Fabrication of MEMS Devices: Fundamentals and State of the Art

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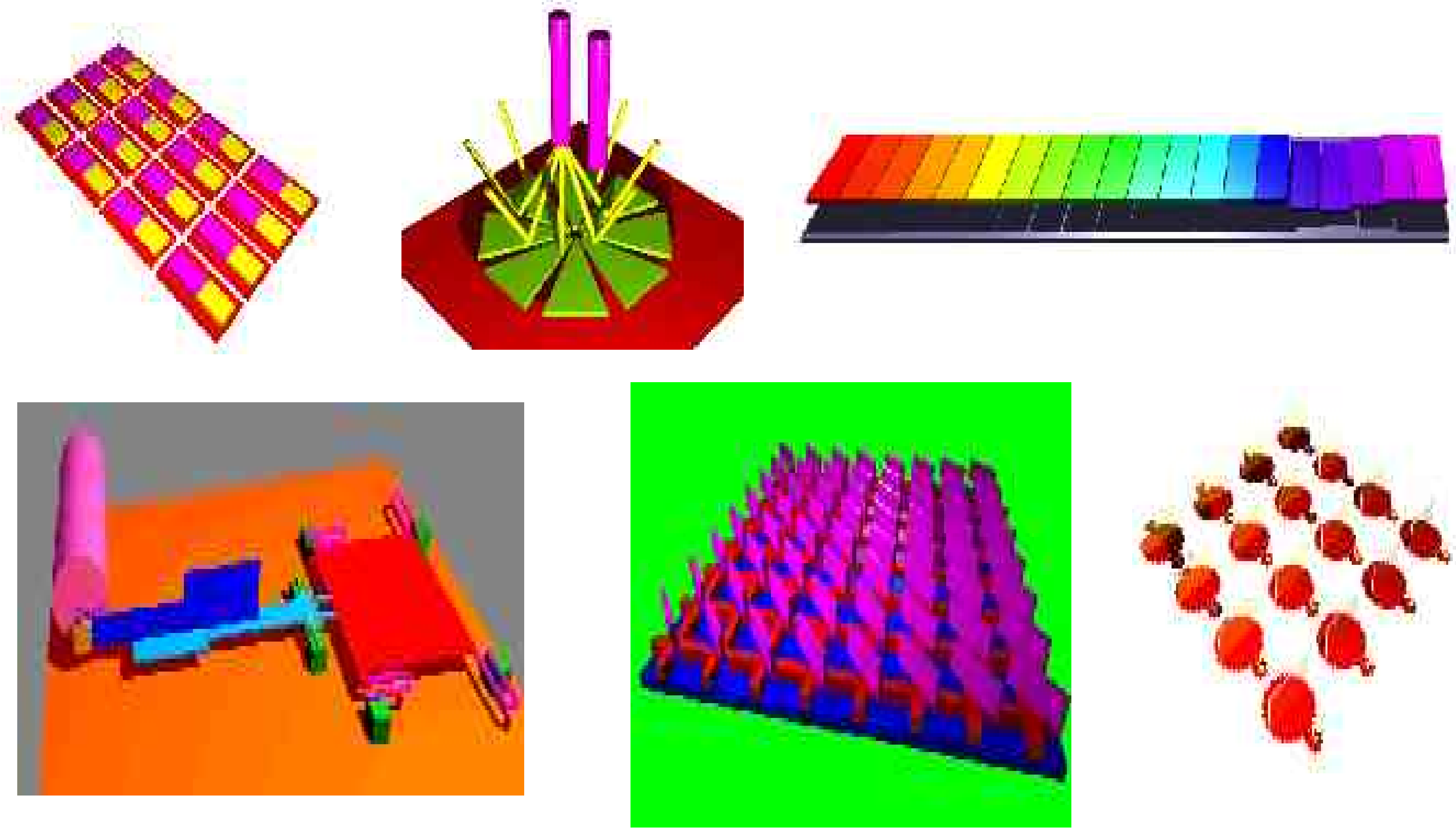
OUTLINE

I. MEMS Basics

II. MEMS Fabrication Fundamentals

III. MEMS Fabrication Processes and Examples
  A. Bulk Micro-machining Processes
    1. Non silicon based HAR
    2. Silicon based
  B. Hybrid Processes
  C. Surface Micro-machining Processes
  D. Soft MEMS Processes

Micro and Nano Machines: Many Different Types of Motion

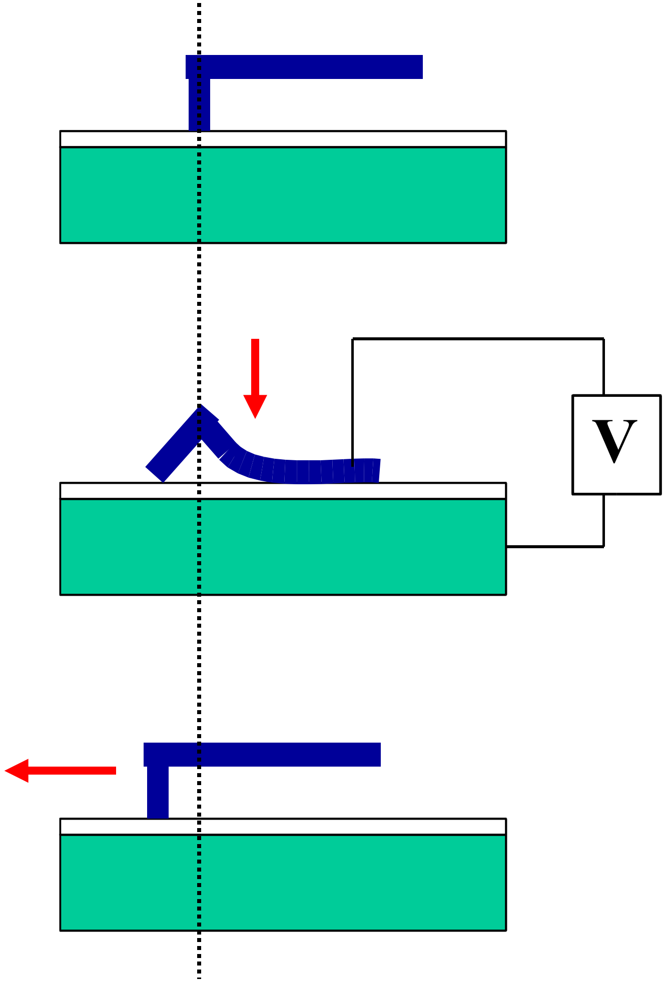


Motion Actuation Methods

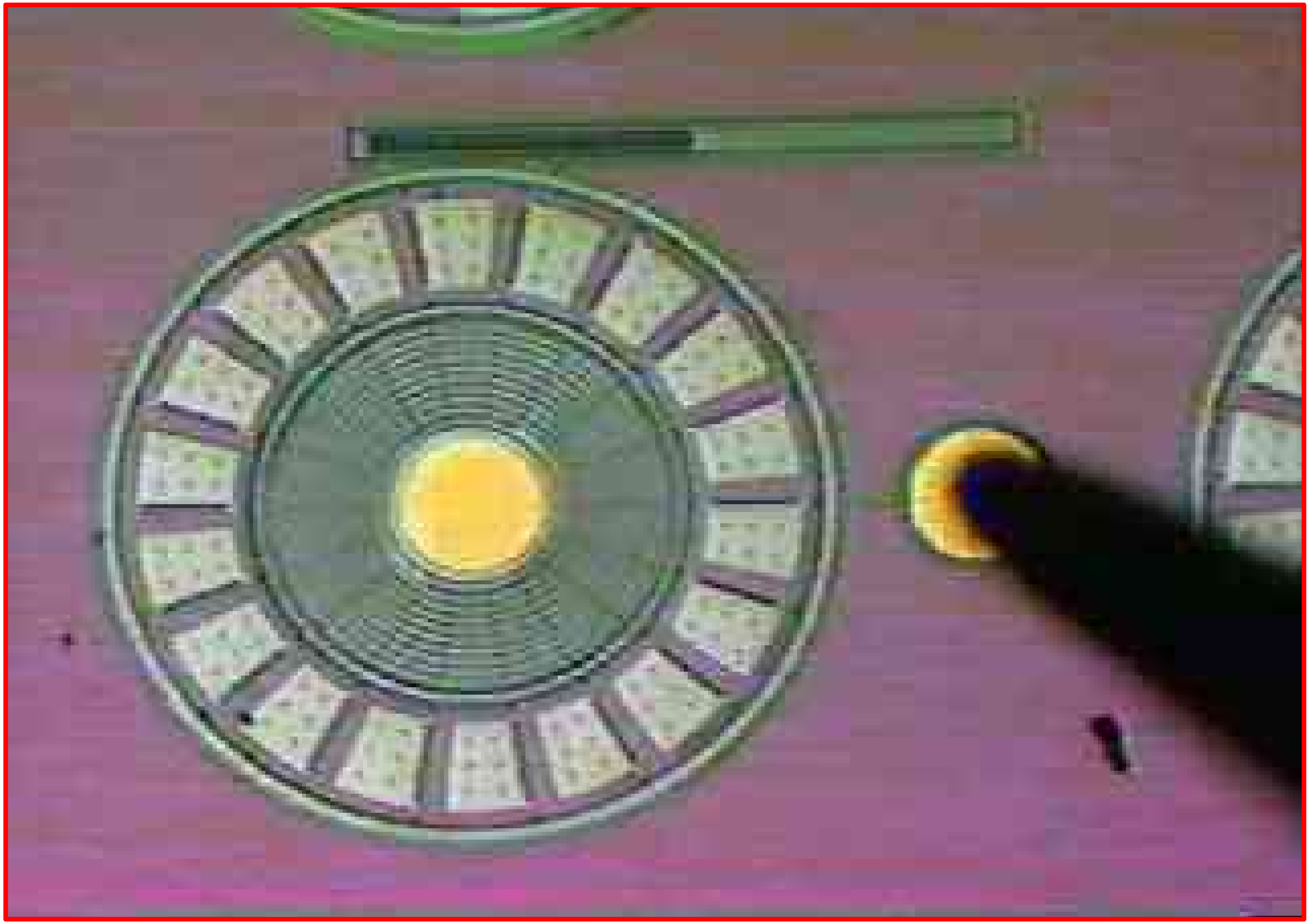
	Voltage Needs	Switching Speed	Current consumption
Electrostatic	**High**	**High**	**Low (none)**
Magnetic	**Low**	**High**	**High**
Thermal	**Low**	**Slow**	**high**

***Others*: piezoelectric, stress relaxation, surface tension, …...**

MEMS and NEMS: In-plane motion



Electrostatic actuation



MEMS FABRICATION BASICS

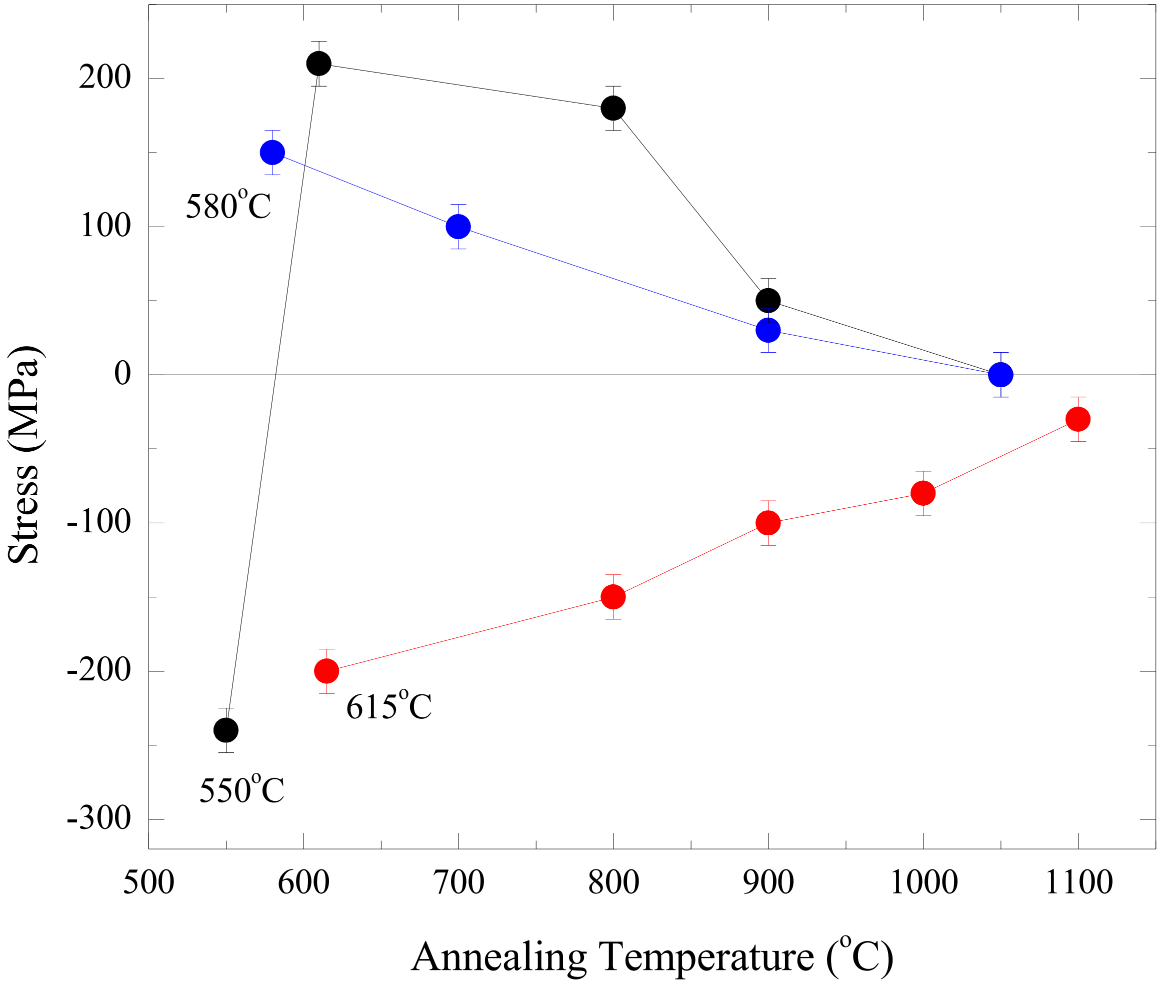
1. **Film Deposition**
2. **Lithography**
3. **Pattern transfer**
4. **Cleaning**
5. **Metrology**
6. **Chemical Mechanical Polishing**
7. **Structure release**

MEMS FABRICATION BASICS: Deposition

Critical Characteristics for MEMS

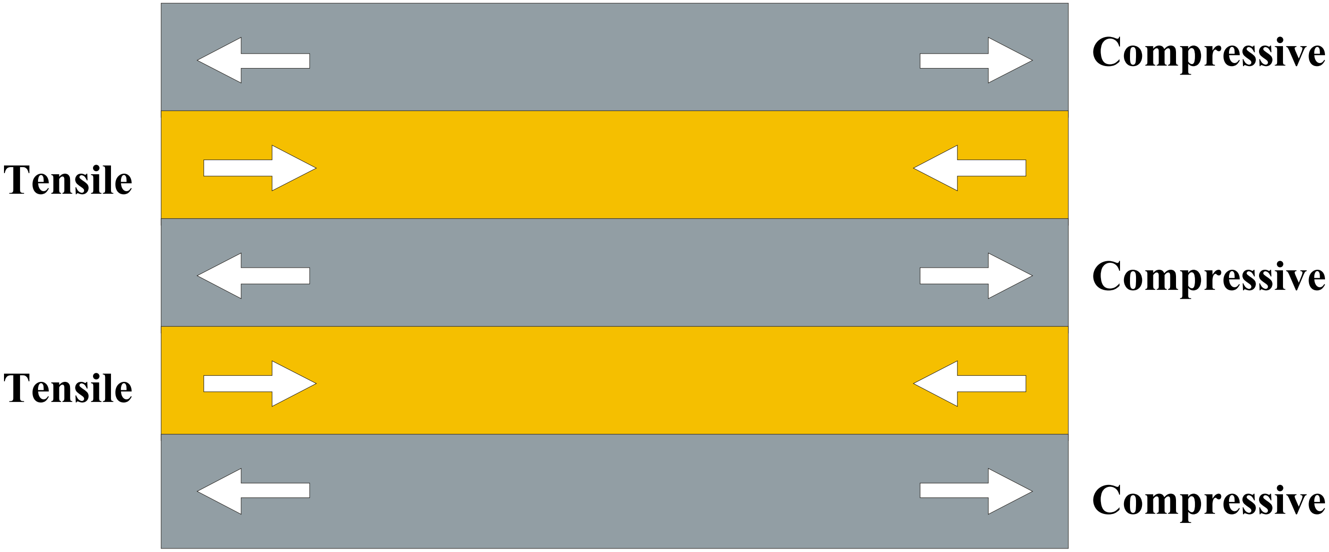
1. **Film stress**
2. **Deposited film gap fill considerations**
3. **Thermal budget considerations**

Controlling Stress in a single layer of poly-Si: Thermal annealing



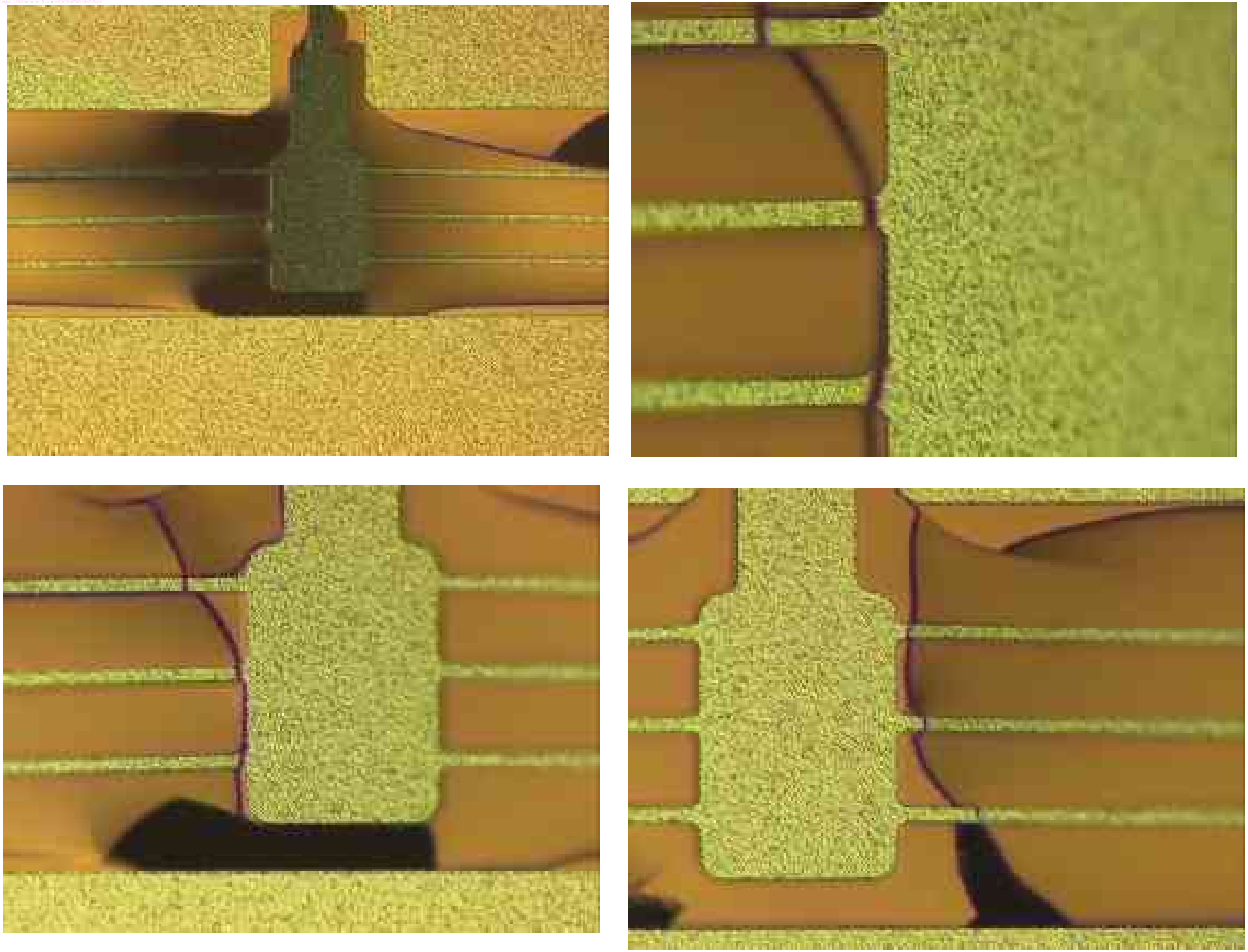
Annealing in N2 at 1050c for 2 hours will reduce the stress to <5MPa/um

Controlling Stress and Gradient Stress with multilayer design



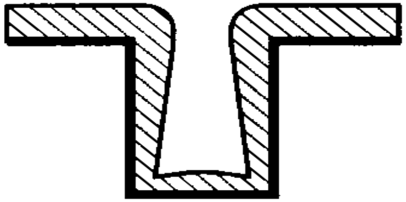
Out-of-plane Stress gradient ~ 2 Mpa/um can be reached. No annealing is needed. This also allows structural design to be customized to compressive or tensile and by varying the layer thickness, a desired stress can be achieved.

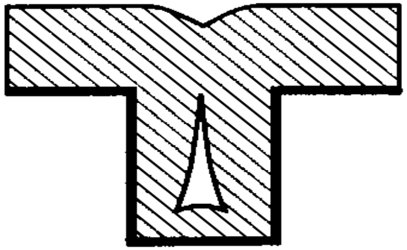
Film stress pattern and process dependencies

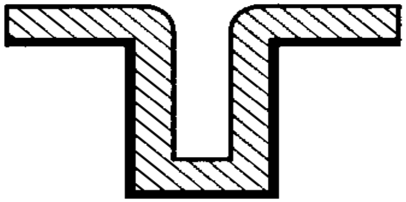


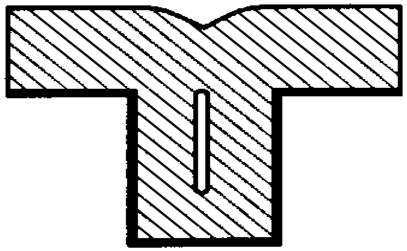
Gap Fill Considerations

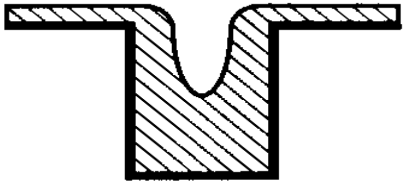
Greater the surface mobility of deposited atoms better the fill.

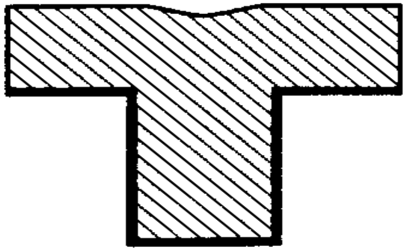

Subconformal


Void


Conformal


Seam


Superconformal
(“superfilling”)


Defect-free

MEMS FABRICATION BASICS: Lithography

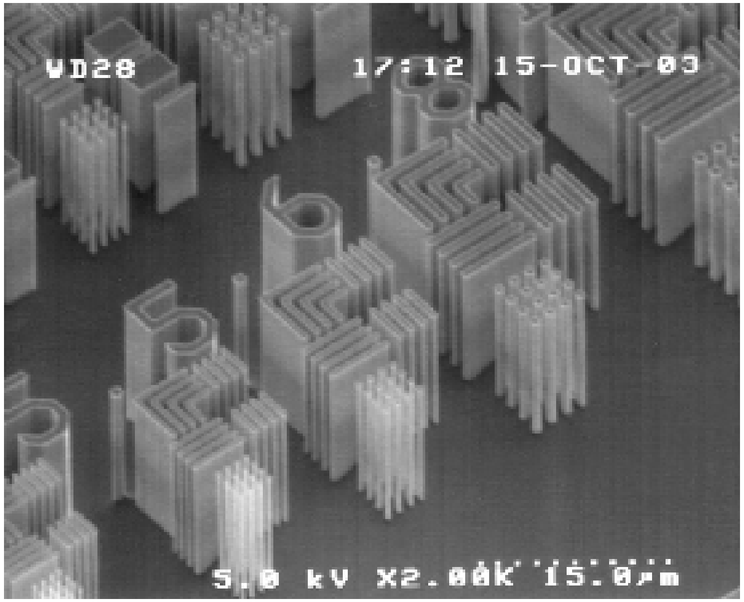
Critical Issues for MEMS

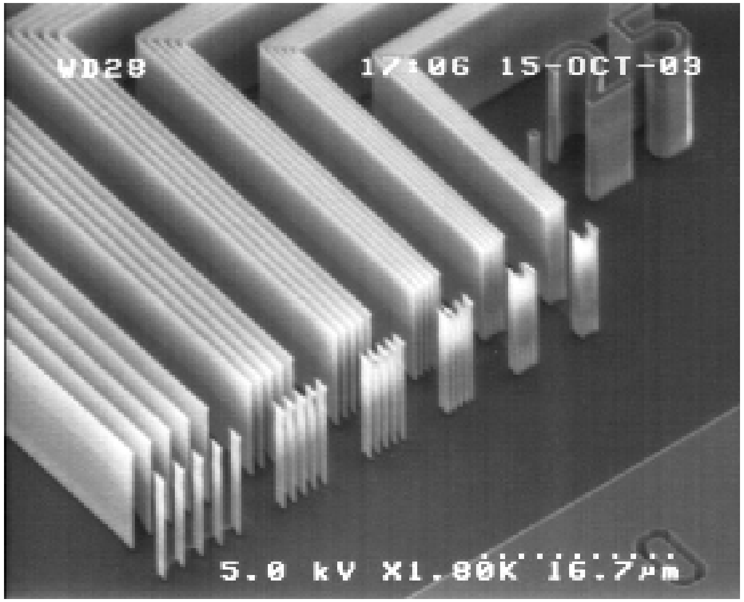
1. Wafer flatness – thick stressed films distort wafers resulting in loading and chucking problems.
2. Depth of focus – thick films result in extreme topography over which fine feature resolution cannot be maintained.
3. Level to level alignment– thick films can result in attenuated or no alignment mark signal compromising alignment capability.
4. Resist material etch selectivity- resist materials for advanced lithography are designed for thin films pattern transfer and may not have sufficient selectivity for dry etch pattern transfer to thick films.

MEMS FABRICATION BASICS: Pattern Transfer

Vertical Comb Drive Etch Process

0.25 um wide, 12um deep fingers, about a factor of 3 more than our initial design target in both width and depth.



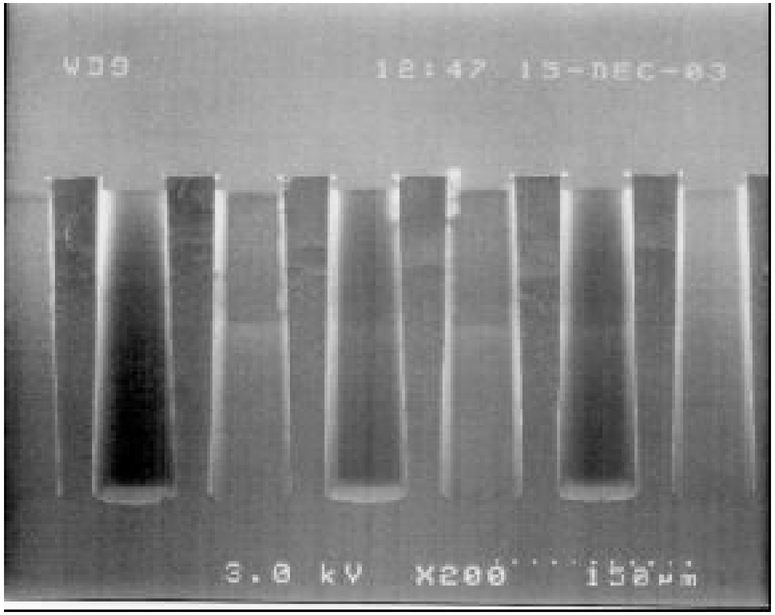


MEMS FABRICATION BASICS: Pattern Transfer

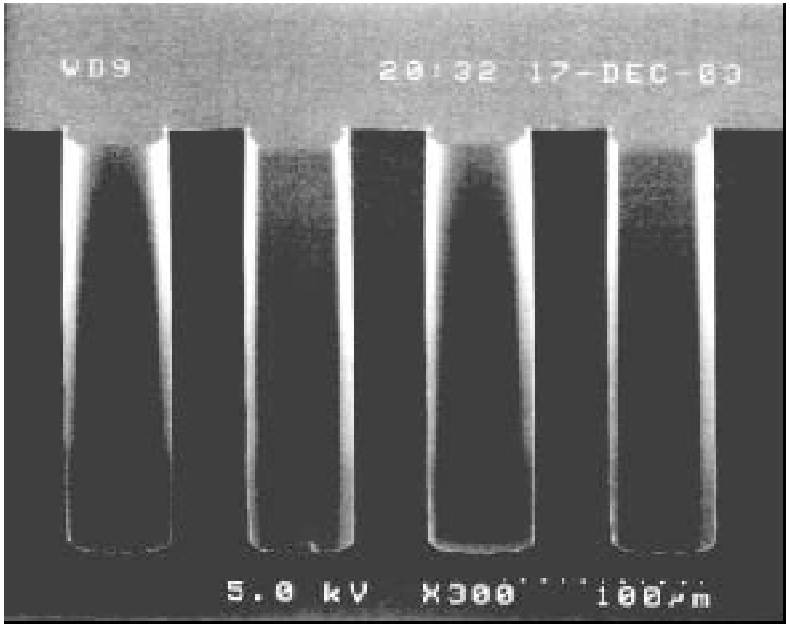
High Aspect Ratio (HAR) Deep Silicon Etching

Bosch process: deposition/etch alternation

C_4F_8 deposition precursor / silicon etch SF_6 and O_2.



50um wide features etched 250um deep with standard Bosch process

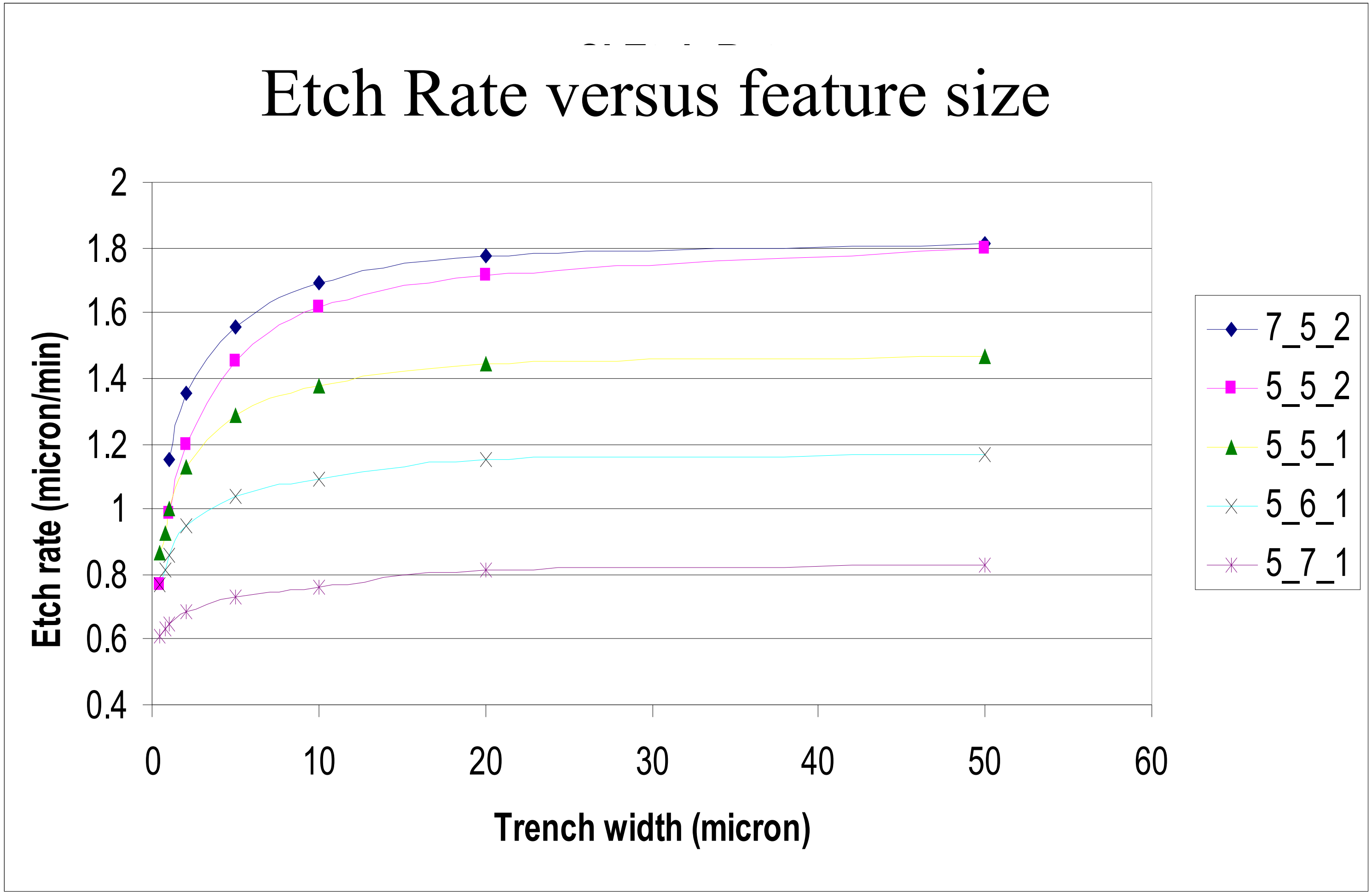


50um wide features etched 240um deep with modified Bosch process

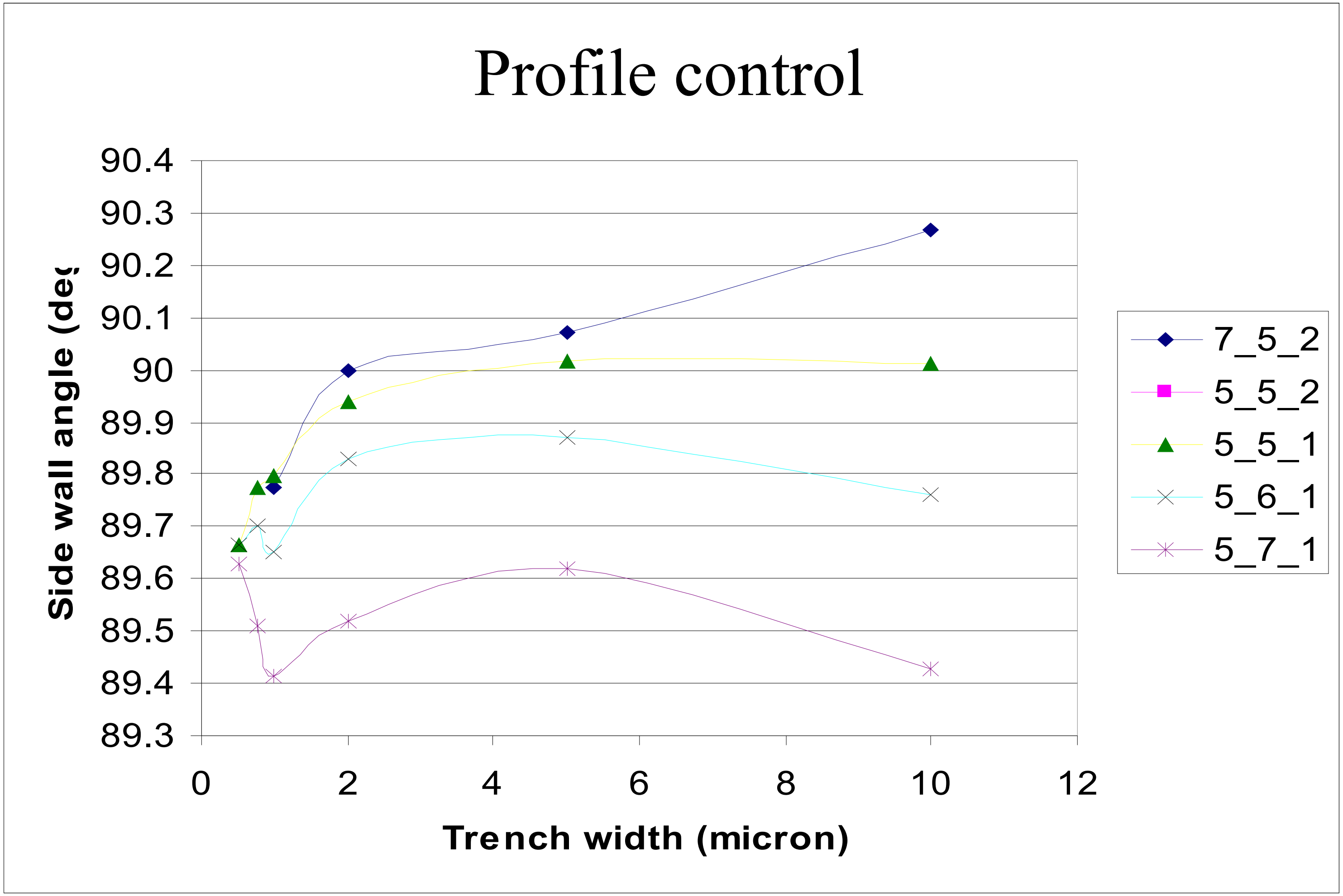
MEMS FABRICATION BASICS: Pattern Transfer

1. Etch Rate versus feature size
2. Profile control-angle and texture
3. Etch mask and etch stop layers
4. Etch rate versus area considerations (loading)
5. Etch uniformity

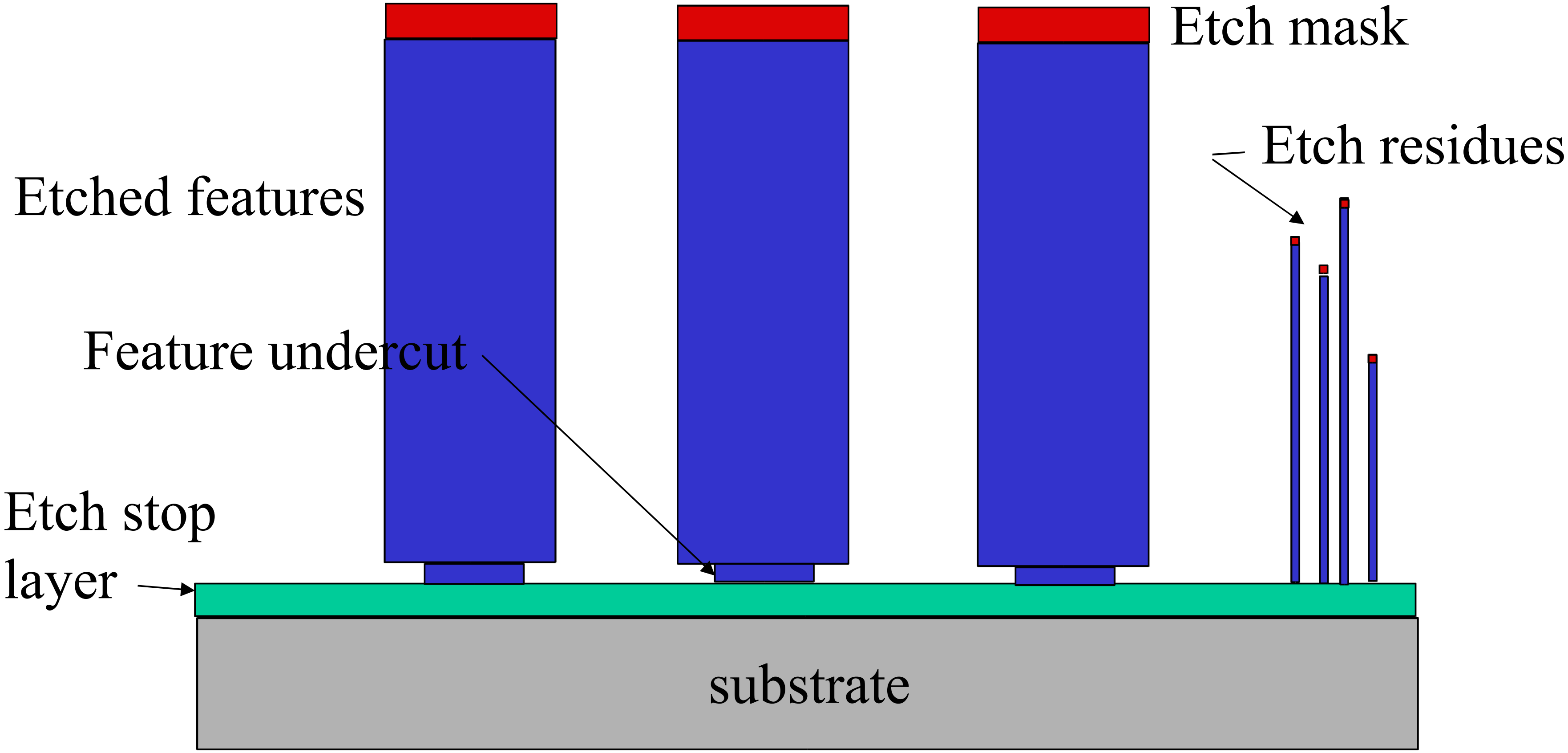
MEMS FABRICATION BASICS: Pattern Transfer



MEMS FABRICATION BASICS: Pattern Transfer

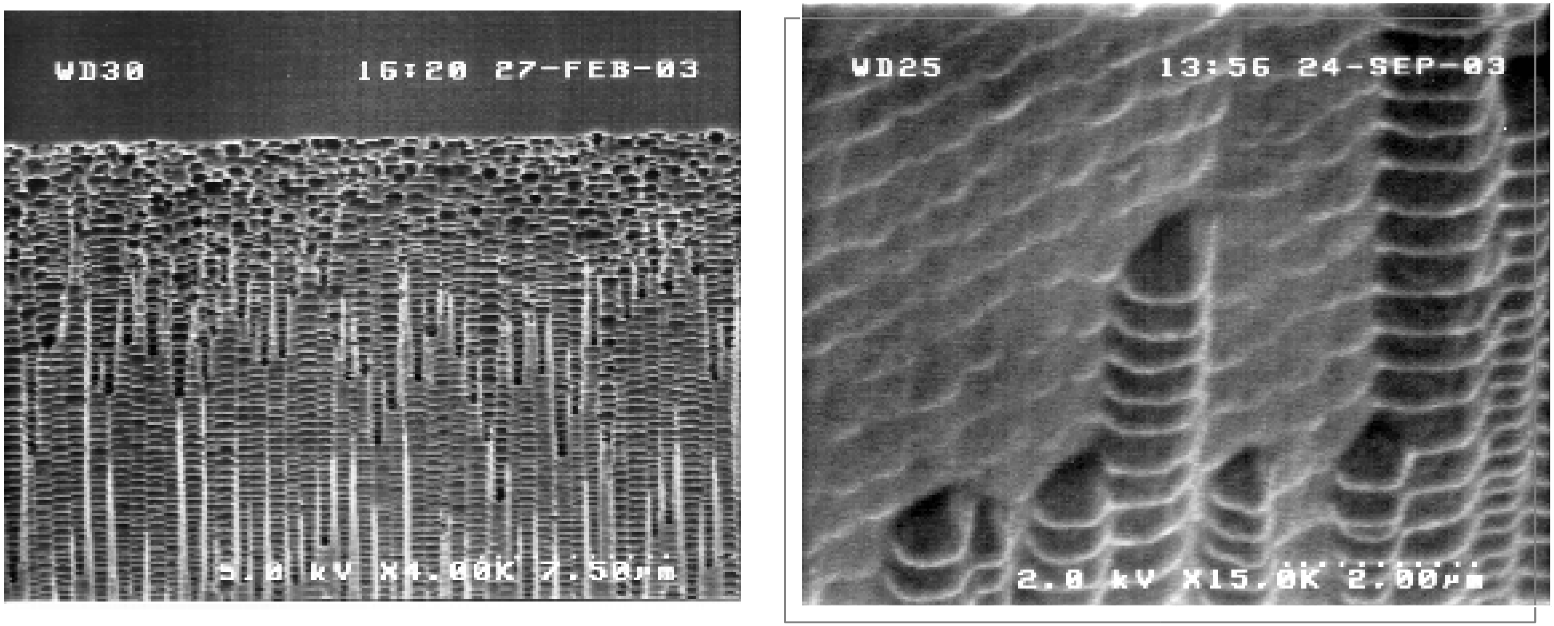


MEMS FABRICATION BASICS: Pattern Transfer



Etch uniformity, etch stop layers, loading, and etch mask layers

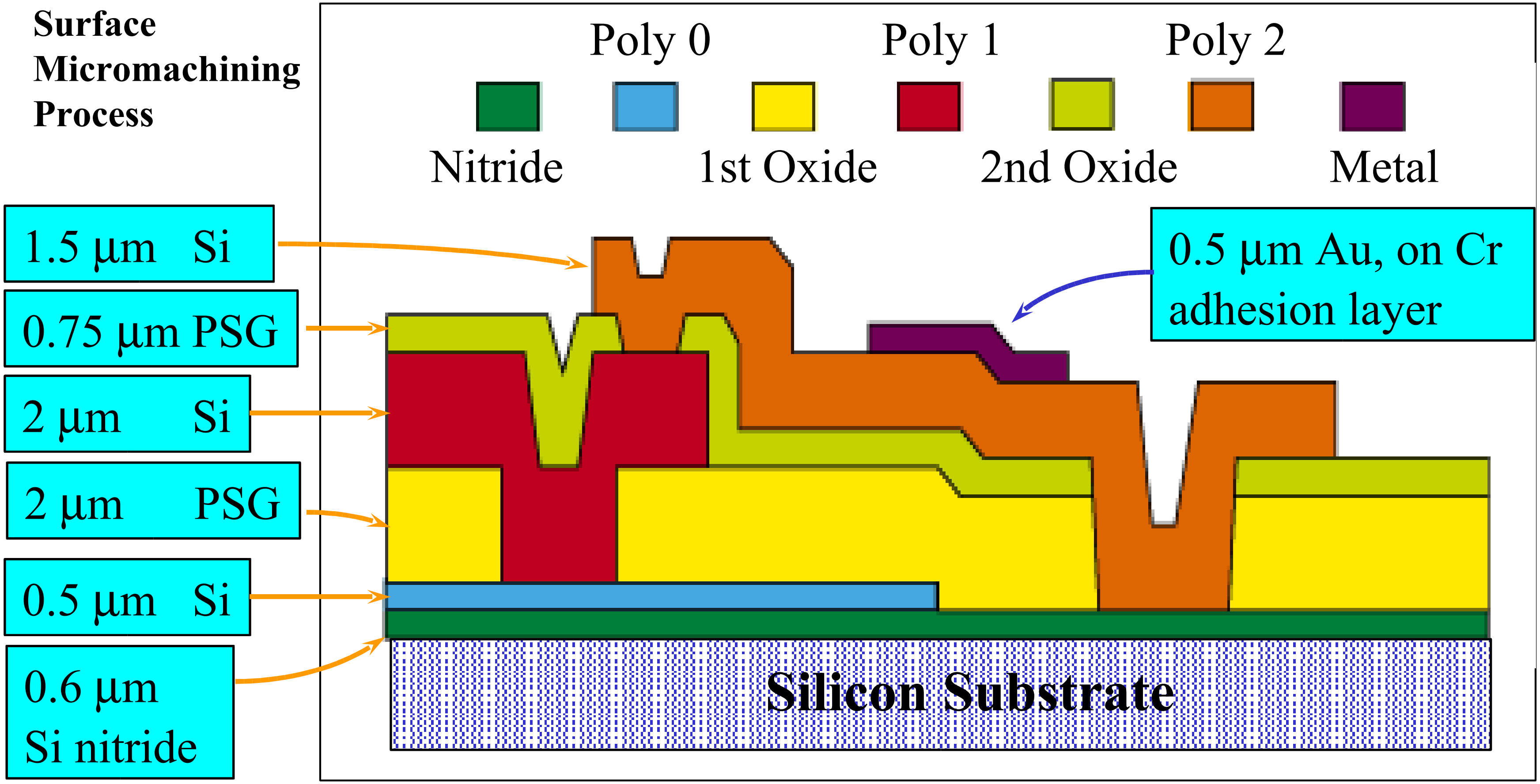
MEMS FABRICATION BASICS: Pattern Transfer



Silicon sidewall – Bosch etch with resist etch mask

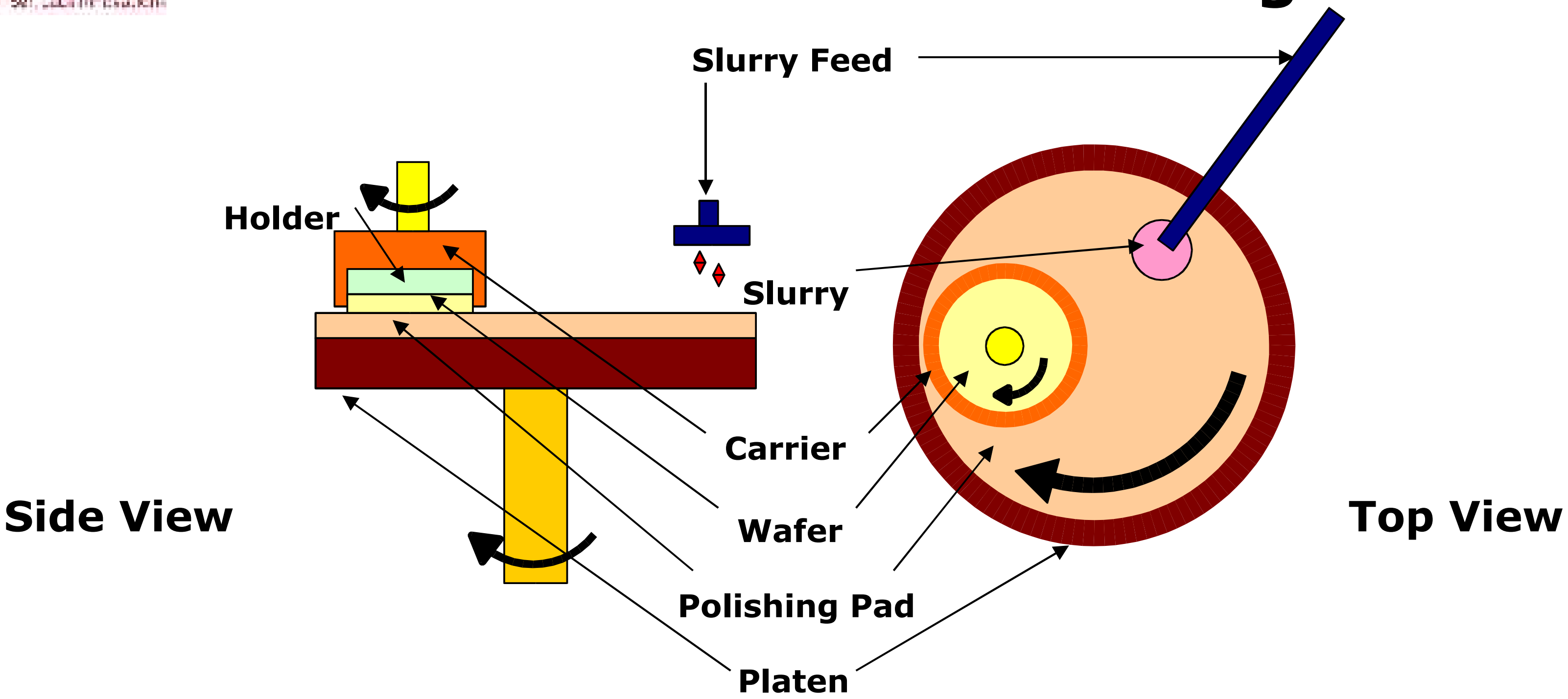
MEMS FABRICATION BASICS: Chemical Mechanical Polishing

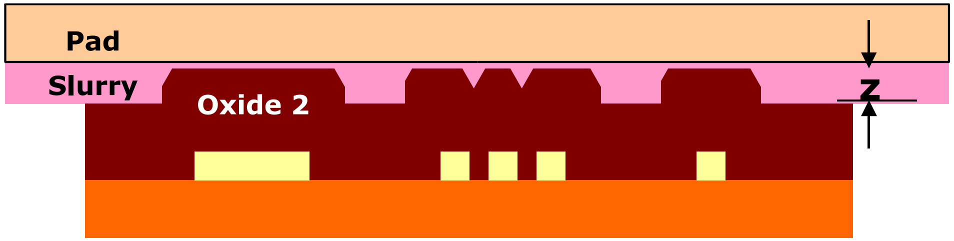
Surface Micromachining Process



Multi-User MEMS Processes (MUMPS) Introduction and Design Rules, rev. 4, 7/15/96, MCNC MEMS Technology Applications Center, Research Triangle Park, NC 27709

Chemical Mechanical Polishing





$$\frac{dz}{dt} = -k_p p v = -\frac{K}{\rho(x,y,z)},$$

z = oxide topography

t = polish time

p = pressure

v = velocity

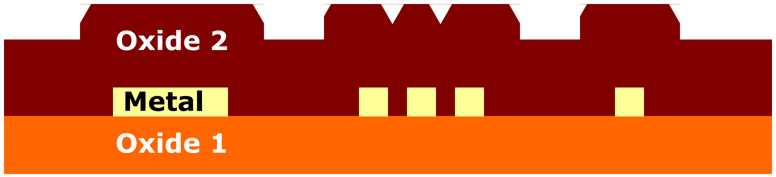
ρ(x,y,z) = pattern density

K_p = Preston constant

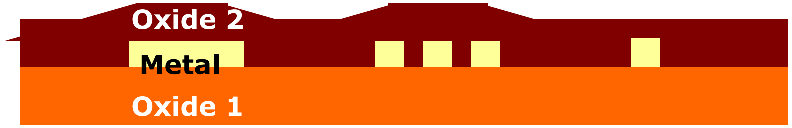
K = Constant

Patten Density Effects

As Deposited Topography

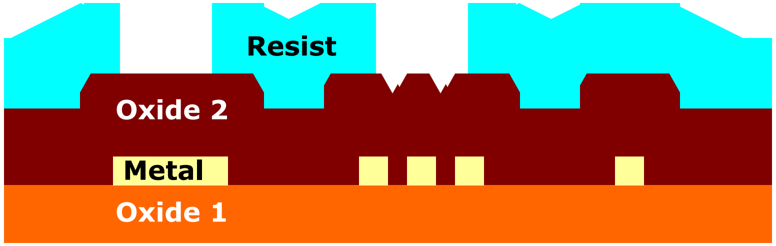


CMP: Local Planarity

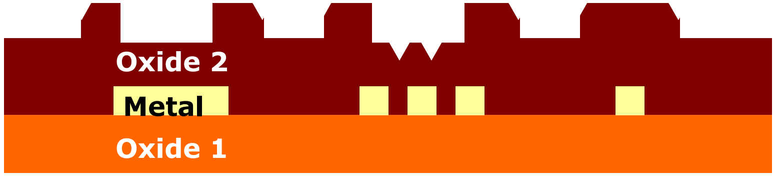


Global Non-Planarity

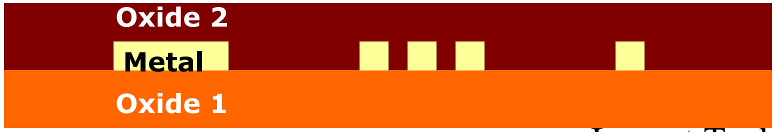
Reverse Tone: Litho



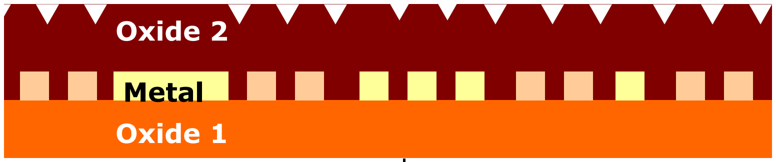
Reverse Tone: Etch



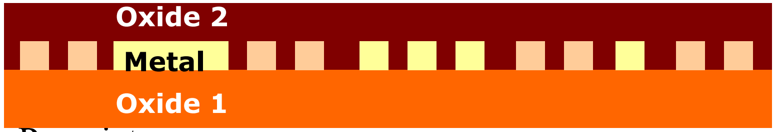
CMP: Global Planarity



Dummy Fill Pattern

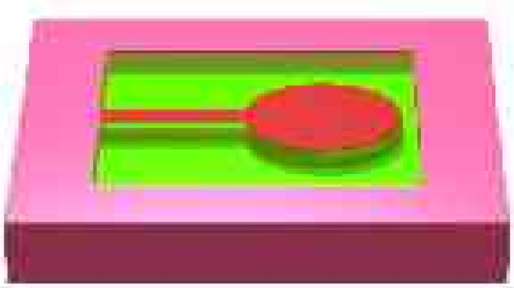


CMP: Global Planarity

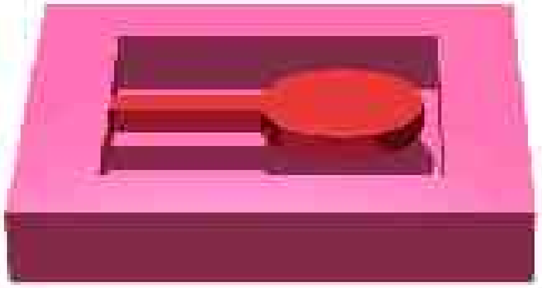


MEMS FABRICATION BASICS: Release

Layers of structural materials, sacrificial layers, and interconnects or electrodes are deposited and patterned.



The sacrificial layers are selectively removed, releasing the moving parts.



Some micromachines self-assemble during release.

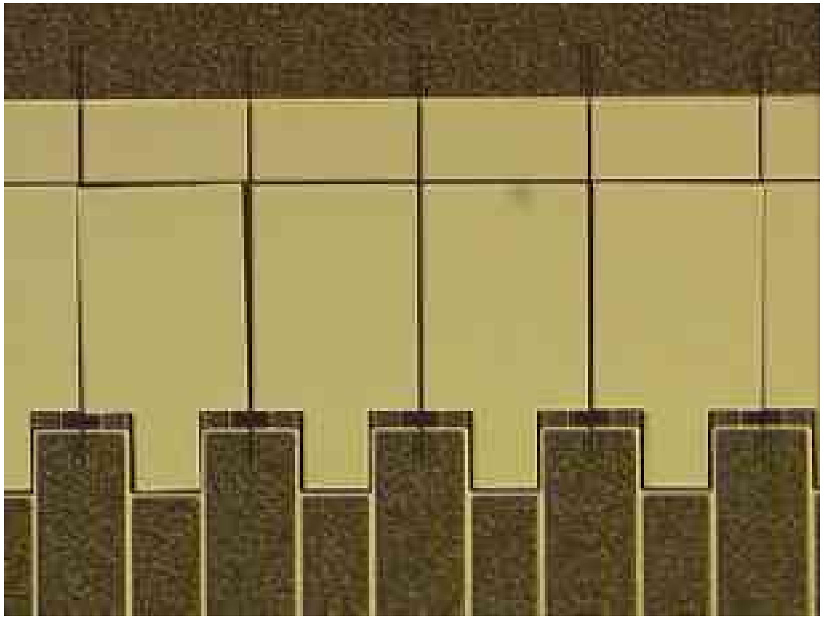
MEMS FABRICATION BASICS: Release

Structural Material	Sacrificial Material	Release Agent
silicon silicon/germanium	silicon dioxide	Aqueos HF HF Gas PAD Etch*
protected silicon	silicon	Xenon difluoride gas*
silicon/germanium	germanium	Hydrogen peroxide*
Germanium	silicon dioxide	Aqueos HF HF Gas

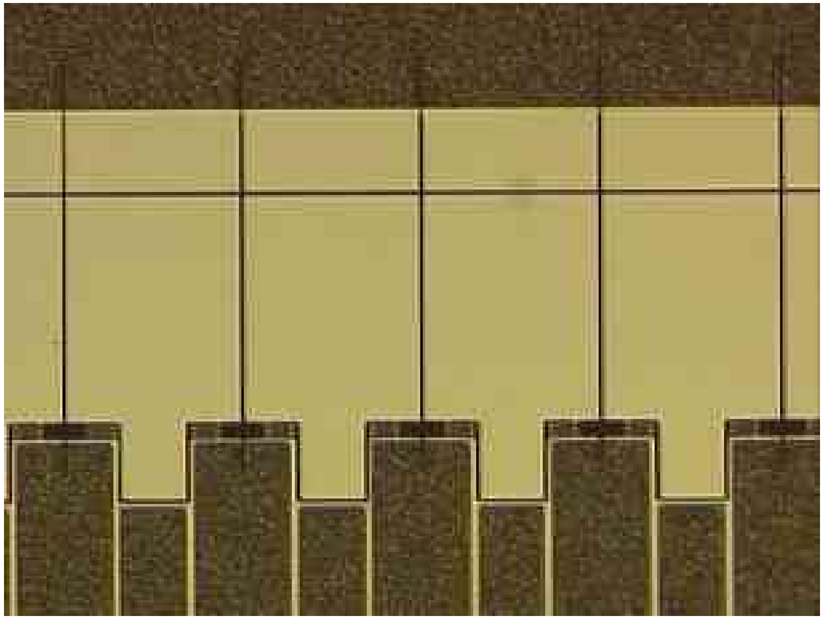
* Will not attack Aluminum metallization

Post wet release processing usually entails rinse with DI water then solvent or critical CO2 dry.

MEMS FABRICATION BASICS: Release



Stiction after release



No stiction

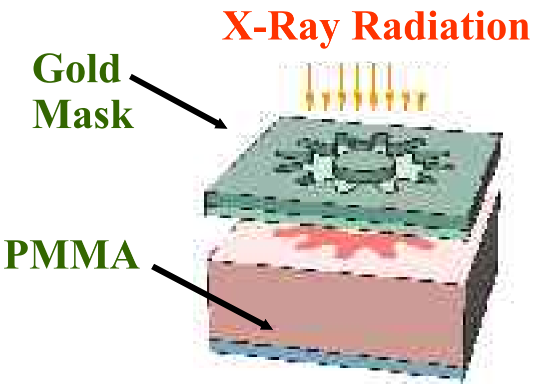
BULK MICROMACHINING:

Non-silicon High Aspect Ratio(HAR) MEMS

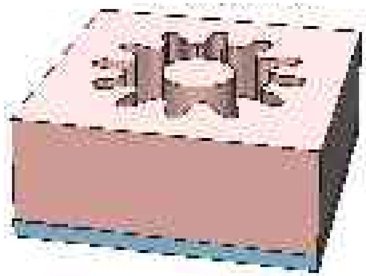
LIGA Nickel High Aspect Ratio (HAR) Micromachining

(Lithographie, Galvanoformung, Abformung (LIGA))

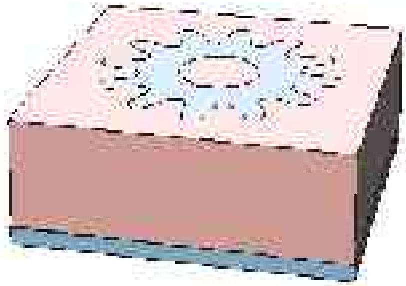
E. W. Becker etal.,),” Microelectron. Eng., vol. 4, pp. 35–36, 1986.



1. Expose PMMA to **Synchrotron radiation**



2. Develop PMMA into mold

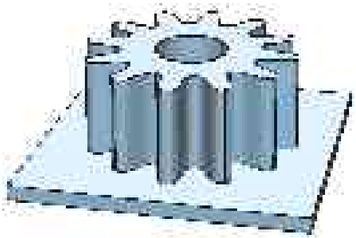


1. Electroplate into mold and remove mold material.–

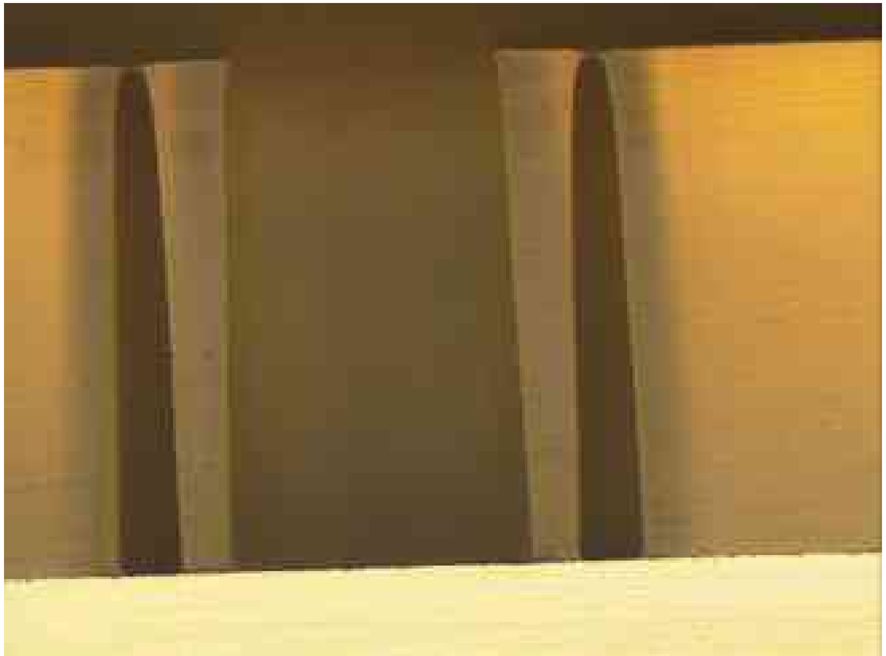
Feature lengths and widths as small as 20um

Feature heights are from 200-300um

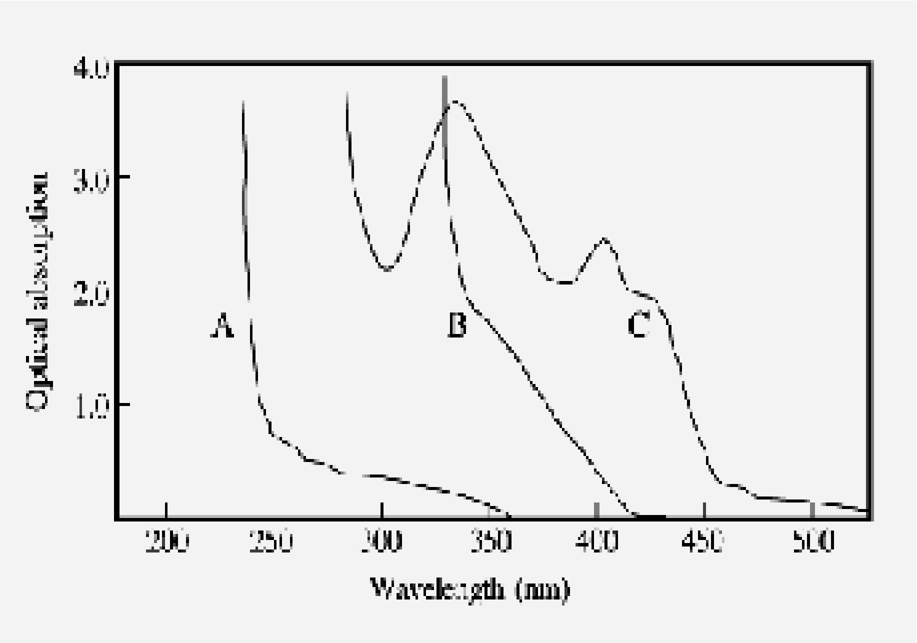
Aspect Ratios > 10



UV-LIGA High Aspect Ratio (HAR) Micro-machining



22umgap,24um line feature Profiles in 290xm thick SU-8 film with non-optimized process.

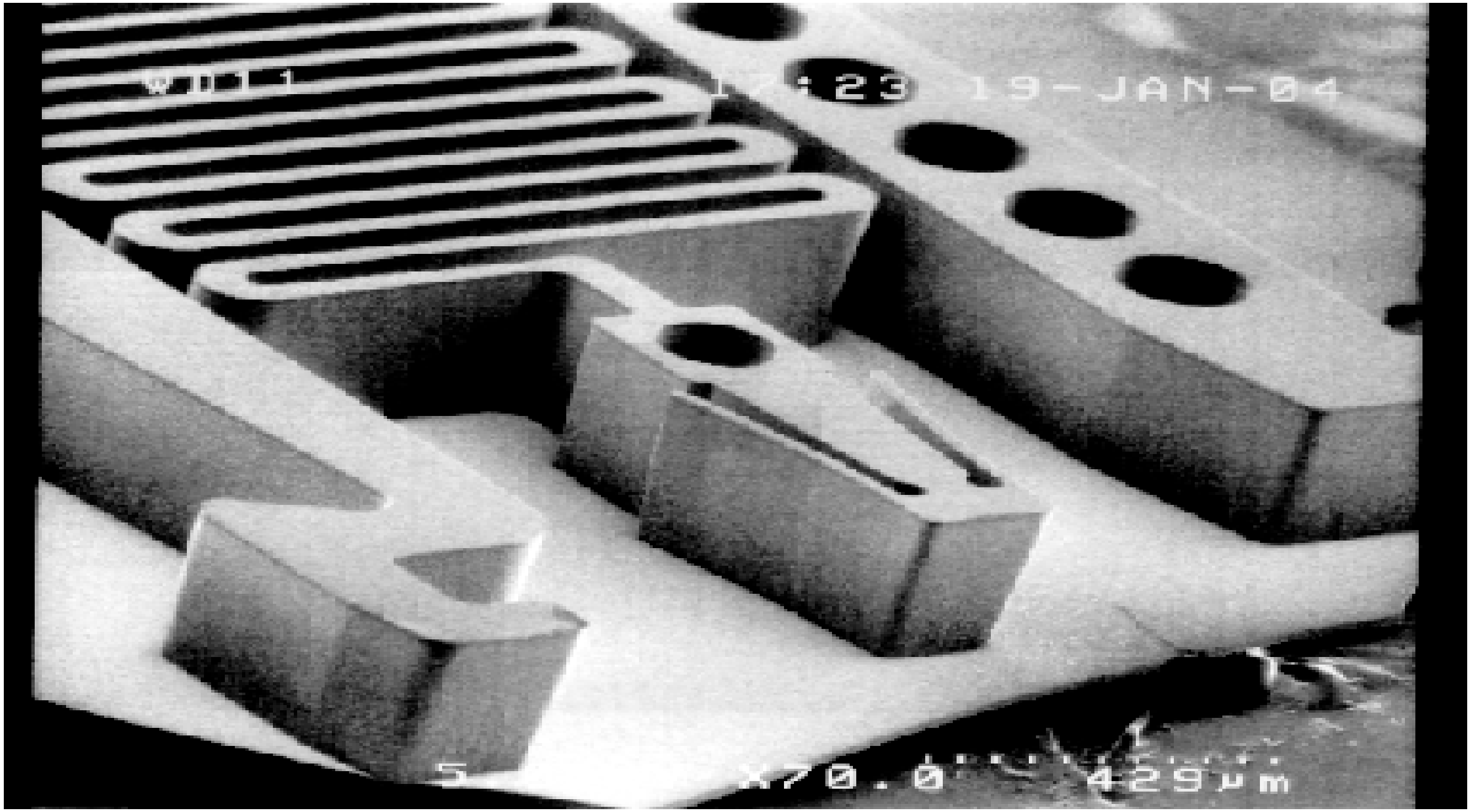


Optical absorption of SU-8 (A) as compared to a diazo type resist system (B) and Dupont RISTON dry film (C)

* Reference: N. LaBianca, and J. Delorme, "High aspect ratio resist for thick film applications", in Proc. SPIE vol. 2438, SPIE, (1995)

BULK MICROMACHINING:

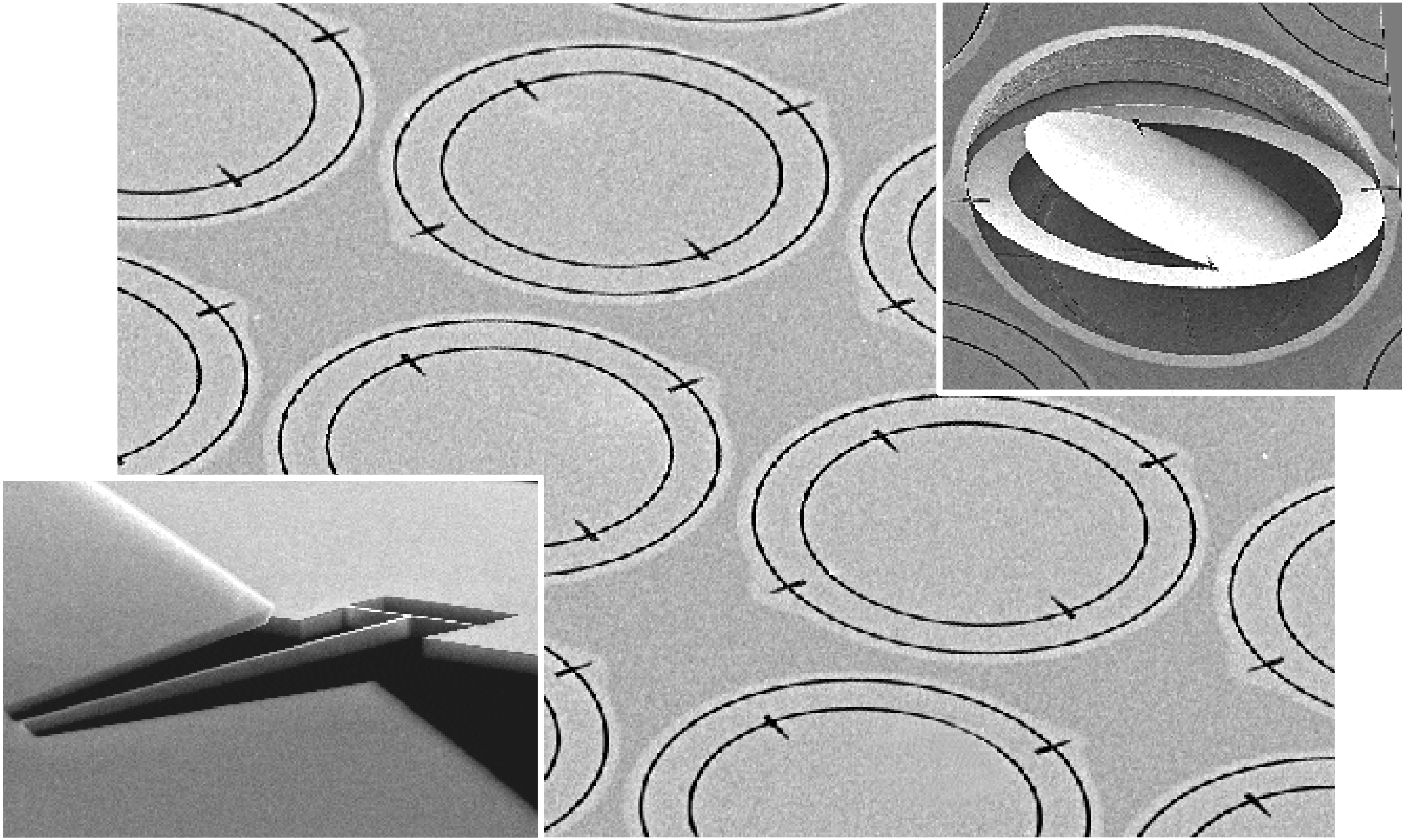
Silicon Dry Etch Based



Bulk machined parts in 300um silicon using Modified Bosch process.

BULK MICROMACHINING: SOI

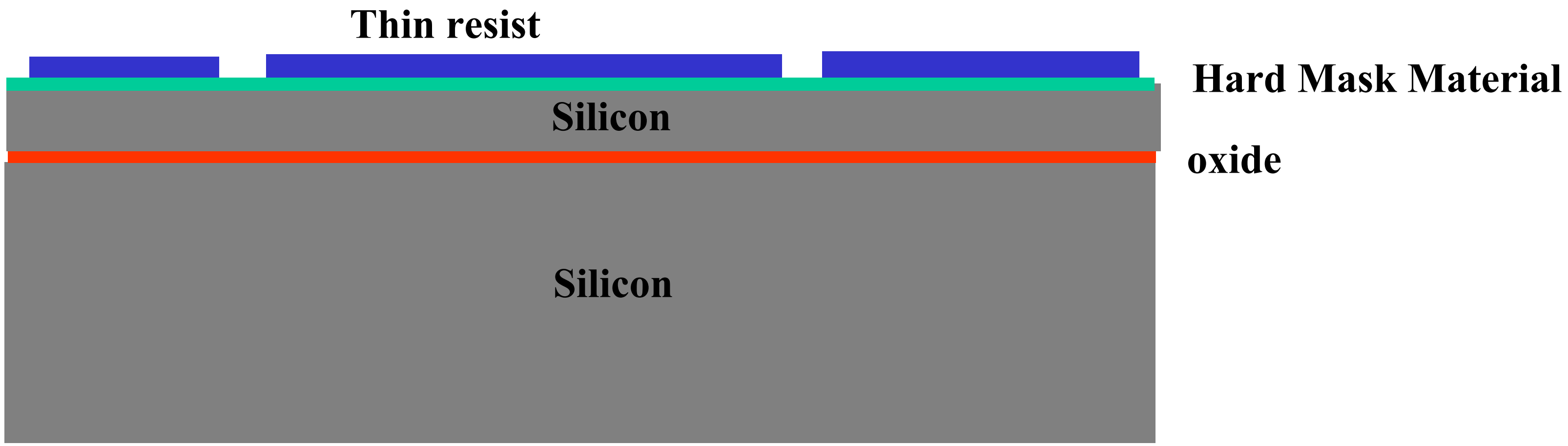
Lucent Lambda Router Mirrors (Bishop etal.)



BULK MICROMACHINING

Pattern Front-side of SOI (Silicon on Insulator) wafer with Mirror Array Pattern:

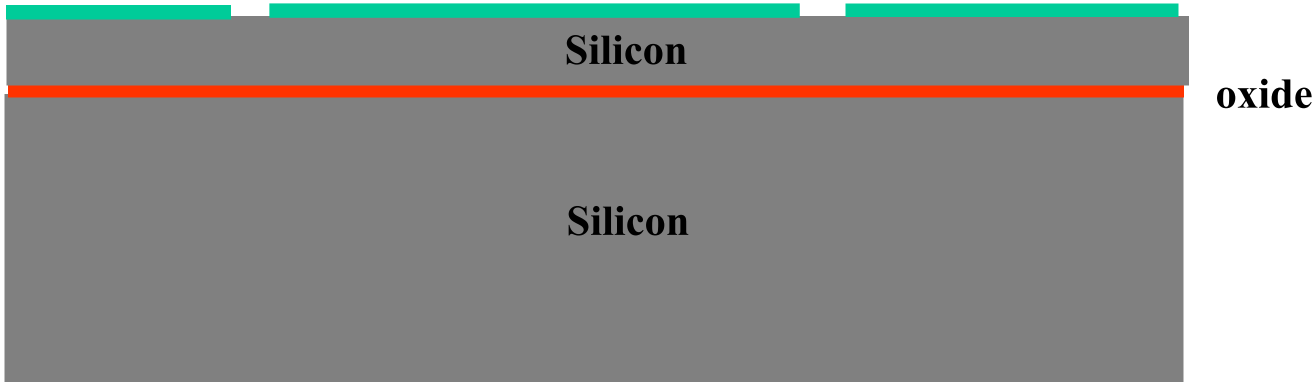
High Throughput, High Resolution, High alignment precision step and repeat exposure tool



BULK MICROMACHINING

Pattern Transfer Resist Pattern into Hard Mask Material with Dry Etch

Strip and clean residual resist



BULK MICROMACHINING

Pattern Transfer Resist Pattern into Hard Mask Material with Dry Etch

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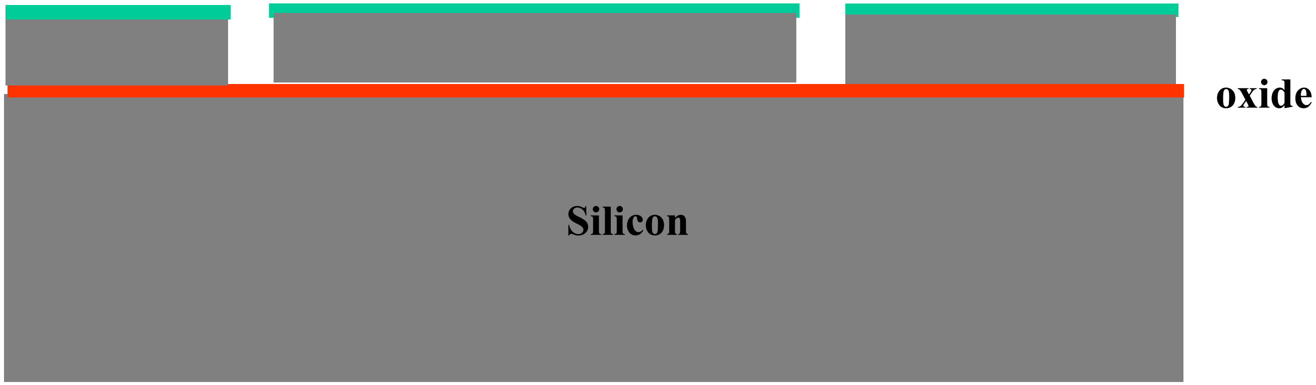
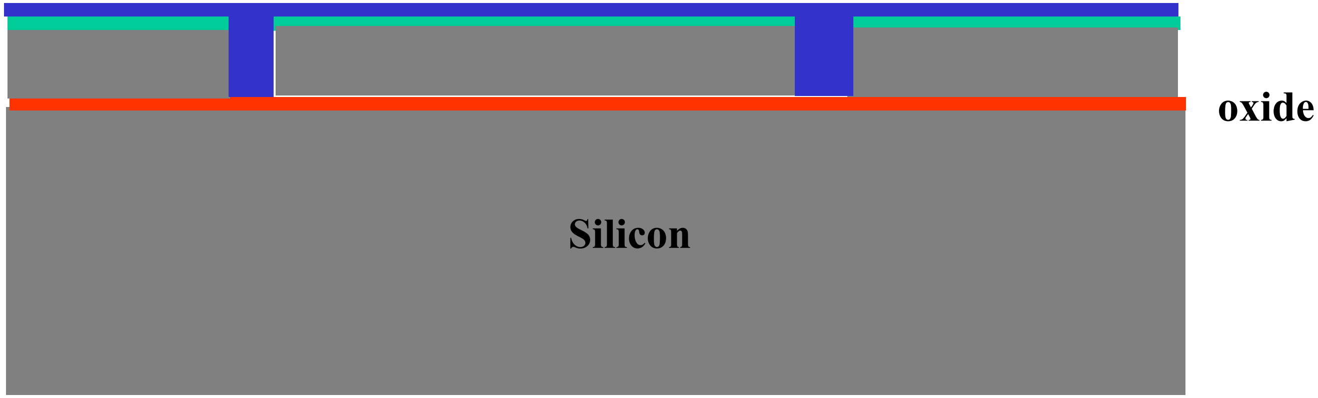


BULK MICROMACHINING

Protective Coat Patterned Front-side

Coating can also act to balance stress for High yield release

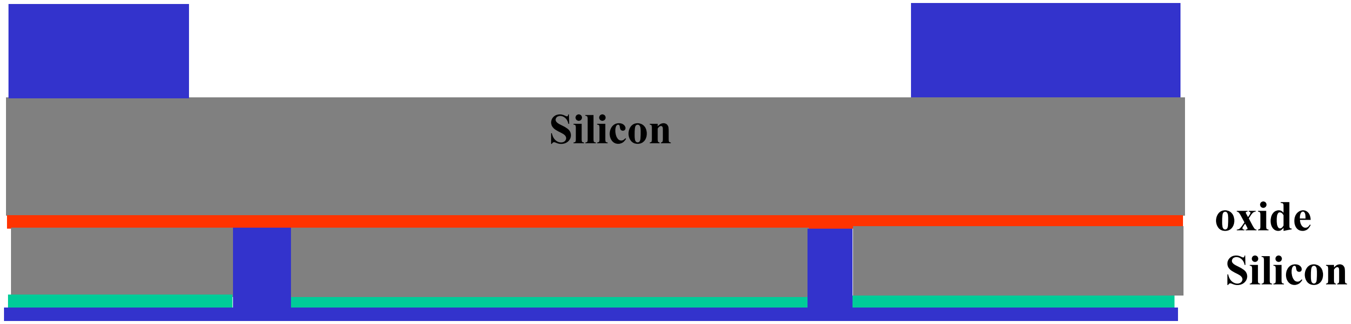


BULK MICROMACHINING

Handle wafer thinning

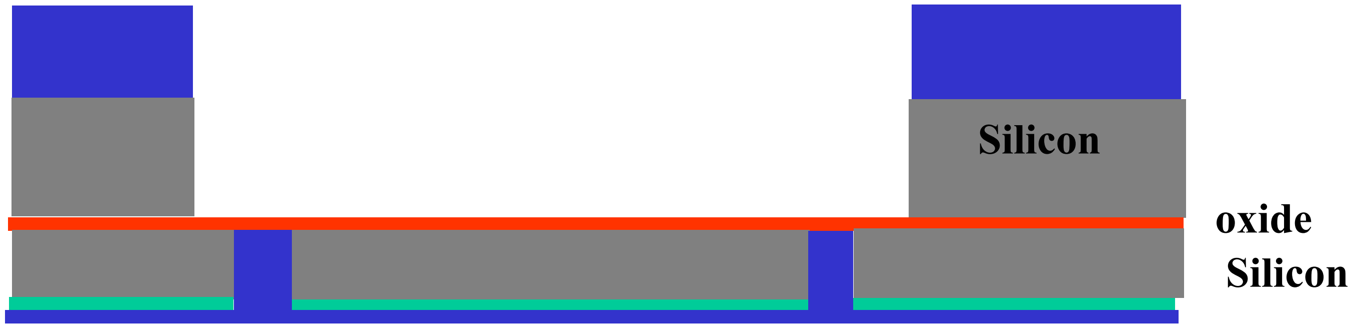
Wafer wet cleaning

Backside lithography with contact printer



BULK MICROMACHINING

Backside Cavity Deep Reactive Ion Etch



BULK MICROMACHINING

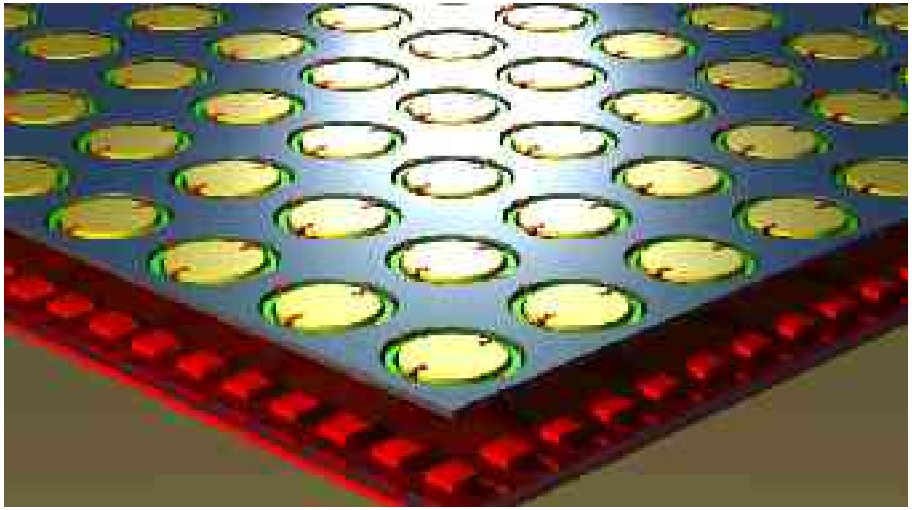
Backside resist strip and clean

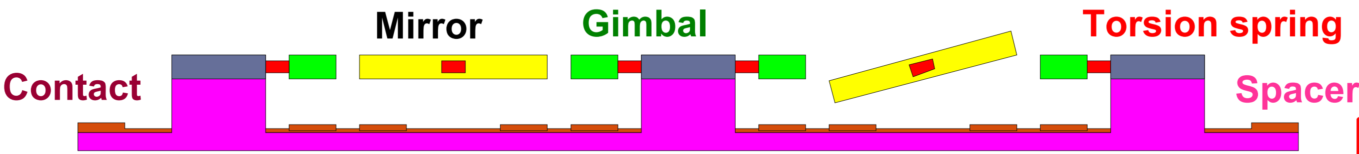
Wafer wet release in HF

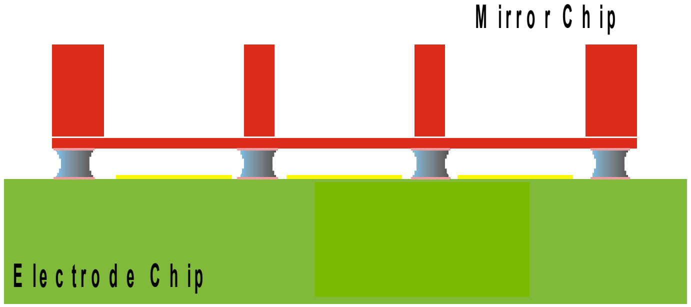
Mirror Coat at Chip Scale

Single-Crystal Silicon Micromirrors

1296 mirror array (36x36)

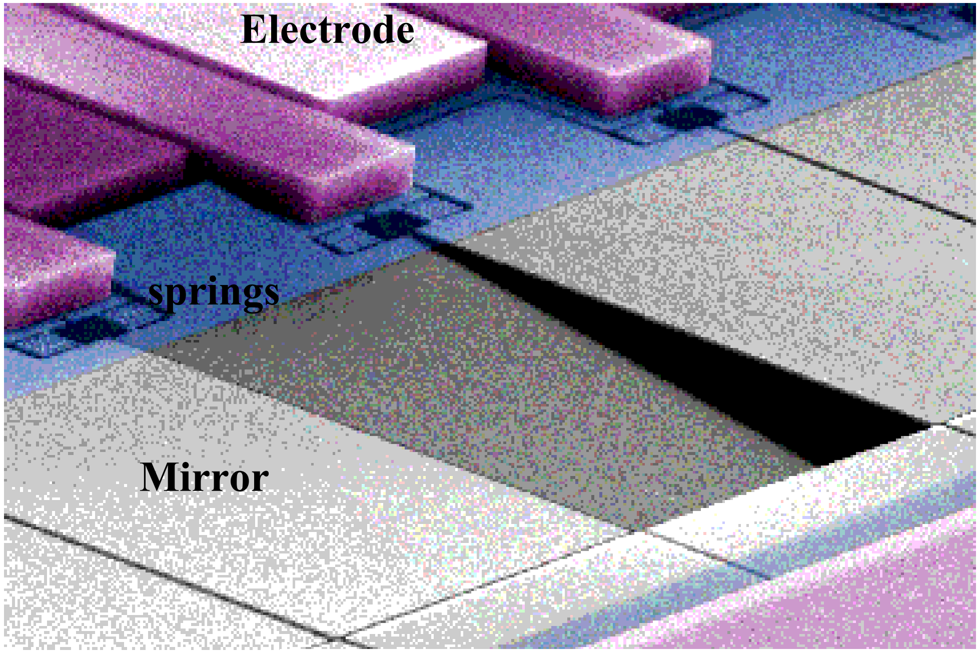


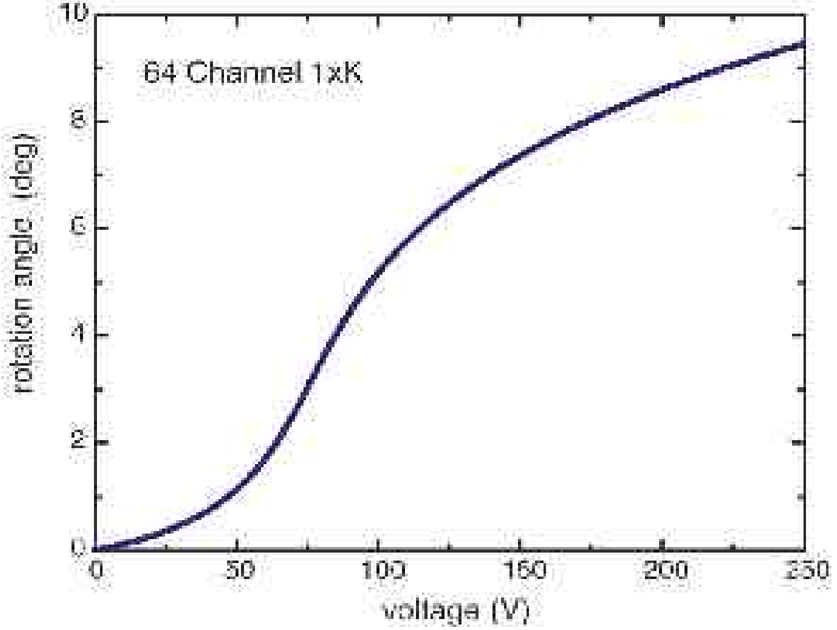


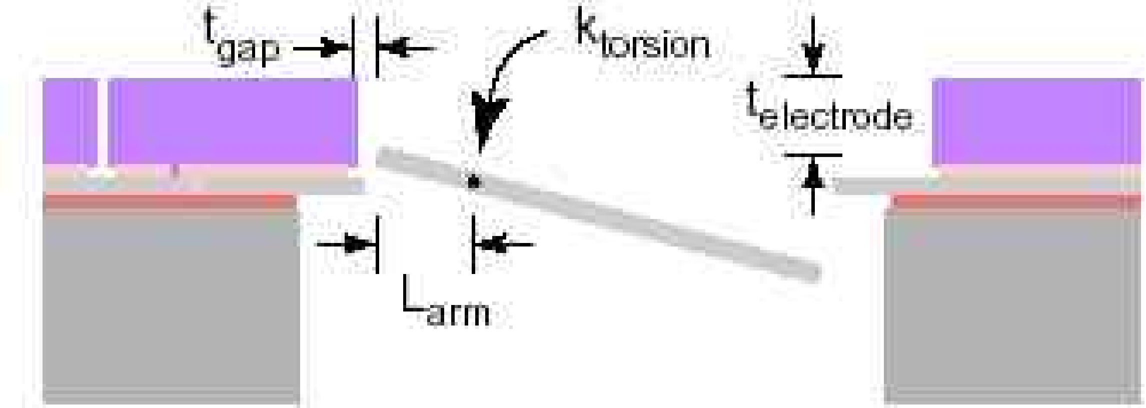


HYBRID MICROMACHINING PROCESS AND EXAMPLE

Monolithic Fringing-Field 1xN Switch





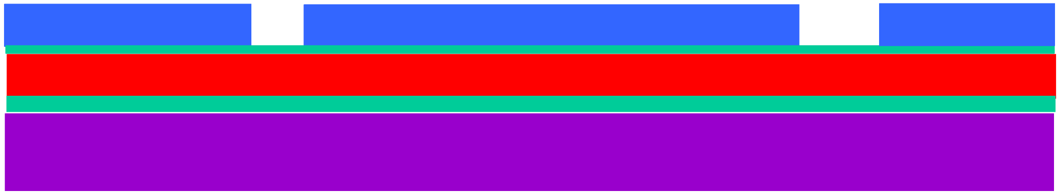


Greywall, Pai etal.
Bell Labs
NJNC
Lucent Technology.

Monolithic Fringing Field Process

SOI wafer: Si on 0.4 um buried oxide on substrate

SOI Lithography: Pattern resist on hard-mask 0.4 um/0.4 um L/S with DUV step and repeat system.



SOI Etch: etch hard-mask, resist strip & clean, Si etch.

Monolithic Fringing Field Process

Plasma enhanced Dielectric Deposition: PETEOS/PE-BPTEOS
Total Thickness = 0.7um

Dielectric flow: 1000 C 1 min N2

W1 Lithography with DUV step and repeat system: 5 um contact size

Photo resist dispense optimized for topography coverage

W1 Etch: contacts to SOI and substrate, plasma strip resist and wet clean wafers

Monolithic Fringing Field Process

Poly 1 Deposition: 10 um Boron doped *0.1-0.2 ohm-cm

Align mark open:

1. PR mask lithography, and etch.

Monolithic Fringing Field Process

Poly1 Lithography:

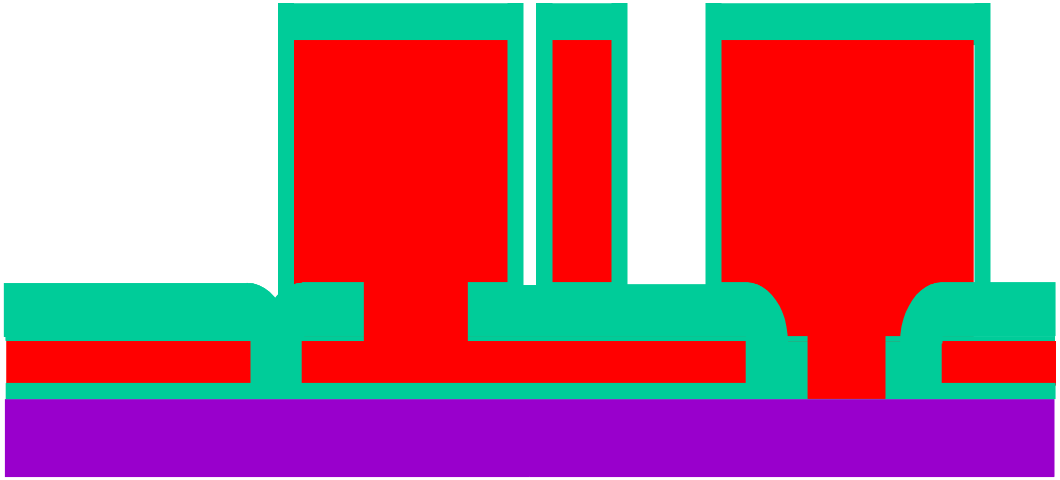
3 um/3 um L/S

Poly 1 Etch: etch 10 um poly, stopping on oxide

Monolithic Fringing Field Process (5/16/02)

Protective Deposition: 0.2 um PETEOS

Backgrind to 285 um



Cavity Opening: etch ~270 um backside Si, stopping on BOX

Monolithic Fringing Field Process (5/16/02)

Full Wafer Release:

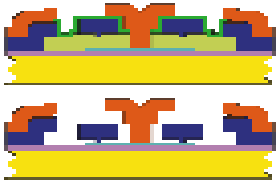
HF 10:1 40 min

Scribe & Break

Al Metalization: 500A mirror front & back, 6000A bond pads

SURFACE MICROMACHINING

Surface Micromachining



Material Systems:

High Temperature: poly-silicon structural and conductor, silicon dioxide sacrificial layer. Wet and dry release systems available.

Low Temperature: poly-silicon germaniun structural and conductor,germanium sacrificial. To date , wet release systems only.

Advantages:

Single side processing eliminates need for special tools and chucking.

Single side processing opens door to foundry fabrication.

Can be scaled to sub-micron using already available tools with some exceptions.

Holds possibility (low temp) for modular integration with optimized CMOS.

Disadvantages:

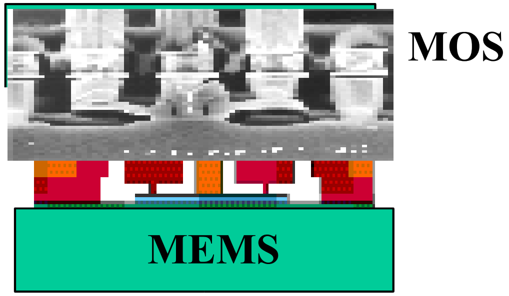
New low temperature materials and fabrication processes must be developed and optimized.

SURFACE MICROMACHINING

MEMS – Electronics Integration

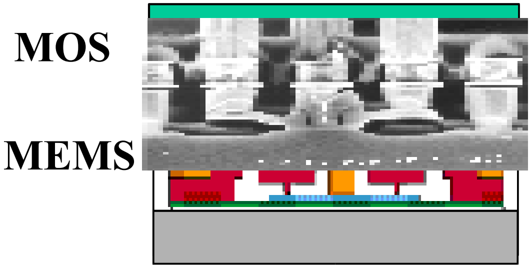
MEMS-on-top

Low cost CMOS foundry
Low temp MEMS process
Minimize interconnect length



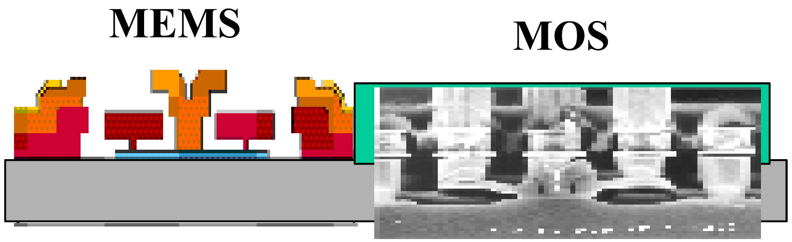
MEMS-MOS Separate

Interconnect number
Interconnect characteristics
Separate process optimization
Low cost CMOS foundry
Complicates packaging



MEMS Inside

More capital investment
High temp MEMS only
Minimize interconnect length



MEMS-Mixed

Processing compromises for both
More capital investment
High temp polysilicon based can be used

SOFT MEMS: Position and Shape control of small droplets of condensed matter through surface patterning and electro-wetting

[redacted]

Tom Krupenkin, Ashley Taylor,
Tobias Schneider,
Shu Yang, Avi Kornblit
Bell Labs, NJNC Lucent Tech.

Contact angle

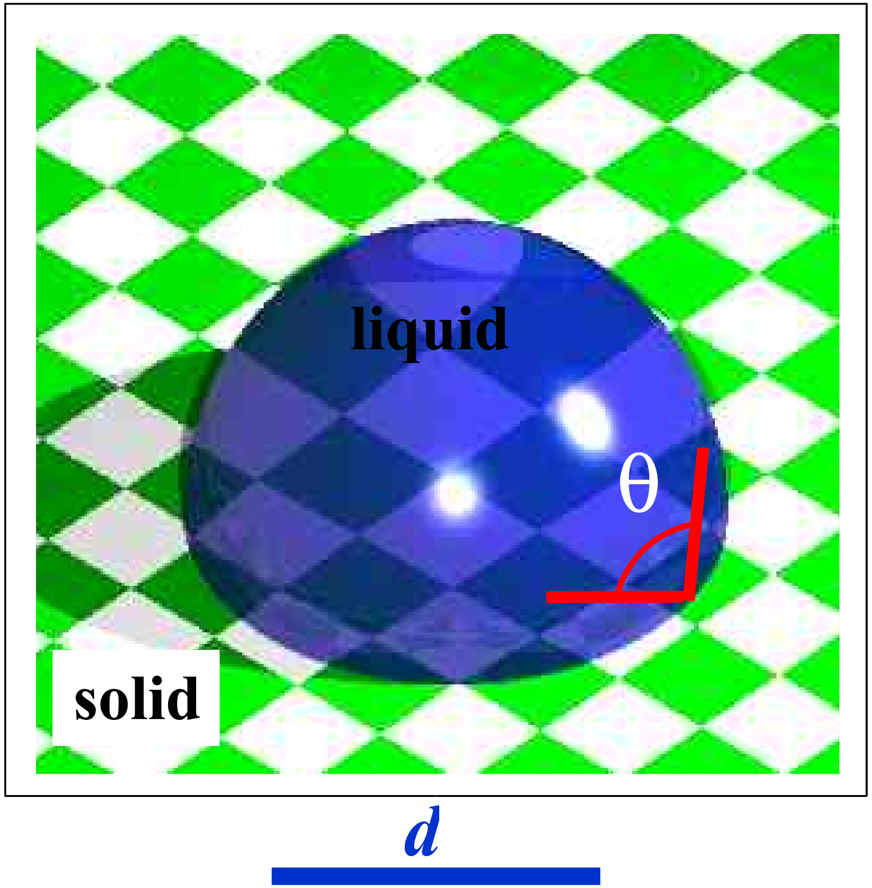
Definition of the contactangle θ

Surface tension dominates

$d \sim 10^1 - 10^3\ \mu m$

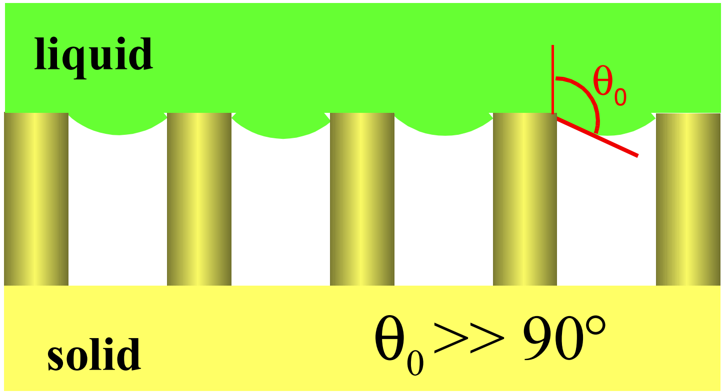
Contact angle θ is determined by the interfacial tensions γ:

$$\cos\theta = \frac{\gamma_{\text{Solid-Vapor}} - \gamma_{\text{Solid-Liquid}}}{\gamma_{\text{Liquid-Vapor}}}$$

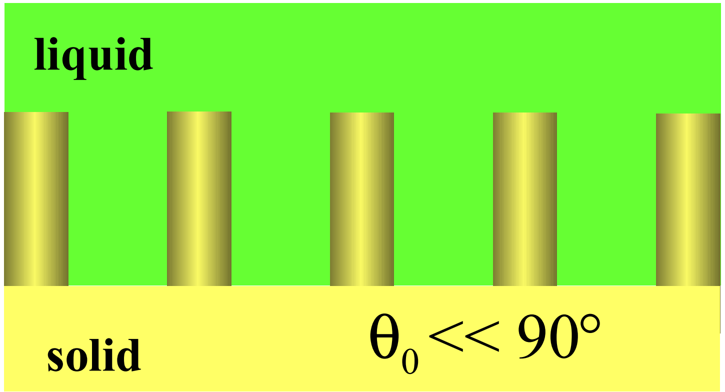


Liquids on nanostructured surfaces

Superhydrophobic



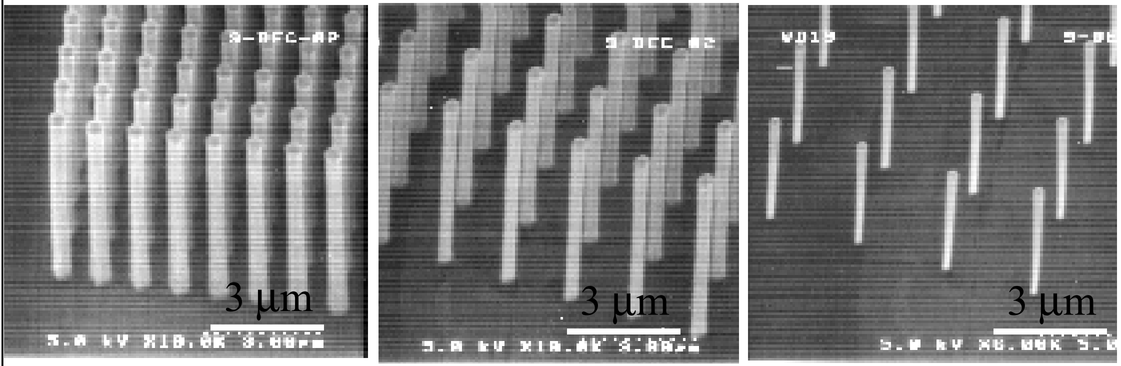
Wetting



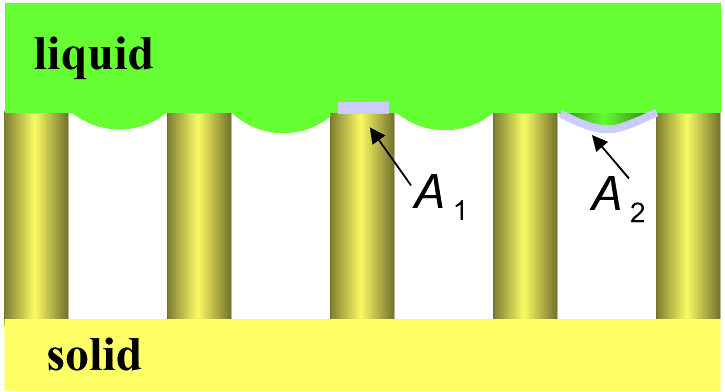
- Surface tension adjustment
- Electrowetting

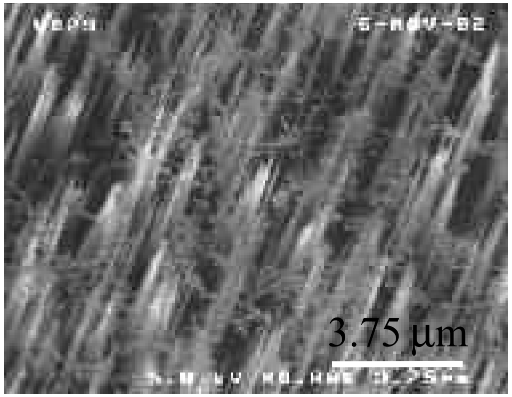
Nanostructured surfaces

Typical examples of the structures currently available for us

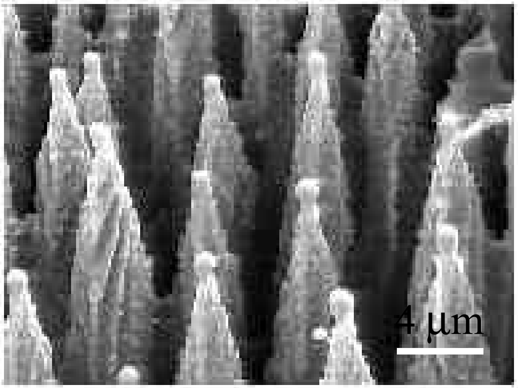


Ashley Taylor (NJNC, 2002)





Ashley Taylor (NJNC, 2002)



Eric Mazur *et. al* (Harvard, 2001)

$$\cos\theta = \frac{\gamma_{\text{Solid-Vapor}} - \gamma_{\text{Soid-Liquid}}}{\gamma_{\text{Liquid-Vapor}}}$$

$$\gamma_{\text{Solid-Liquid}} = f\,\gamma_{\text{S-L}} + (1-f)\,\gamma_{\text{L-V}}$$

$$f = A_1 / A_2$$

Cassie & Baxter (1944)

Nanostructured surfaces

Droplet transport:

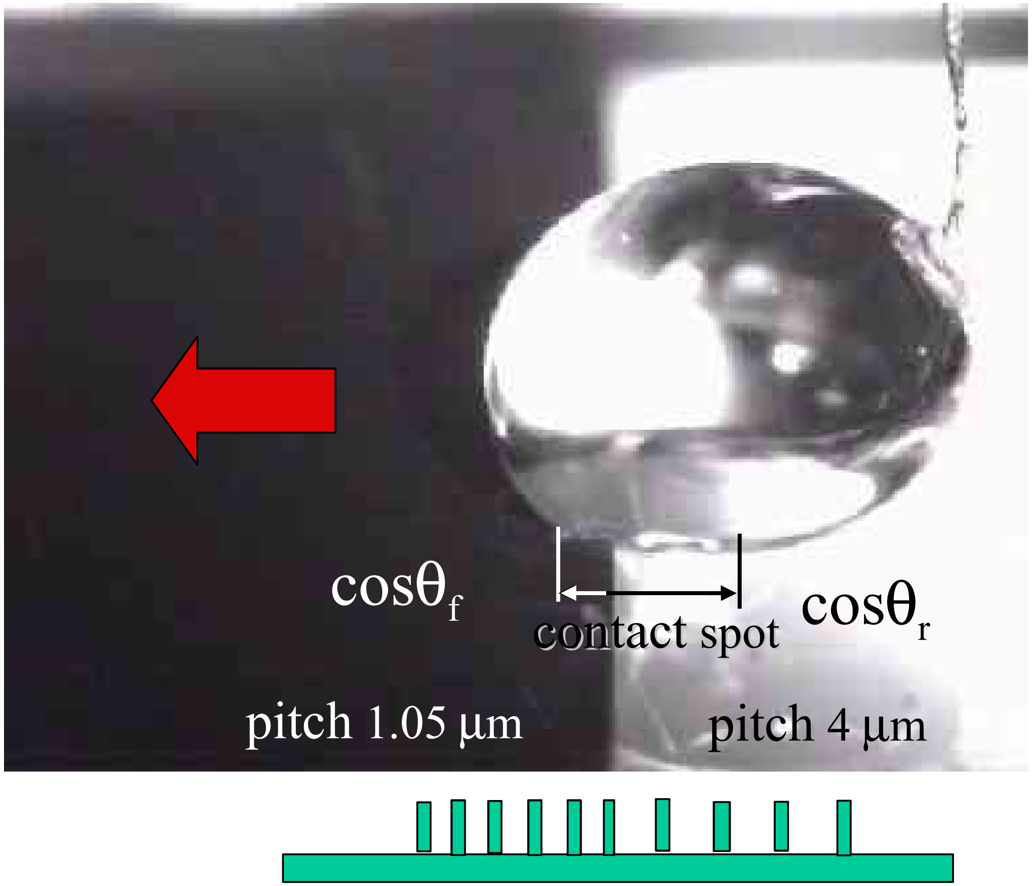
Molten salt*, $\gamma = 62$ mN/m

*1-ethyl-3-methyl-1 H-imidazolium tetrafluoroborate

$$dF = \gamma_{LV} (\cos\theta_f - \cos\theta_r)dy$$

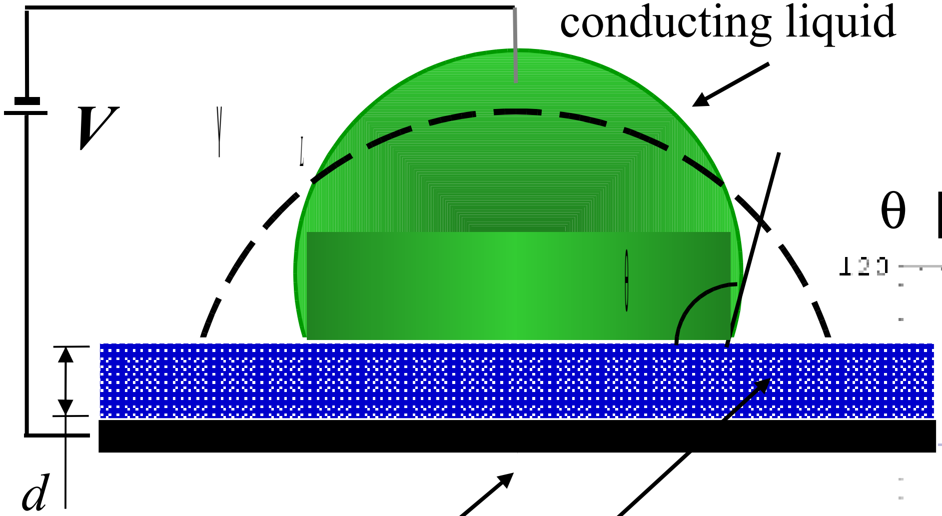
$$\cos\theta_f - \cos\theta_r =$$
$$(f_f - f_r)(\cos\theta_0 + 1) \quad f_f > f_r$$

$$f = A_1 / A_2$$



Electrowetting

θ can be reversibly changed using electrowetting



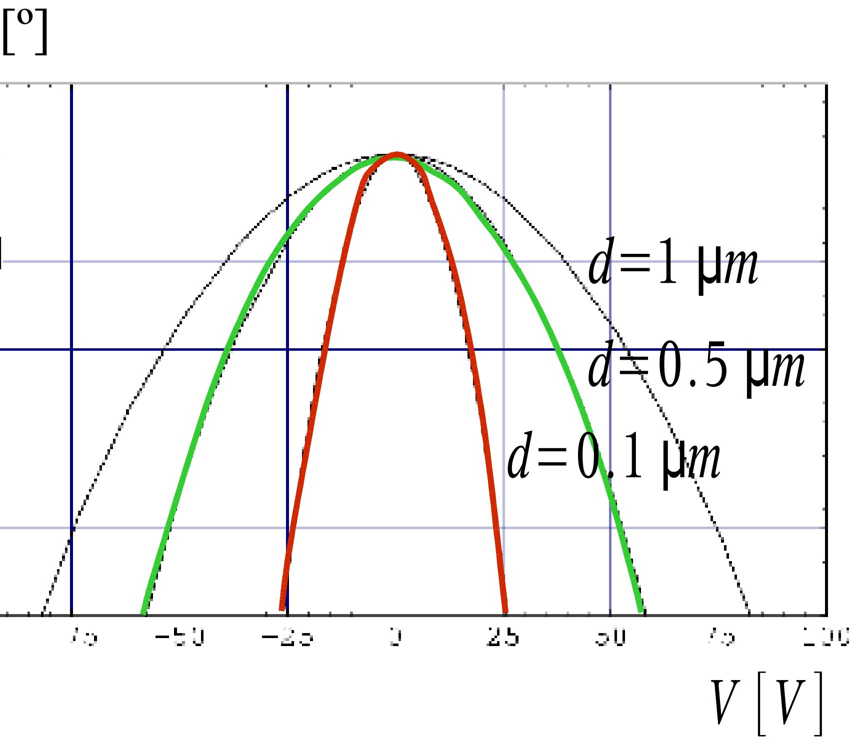
conducting liquid

conductive electrode

insulating layer, thickness d, dielectric constant ε_r

Example: Water droplet on Cytop® surface $\gamma_L = 72$ mN/m

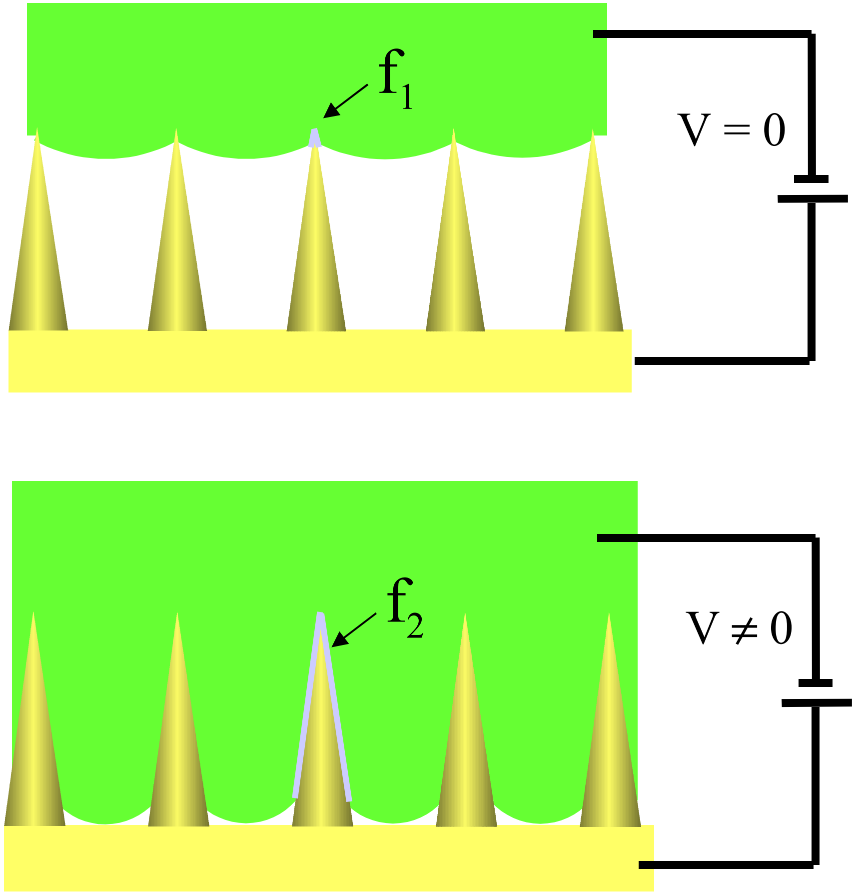
$\varepsilon_r = 2.1$ $\theta(V=0) = 112^\circ$



$$\cos\theta(V) = \cos\theta(V=0) + \frac{\varepsilon_0 \varepsilon_r}{2d\gamma_L} V^2$$

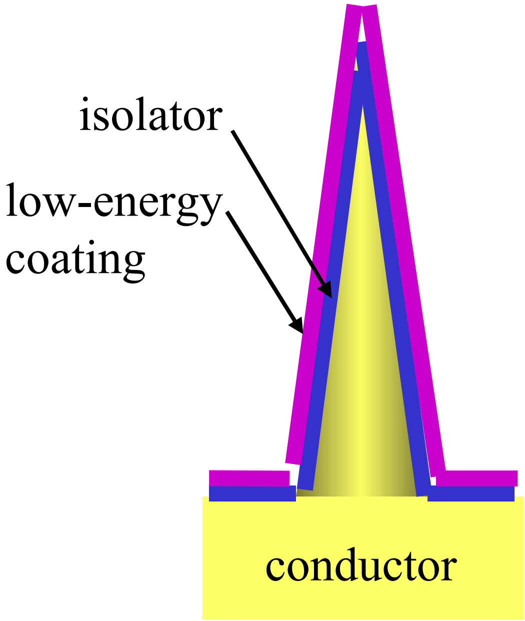
Nanostructured surfaces

Electrowetting



$$f_2 >> f_1$$

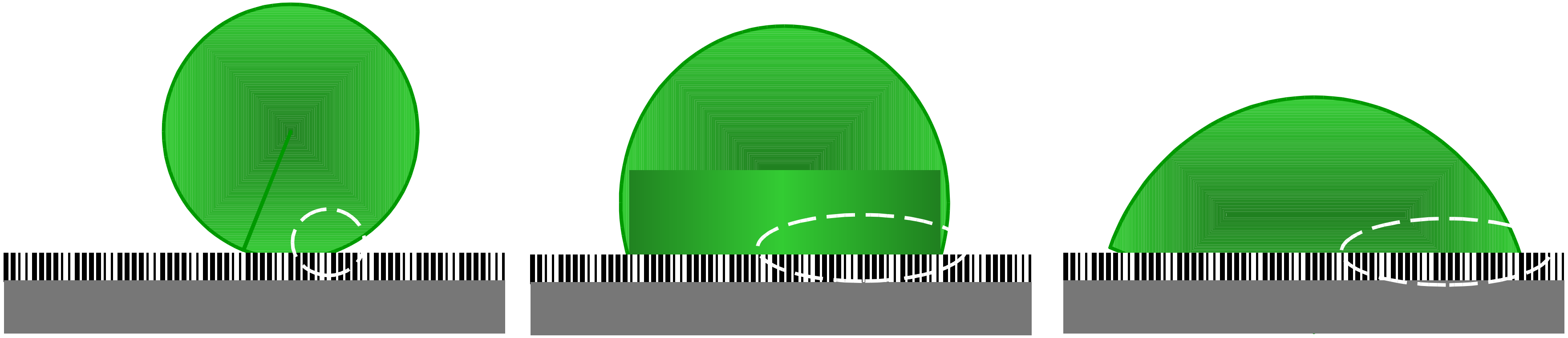
$$\cos\theta \sim f$$



potentially strongly nonlinear effect
contact angle control
contact angle hysteresis control
potentially very low voltage

Nanostructured surfaces

Microscopic picture



rolling ball

no penetration

sticky droplet

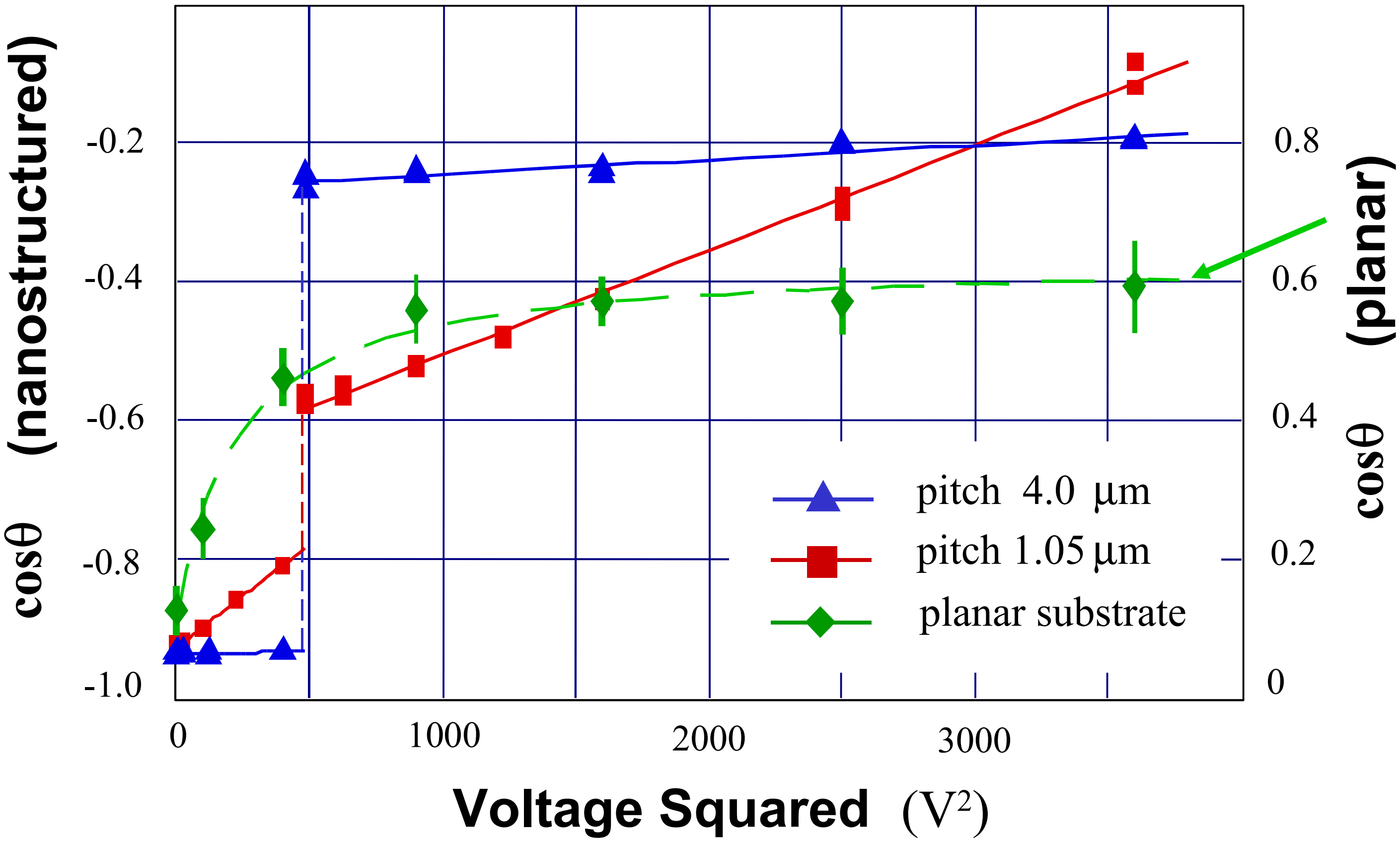
complete penetration

electrowetted droplet

complete penetration

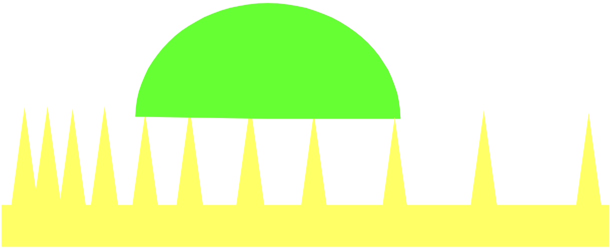
Electrically induced transitions

Rolling ball - Sticky droplet transition

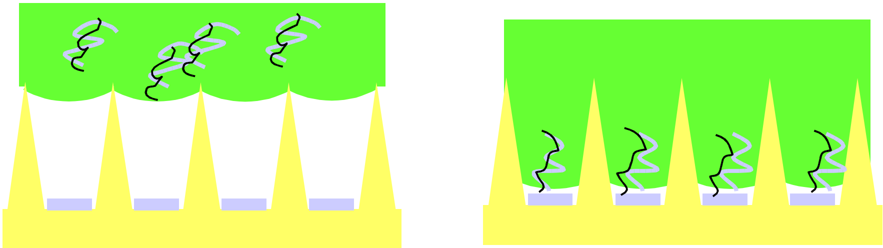


Other Applications

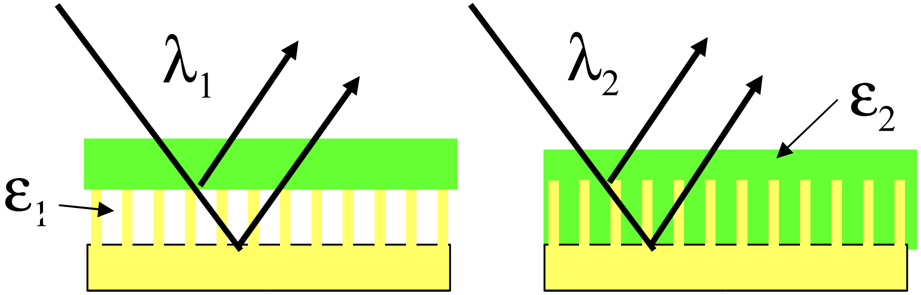
Controllable transport networks



Chemical and bio-sensors



Dynamic wavelength selective filters



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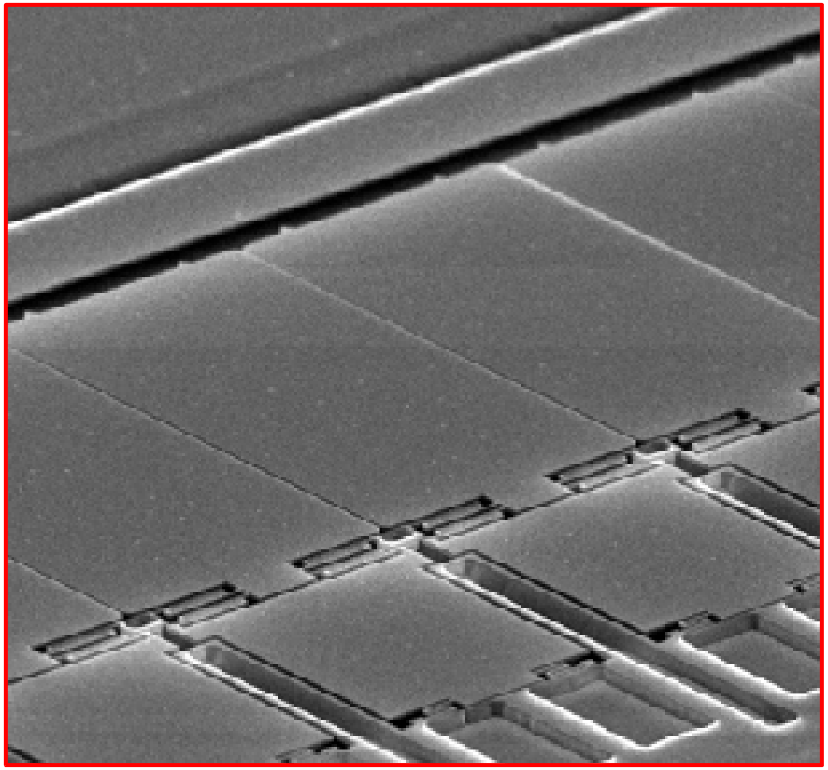
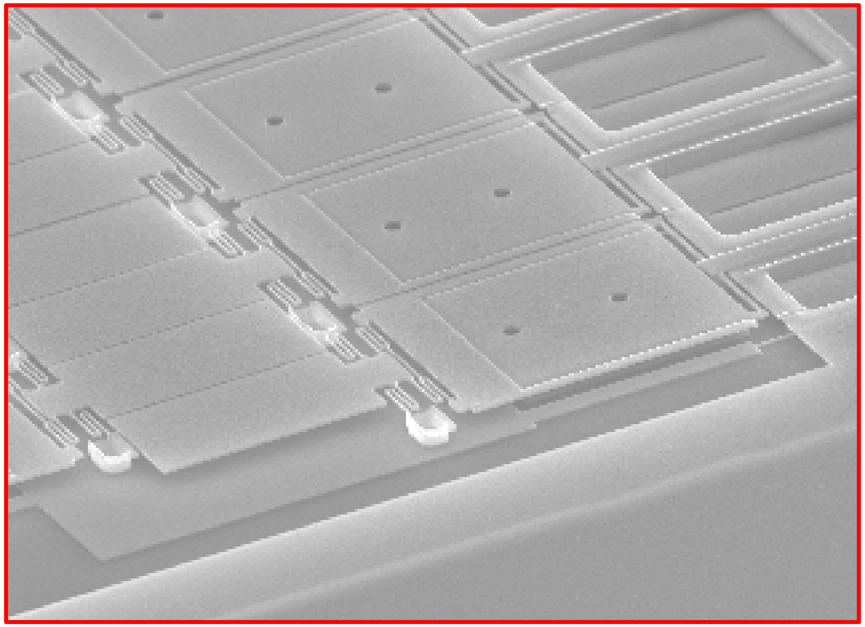
MEMS FABRICATION BASICS: Deposition

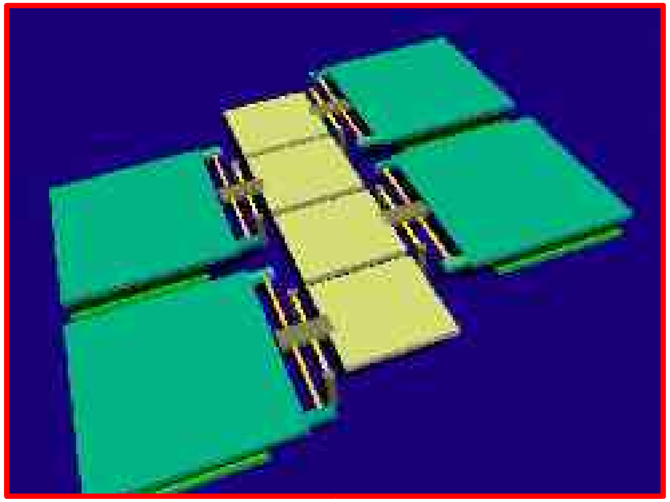
Critical Issues for MEMS

Currently available materials (polysilicon and single crystal Silicon) are either not possible at low temperatures.(<600C) or cannot be made low stress at low temperature. Low temperature, low stress materials such as poly Si-Ge are currently being developed but they have not been rigorously tested for reliability for long term reliability.

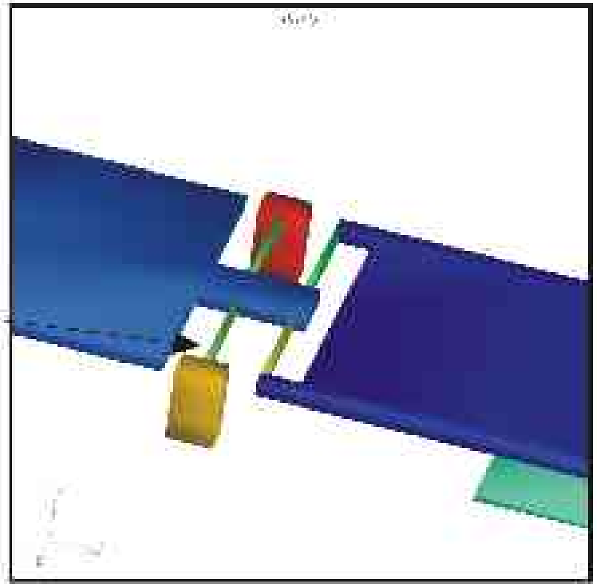
- >10 degrees of continuous tilt
- 10 µm to 200 µm mirrors
- actuation voltage < 100V
- high speed
- high fill factor (0.3 µm gap btw mirrors)
- no electromechanical crosstalk
- surface-micromachined

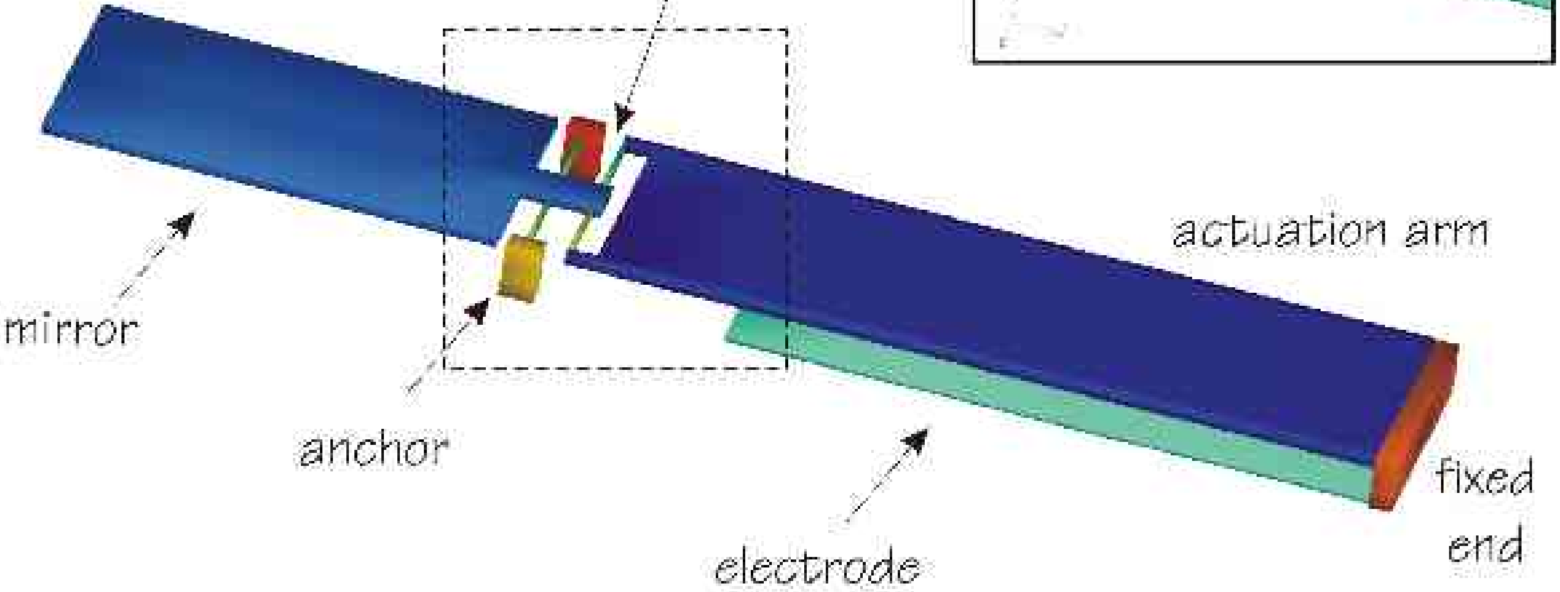


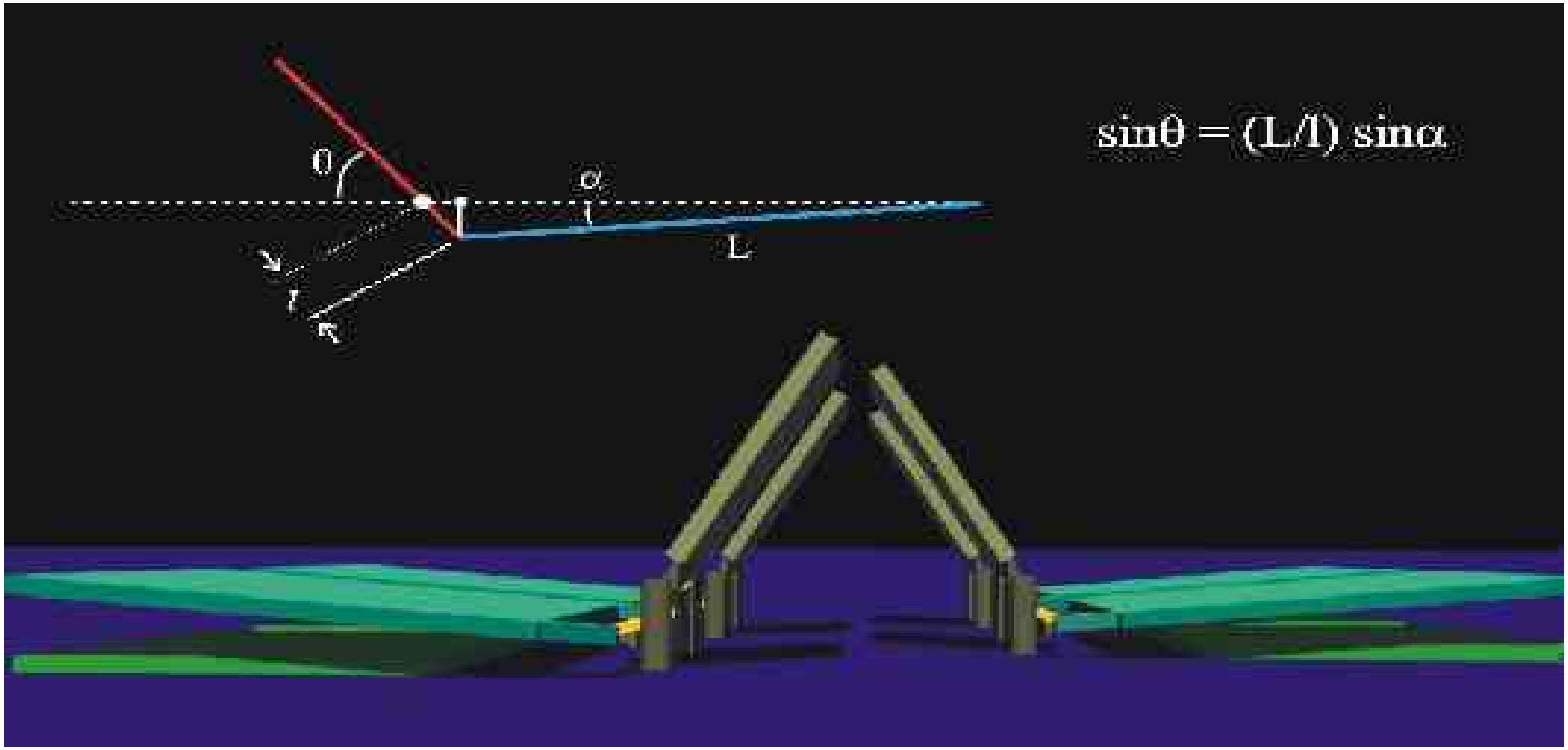




Double Hinge Mecanism





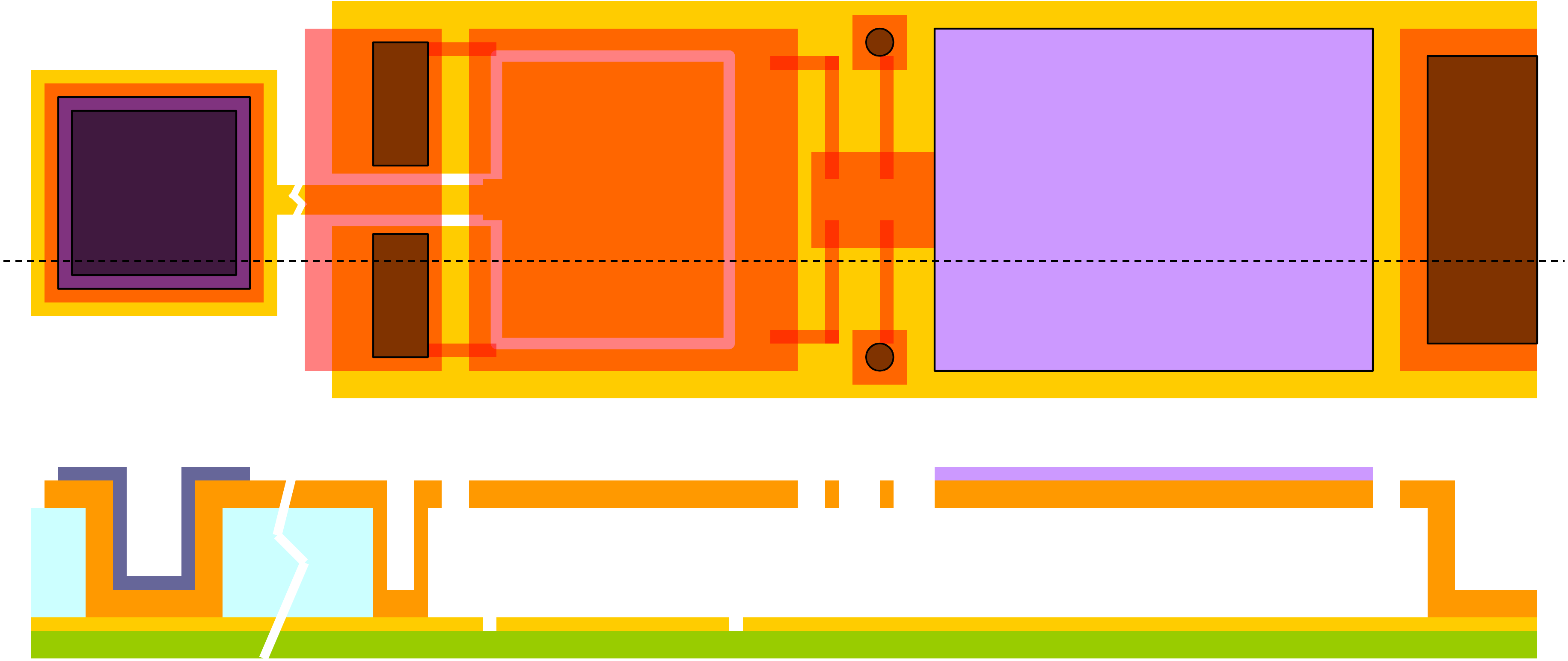


The *transmission mechanism* increases work produced by the actuator:

- **larger area can be used**
- **actuator gap can be decreased,**

while maintaining the required range of motion

Process Flow



🟩	**Si-Rich Nitride**	**0.5um**	🟧	**PolySilicon**	**1.0um**
🟨	**PolySilicon**	**0.5um**	▨	**Pad Metal**	**0.6um**
🟦	**Sacrificial Si Oxide**	**4.0um**	🟪	**Mirror Metal**	**0.04um**

BULK MICROMACHINING:

Overview

Superhydrophobic microfabricated surfaces

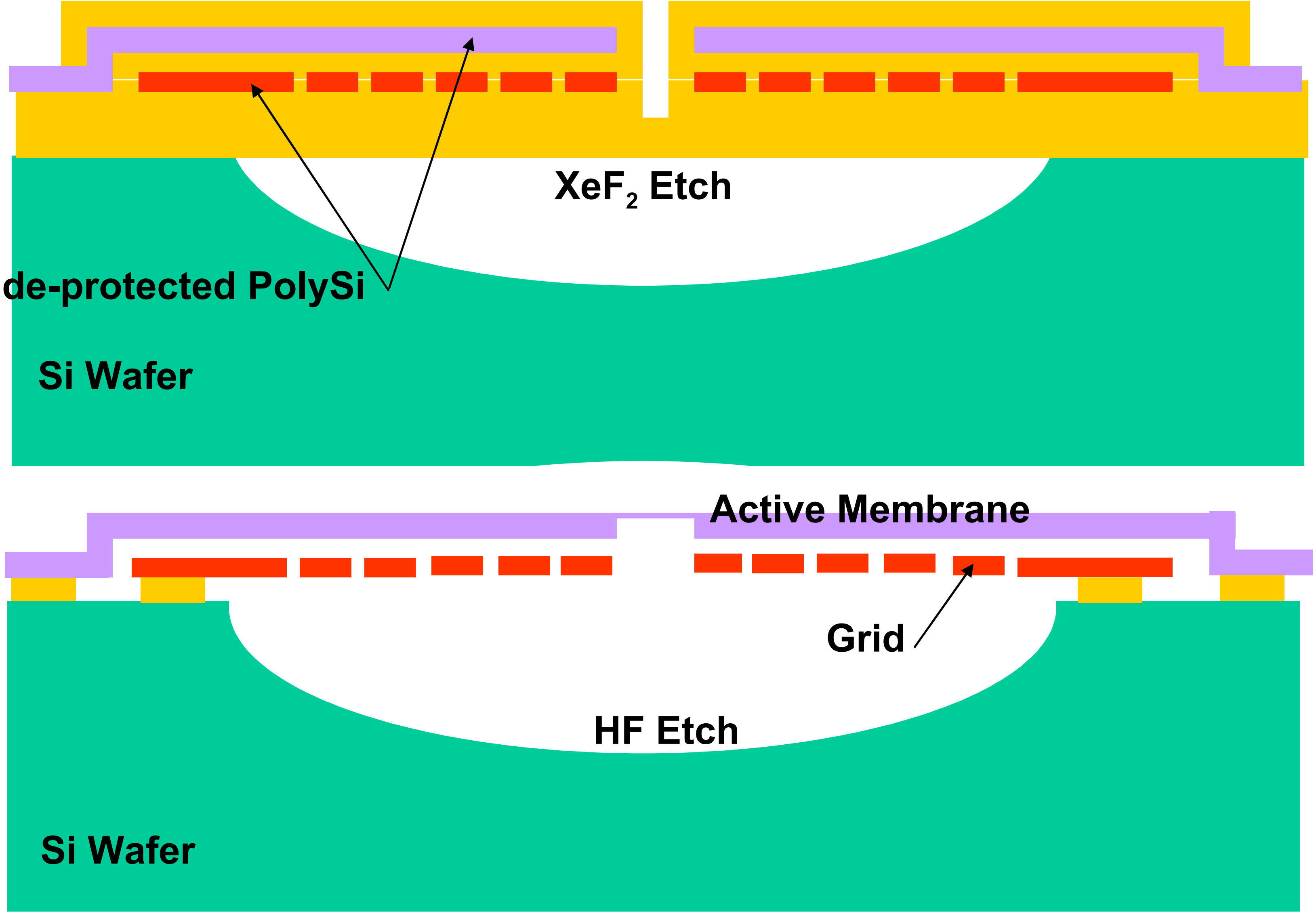
+

Electrowetting

⬇

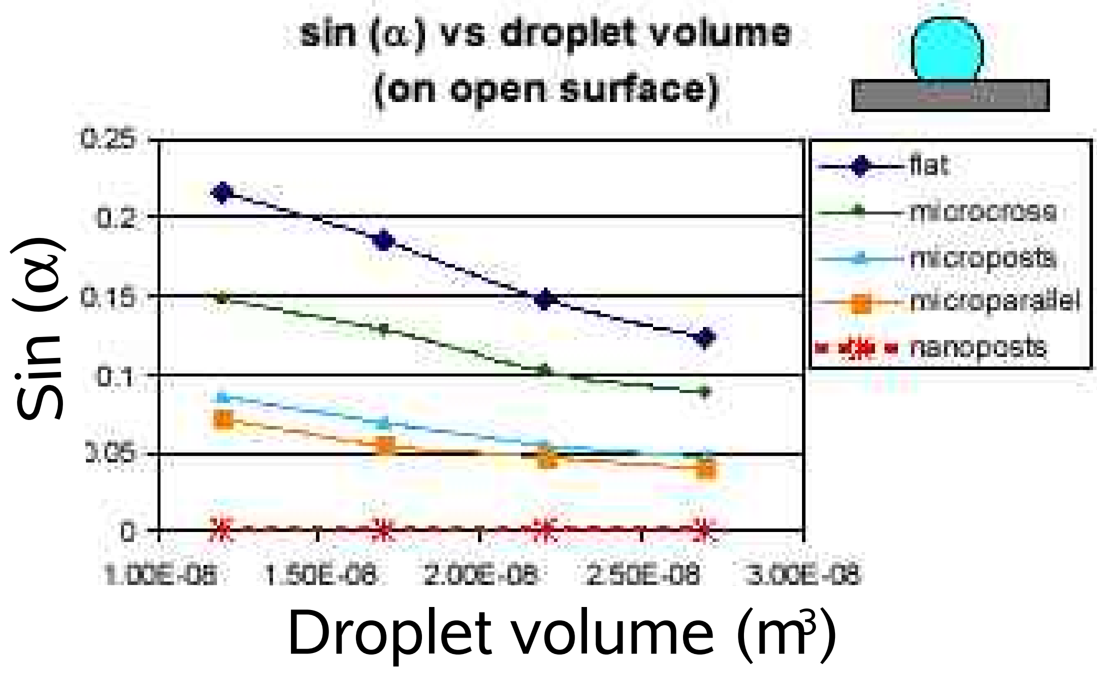
Control droplet movement and wetting

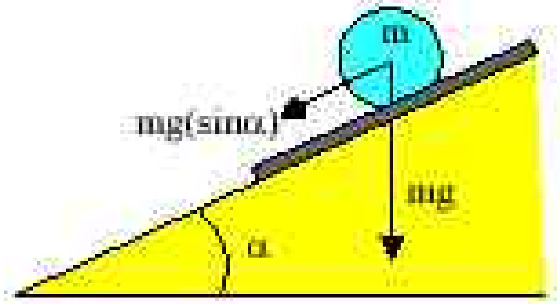
Dry Release of Protected Silicon Structures



Superhydrophobic Surfaces

Mobility



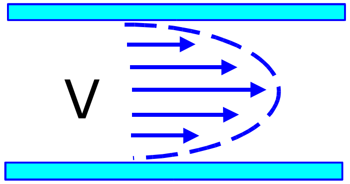


Joonwon Kim & "CJ" Kim (UCLA, 2002)

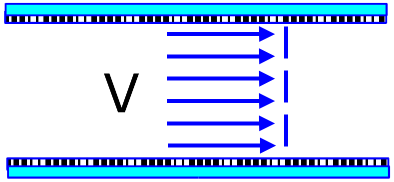
Applications: Micro and Nano-fluidics

High mobility and super-repellency based

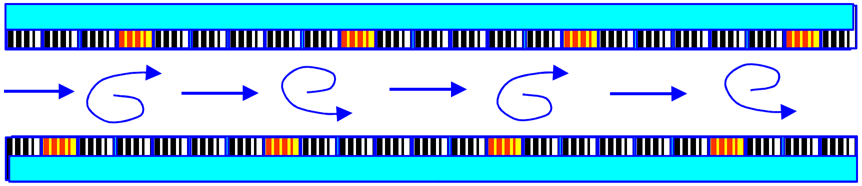
no slip

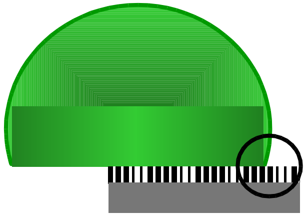


complete slip

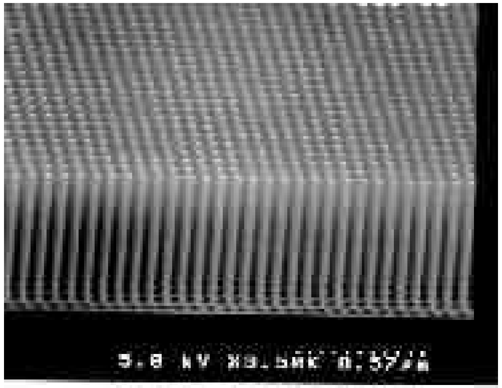


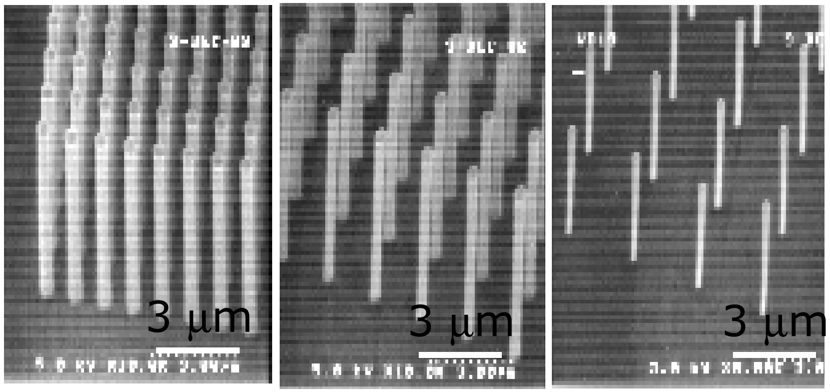
tunable microfluidic mixer



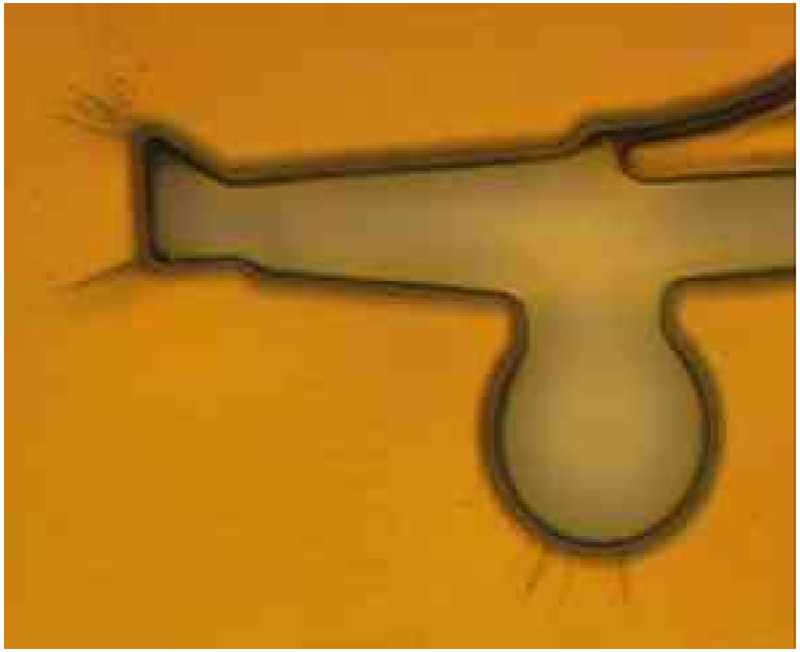


Liquid- solid contact angle

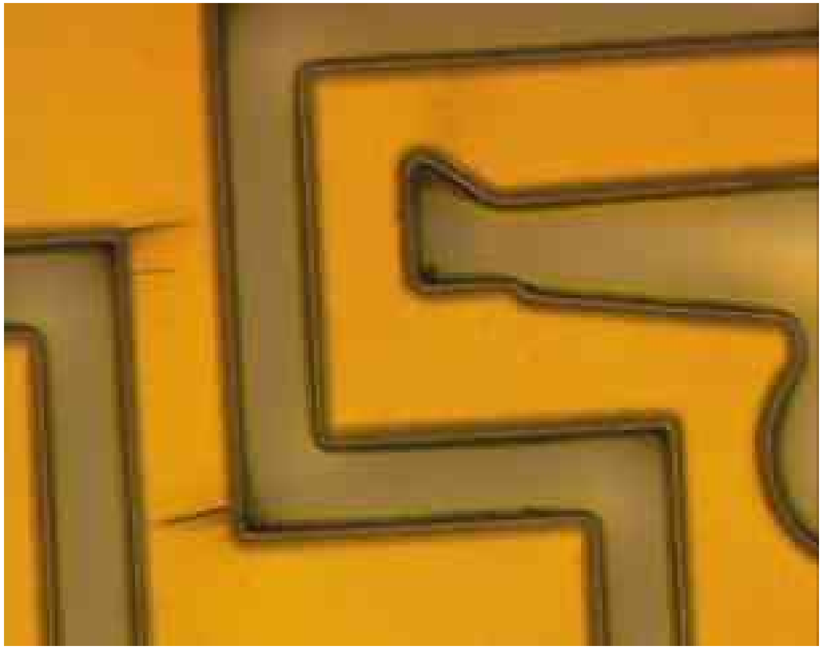




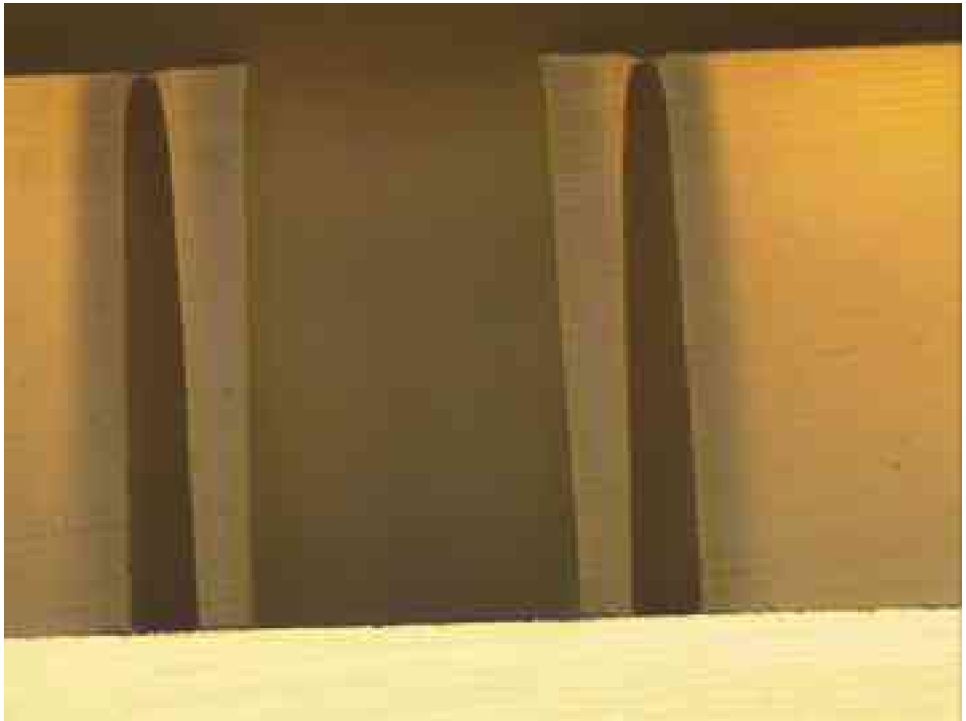
STRESS RELIEF BORDER



No Border

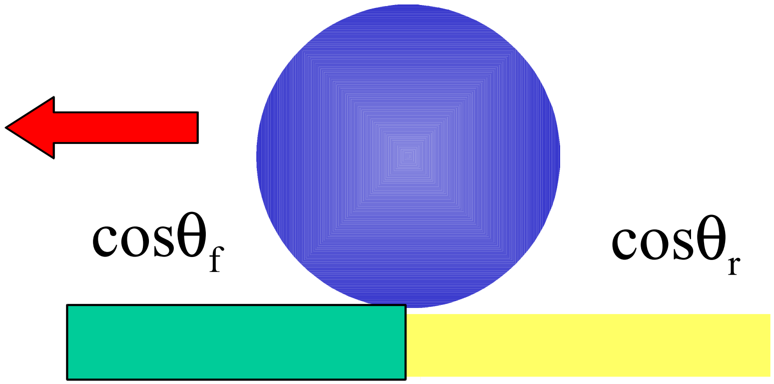


100um Border-100um space



SU-8 290um thick,coded 25um gap, 22um feature

Droplet Movement



$$dF = \gamma_{LV}\,(\cos\theta_f - \cos\theta_r)dy$$

- **Electrostatic**

$$\cos\theta_f - \cos\theta_r = K(V_f^2 - V_r^2) \qquad V_f^2 > V_r^2$$

- **Area density**

$$\cos\theta_f - \cos\theta_r = (f_f - f_r)(\cos\theta_0 + 1) \qquad f_f > f_r$$

$$f = A_1 / A_2$$

MEMS FABRICATION

Premise: as with semiconductor fabrication
the need for increasing functionality of MEMS devices in time will lead to a need for more, smaller components on individual devices. This in turn will necessitate the need for advanced fabrication equipment and processes and integration of control electronics and MEMS on a single substrate.