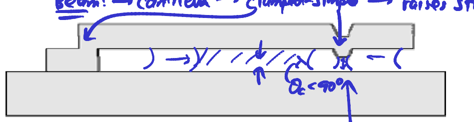
Avoiding Stiction

- Reduce droplet area via mechanical design approaches

Beam: → cantilever → clamped-simple → raises stiffness : $F_{restore} = kx$



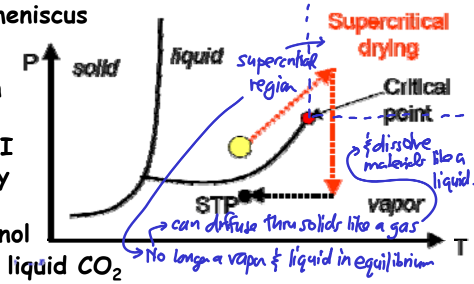
Standoff Bumps ① reduced A (but, reduces g)

Meniscus-Shaping Features

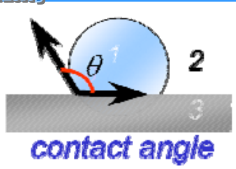
- Avoid liquid-vapor meniscus formation
  - Use solvents that sublimate
  - Use vapor-phase sacrificial layer etch
- Modify surfaces to change the meniscus shape from concave (small contact angle) to convex (large contact angle)
  - Use teflon-like films
  - Use hydrophobic self-assembled monolayers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

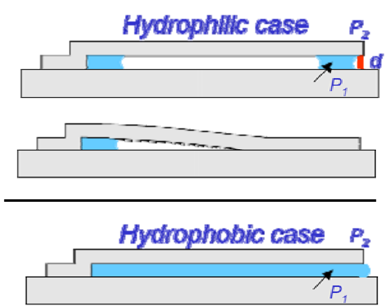


Hydrophilic Versus Hydrophobic



Lotus Surface [Univ. Mainz]

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

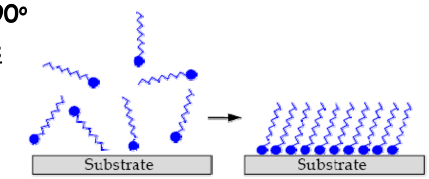


Tailoring Contact Angle Via SAM's

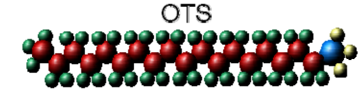
- Can reduce stiction by tailoring surfaces so that they induce a water contact angle > 90°

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

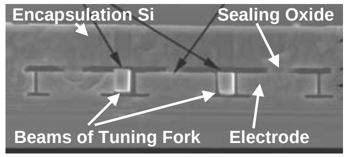


$CH_3(CH_2)_{17}SiCl_3$

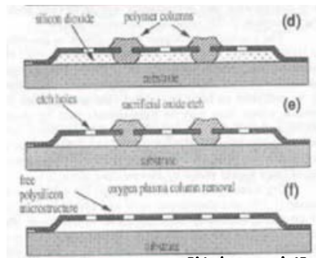
	θ_{water}
ODT SAM	112 ± 0.7°
SiO_2	<10°

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]

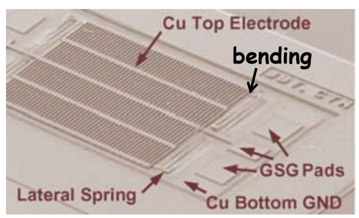


[Kobayashi]

Residual Stress

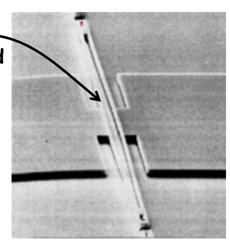
Residual Stress in Thin Films

- 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



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

Buckled Double-Ended Tuning Fork



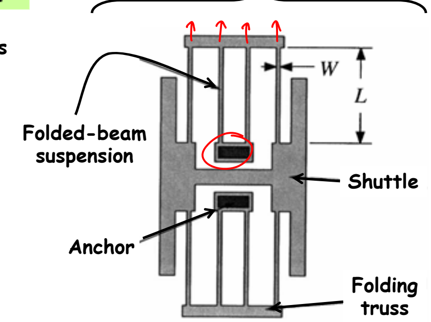
Need to Control Film Stress

- Resonance frequency expression for a lateral resonator:

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

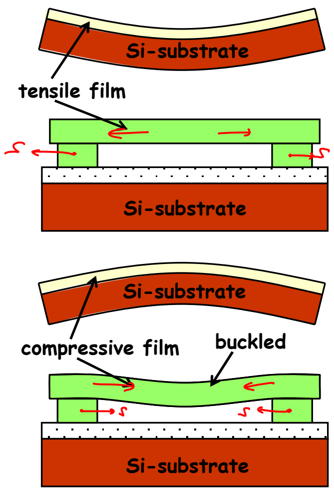
Since W « L, the stress term will dominate if $\sigma_r \sim E_y$

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



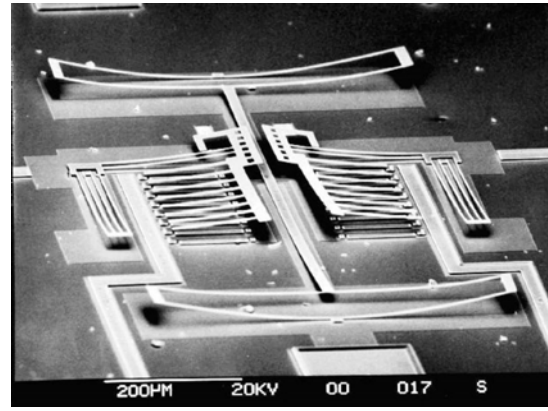
Tensile Versus Compressive Stress

- 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



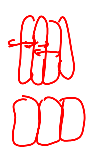
Vertical Stress Gradients

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



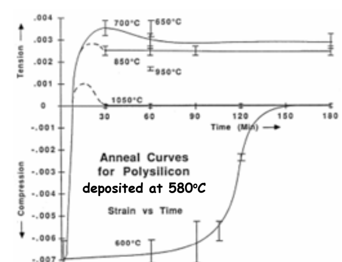
Stress in Polysilicon Films

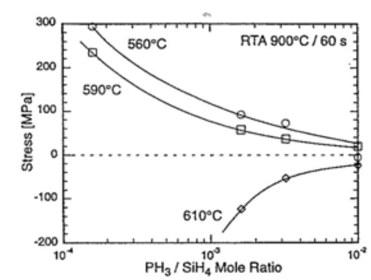
- Stress depends on crystal structure, which in turn depends upon the deposition temperature
- Temperature ≤ 600°C
  - Films are initially amorphous,then crystallize
  - Get equiaxed crystals, largely isotropic
  - Crystals have higher density → tensile stress
  - Small stress gradient
- Temperature ≥ 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



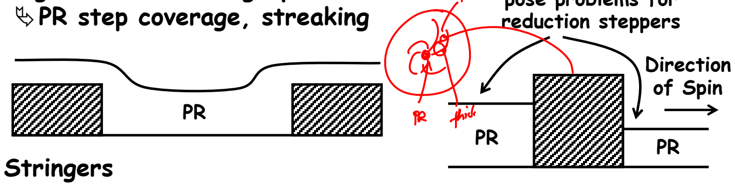


- Rapid thermal anneal (RTA) also effective (surprisingly)

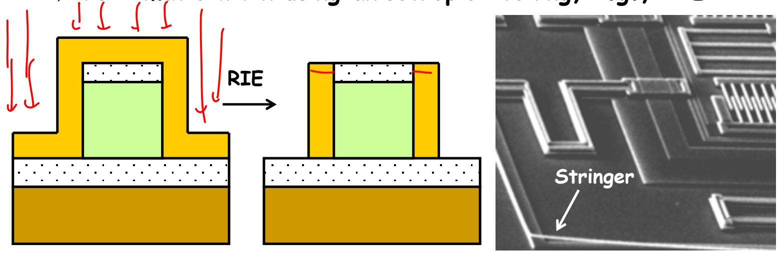
Topography Issues

- Degradation of lithographic resolution
  - PR step coverage, streaking

Thickness differences pose problems for reduction steppers

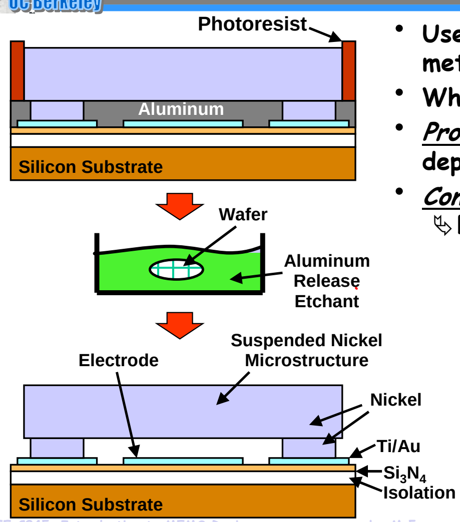


- Stringers
  - Problematic when using anisotropic etching, e.g., RIE

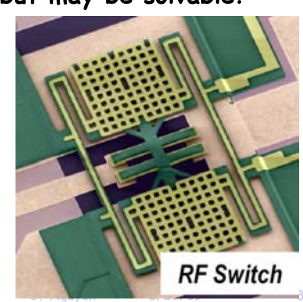


Nickel Surface-Micromachining Process Flow

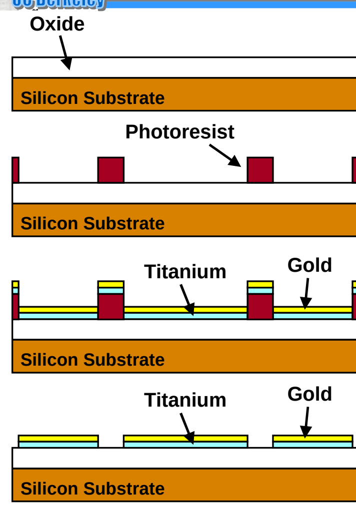
Electroplating: Metal MEMS



- 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?



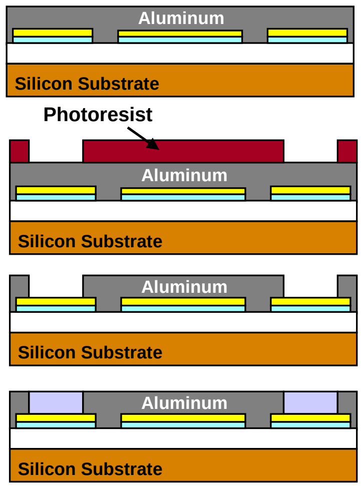
Nickel Metal Surface-Micromachining



- 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

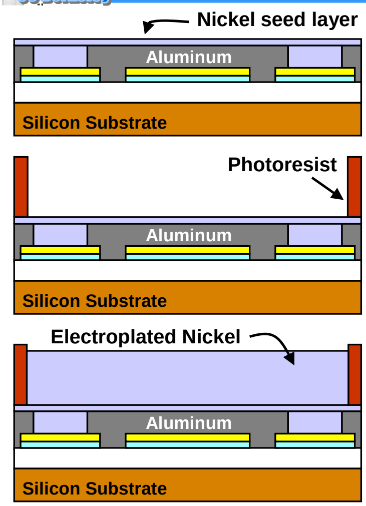
UC Berkeley



- 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

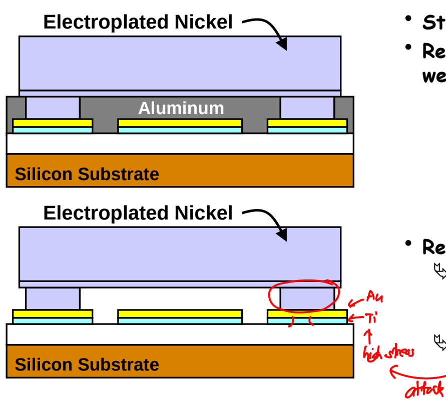
UC Berkeley



- 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

UC Berkeley

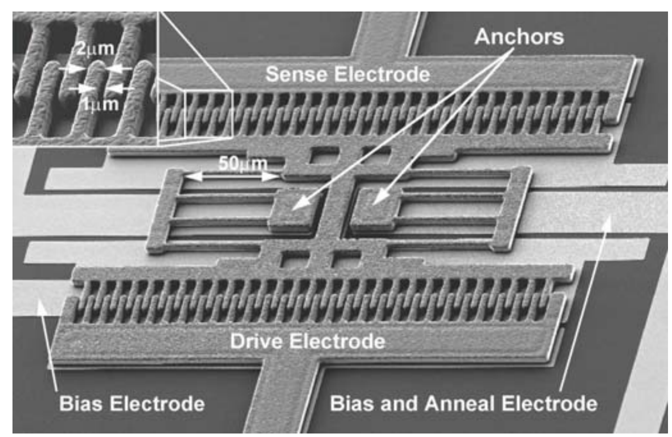


- Strip the PR in PRS2000
- Remove the Ni seed layer in Ni wet etchant
- Release the structures
  - Use a $K_4Fe(CN)_6/NaOH$ etchant that attacks Al while leaving Ni and Au intact
  - Etch selectivity > 100:1 for Al:Ni and Al:Au

Nickel Surface-Micromachining Example

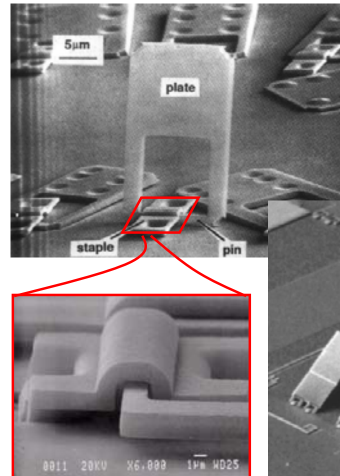
UC Berkeley

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



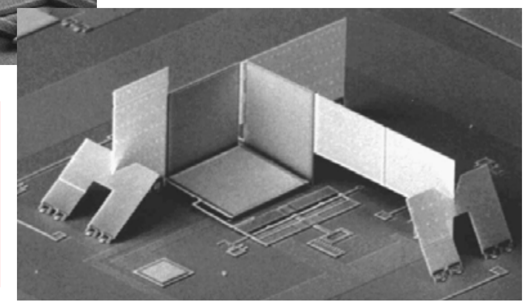
3D "Pop-up" MEMS

Pop-Up MEMS



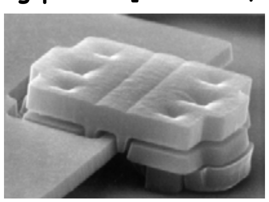
First MEMS hinge
[K. Pister, et al., 1992]

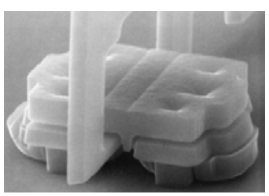
Corner Cube Reflector
[v. Hsu, 1999]



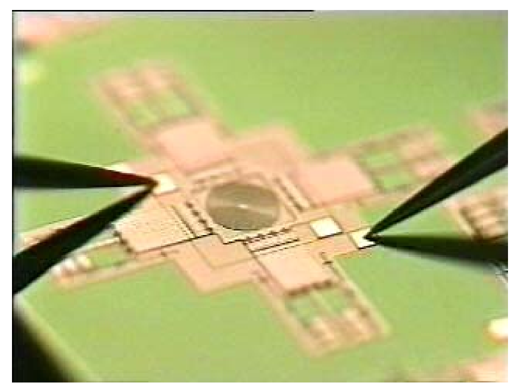
Pop-Up MEMS

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

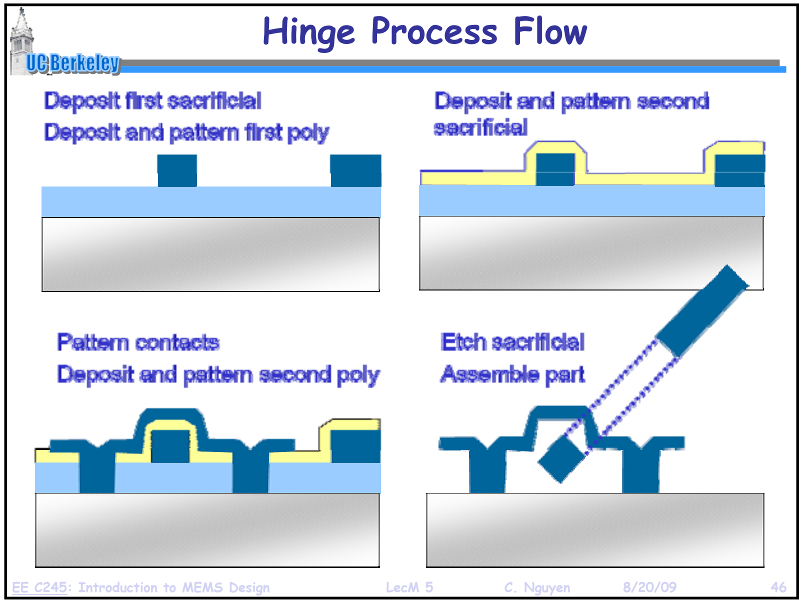




3D Direct-Assembled Tunable *L*



[Ming Wu, UCLA]


Hinge Process Flow
UC Berkeley
Deposit first sacrificial
Deposit and pattern first poly
Deposit and pattern second sacrificial
Pattern contacts
Deposit and pattern second poly
Etch sacrificial
Assemble part
EE C245: Introduction to MEMS Design
LecM 5
C. Nguyen
8/20/09
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