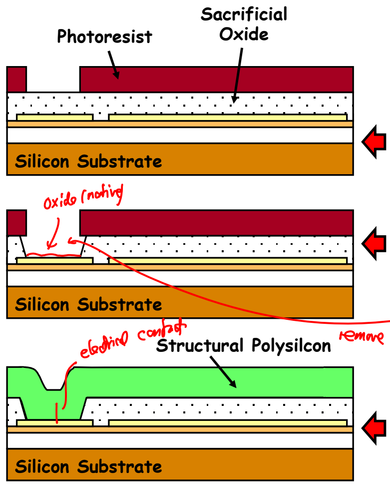
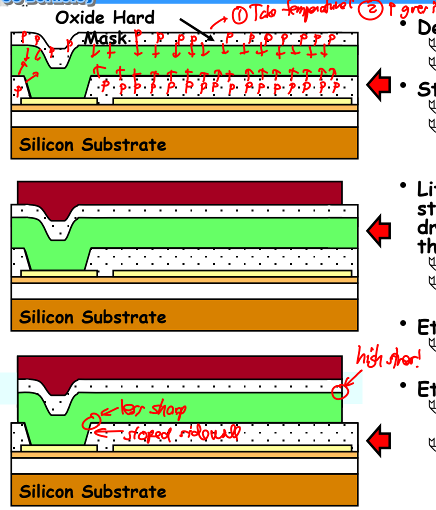
Surface-Micromachining Process Flow



- Deposit sacrificial PSG:
  - Target = 2μm
  - 1 hr. 40 min. LPCVD @450°C
- Densify the PSG
  - Anneal @950°C for 30 min.
- Lithography to define anchors using the ANCHOR(df) mask
  - Align to the poly1 layer
- Etch anchors
  - RIE using $CHF_3/CF_4/He$ @350W,2.8Torr
  - Remove PR in PRS2000
  - Quick wet dip in 10:1 HF to remove native oxide
- Deposit structural polySi a sandwich dope it
  - Target = 2μm
  - In-situ Phosphorous-doped
  - 11 hrs. LPCVD @650°C

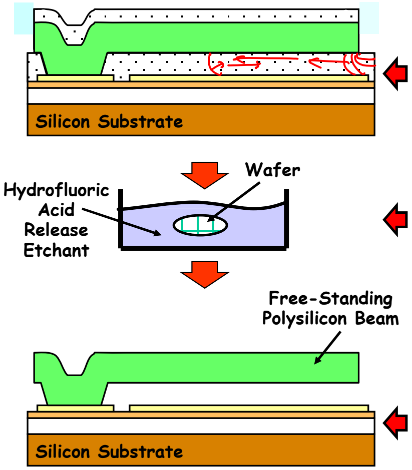
Surface-Micromachining Process Flow

① T do temperature? ② P goes into poly symmetrically ← good for stress!



- Deposit oxide hard mask
  - Target = 500nm
  - 25 min. LPCVD @450°C PSG
- Stress Anneal → anneal →
  - 1 hr. @ 1050°C
  - Or RTA for 1 min. @ 1100°C in 50 sccm N_2
- Lithography to define poly2 structure (e.g., shuttle, springs, drive & sense electrodes) using the POLY2(cf) mask
  - Align to the anchor layer
  - Hard bake the PR longer to make it stronger
- Etch oxide mask first
  - RIE using $CHF_3/CF_4/He$ @350W,2.8Torr
- Etch structural polysilicon
  - RIE using $CCl_4/He/O_2$ @300W,280mTorr
  - Use 1 min. etch/1 min. rest increments to prevent excessive temperature

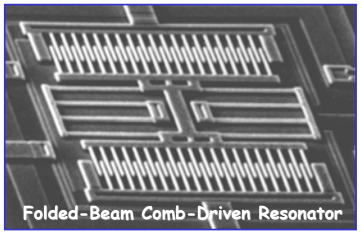
Surface-Micromachining Process Flow

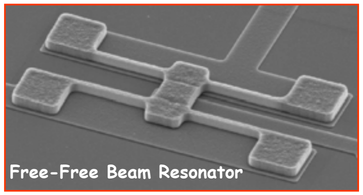


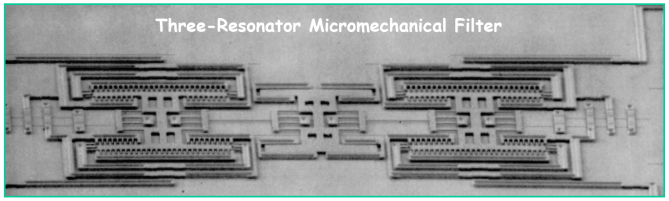
- Remove PR (more difficult)
  - Ash in O_2 plasma
  - Soak in PRS2000
- Release the structures
  - Wet etch in HF for a calculated time that insures complete undercutting
  - If 5:1 BHF, then ~ 30 min.
  - If 48.8 wt. % HF, ~ 1 min.
- Keep structures submerged in DI water after the etch
- Transfer structures to methanol
- Supercritical CO_2 dry release

Polysilicon Surface-Micromachined Examples

- **Below**: All surface-micromachined in polysilicon using variants of the described process flow


Folded-Beam Comb-Driven Resonator


Free-Free Beam Resonator

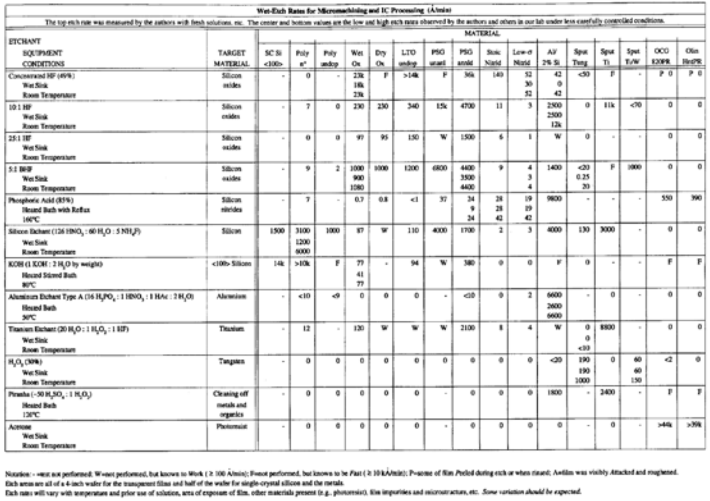

Three-Resonator Micromechanical Filter

Structural/Sacrifical Material Combinations

Structural Material	Sacrificial Material	Etchant
Poly-Si	SiO_2, PSG, LTO	HF, BHF
Al	Photoresist	O_2 plasma
SiO_2	Poly-Si	XeF_2
Al	Si	TMAH, XeF_2
Poly-SiGe	Poly-Ge	H_2O_2, hot H_2O

- Must consider other layers, too, as release etchants generally have a finite E.R. on any material
- Ex: concentrated HF (48.8 wt. %)
  - Polysilicon E.R. ~ 0
  - Silicon nitride E.R. ~ 1-14 nm/min
  - Wet thermal SiO_2 ~ 1.8-2.3 μm/min
  - Annealed PSG ~ 3.6 μm/min
  - Aluminum (Si rich) ~ 4 nm/min (much faster in other Al)

Wet Etch Rates (f/ K. Williams)



Wet-Etch Rates for Micromachining and IC Processing (Å/min)

The top etch rate was measured by the authors with fresh solutions, etc. The center and bottom values are the low and high etch rates observed by the authors and others in our lab under less carefully controlled conditions.

ETCHANT EQUIPMENT CONDITIONS	TARGET MATERIAL	SC Si <100>	Poly n⁺	Poly undop	Wet Ox	Dry Ox	LTO undop	PSG unanl	PSG annld	Stoic Nitrid	Low-σ Nitrid	Al/2% Si	Sput Tung	Sput Ti	Sput Ti/W	OCG 820PR	Olin HntPR
Concentrated HF (49%) Wet Sink Room Temperature	Silicon oxides	-	0	-	23k 18k 23k	F	>14k	F	36k	140	52 30 52	42 0 42	<50	F	-	P 0	P 0
10:1 HF Wet Sink Room Temperature	Silicon oxides	-	7	0	230	230	340	15k	4700	11	3	2500 2500 12k	0	11k	<70	0	0
25:1 HF Wet Sink Room Temperature	Silicon oxides	-	0	0	97	95	150	W	1500	6	1	W	0	-	-	0	0
5:1 BHF Wet Sink Room Temperature	Silicon oxides	-	9	2	1000 900 1080	1000	1200	6800	4400 3500 4400	9	4 3 4	1400	<20 0.25 20	F	1000	0	0
Phosphoric Acid (85%) Heated Bath with Reflux 160°C	Silicon nitrides	-	7	-	0.7	0.8	<1	37	24 9 24	28 28 42	19 19 42	9800	-	-	-	550	390
Silicon Etchant (126 HNO_3 : 60 H_2O : 5 NH_4F) Wet Sink Room Temperature	Silicon	1500	3100 1200 6000	1000	87	W	110	4000	1700	2	3	4000	130	3000	-	0	0
KOH (1 KOH : 2 H_2O by weight) Heated Stirred Bath 80°C	<100> Silicon	14k	>10k	F	77 41 77	-	94	W	380	0	0	F	0	-	-	F	F
Aluminum Etchant Type A (16 H_3PO_4 : 1 HNO_3 : 1 HAc : 2 H_2O) Heated Bath 50°C	Aluminum	-	<10	<9	0	0	0	-	<10	0	2	6600 2600 6600	-	0	-	0	0
Titanium Etchant (20 H_2O : 1 H_2O_2 : 1 HF) Wet Sink Room Temperature	Titanium	-	12	-	120	W	W	W	2100	8	4	W	0 0 <10	8800	-	0	0
H_2O_2 (30%) Wet Sink Room Temperature	Tungsten	-	0	0	0	0	0	0	0	0	0	<20	190 190 1000	0	60 60 150	<2	0
Piranha (~50 H_2SO_4 : 1 H_2O_2) Heated Bath 120°C	Cleaning off metals and organics	-	0	0	0	0	0	-	0	0	0	1800	-	2400	-	F	F
Acetone Wet Sink Room Temperature	Photoresist	-	0	0	0	0	0	-	0	0	0	0	-	0	-	>44k	>39k

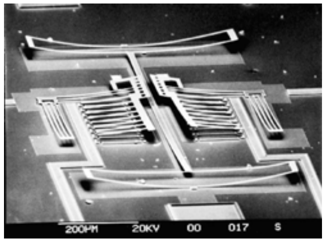
Notation: - =test not performed; W=not performed, but known to Work (≥ 100 Å/min); F=not performed, but known to be Fast (≥ 10 kÅ/min); P=some of film Peeled during etch or when rinsed; A=film was visibly Attacked and roughened.
Etch areas are all of a 4-inch wafer for the transparent films and half of the wafer for single-crystal silicon and the metals.
Etch rates will vary with temperature and prior use of solution, area of exposure of film, other materials present (e.g., photoresist), film impurities and microstructure, etc. *Some variation should be expected.*

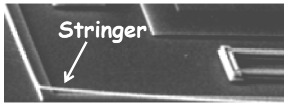
Film Etch Chemistries

- For some popular films:

Material	Wet etchant	Etch rate [nm/min]	Dry etchant	Etch rate [nm/min]
Polysilicon	HNO_3:H_2O:NH_4F	120-600	SF_6 + He	170-920
Silicon nitride	H_3PO_4	5	SF_6	150-250
Silicon dioxide	HF	20-2000	CHF_3 + O_2	50-150
Aluminum	H_3PO_4:HNO_3:CH_3COOH	660	Cl_2 + $SiCl_4$	100-150
Photoresist	Acetone	>4000	O_2	35-3500
Gold	KI	40	n/a	n/a

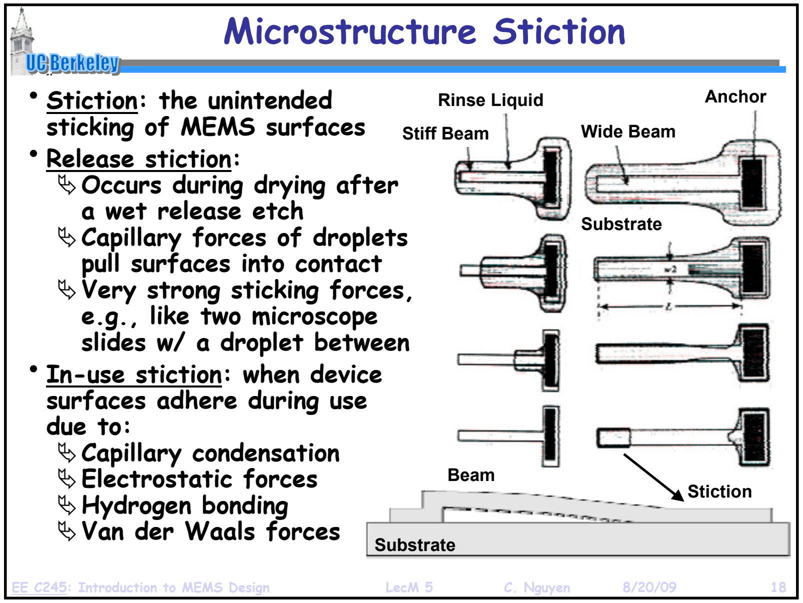
Issues in Surface Micromachining





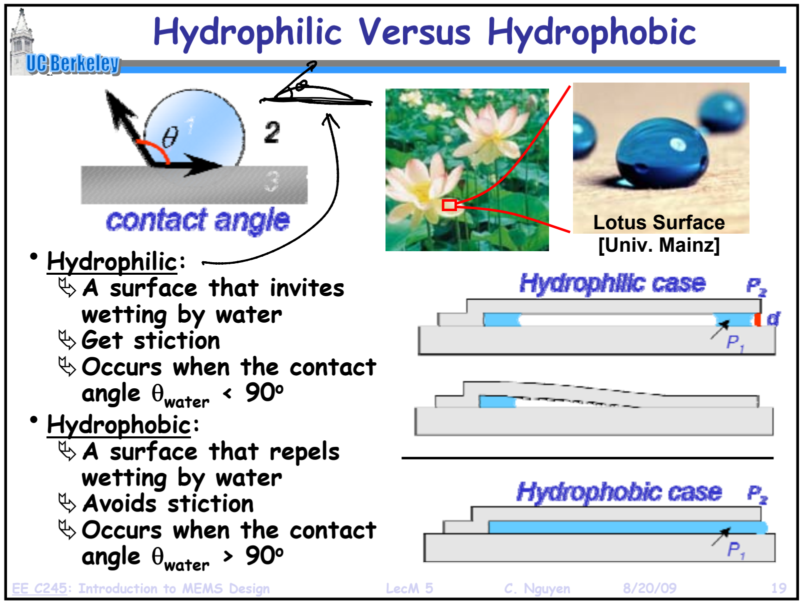
- __Stiction__: sticking of released devices to the substrate or to other on-chip structures
  - Difficult to tell if a structure is stuck to substrate by just looking through a microscope
- Residual Stress in Thin Films
  - Causes bending or warping of microstructures
  - Limits the sizes (and sometimes geometries) of structures
- Topography
  - Stringers can limit the number of structural levels

Microstructure Stiction



Microstructure Stiction

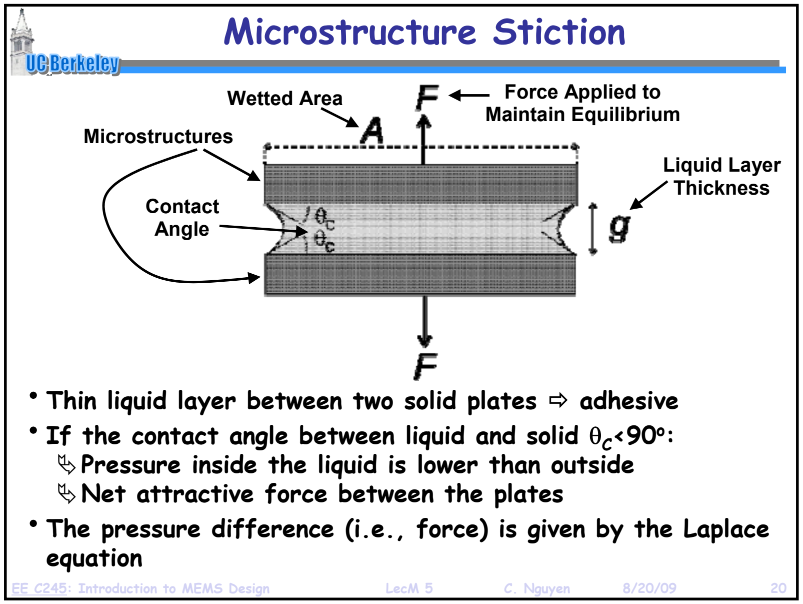
- **Stiction**: the unintended sticking of MEMS surfaces
- **Release stiction**:
  - Occurs during drying after a wet release etch
  - Capillary forces of droplets pull surfaces into contact
  - Very strong sticking forces, e.g., like two microscope slides w/ a droplet between
- **In-use stiction**: 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]

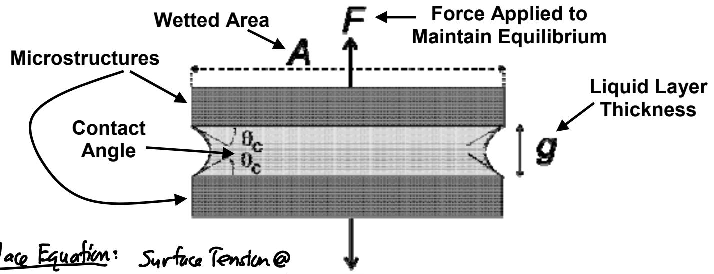
- **Hydrophilic**:
  - A surface that invites wetting by water
  - Get stiction
  - Occurs when the contact angle $\theta_{water} < 90^\circ$
- **Hydrophobic**:
  - A surface that repels wetting by water
  - Avoids stiction
  - Occurs when the contact angle $\theta_{water} > 90^\circ$



Microstructure Stiction

- Thin liquid layer between two solid plates ⇨ adhesive
- If the contact angle between liquid and solid $\theta_c < 90^\circ$:
  - 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:

Surface Tension @ the Liq.-Air Interface

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

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

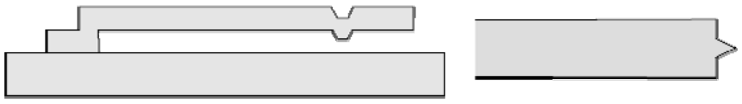
Pressure Difference @ the Liquid-Air Interface

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

Force needed to keep the plates apart
⇒ (+) force means a (-) Laplace pressure

Avoiding Stiction

- Reduce droplet area via mechanical design approaches



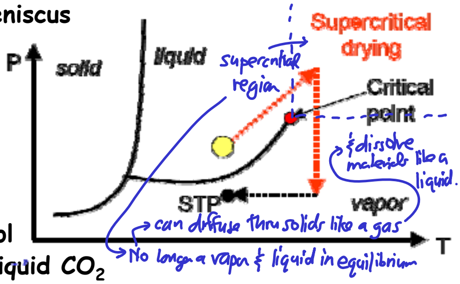
Standoff Bumps

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)

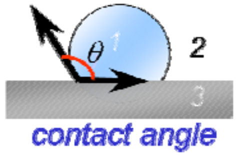
Supercritical CO_2 Drying

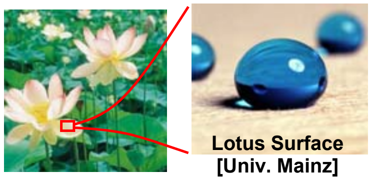
- A method for stictionless drying of released microstructures by immersing them in CO_2 at its supercritical point
- **Basic Strategy**: Eliminate surface tension-derived sticking by avoiding a liquid-vapor meniscus



- **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

Hydrophilic Versus Hydrophobic





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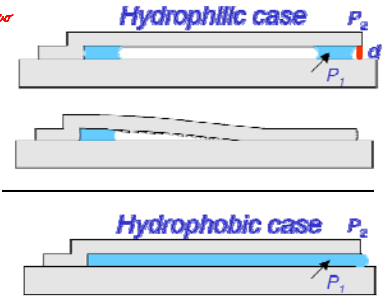
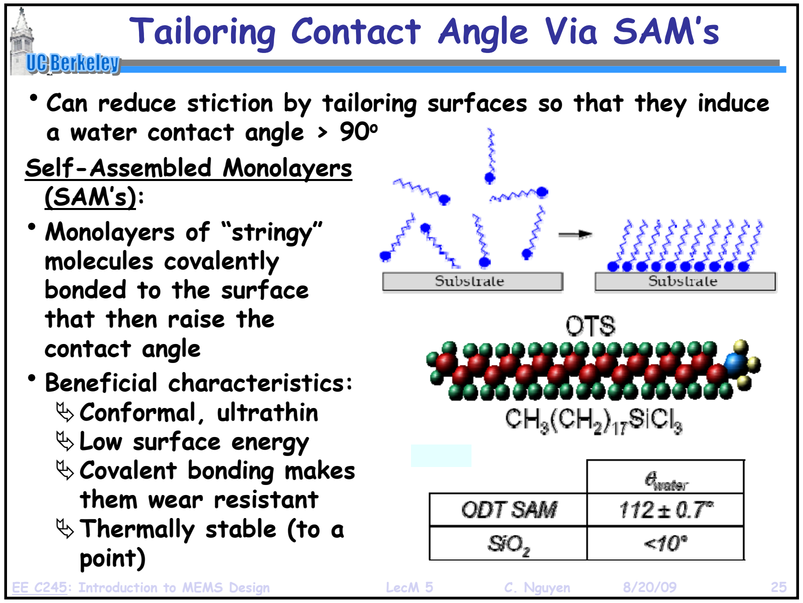
nongrav





Tailoring Contact Angle Via SAM's

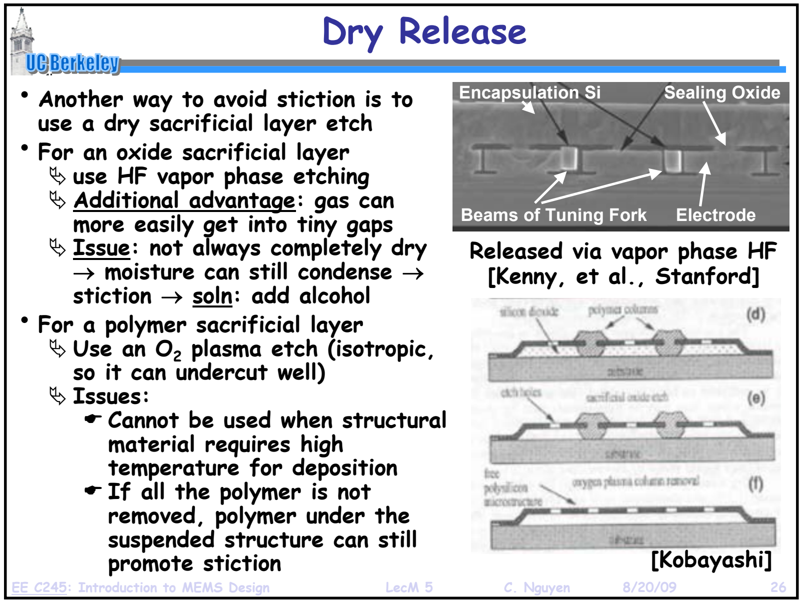
- Can reduce stiction by tailoring surfaces so that they induce a water contact angle > 90°

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)

$CH_3(CH_2)_{17}SiCl_3$

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



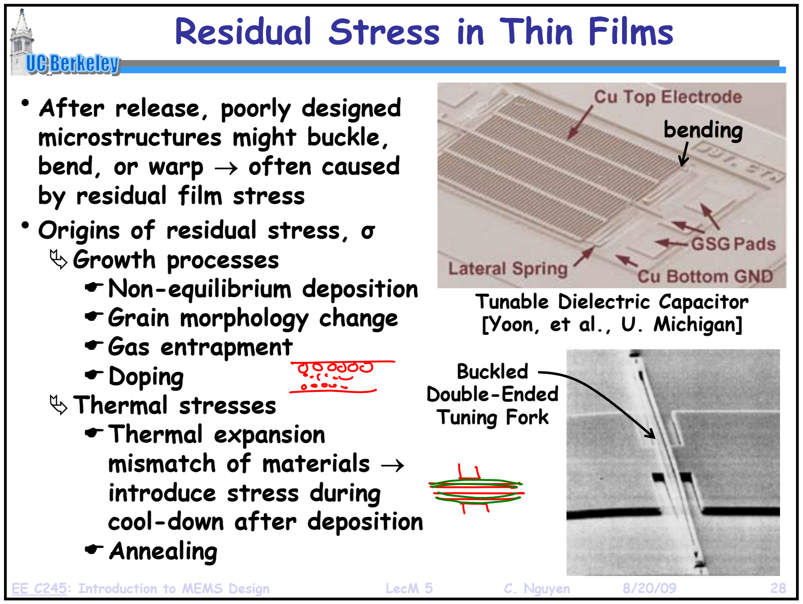
Dry Release

- 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

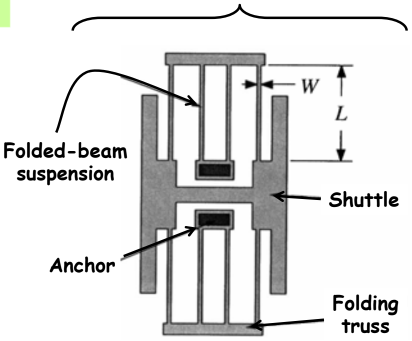
Need to Control Film Stress

- Resonance frequency expression for a lateral resonator:

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

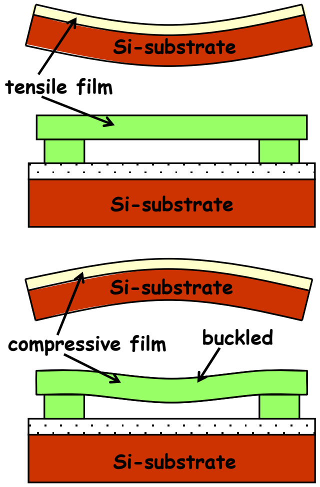
Since W « L, the stress term will dominate if $\sigma_r \sim E_y$

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



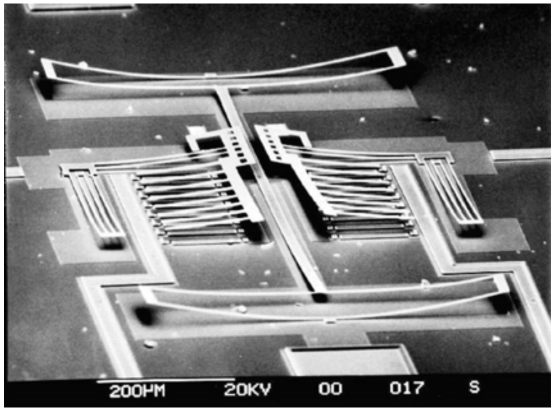
Tensile Versus Compressive Stress

- 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



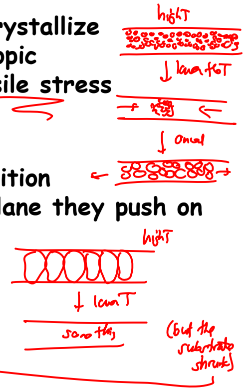
Vertical Stress Gradients

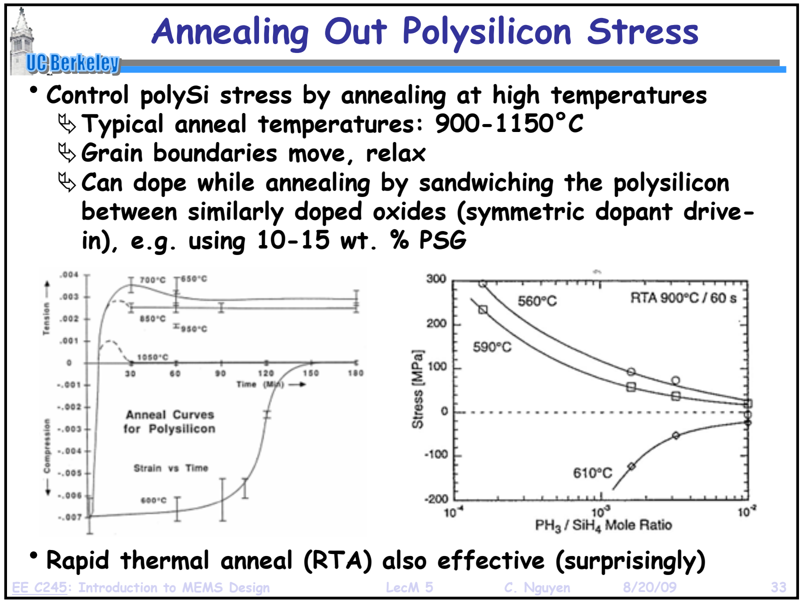
- Variation of residual stress in the direction of film growth
- Can warp released structures in z-direction



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)