

Structural/Sacrificial Material Combinations

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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 ₂ O ₂ , hot H ₂ O

• 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 SiO₂ ~ 1.8-2.3 μm/min
- Annealed PSG ~ 3.6 μm/min
- Aluminum (Si rich) ~ 4 nm/min (much faster in other Al)

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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

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Hydrophilic Versus Hydrophobic

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

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Microstructure Stiction

- Thin liquid layer between two solid plates \Rightarrow 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

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Microstructure Stiction Modeling

Laplace Equation: Surface Tension @ the Liqu-Air Interface

$$\Delta P_{la} = \frac{\gamma_{la}}{r} \leftarrow r \leftarrow \text{Radius of Curvature of the Liqu-Air Interface}$$

Pressure Difference @ the Meniscus (-) if concave

$$[r = -\frac{(g/2)}{\cos \theta_c}] \rightarrow F = -\Delta P_{la} A = \frac{2A\gamma_{la} \cos \theta_c}{g}$$

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

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Avoiding Stiction

- Reduce droplet area via mechanical design approaches
- Avoid liquid-vapor meniscus formation
 - Use solvents that sublime
 - 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)

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Supercritical CO₂ Drying

- A method for stictionless drying of released microstructures by immersing them in CO₂ 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 CO₂
 - Apply heat & pressure to take the CO₂ past its critical pt.
 - Vent to lower pressure and allow the supercritical CO₂ to revert to gas → liquid-to-gas Xsition in supercritical region means no capillary forces to cause stiction

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 - Occurs when the contact angle $\theta_{\text{water}} > 90^\circ$

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Tailoring Contact Angle Via SAM's

- Can reduce stiction by tailoring surfaces so that they induce a water contact angle $> 90^\circ$

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)

	θ_{water}
ODT SAM	$112 \pm 0.7^\circ$
SiO_2	$< 10^\circ$

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Dry Release

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- 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 → solv: add alcohol
- For a polymer sacrificial layer
 - Use an O₂ 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]

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Residual Stress

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Residual Stress in Thin Films

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- 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

Cu Top Electrode bending
GSG Pads
Lateral Spring
Cu Bottom GND
Tunable Dielectric Capacitor [Yoon, et al., U. Michigan]
Buckled Double-Ended Tuning Fork

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Need to Control Film Stress

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- Resonance frequency expression for a lateral resonator:

$$f_0 \approx \frac{1}{2\pi} \sqrt{\frac{4E_y t W^3}{ML^3} + \frac{24\sigma_r t W}{5ML}}$$

↑ Basic term ↑ Stress term

Since $W \ll L$, 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

Folded-beam suspension
Shuttle
Anchor
Folding truss

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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

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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 $\leq 600^{\circ}\text{C}$
 - Films are initially amorphous, then crystallize
 - Get equiaxed crystals, largely isotropic
 - Crystals have higher density \rightarrow tensile stress
 - Small stress gradient
- Temperature $\geq 600^{\circ}\text{C}$
 - Columnar crystals grow during deposition
 - As crystals grow vertically and in-plane they push on neighbors \rightarrow compressive stress
 - Positive stress gradient

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Annealing Out Polysilicon Stress

- Control polySi stress by annealing at high temperatures
 - Typical anneal temperatures: $900-1150^{\circ}\text{C}$
 - 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

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Topography Issues

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- Degradation of lithographic resolution
 - PR step coverage, streaking
- Stringers
 - Problematic when using anisotropic etching, e.g., RIE

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Nickel Surface-Micromachining Process Flow

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Electroplating: Metal MEMS

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

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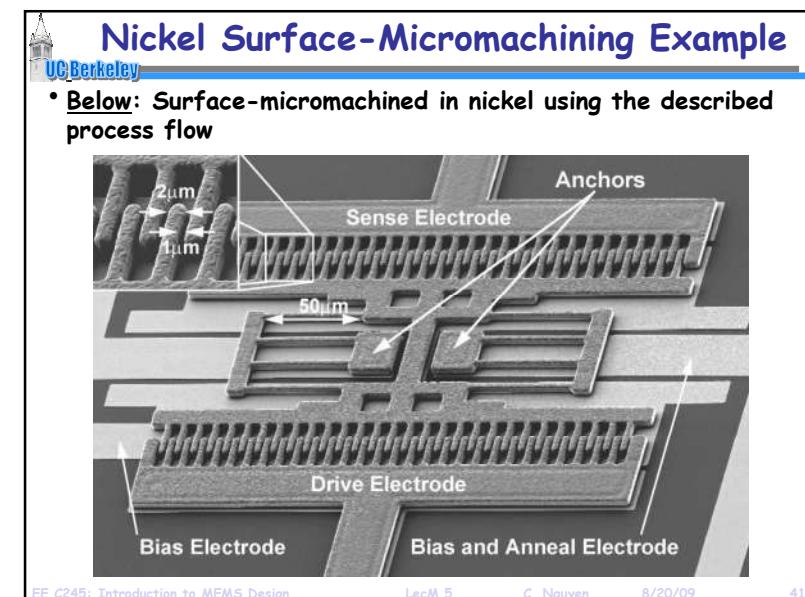
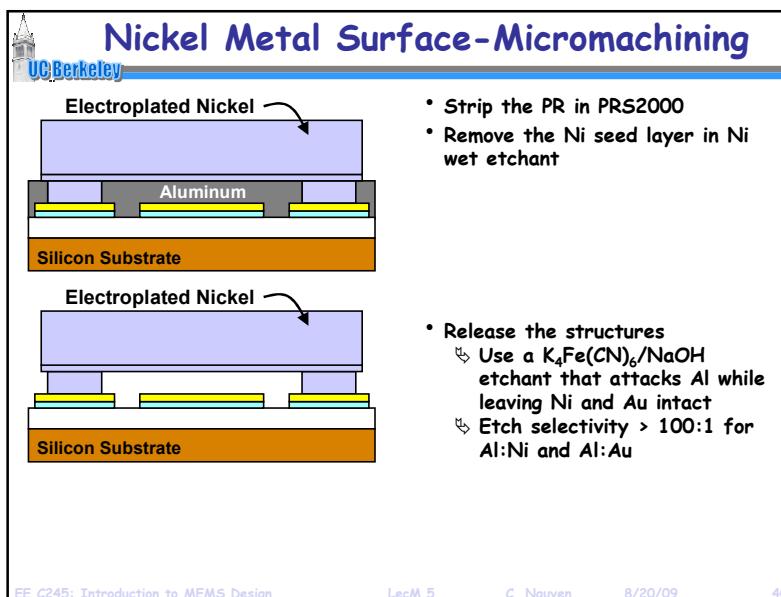
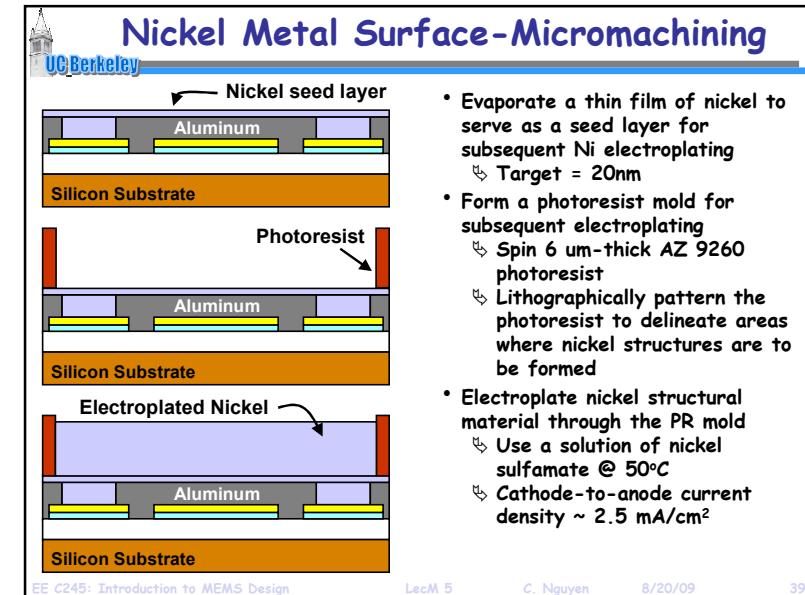
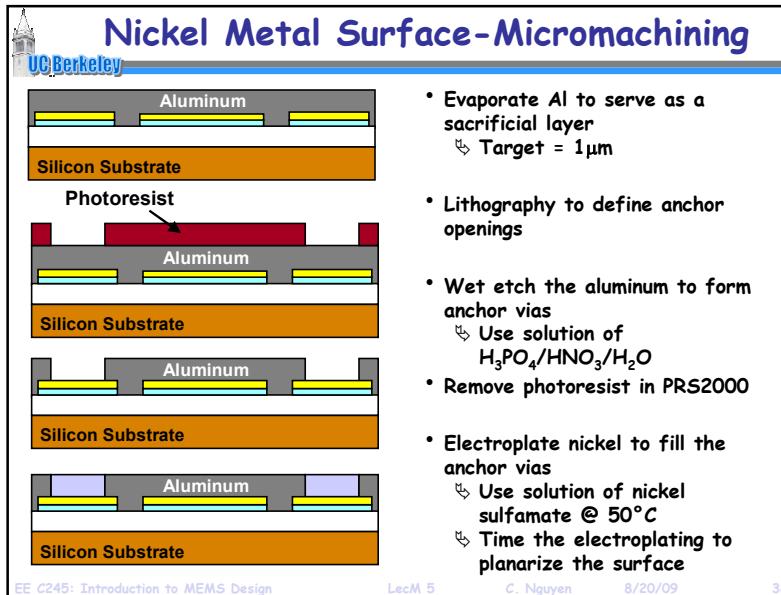
Nickel Metal Surface-Micromachining

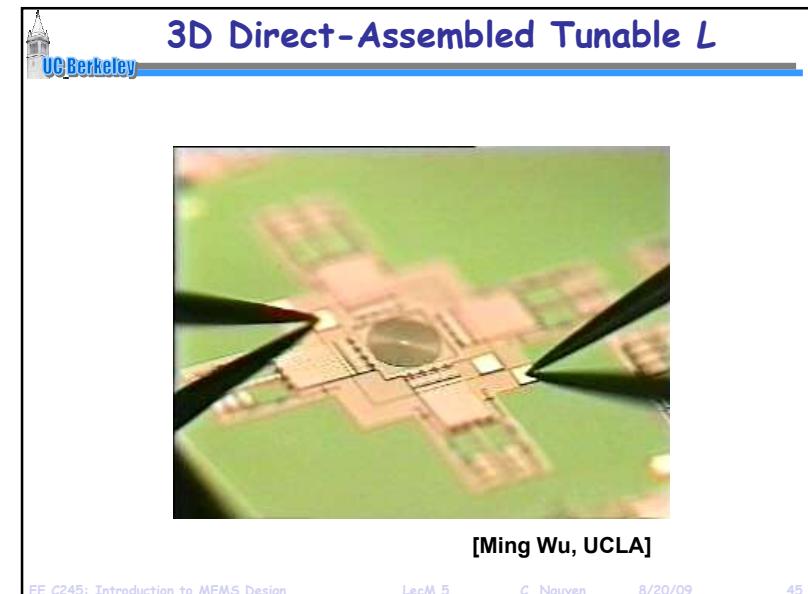
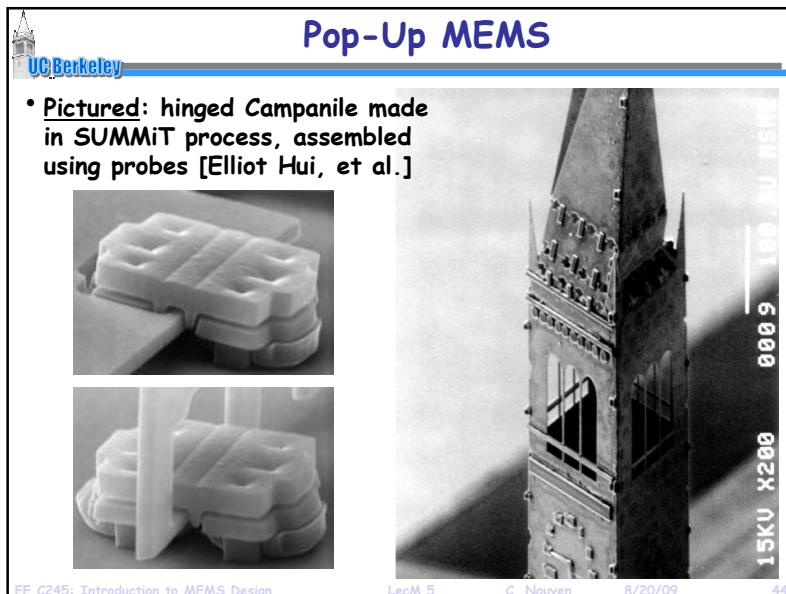
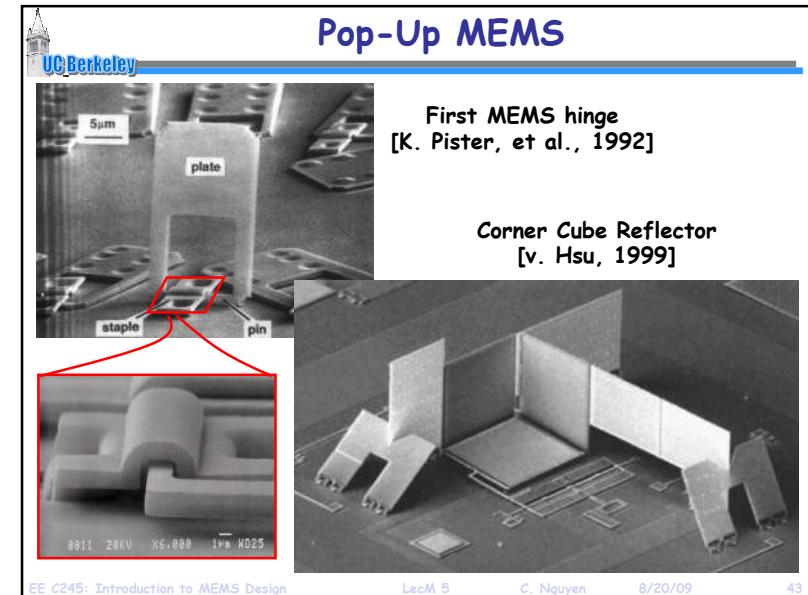
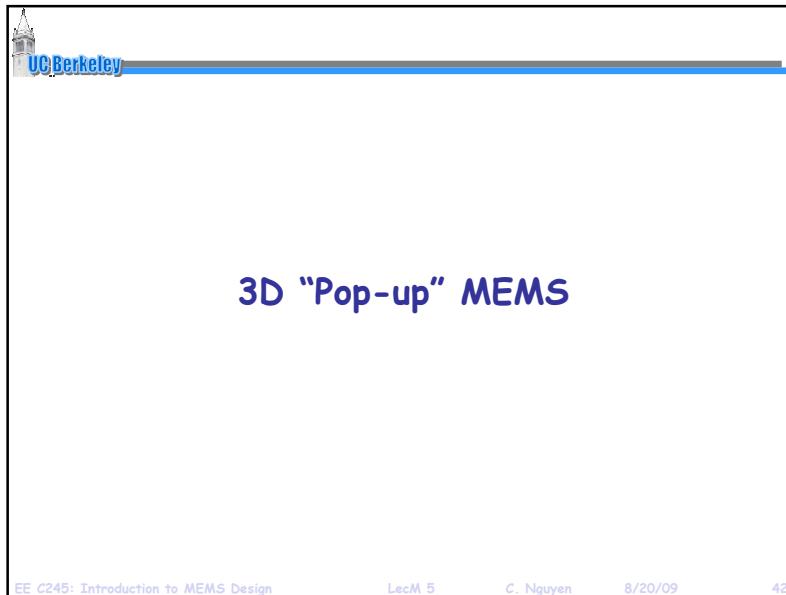
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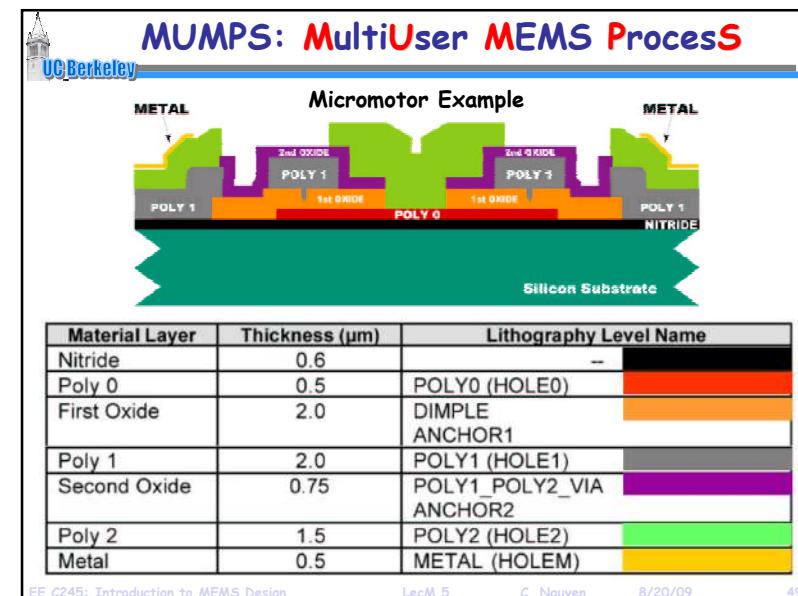
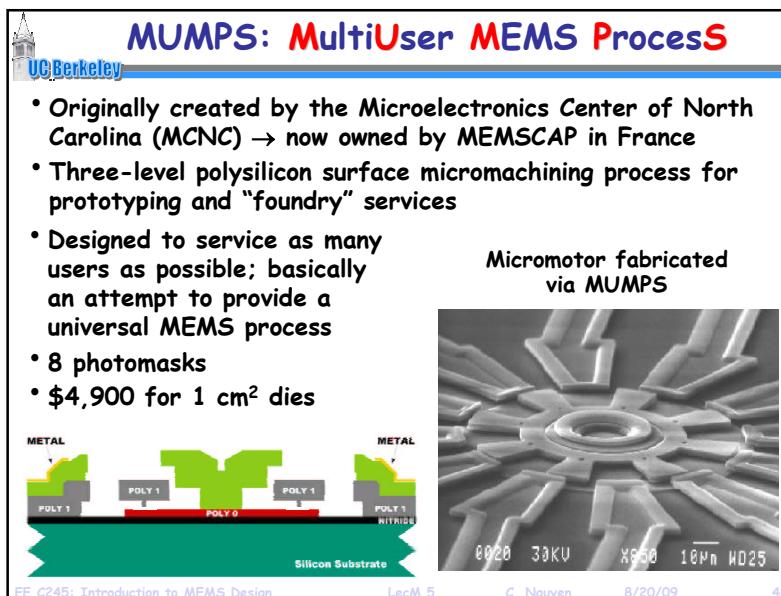
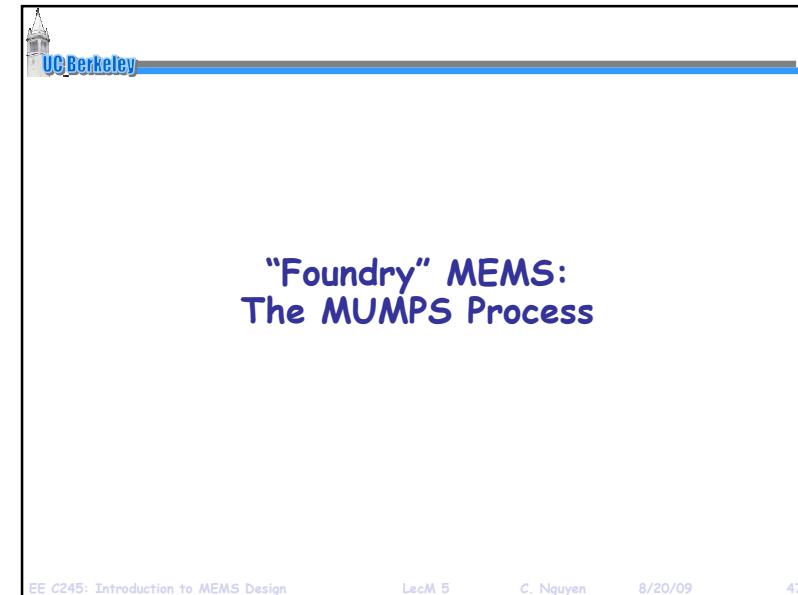
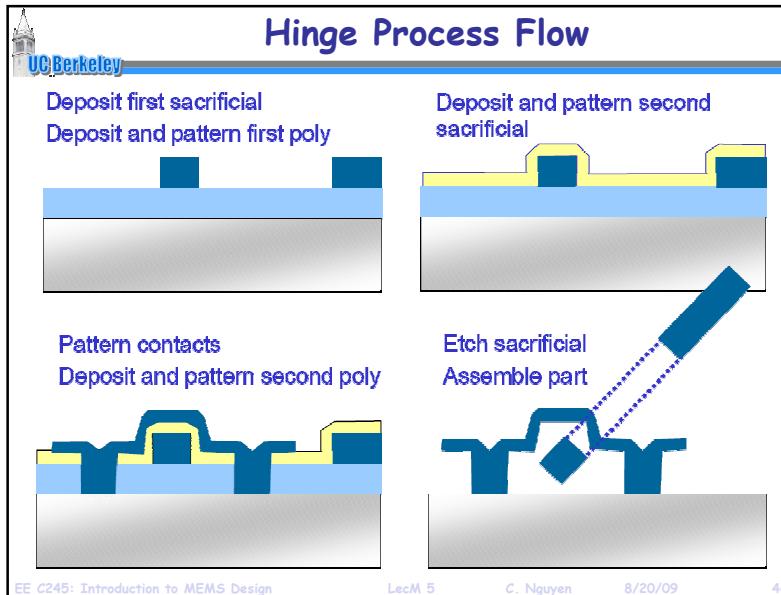
- Deposit isolation LTO:
 - Target = 2μm
 - 1 hr. 40 min. LPCVD @450°C
- Densify the LTO
 - Anneal @950°C for 30 min.
- Define metal interconnect via lift-off
 - Spin photoresist and pattern lithographically to open areas where interconnect will stay
 - Evaporate a Ti/Au layer
 - Target = 30nm Ti
 -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

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Lecture 8m1: Surface Micromachining







Masks in polyMUMPS

Minimum set of masks that must be used in MUMPS

Mnemonic level name	Field type	Purpose
POLY0	light	pattern ground plane
ANCHOR1	dark	open holes for Poly 1 to Nitride or Poly 0 connection
DIMPLE	dark	create dimples/bushings for Poly 1
POLY1	light	pattern Poly 1
POLY1_POLY2_VIA	dark	open holes for Poly 1 to Poly 2 connection
ANCHOR2	dark	open holes for Poly 2 to Nitride or Poly 0 connection
POLY2	light	pattern Poly 2
METAL	light	pattern Metal
HOLE0	dark	provide holes for POLY0
HOLE1	dark	provide release holes for POLY1
HOLE2	dark	provide release holes for POLY2
HOLEM	dark	provide release holes in METAL

Extra masks for more flexibility & ease of release

- Field type:
 - Light (or clear) field (cf): in layout, boxes represent features that will stay through fabrication
 - Dark field (df): in layout, boxes represent holes to be cut out

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MUMPS Process Flow

- Deposit PSG on the starting n-type (100) wafers
- Anneal to heavily dope the wafers
- Remove the PSG
- LPCVD 600 nm of low stress nitride
- LPCVD 500 nm of polysilicon
- Lithography using the POLY0(cf) mask and RIE etching to pattern the poly0 ground plane layer
- LPCVD 2 μm of PSG as the 1st sacrificial layer
- Lithography using the DIMPLE(df) mask (align to poly0)
- RIE 750 nm deep to form dimple vias
- Lithography using the ANCHOR1 (df) mask (align to poly0)
- RIE anchor vias down to the nitride surface

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MUMPS Process Flow (cont.)

- LPCVD 2 μ undoped polysilicon
- LPCVD 200 nm of PSG
- Anneal for 1 hr. @ 1050°C
 - ↳ This both dopes the polysilicon and reduces its residual stress
- Lithography using the POLY1(cf) mask to define structures (align to anchor1)
- RIE the PSG to create a hard mask first, then ...
- RIE the polysilicon
- LPCVD 750 nm of PSG
- Lithography using the P1_P2_VIA (df) mask to define contacts to the poly1 layer (align to poly1)

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MUMPS Process Flow (cont.)

- Recoat with photoresist and do lithography using the ANCHOR2(df) mask to define openings where poly2 contacts nitride or poly0 (align to poly0)
- RIE the PSG at ANCHOR2 openings
- LPCVD 1.5 μm undoped polysilicon
- LPCVD 200 nm PSG as a hard mask and doping source
- Anneal for 1 hr @ 1050°C to dope the polysilicon and reduce residual stress
- Lithography using the POLY2(cf) mask (align to anchor2)
- RIE PSG hard mask
- RIE poly2 film
- Remove PR and hard mask

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MUMPS Process Flow (cont.)

The diagram illustrates the final structure of a micromotor. It features a central circular cavity surrounded by a multi-layered structure. The layers are labeled from top to bottom: METAL, 3rd OXIDE, POLY 1, 1st OXIDE, POLY 0, 1st OXIDE, POLY 1, NITRISE, and METAL. Below this structure is a silicon substrate. Arrows point from the text to specific parts of the diagram.

- Lithography using the METAL (df) mask (align to poly2)
- Evaporate titanium (Ti) (as an adhesion layer for gold)
- Evaporate gold (Au)
- Liftoff to remove PR and define metal interconnects
- Coat wafers with protective PR
- Dice wafers
- Ship to customer
- Customer releases structures by dipping and agitating dies in a 48.8 wt. % HF solution or via vapor phase HF
- Anti-stiction dry, if needed

Final Structure: Micromotor

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MUMPS: MultiUser MEMS ProcesS

The image shows a scanning electron micrograph (SEM) of a micromotor. The motor has a complex, multi-layered structure with a central cavity and radiating arms. The image includes technical details at the bottom: 0020 30KV X600 10μm WD25.

- Originally created by the Microelectronics Center of North Carolina (MCNC) → now owned by MEMSCAP in France
- Three-level polysilicon surface micromachining process for prototyping and "foundry" services
- Designed to service as many users as possible; basically an attempt to provide a universal MEMS process
- 8 photomasks
- \$4,900 for 1 cm² dies

Micromotor fabricated via MUMPS

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polyMUMPS Minimum Feature Constraints

The diagram shows a cross-section of a polysilicon feature (Poly0) on an oxide layer (Oxide1). A red box highlights the feature size, which is determined by the sum of the Poly0 width and the distance to the adjacent Oxide1 edge. Red arrows indicate violations resulting in missing, under/oversized, or fused features.

- Minimum feature size
 - Determined by MUMPS' photolithographic resolution and alignment precision
 - Violations result in missing (unanchored), under/oversized, or fused features
 - Use minimum feature only when absolutely necessary

	Nominal [μm]	Min Feature [μm]	Min Spacing [μm]
POLY0, POLY1, POLY2	3	2	2
POLY1_POLY2_VIA	3	2	2
ANCHOR1, ANCHOR2	3	3	2
DIMPLE	3	2	3
METAL	3	3	3
HOLE1, HOLE2	4	3	3
HOLEM	5	4	4

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MUMPS Design Rules (cont.)

The diagram shows cross-sectional views of various MUMPS structures. It includes labels for Oxide1, Poly0, POLYO, and ANCHOR1. A legend provides information on cross sections and mask levels.

Rule	Rule Letter	Figure #	Min. Value (μm)
POLY0 space to ANCHOR1	A	2.5	4.0
POLY0 enclose ANCHOR1	B	2.5	4.0
POLY0 enclose POLY1	C	2.6	4.0
POLY0 enclose POLY2	D	2.7	5.0
POLY0 enclose ANCHOR2	E	2.8	5.0
POLY0 space to ANCHOR2	F	2.8	5.0

Cross Sections

Poly0	Oxide1	Oxide2
Poly1	Poly2	Metal

Mask Levels

Poly0	Anchor1	Poly1-Poly2_Via
Poly2	Anchor2	Metal
Dimple		

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MUMPS Design Rules (cont.)

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Rule	Min. Value (μm)
POLY1 enclose ANCHOR1	G 4.0
POLY1 enclose DIMPLE	N 4.0
POLY1 enclose POLY1_Poly2_VIA	H 4.0
POLY1 enclose POLY2	O 4.0
POLY1 space to ANCHOR2	K 3.0
*Lateral etch holes space in POLY1	R ≤ 30 (max. value)

Cross Sections

Mask Levels

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MUMPS Design Rules (cont.)

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Rule	Rule Letter	Figure #	Min. Value (μm)
POLY0 space to ANCHOR1	A	2.5	4.0
POLY0 enclose ANCHOR1	B	2.5	4.0
POLY0 enclose POLY1	C	2.6	4.0
POLY0 enclose POLY2	D	2.7	5.0
POLY0 enclose ANCHOR2	E	2.8	5.0
POLY0 space to ANCHOR2	F	2.8	5.0

Rule	Rule Letter	Figure #	Min. Value (μm)
POLY1 enclose ANCHOR1	G	2.6	4.0
POLY1 enclose DIMPLE	N	2.13	4.0
POLY1 enclose POLY1_Poly2_VIA	H	2.9, 2.11	4.0
POLY1 enclose POLY2	O	2.14	4.0
POLY1 space to ANCHOR2	K	2.11	3.0
*Lateral etch holes space in POLY1	R	2.15	≤ 30 (max. value)

Rule	Rule Letter	Figure #	Min. Value (μm)
POLY2 enclose ANCHOR2	J	2.7, 2.10	5.0
POLY2 enclose POLY1_Poly2_VIA	L	2.9	4.0
POLY2 cut-in POLY1	P	2.14	5.0
POLY2 cut-out POLY1	Q	2.14	4.0
POLY2 enclose METAL	M	2.12	3.0
POLY2 space to POLY1	I	2.10	3.0
HOLE2 enclose HOLE1	T	2.16	2.0
HOLEM enclose HOLE2	U	2.16	2.0
*Lateral etch holes space in POLY2	S	2.15	≤ 30 (max. value)

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MUMPS Design Rules (cont.)

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Level 1	Level 2	Min. Feature	Min. Spacing	Enclose	Spacing	Cut- In	Cut- Out
POLY0	-	2	2				
	ANCHOR1			4/B/2.5	4/A/2.5		
	POLY1			4/C/2.6			
	ANCHOR2			5/E/2.8	5/F/2.8		
	POLY2			5/D/2.7			
POLY1	-	2	2 / 2.5 ²				
	POLY0						
	ANCHOR1			4/G/2.6			
	ANCHOR2				3/K/2.11		
	POLY2			4/O/2.14			
	DIMPLE			4/N/2.13			
	POLY1_Poly2_VIA			4/H/2.9			
POLY2	-	2	2 / 2.5 ²				
	POLY0						
	POLY1				3/I/2.10	5/P/2.14	4/Q/2.14
	VIA			4/L/2.9			
	ANCHOR2			5/J/2.7			
	METAL			3/M/2.12			
	HOLEM	HOLE2		2/U/2.16			
HOLE2	HOLE1		2/T/2.16				

TABLE 2.7. PolyMUMPs design rule reference sheet. Table shows minimum dimensions (μm), rule name, and figure number, respectively.

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