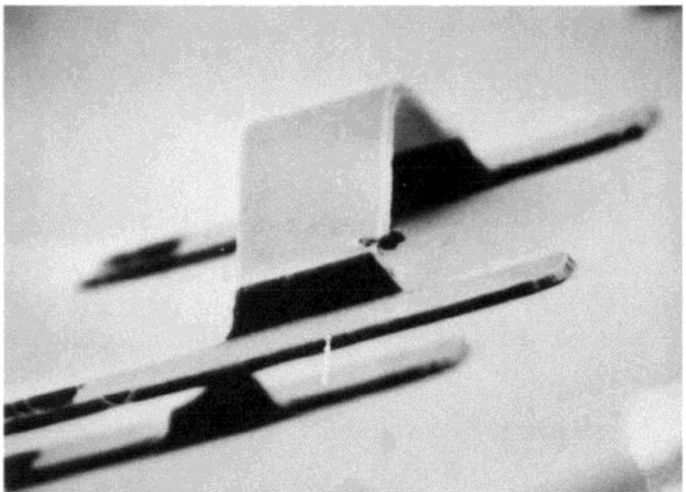
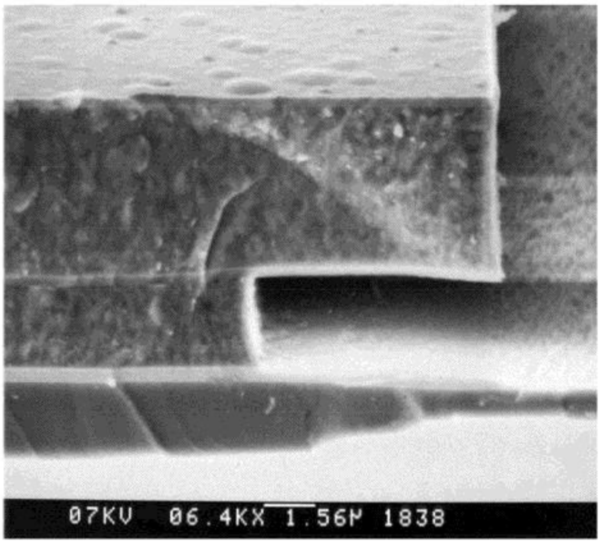
Residual stress in thin films



Sacrificial layer etching



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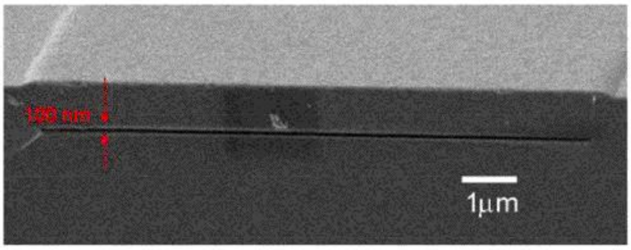
About scaling:

It took nature forever* to make this arch

* ~million years i.e. tens of ppms of the age of the universe

Going to nano:

It takes us forever* to make this nanochannel



* ~ 100,000 seconds i.e. tens of ppms of the age of a microfabrication expert

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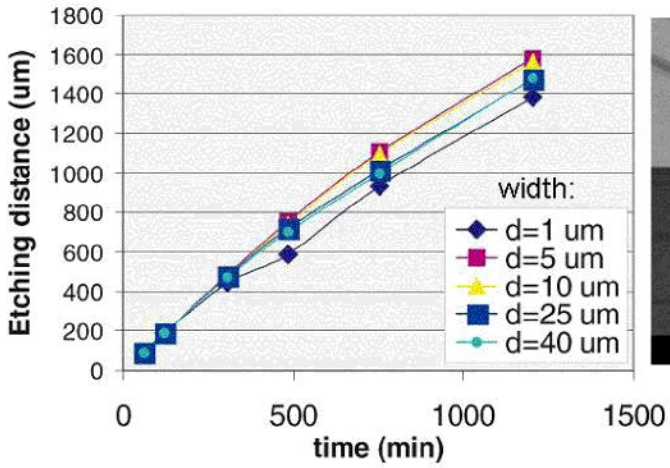
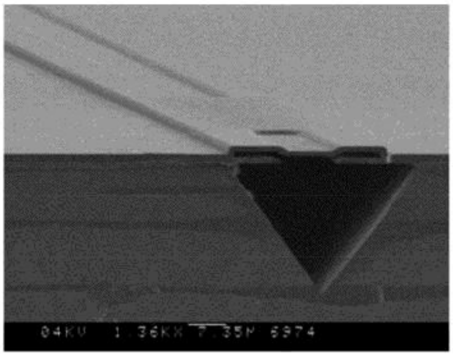
Removal of layer in microchannel

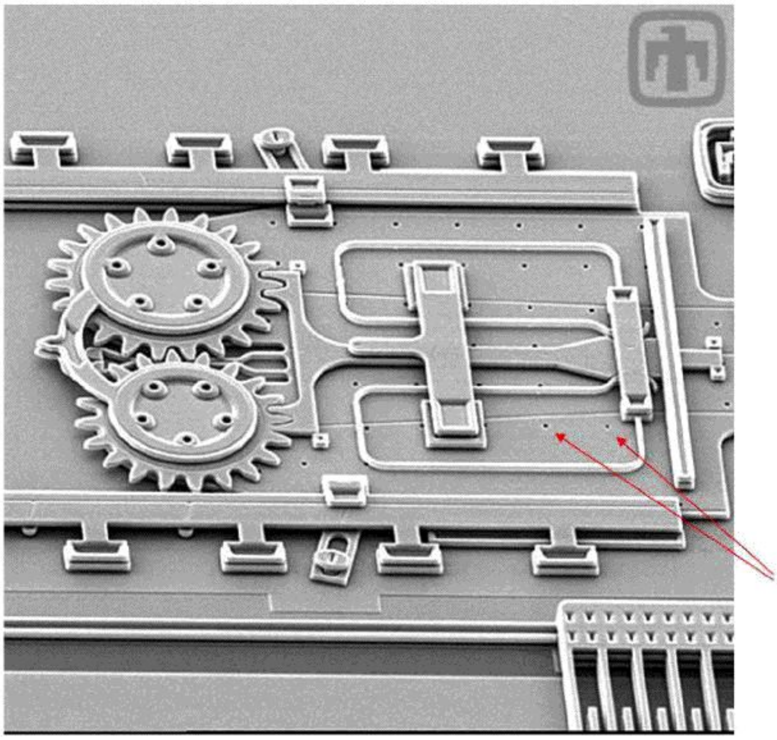




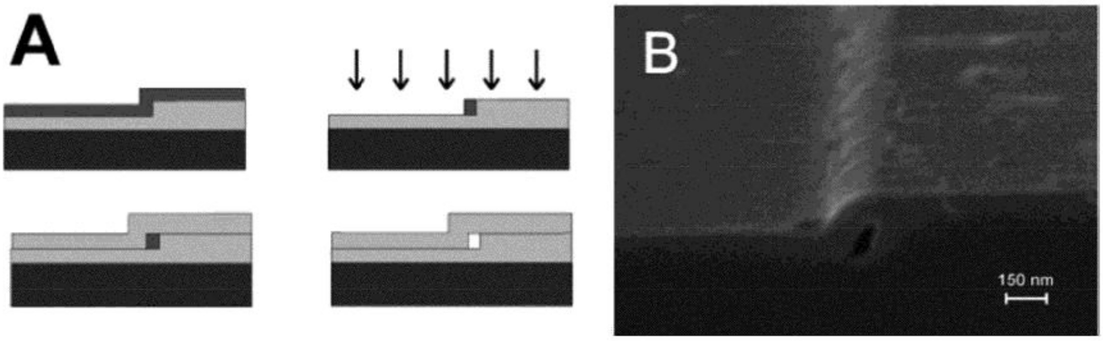
2 μm poly-Si layer in 25 wt% KOH solution at 74 ◦C

Berenschot e.a. J. Micromech. Microeng. 12, 621-624 (2002)

Access holes for etching



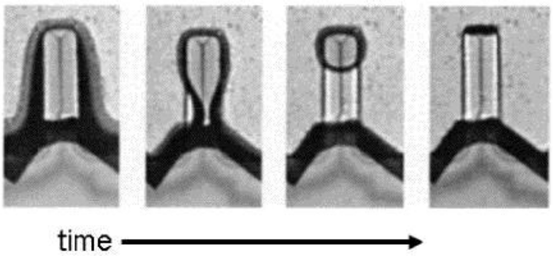
Nanochannels

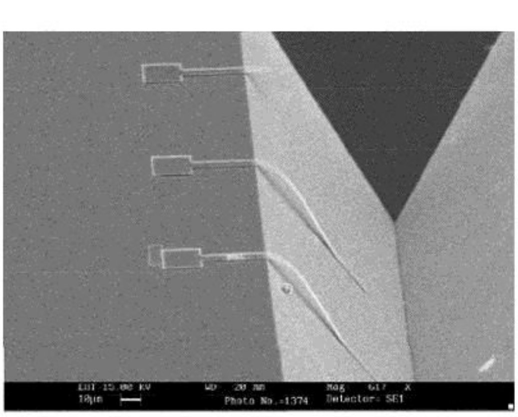


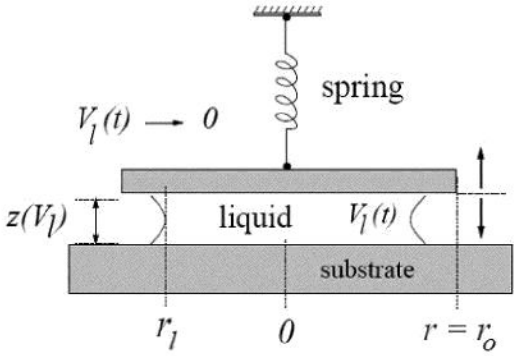
Step A from: Kim e.a. Appl. Phys. Lett. 79, 3812-3814 (2001)
Complete proces: Tas e.a. Nanolett. 2, 1031-1032 (2002)
Etching time (L = 0.64 mm) is 15 hrs

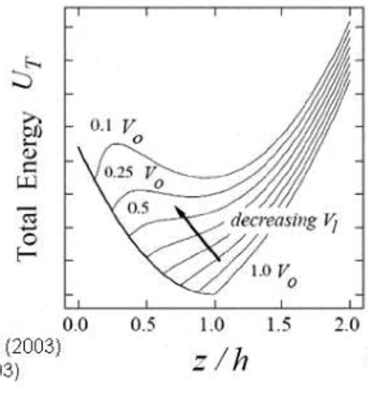
Stiction

Stiction cause: surface tension during drying



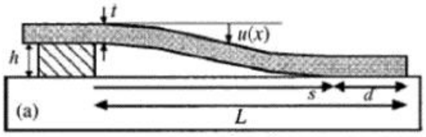






Review: Zhao e.a. J.Adhesion Sci.Technol.17, 519-546 (2003)
Theoretical model: Mastrangelo e.a J.MEMS 2, 44 (1993)

Maximum dimensions without stiction



$$L_{\max} = \left(\frac{3Et^3h^2}{8W_a}\right)^{1/4}$$

For other structures: $$L_{\max}, w_{\max}, R_P\big|_{\max} = \left(\frac{b+\sqrt{b^2+4c}}{2}\right)^{1/2}$$

Microstructure	b	c
Doubly clamped beam	$\frac{512}{105}\frac{\sigma_R h^2 t}{W_a}$	$\frac{128}{5}\left[1+\frac{256}{2205}\left(\frac{h}{t}\right)^2\right]\frac{Et^3h^2}{W_a}$
Square plate	$\frac{5022}{301}\frac{\sigma_R h^2 t}{W_a}$	$\left[1+\frac{12}{31}\left(\frac{h}{t}\right)^2\right]\frac{186Et^3h^2}{(1-\nu^2)W_a}$
Circular plate	$\frac{17}{4}\frac{\sigma_R h^2 t}{W_a}$	$\frac{40Et^3h^2}{3(1-\nu^2)W_a}$

ν: Poisson's ratio
σ_R: residual stress
E: Young's modulus

L, w, R_P are the length of the doubly clamped beam, width of the square plate and radius of the circular plate, respectively

Zhao e.a. J.Adhesion Sci.Technol.17, 519-546 (2003)

Avoid stiction: anti-stiction coatings

Laplace pressure:

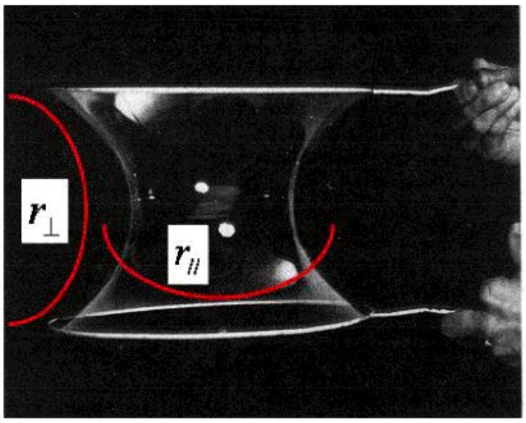
$$\Delta P = \gamma\left(\frac{1}{r_{\parallel}} + \frac{1}{r_{\perp}}\right)$$

For long beams/cantilevers:

$$\Delta P = \frac{\gamma}{r_{\perp}} = \frac{2\gamma\cos\theta}{d}$$

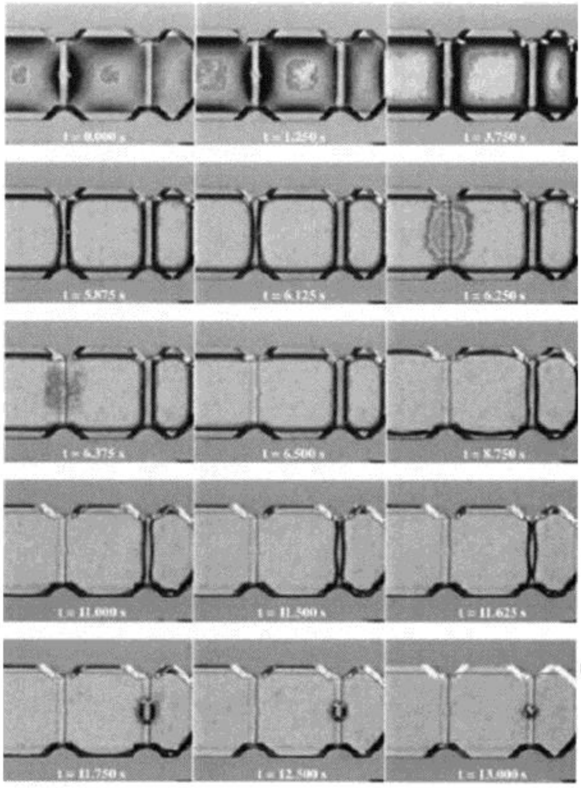
For hydrophilic surfaces: $\theta < 90^{\circ}$
resulting in an attractive capillary force

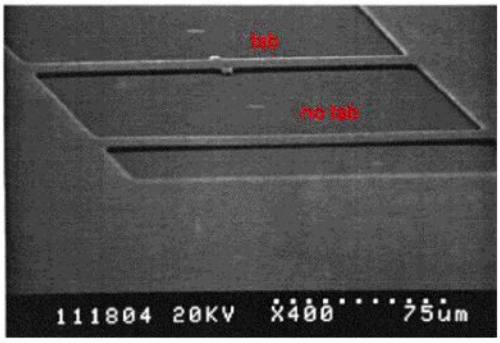
Solution: hydrophobic coating (e.g. fluorocarbon)

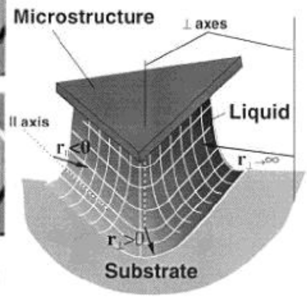


Review: Maboudian e.a. Surf. Sci. Rep. 30, 207-269 (1998)

Avoid stiction: tabs at side of beam







Laplace pressure:

$$\Delta P = \gamma\left(\frac{1}{r_{\parallel}} + \frac{1}{r_{\perp}}\right)$$

Abe e.a. J. Micromech. Microeng. 6, 213-217 (1996)

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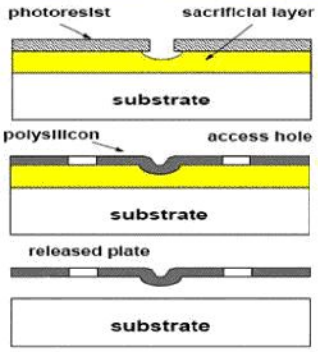
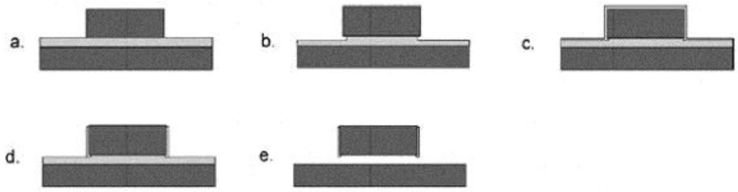
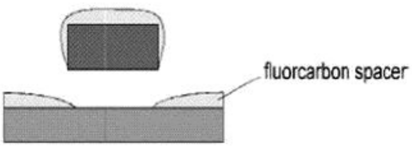
Avoid stiction: reduce contact area



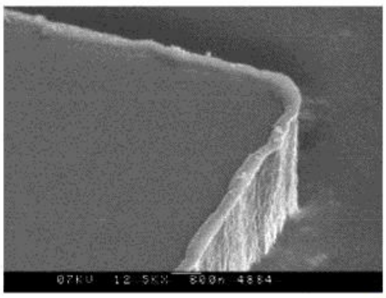
Bumps

Side-wall spacers





alternative type



Review: Tas e.a. J. Micromech. Microeng. 6, 385-397 (1996)

Alternative: increase surface roughness

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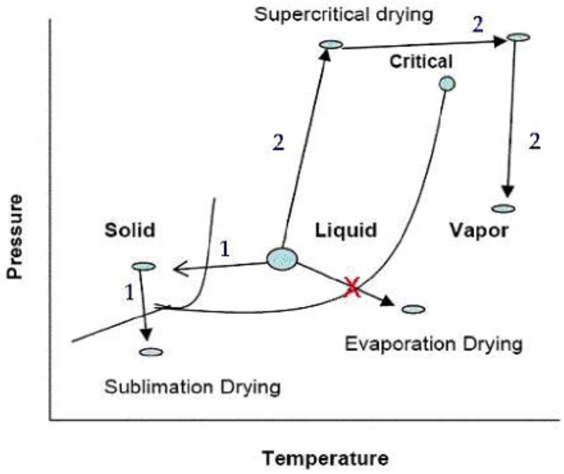
Avoid stiction: avoid meniscus



1. **freeze drying (e.g. cyclohexane)**
2. **supercritical drying (CO_2)**

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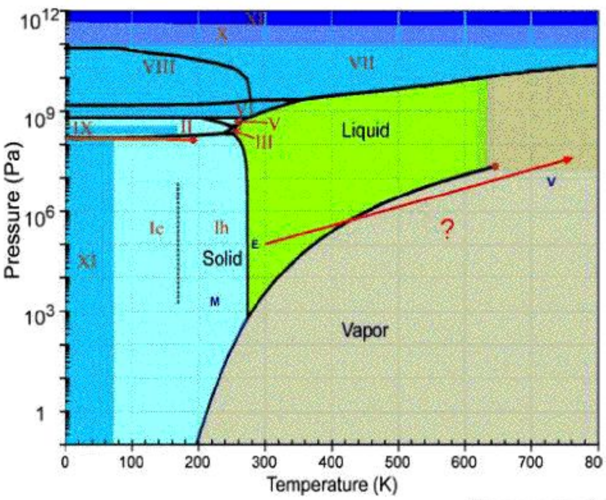
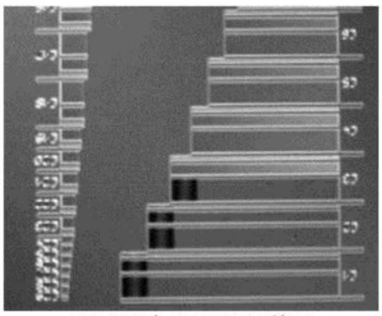
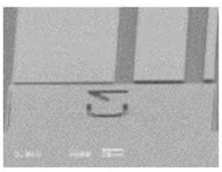
Avoid stiction: "flash" release

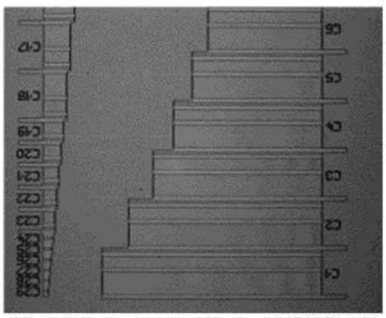


phase diagram of water



normal evaporation





"flash" evaporation at 600 ^{o}C

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Deladi e.a. Proc. SAFE 2003, http://www.stw.nl/programmas/safe/

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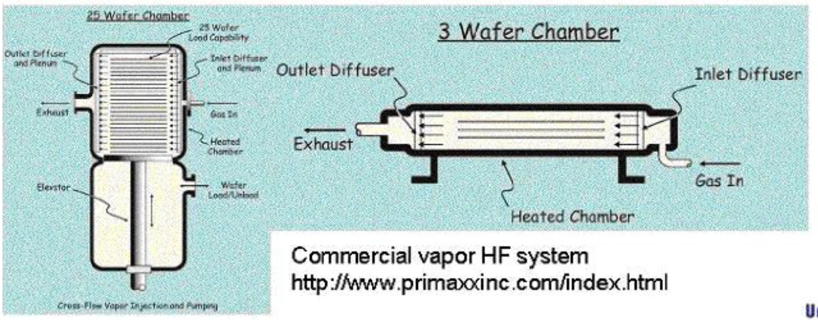
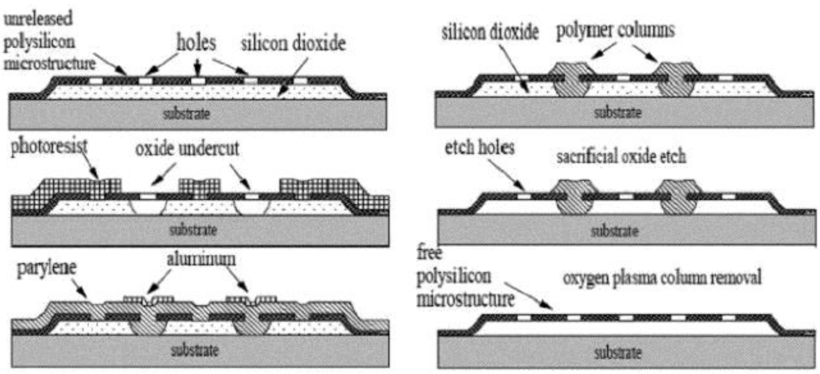
Avoid stiction: dry release

- HF vapor phase etching of sacrificial silicon dioxide layer under (poly)silicon or silicon nitride microstructure
- XeF_2 vapor or plasma etching of sacrificial (poly)silicon under silicon oxide or nitride microstructure
- O_2 plasma etching of polymeric sacrificial layer (e.g. photoresist under Al microstructure



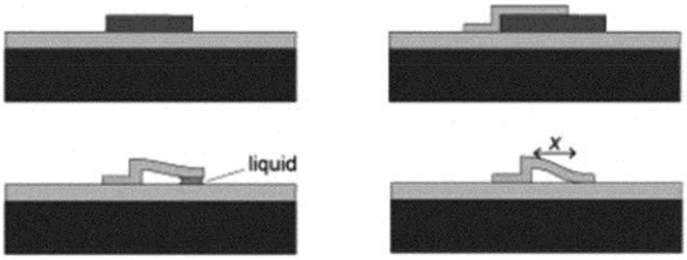
Commercial vapor HF system
http://www.primaxxinc.com/index.html

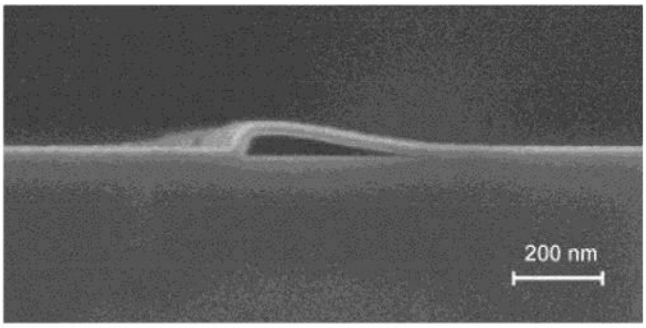
Avoid stiction: increase stiffness (temporarily)



C. H. Mastrangelo, "Suppression of stiction in MEMS," invited paper, 1999 Spring MRS Meeting, Boston, MA, Dec 1999; available from: http://www.eecs.umich.edu/chm-group/

How to use stiction





Tas e.a. Nanolett. 2, 1031-1032 (2002)
Etching time is 4 min.

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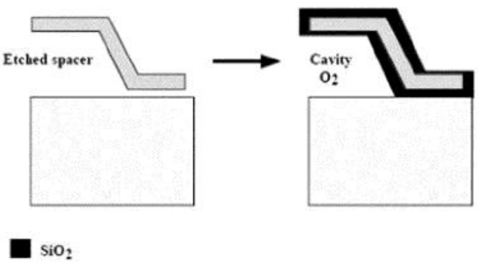
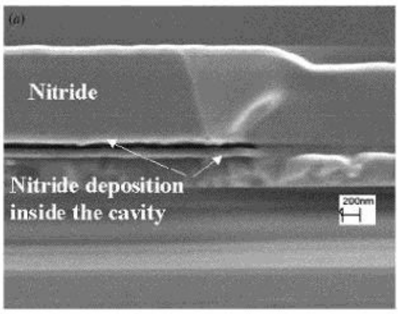
Sealing of microstructure



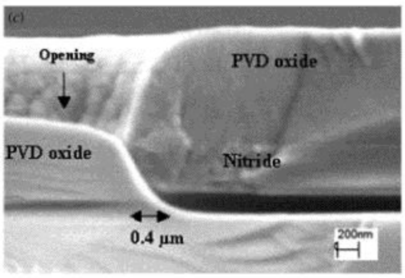
reactive sealing by thermal oxidation of silicon

Important issues:

- pressure remaining in the cavity
- step coverage
- film deposited in cavity

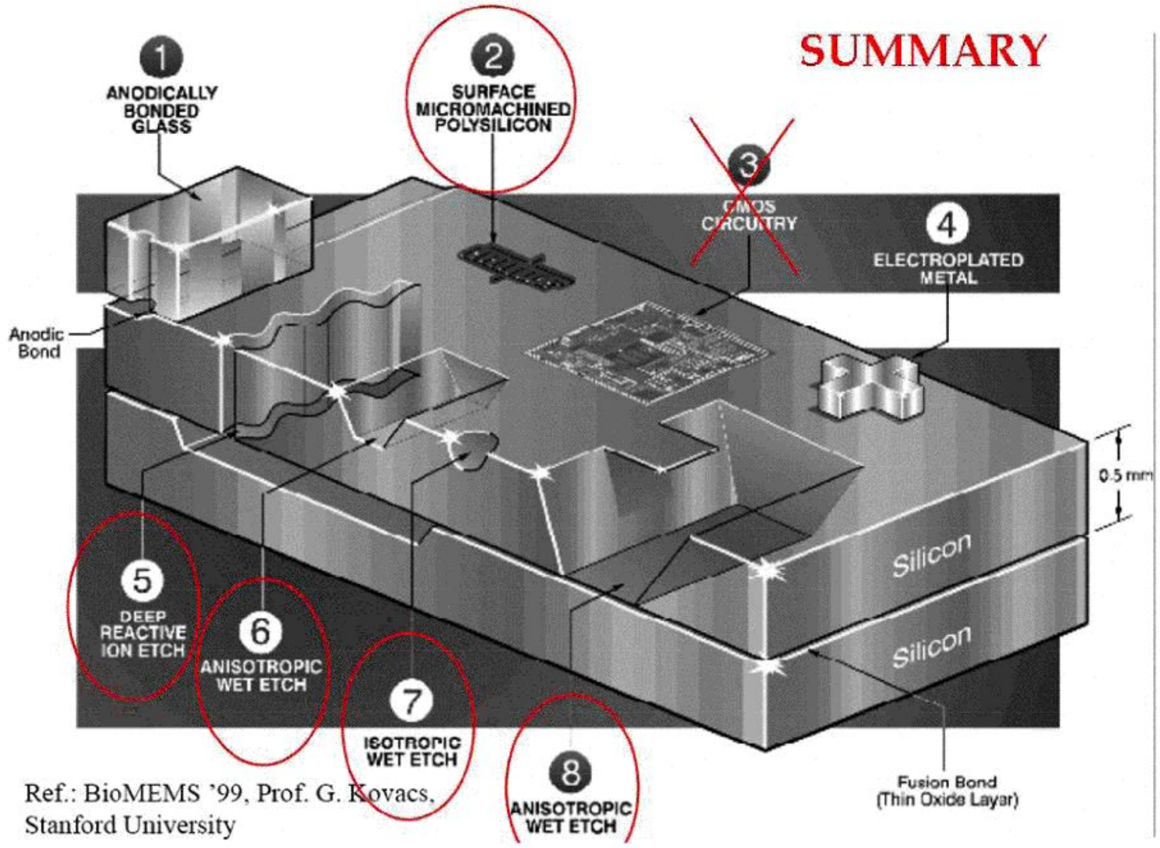


LPCVD silicon nitride



PVD silicon oxide

MESA+ Review: Belgacem e.a. J. Micromech. Microeng. 14, 299-304 (2004) University of Twente The Netherlands


SUMMARY
1
ANODICALLY BONDED GLASS
2
SURFACE MICROMACHINED POLYSILICON
3
CMOS CIRCUITRY
4
ELECTROPLATED METAL
Anodic Bond
0.5 mm
Silicon
Silicon
5
DEEP REACTIVE ION ETCH
6
ANISOTROPIC WET ETCH
7
ISOTROPIC WET ETCH
8
ANISOTROPIC WET ETCH
Fusion Bond
(Thin Oxide Layar)
Ref.: BioMEMS '99, Prof. G. Kovacs,
Stanford University