EE C245 – ME C218 Introduction to MEMS Design Fall 2011

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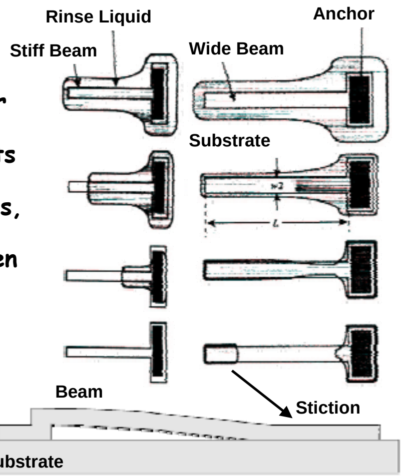
Lecture Module 5: Surface Micromachining

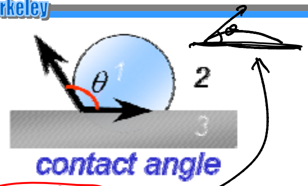
Microstructure Stiction

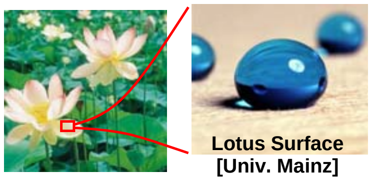
Microstructure Stiction

- **Stiction**: the unintended sticking of MEMS surfaces
- **Release stiction**:
  - Occurs during drying after a wet release etch
  - Capillary forces of droplets pull surfaces into contact
  - Very strong sticking forces, e.g., like two microscope slides w/ a droplet between
- **In-use stiction**: when device surfaces adhere during use due to:
  - Capillary condensation
  - Electrostatic forces
  - Hydrogen bonding
  - Van der Waals forces

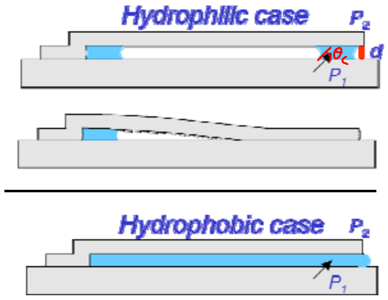


Hydrophilic Versus Hydrophobic




Lotus Surface [Univ. Mainz]

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



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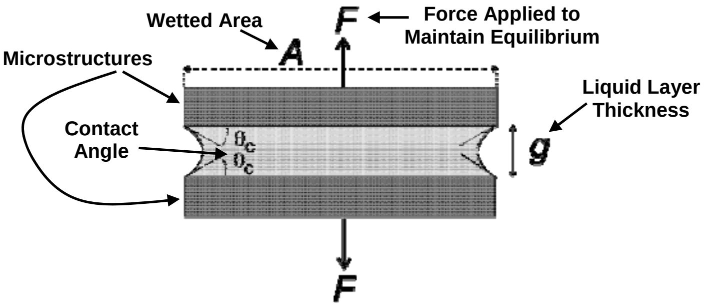
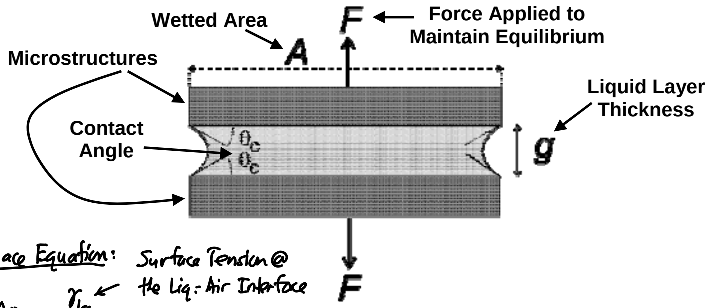
Microstructure Stiction



- 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:

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

γ_{la} ← Surface Tension @ the Liq.-Air Interface

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

Δp_{la} ← Pressure Difference @ the Liquid-Air Interface

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

← Force needed to keep the plates apart

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

Avoiding Stiction

- Reduce droplet area via mechanical design approaches

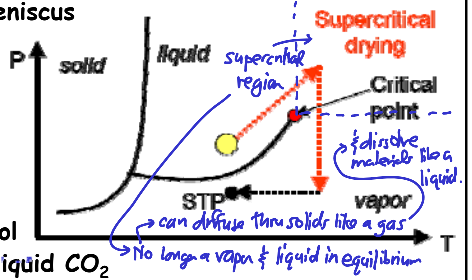
Standoff Bumps

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
- 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



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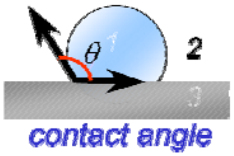

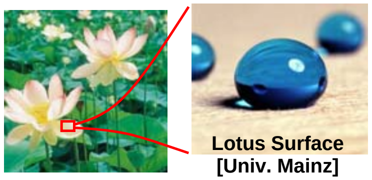
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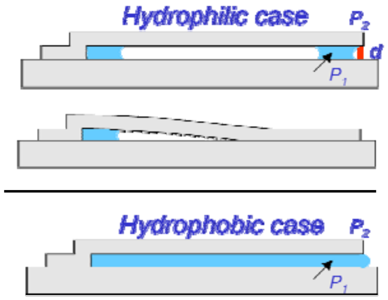
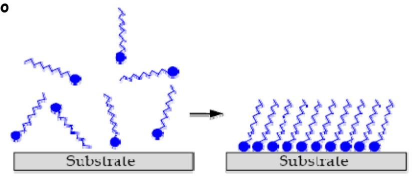


Tailoring Contact Angle Via SAM's

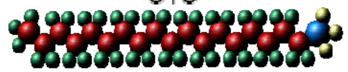
- Can reduce stiction by tailoring surfaces so that they induce a water contact angle > 90°

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

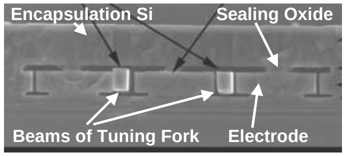


$CH_3(CH_2)_{17}SiCl_3$

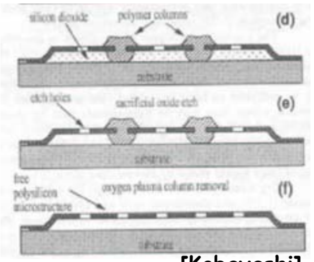
	θ_{water}
ODT SAM	112 ± 0.7°
SiO_2	<10°

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

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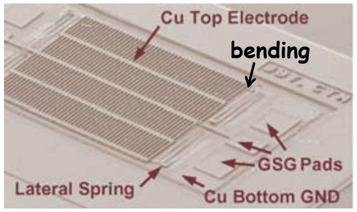
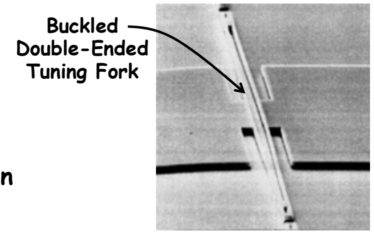
Residual Stress in Thin Films

- 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]



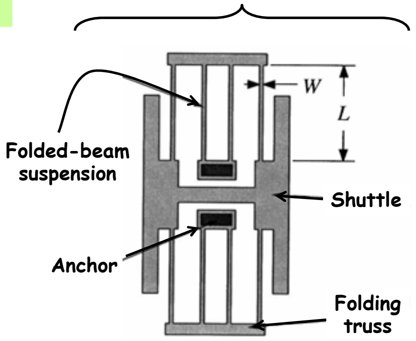
Need to Control Film Stress

- Resonance frequency expression for a lateral resonator:

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

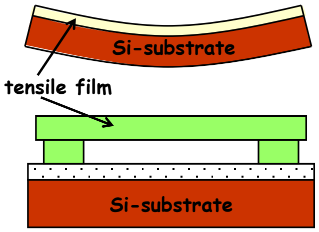
Since W « L, the stress term will dominate if σ_r ~ E_y

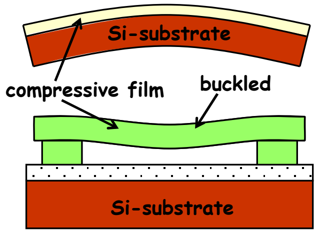
E_y = Young's modulus
σ_r = stress
t = thickness
W = beam width
L = beam length
M = mass



Tensile Versus Compressive Stress

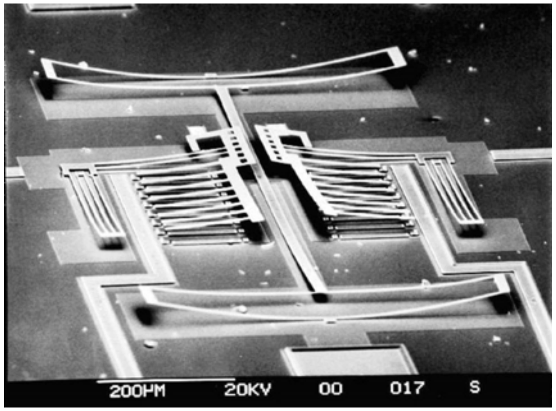
- Under tensile stress, a film wants to shrink w/r to its substrate
  - Caused, e.g., by differences in film vs. substrate thermal expansion coefficients
  - If suspended above a substrate and anchored to it at two points, the film will be "stretched" by the substrate
- Under compressive stress, a film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



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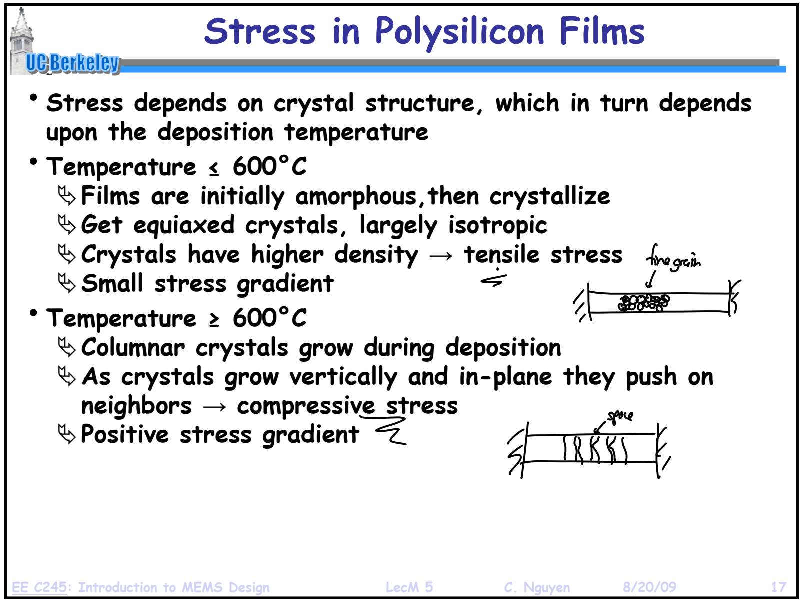

Stress in Polysilicon Films

- 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

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