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# EE C247B - ME C218 Introduction to MEMS Design Spring 2018

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Lecture Module 5: Surface Micromachining

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## Lecture Outline

- Reading: Senturia Chpt. 3, Jaeger Chpt. 11, Handout: "Surface Micromachining for Microelectromechanical Systems"
- Lecture Topics:
  - ↪ Polysilicon surface micromachining
  - ↪ Stiction
  - ↪ Residual stress
  - ↪ Topography issues
  - ↪ Nickel metal surface micromachining
  - ↪ 3D "pop-up" MEMS
  - ↪ Foundry MEMS: the "MUMPS" process
  - ↪ The Sandia SUMMIT process

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## Polysilicon Surface-Micromachining

- Uses IC fabrication instrumentation exclusively
- Variations: sacrificial layer thickness, fine- vs. large-grained polysilicon, *in situ* vs.  $\text{POCl}_3$ -doping

300 kHz Folded-Beam Micromechanical Resonator

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## Polysilicon

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### Why Polysilicon?

- Compatible with IC fabrication processes
  - ↳ Process parameters for gate polysilicon well known
  - ↳ Only slight alterations needed to control stress for MEMS applications
- Stronger than stainless steel: fracture strength of polySi ~ 2-3 GPa, steel ~ 0.2GPa-1GPa
- Young's Modulus ~ 140-190 GPa
- Extremely flexible: maximum strain before fracture ~ 0.5%
- Does not fatigue readily
  
- Several variations of polysilicon used for MEMS
  - ↳ LPCVD polysilicon deposited undoped, then doped via ion implantation, PSG source,  $\text{POCl}_3$ , or B-source doping
  - ↳ In situ-doped LPCVD polysilicon
  - ↳ Attempts made to use PECVD silicon, but quality not very good (yet) → etches too fast in HF, so release is difficult

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### Polysilicon Surface-Micromachining Process Flow

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### Layout and Masking Layers

- **At Left:** Layout for a folded-beam capacitive comb-driven micromechanical resonator
- **Masking Layers:**
  - 1<sup>st</sup> Polysilicon: POLY1(cf) *dark field*
  - Anchor Opening: ANCHOR(df) *dark field*
  - 2<sup>nd</sup> Polysilicon: POLY2(cf) *clear field*
- Capacitive comb-drive for linear actuation
- Folded-beam support structure for stress relief

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### Surface-Micromachining Process Flow

#### Cross-sections through A-A'

- 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:
  - ↳  $\text{CCl}_4/\text{He}/\text{O}_2$  @300W, 280mTorr
- Remove photoresist in PRS2000

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### 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  $\text{CHF}_3/\text{CF}_4/\text{He}$  @350W, 2.8Torr
  - ⊗ Remove PR in PRS2000
  - ⊗ Quick wet dip in 10:1 HF to remove native oxide
- Deposit structural polySi
  - ⊗ Target = 2μm
  - ⊗ In-situ Phosphorous-doped
  - ⊗ 11 hrs. LPCVD @650°C

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### 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  $\text{N}_2$
- 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  $\text{CHF}_3/\text{CF}_4/\text{He}$  @350W, 2.8Torr
- Etch structural polysilicon
  - ⊗ RIE using  $\text{CCl}_4/\text{He}/\text{O}_2$  @300W, 280mTorr
  - ⊗ Use 1 min. etch/1 min. rest increments to prevent excessive temperature

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### Surface-Micromachining Process Flow

- Remove PR (more difficult)
  - ⊗ Ash in  $\text{O}_2$  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  $\text{CO}_2$  dry release

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### 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

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### Structural/Sacrificial Material Combinations

Structural Material	Sacrificial Material	Etchant
Poly-Si	SiO <sub>2</sub> , PSG, LTO	HF, BHF
Al	Photoresist	O <sub>2</sub> plasma
SiO <sub>2</sub>	Poly-Si	XeF <sub>2</sub>
Al	Si	TMAH, XeF <sub>2</sub>
Poly-SiGe	Poly-Ge	H <sub>2</sub> O <sub>2</sub> , hot H <sub>2</sub> 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 SiO<sub>2</sub> ~ 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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### Wet Etch Rates (f/ K. Williams)

Wet Etch Rates for Micromachining and IC Processing (Acheson)

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 values to use for under fully controlled conditions.

ETCHANT	REQUIREMENT	TARGET MATERIAL	MATERIAL																					
			SiC	Si	Poly	Poly	SiO <sub>2</sub>	Dry	SiO <sub>2</sub>	PSG	PSG	SiO <sub>2</sub>	SiO <sub>2</sub>	Al	SiO <sub>2</sub>	SiO <sub>2</sub>	SiO <sub>2</sub>	SiO <sub>2</sub>	SiO <sub>2</sub>	SiO <sub>2</sub>				
Concentrated HF (48.8 wt. %)	Wet Etch	Silicon nitride	-	0	-	-	230	180	230	340	150	4700	11	3	2000	2000	120	42	<50	F	F	F	F	
10:1 HF	Wet Etch	Silicon nitride	-	7	0	230	230	340	150	4700	11	3	2000	2000	120	42	<50	F	F	F	F	F	F	
20:1 HF	Wet Etch	Silicon nitride	-	0	0	97	95	120	W	1500	5	1	W	0	-	-	-	-	-	-	-	-	-	
5:1 BHF	Wet Etch	Silicon nitride	-	9	2	1000	1000	1200	600	400	9	4	1400	<20	F	3000	0	0	0	0	0	0	0	0
Phosphoric Acid (85%)	Wet Etch	Silicon nitride	-	3	-	0.7	0.8	<1	37	34	28	18	5000	-	-	-	-	-	-	-	-	-	-	
Silicon Etchant (10:1 HNO <sub>3</sub> :40:1 H <sub>2</sub> O <sub>2</sub> )	Wet Etch	Silicon nitride	-	1500	2100	1000	97	W	110	4000	1700	3	3	4000	130	3000	-	-	-	-	-	-	-	
KOH (1.0N) (3:1 H <sub>2</sub> O by weight)	Wet Etch	Aluminum Etchant	-	<100	140	>10k	F	77	-	94	W	300	0	0	F	0	-	-	-	-	-	-	-	
Aluminum Etchant Type A (10:1 H <sub>2</sub> PO <sub>4</sub> :1 HNO <sub>3</sub> :1 H <sub>2</sub> O)	Wet Etch	Aluminum Etchant	-	<10	<9	0	0	0	0	<10	0	2	6000	-	0	-	-	-	-	-	-	-	-	
Thiamine Etchant (20:1 H <sub>2</sub> O:1 H <sub>2</sub> O <sub>2</sub> :1 HF)	Wet Etch	Thiamine Etchant	-	13	-	120	W	W	W	2100	8	4	W	0	8000	-	-	-	-	-	-	-	-	
H <sub>2</sub> A (50%)	Wet Etch	Tungsten	-	0	0	0	0	0	0	0	0	0	0	<20	300	0	60	<10	0	0	0	0	0	
PhosA (1:10 H <sub>2</sub> PO <sub>4</sub> :1 H <sub>2</sub> O)	Wet Etch	Cleaning of residual organics	-	0	0	0	0	0	0	0	0	0	1000	-	2400	0	150	-	-	-	-	-	-	
Acetic	Wet Etch	Photoresist	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

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### Film Etch Chemistries


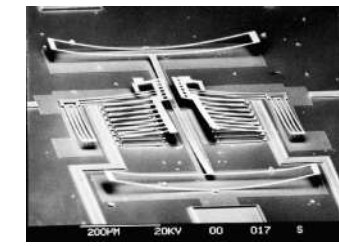
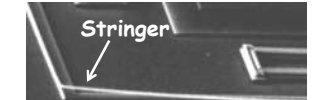
- For some popular films:

Material	Wet etchant	Etch rate [nm/min]	Dry etchant	Etch rate [nm/min]
Polysilicon	HNO <sub>3</sub> :H <sub>2</sub> O: NH <sub>4</sub> F	120-600	SF <sub>6</sub> + He	170-920
Silicon nitride	H <sub>3</sub> PO <sub>4</sub>	5	SF <sub>6</sub>	150-250
Silicon dioxide	HF	20-2000	CHF <sub>3</sub> + O <sub>2</sub>	50-150
Aluminum	H <sub>3</sub> PO <sub>4</sub> :HNO <sub>3</sub> : CH <sub>3</sub> COOH	660	Cl <sub>2</sub> + SiCl <sub>4</sub>	100-150
Photoresist	Acetone	>4000	O <sub>2</sub>	35-3500
Gold	KI	40	n/a	n/a

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### 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

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## Microstructure Stiction

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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

*contact angle*

Lotus Surface [Univ. Mainz]

- **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  $\theta_{\text{water}} > 90^\circ$

*Hydrophilic case*     $P_2$      $P_1$      $d$

*Hydrophobic case*     $P_2$      $P_1$

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