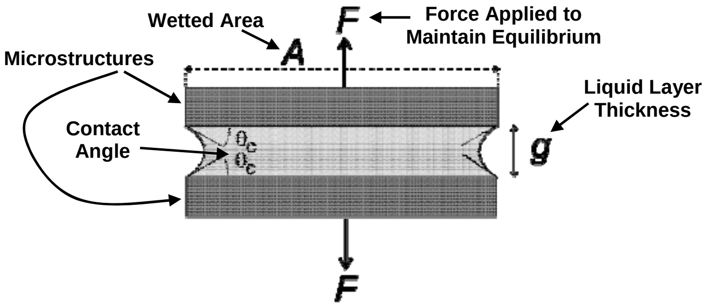
Lecture Outline

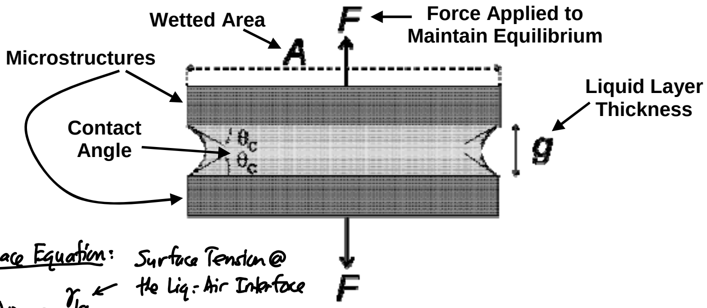
- Reading: Senturia Chpt. 3, Jaeger Chpt. 11, Handout: "Surface Micromachining for Microelectromechanical Systems"
- Lecture Topics:
  - Polysilicon surface micromachining
  - Stiction
  - Residual stress
  - Topography issues
  - Nickel metal surface micromachining
  - 3D "pop-up" MEMS
  - Foundry MEMS: the "MUMPS" process
  - The Sandia SUMMIT process

Microstructure Stiction



- Thin liquid layer between two solid plates ⇨ adhesive
- If the contact angle between liquid and solid $\theta_c < 90°$:
  - Pressure inside the liquid is lower than outside
  - Net attractive force between the plates
- The pressure difference (i.e., force) is given by the Laplace equation

Microstructure Stiction Modeling



Laplace Equation:

$$\Delta p_{la} = \frac{\gamma_{la}}{r}$$

Surface Tension @ the Liq-Air Interface

Radius of Curvature of the Meniscus ((-) if concave)

Pressure Difference @ the Liquid-Air Interface

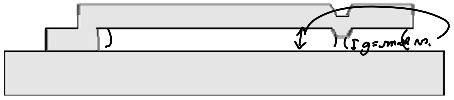
$$\left[r = -\frac{(g/2)}{\cos\theta_c}\right] \Longrightarrow \boxed{F = -\Delta p_{la} A = \frac{2A\gamma_{la}\cos\theta_c}{g}}$$

Force needed to keep the plates apart

⇒ (+) force means a (-) Laplace pressure

Avoiding Stiction

- Reduce droplet area via mechanical design approaches



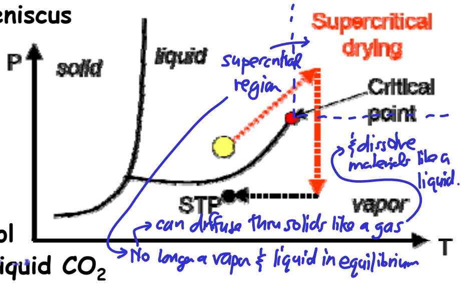
Standoff Bumps

Meniscus-Shaping Features

- Avoid liquid-vapor meniscus formation
  - Use solvents that sublimate
  - Use vapor-phase sacrificial layer etch
- Modify surfaces to change the meniscus shape from concave (small contact angle) to convex (large contact angle)
  - Use teflon-like films
  - Use hydrophobic self-assembled monolayers (SAMs)

Supercritical CO_2 Drying

- A method for stictionless drying of released microstructures by immersing them in CO_2 at its supercritical point
- **Basic Strategy**: Eliminate surface tension-derived sticking by avoiding a liquid-vapor meniscus



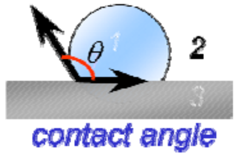
& dissolve materials like a liquid.

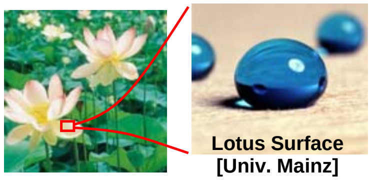
can diffuse thru solids like a gas

No longer a vapor & liquid in equilibrium

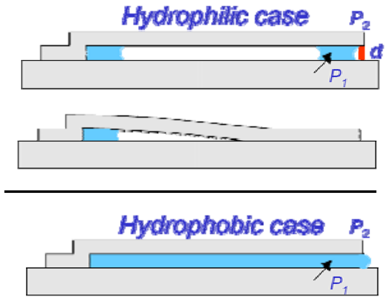
- **Procedure**:
  - Etch oxide in solution of HF
  - Rinse thoroughly in DI water, but do not dry
  - Transfer the wafer from water to methanol
  - Displace methanol w/ liquid CO_2
  - Apply heat & pressure to take the CO_2 past its critical pt.
  - Vent to lower pressure and allow the supercritical CO_2 to revert to gas → liquid-to-gas Xsition in supercritical region means no capillary forces to cause stiction

Hydrophilic Versus Hydrophobic




Lotus Surface
[Univ. Mainz]

- **Hydrophilic**:
  - A surface that invites wetting by water
  - Get stiction
  - Occurs when the contact angle θ_{water} < 90°
- **Hydrophobic**:
  - A surface that repels wetting by water
  - Avoids stiction
  - Occurs when the contact angle θ_{water} > 90°

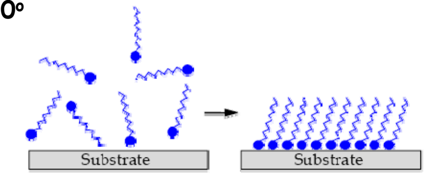


Tailoring Contact Angle Via SAM's

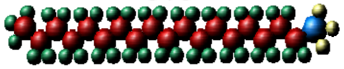
- Can reduce stiction by tailoring surfaces so that they induce a water contact angle > 90°

Self-Assembled Monolayers (SAM's):

- Monolayers of "stringy" molecules covalently bonded to the surface that then raise the contact angle
- Beneficial characteristics:
  - Conformal, ultrathin
  - Low surface energy
  - Covalent bonding makes them wear resistant
  - Thermally stable (to a point)



OTS

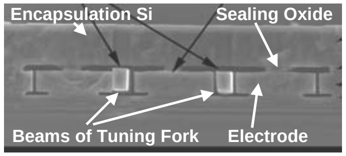


$CH_3(CH_2)_{17}SiCl_3$

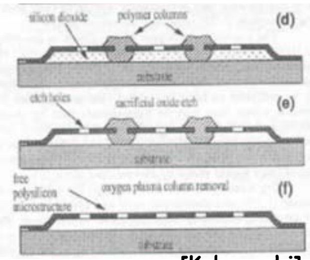
	θ_{water}
ODT SAM	112 ± 0.7°
SiO_2	<10°

Dry Release

- Another way to avoid stiction is to use a dry sacrificial layer etch
- For an oxide sacrificial layer
  - use HF vapor phase etching
  - **Additional advantage**: gas can more easily get into tiny gaps
  - **Issue**: not always completely dry → moisture can still condense → stiction → **soln**: add alcohol
- For a polymer sacrificial layer
  - Use an O_2 plasma etch (isotropic, so it can undercut well)
  - Issues:
    - Cannot be used when structural material requires high temperature for deposition
    - If all the polymer is not removed, polymer under the suspended structure can still promote stiction



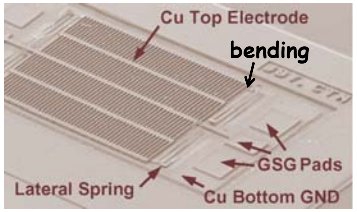
Released via vapor phase HF [Kenny, et al., Stanford]



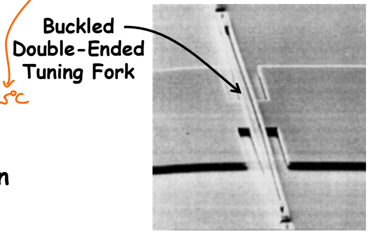
[Kobayashi]

Residual Stress

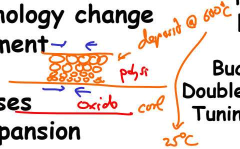
Residual Stress in Thin Films



Tunable Dielectric Capacitor [Yoon, et al., U. Michigan]



- After release, poorly designed microstructures might buckle, bend, or warp → often caused by residual film stress
- Origins of residual stress, σ
  - ↳ Growth processes
    - ☛ Non-equilibrium deposition
    - ☛ Grain morphology change
    - ☛ Gas entrapment
    - ☛ Doping
  - ↳ Thermal stresses
    - ☛ Thermal expansion mismatch of materials → introduce stress during cool-down after deposition
    - ☛ Annealing



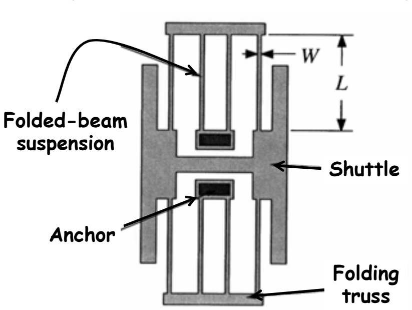
Need to Control Film Stress

- Resonance frequency expression for a lateral resonator:

$$f_0 \approx \frac{1}{2\pi}\sqrt{\underbrace{\frac{4E_y tW^3}{ML^3}}_{\text{Basic term}}+\underbrace{\frac{24\sigma_r tW}{5ML}}_{\text{Stress term}}}$$

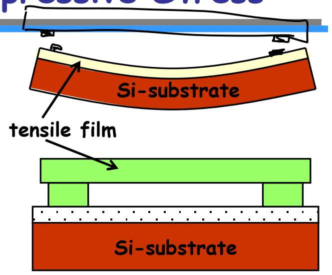
Since W « L, the stress term will dominate if $\sigma_r \sim E_y$

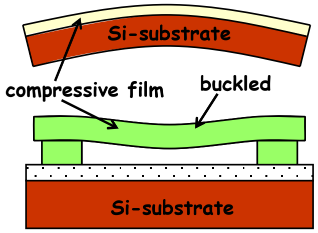
E_y = Young's modulus
σ_r = stress
t = thickness
W = beam width
L = beam length
M = mass



Tensile Versus Compressive Stress

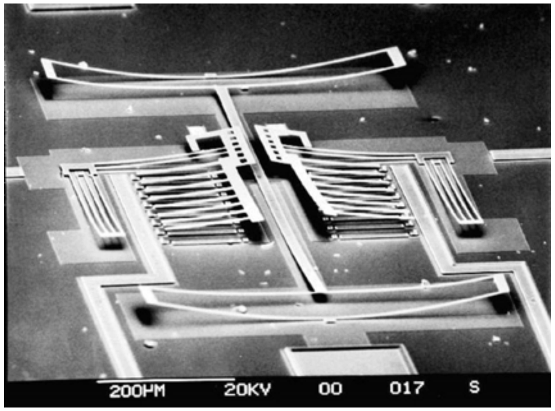
- Under tensile stress, a film wants to shrink w/r to its substrate
  - ↳ Caused, e.g., by differences in film vs. substrate thermal expansion coefficients
  - ↳ If suspended above a substrate and anchored to it at two points, the film will be "stretched" by the substrate
- Under compressive stress, a film wants to expand w/r to its substrate
  - ↳ If suspended above a substrate and anchored to it at two points, the film will buckle over the substrate





Vertical Stress Gradients

- Variation of residual stress in the direction of film growth
- Can warp released structures in z-direction

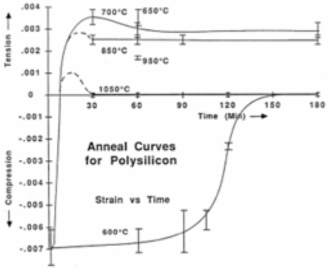


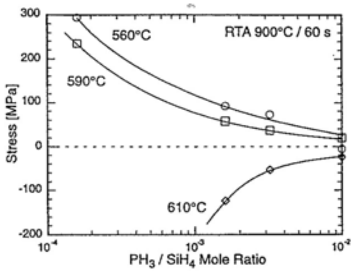
Stress in Polysilicon Films

- Stress depends on crystal structure, which in turn depends upon the deposition temperature
- Temperature ≤ 600°C
  - Films are initially amorphous, then crystallize
  - Get equiaxed crystals, largely isotropic
  - Crystals have higher density → tensile stress
  - Small stress gradient
- Temperature ≥ 600°C
  - Columnar crystals grow during deposition
  - As crystals grow vertically and in-plane they push on neighbors → compressive stress
  - Positive stress gradient

Annealing Out Polysilicon Stress

- Control polySi stress by annealing at high temperatures
  - Typical anneal temperatures: 900-1150°C
  - Grain boundaries move, relax
  - Can dope while annealing by sandwiching the polysilicon between similarly doped oxides (symmetric dopant drive-in), e.g. using 10-15 wt. % PSG

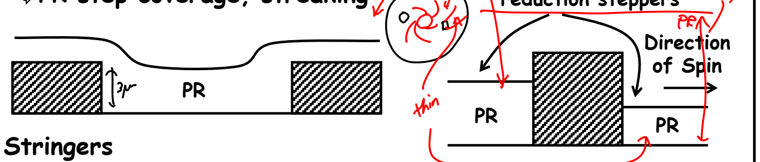




- Rapid thermal anneal (RTA) also effective (surprisingly)

Topography Issues

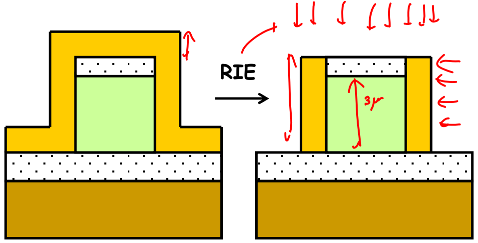
- Degradation of lithographic resolution
  - PR step coverage, streaking

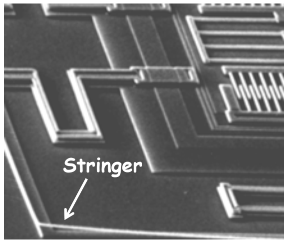


Thickness differences pose problems for reduction steppers

Direction of Spin

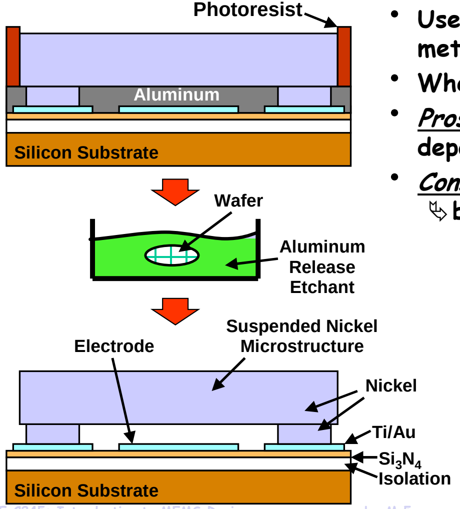
- Stringers
  - Problematic when using anisotropic etching, e.g., RIE



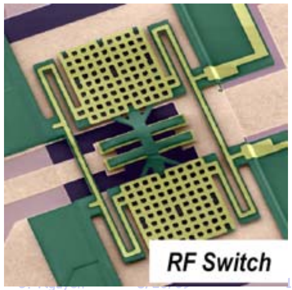


Nickel Surface-Micromachining Process Flow

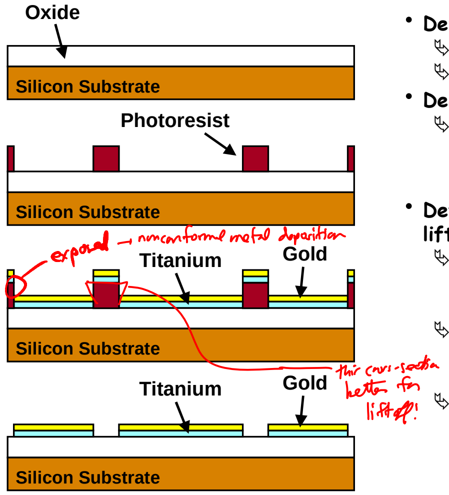
Electroplating: Metal MEMS



- Use electroplating to obtain metal μstructures
- When thick: call it "LIGA"
- *Pros*: fast low temp deposition, very conductive
- *Cons*: drift, low mech. *Q*
  - but may be solvable?



Nickel Metal Surface-Micromachining

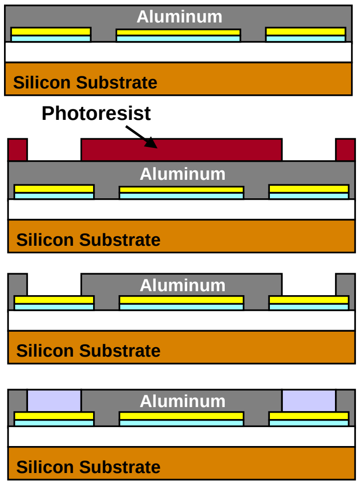


exposed → nonconformal metal deposition

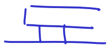
this cross-section better for liftoff!

- Deposit isolation LTO:
  - Target = 2μm
  - 1 hr. 40 min. LPCVD @450°C
- Densify the LTO
  - Anneal @950°C for 30 min.
- Define metal interconnect via lift-off
  - Spin photoresist and pattern lithographically to open areas where interconnect will stay
  - Evaporate a Ti/Au layer
    - Target = 30nm Ti
    - Target = 270nm Au
  - Remove photoresist in PRS2000→ Ti/Au atop the photoresist also removed

Nickel Metal Surface-Micromachining



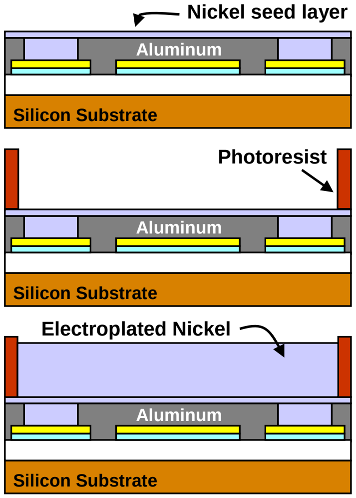
- Evaporate Al to serve as a sacrificial layer
  - Target = 1μm
- Lithography to define anchor openings
- Wet etch the aluminum to form anchor vias
  - Use solution of $H_3PO_4/HNO_3/H_2O$



- Remove photoresist in PRS2000

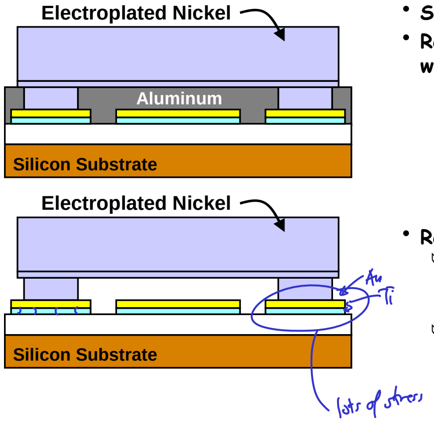
- Electroplate nickel to fill the anchor vias
  - Use solution of nickel sulfamate @ 50°C
  - Time the electroplating to planarize the surface

Nickel Metal Surface-Micromachining



- Evaporate a thin film of nickel to serve as a seed layer for subsequent Ni electroplating
    - Target = 20nm
- Form a photoresist mold for subsequent electroplating
    - Spin 6 um-thick AZ 9260 photoresist
    - Lithographically pattern the photoresist to delineate areas where nickel structures are to be formed
- Electroplate nickel structural material through the PR mold
    - Use a solution of nickel sulfamate @ 50°C
    - Cathode-to-anode current density ~ 2.5 mA/cm²

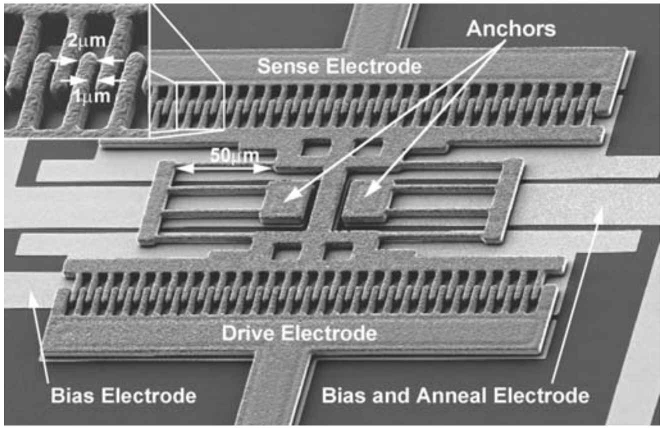
Nickel Metal Surface-Micromachining



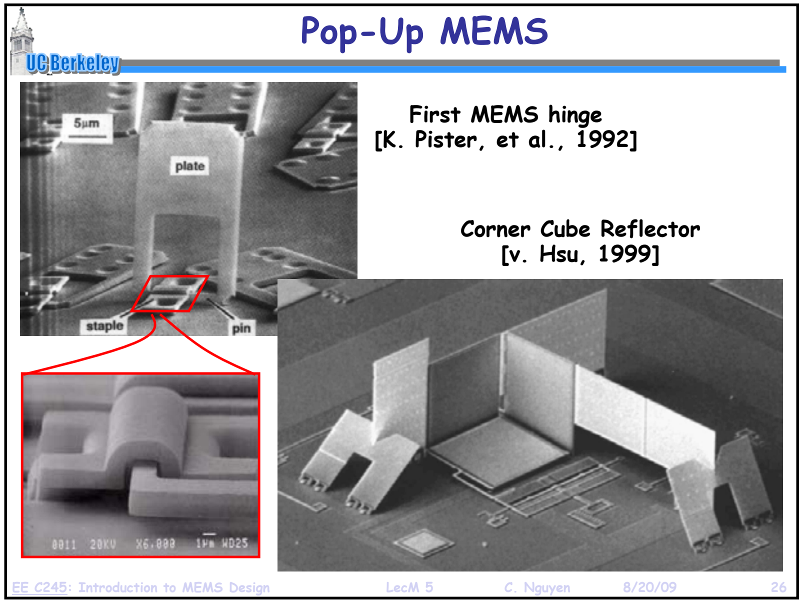
- Strip the PR in PRS2000
- Remove the Ni seed layer in Ni wet etchant
- Release the structures
    - Use a $K_4Fe(CN)_6$/NaOH etchant that attacks Al while leaving Ni and Au intact
    - Etch selectivity > 100:1 for Al:Ni and Al:Au

Nickel Surface-Micromachining Example

- Below: Surface-micromachined in nickel using the described process flow



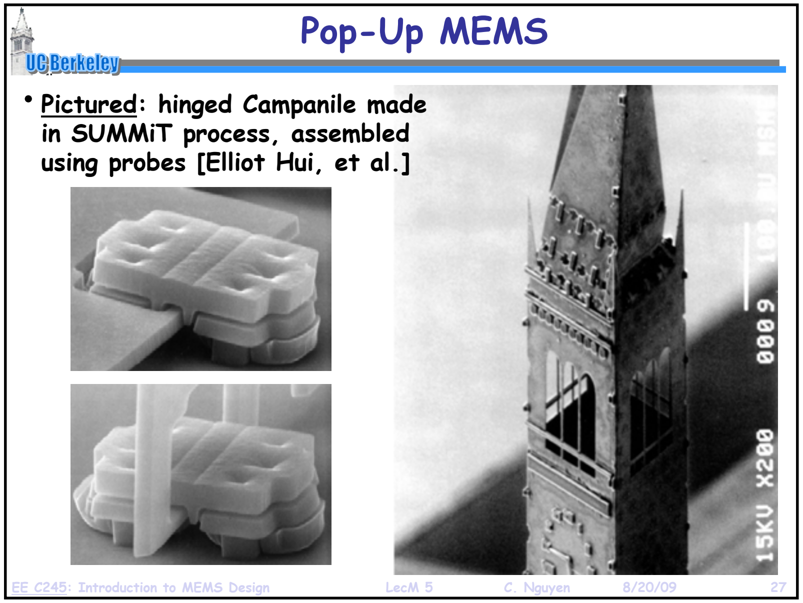
3D "Pop-up" MEMS



Pop-Up MEMS

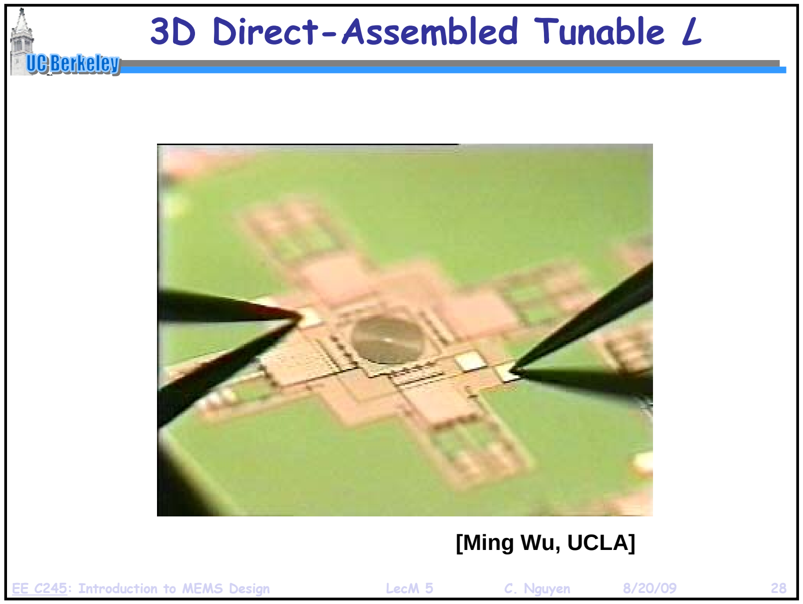
First MEMS hinge
[K. Pister, et al., 1992]

Corner Cube Reflector
[v. Hsu, 1999]



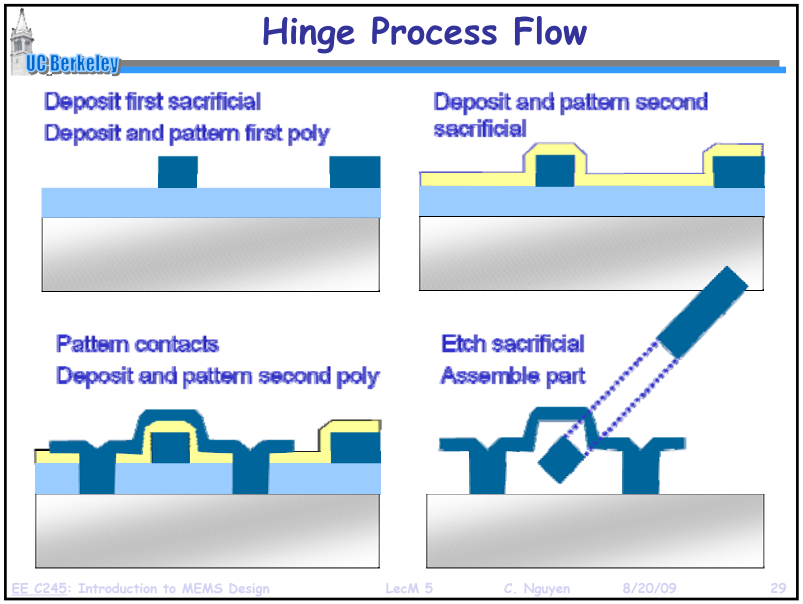
Pop-Up MEMS

- **Pictured**: hinged Campanile made in SUMMiT process, assembled using probes [Elliot Hui, et al.]



3D Direct-Assembled Tunable *L*

[Ming Wu, UCLA]



Hinge Process Flow

Deposit first sacrificial
Deposit and pattern first poly

Deposit and pattern second sacrificial

Pattern contacts
Deposit and pattern second poly

Etch sacrificial
Assemble part