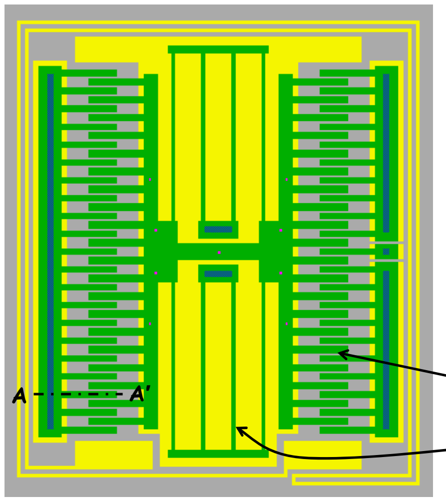
## Layout and Masking Layers

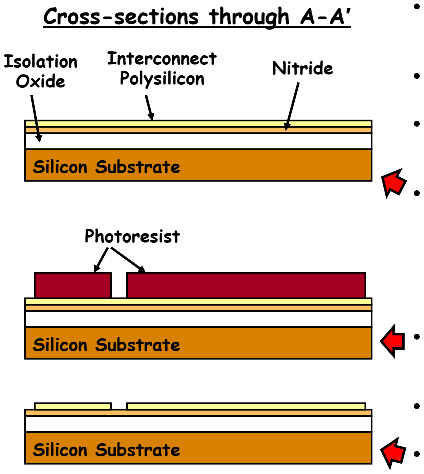


- **At Left**: Layout for a folded-beam capacitive comb-driven micromechanical resonator
- **Masking Layers**:
  - 🟨 1st Polysilicon: POLY1(cf)
  - 🟦 Anchor Opening: ANCHOR(df)
  - 🟩 2nd Polysilicon: POLY2(cf)

Capacitive comb-drive for linear actuation

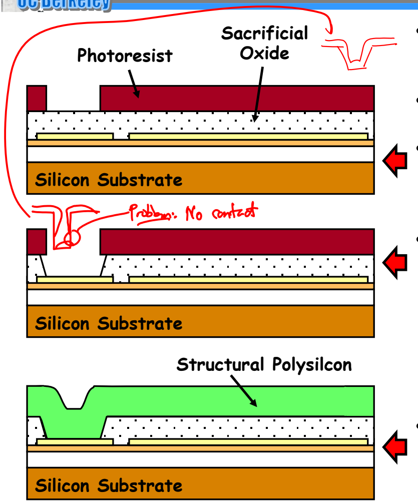
Folded-beam support structure for stress relief

## Surface-Micromachining Process Flow



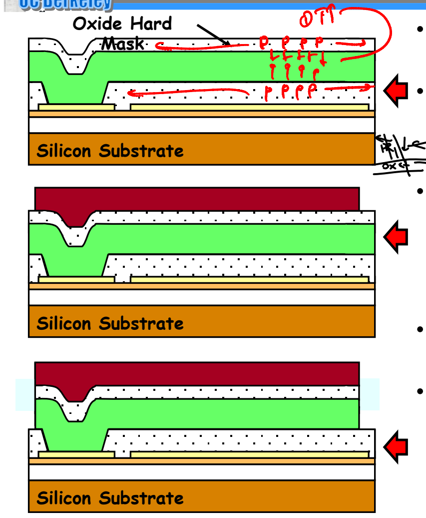
- Deposit isolation LTO (or PSG):
  - Target = 2μm
  - 1 hr. 40 min. LPCVD @450°C
- Densify the LTO (or PSG)
  - Anneal @950°C for 30 min.
- Deposit nitride:
  - Target = 100nm
  - 22 min. LPCVD @800°C
- Deposit interconnect polySi:
  - Target = 300nm
  - In-situ Phosphorous-doped
  - 1 hr. 30 min. LPCVD @650°C
- Lithography to define poly1 interconnects using the POLY1(cf) mask
- RIE polysilicon interconnects:
  - $CCl_4/He/O_2$ @300W,280mTorr
- Remove photoresist in PRS2000

## Surface-Micromachining Process Flow



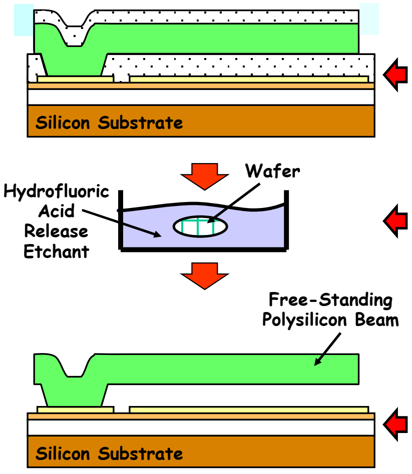
- Deposit sacrificial PSG:
  - Target = 2μm
  - 1 hr. 40 min. LPCVD @450°C
- Densify the PSG
  - Anneal @950°C for 30 min.
- Lithography to define anchors using the ANCHOR(df) mask
  - Align to the poly1 layer
- Etch anchors
  - RIE using $CHF_3/CF_4/He$ @350W,2.8Torr
  - Remove PR in PRS2000
  - Quick wet dip in 10:1 HF to remove native oxide
- Deposit structural polySi 610°C
  - Target = 2μm
  - In-situ Phosphorous-doped
  - 11 hrs. LPCVD @650°C

## Surface-Micromachining Process Flow



- Deposit oxide hard mask
  - Target = 500nm
  - 25 min. LPCVD @450°C
- Stress 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

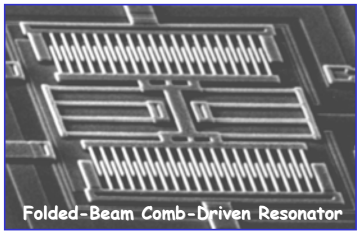
## Surface-Micromachining Process Flow

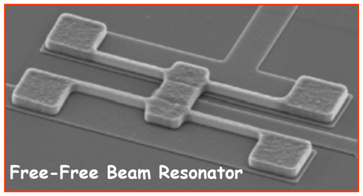


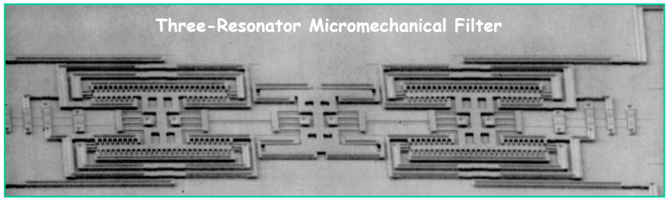
- Remove PR (more difficult)
  - Ash in $O_2$ plasma
  - Soak in PRS2000
- Release the structures
  - Wet etch in HF for a calculated time that insures complete undercutting
  - If 5:1 BHF, then ~ 30 min.
  - If 48.8 wt. % HF, ~ 1 min.
- Keep structures submerged in DI water after the etch
- Transfer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

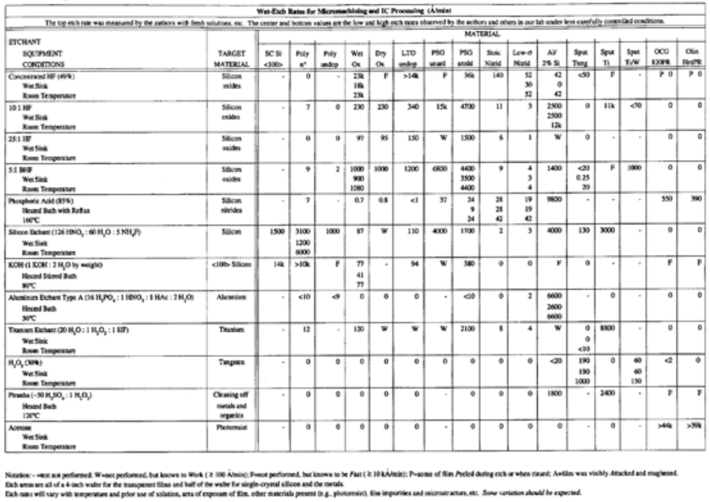

Three-Resonator Micromechanical Filter

## 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 ~~n~~$\mu$m/min
  - Annealed PSG ~ 3.6 ~~n~~$\mu$m/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<br>EQUIPMENT<br>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%)<br>Wet Sink<br>Room Temperature | Silicon oxides | - | 0 | - | 23k<br>18k<br>23k | F | >14k | F | 36k | 140 | 52<br>30<br>52 | 42<br>0<br>42 | <50 | F | - | P 0 | P 0 |
| 10:1 HF<br>Wet Sink<br>Room Temperature | Silicon oxides | - | 7 | 0 | 230 | 230 | 340 | 15k | 4700 | 11 | 3 | 2500<br>2500<br>12k | 0 | 11k | <70 | 0 | 0 |
| 25:1 HF<br>Wet Sink<br>Room Temperature | Silicon oxides | - | 0 | 0 | 97 | 95 | 150 | W | 1500 | 6 | 1 | W | 0 | - | - | 0 | 0 |
| 5:1 BHF<br>Wet Sink<br>Room Temperature | Silicon oxides | - | 9 | 2 | 1000<br>900<br>1080 | 1000 | 1200 | 6800 | 4400<br>3500<br>4400 | 9 | 4<br>3<br>4 | 1400 | <20<br>0.25<br>20 | F | 1000 | 0 | 0 |
| Phosphoric Acid (85%)<br>Heated Bath with Reflux<br>160°C | Silicon nitrides | - | 7 | - | 0.7 | 0.8 | <1 | 37 | 24<br>9<br>24 | 28<br>28<br>42 | 19<br>19<br>42 | 9800 | - | - | - | 550 | 390 |
| Silicon Etchant (126 $HNO_3$ : 60 $H_2O$ : 5 $NH_4F$)<br>Wet Sink<br>Room Temperature | Silicon | 1500 | 3100<br>1200<br>6000 | 1000 | 87 | W | 110 | 4000 | 1700 | 2 | 3 | 4000 | 130 | 3000 | - | 0 | 0 |
| KOH (1 KOH : 2 $H_2O$ by weight)<br>Heated Stirred Bath<br>80°C | <100> Silicon | 14k | >10k | F | 77<br>41<br>77 | - | 94 | W | 380 | 0 | 0 | F | 0 | - | - | F | F |
| Aluminum Etchant Type A (16 $H_3PO_4$ : 1 $HNO_3$ : 1 HAc : 2 $H_2O$)<br>Heated Bath<br>50°C | Aluminum | - | <10 | <9 | 0 | 0 | 0 | - | <10 | 0 | 2 | 6600<br>2600<br>6600 | - | 0 | - | 0 | 0 |
| Titanium Etchant (20 $H_2O$ : 1 $H_2O_2$ : 1 HF)<br>Wet Sink<br>Room Temperature | Titanium | - | 12 | - | 120 | W | W | W | 2100 | 8 | 4 | W | 0<br>0<br><10 | 8800 | - | 0 | 0 |
| $H_2O_2$ (30%)<br>Wet Sink<br>Room Temperature | Tungsten | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | <20 | 190<br>190<br>1000 | 0 | 60<br>60<br>150 | <2 | 0 |
| Piranha (~50 $H_2SO_4$ : 1 $H_2O_2$)<br>Heated Bath<br>120°C | Cleaning off metals and organics | - | 0 | 0 | 0 | 0 | 0 | - | 0 | 0 | 0 | 1800 | - | 2400 | - | F | F |
| Acetone<br>Wet Sink<br>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 (≥ 10kÅ/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.*

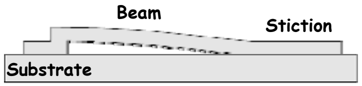
## Film Etch Chemistries

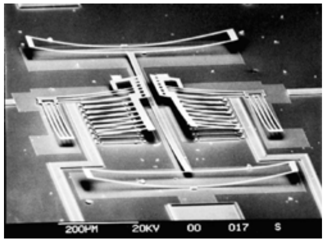
- For some popular films:

| Material | Wet etchant | Etch rate [nm/min] | Dry etchant | Etch rate [nm/min] |
|---|---|---|---|---|
| Polysilicon | $HNO_3$:$H_2O$:<br>$NH_4F$ | 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 | $H_3PO_4$:$HNO_3$:<br>$CH_3COOH$ | 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

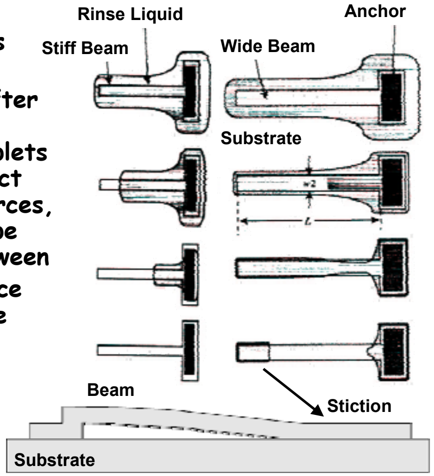


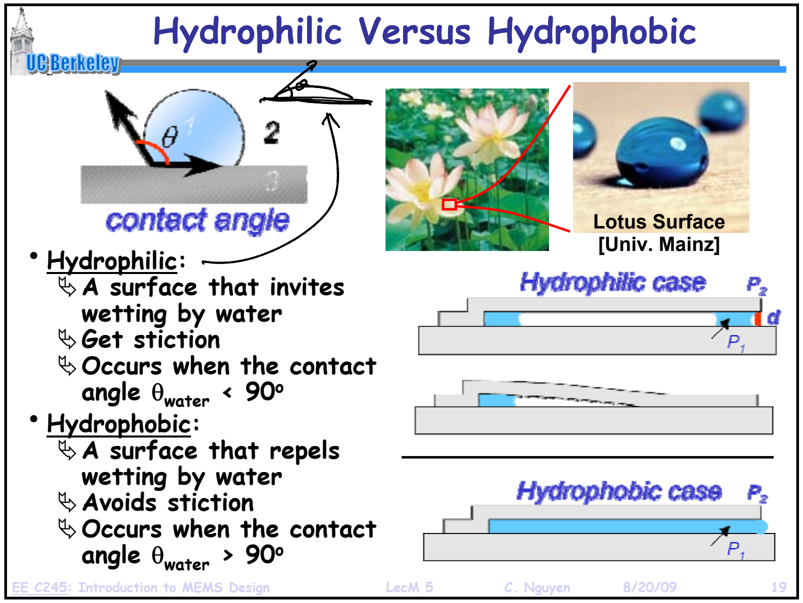


## Microstructure Stiction

## Microstructure Stiction

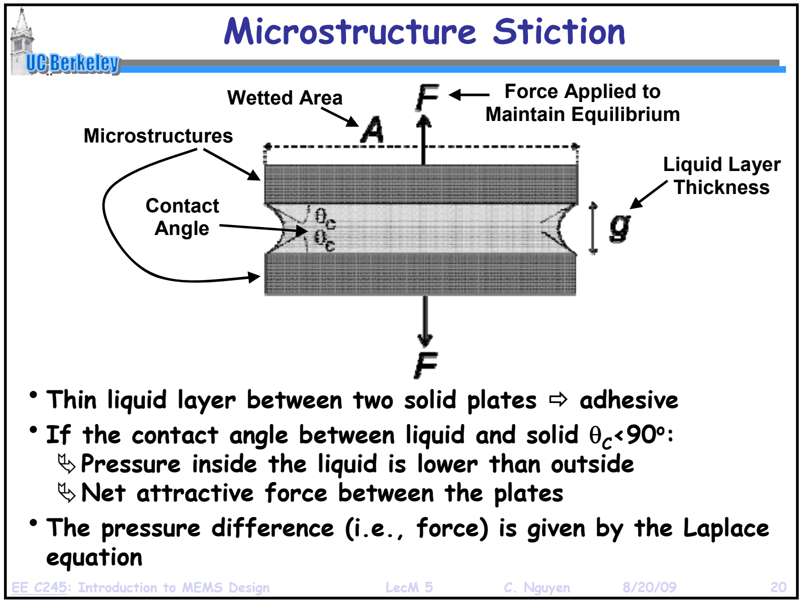
- **Stiction**: the unintended sticking of MEMS surfaces
- **Release stiction**:
  - ↳ Occurs during drying after a wet release etch
  - ↳ Capillary forces of droplets pull surfaces into contact
  - ↳ Very strong sticking forces, e.g., like two microscope slides w/ a droplet between
- **In-use stiction**: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





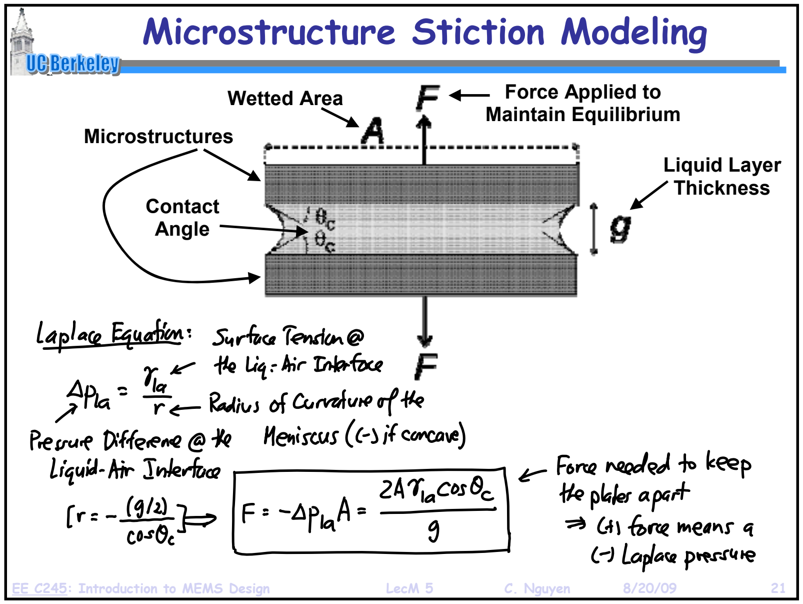
## Hydrophilic Versus Hydrophobic

- 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 $\theta_{water} > 90°$



## 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:

Surface Tension @ the Liq.-Air Interface

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

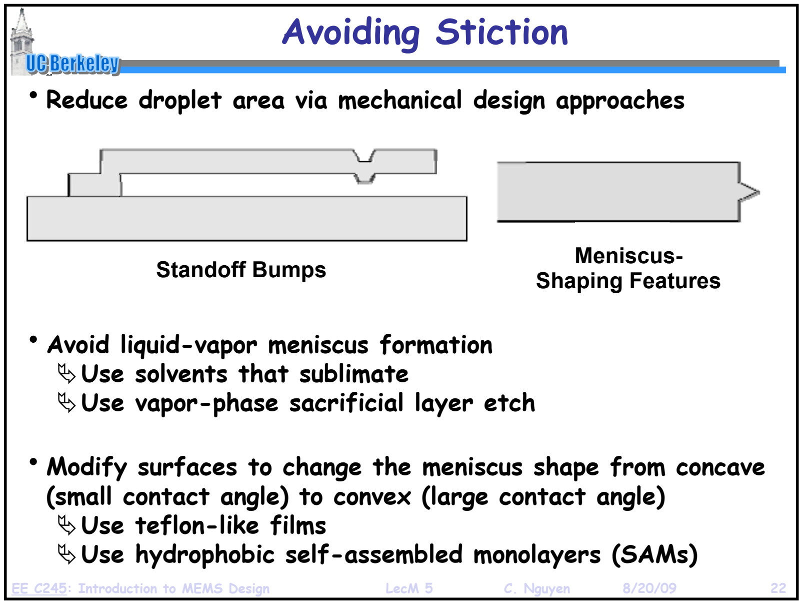
Radius of Curvature of the Meniscus ((-) if concave)

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

- 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)