EE C247B – ME C218
Introduction to MEMS Design
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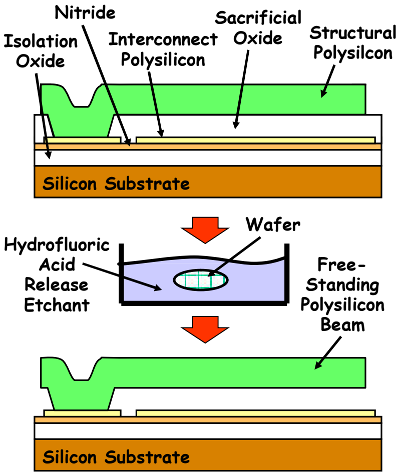
Lecture Module 5: Surface Micromachining

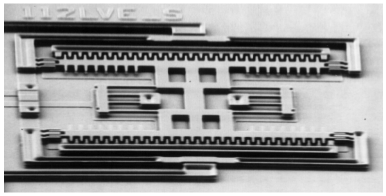
Lecture Outline

- 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

Polysilicon Surface-Micromachining



- Uses IC fabrication instrumentation exclusively
- *Variations*: sacrificial layer thickness, fine- vs. large-grained polysilicon, *in situ* vs. $POCL_3$-doping



300 kHz Folded-Beam Micromechanical Resonator

Polysilicon

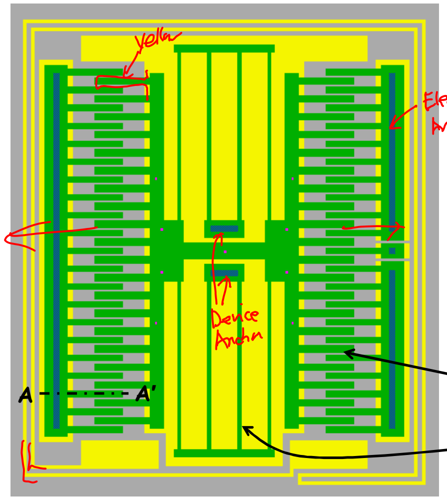
Why Polysilicon?

- 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, $POCl_3$, 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

Polysilicon Surface-Micromachining Process Flow

Layout and Masking Layers



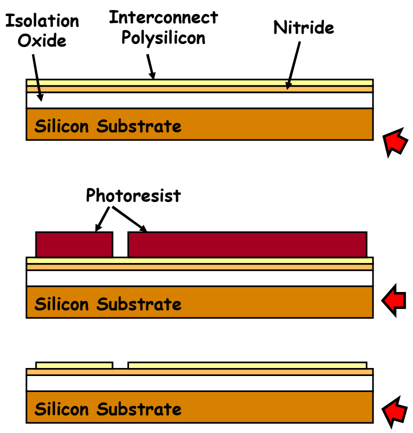
- At Left: Layout for a folded-beam capacitive comb-driven micromechanical resonator
- Masking Layers:
  - 🟨 1st Polysilicon: POLY1(cf) dark field
  - 🟦 Anchor Opening: ANCHOR(df)
  - 🟩 2nd Polysilicon: POLY2(cf) ← clear field

Capacitive comb-drive for linear actuation

Folded-beam support structure for stress relief

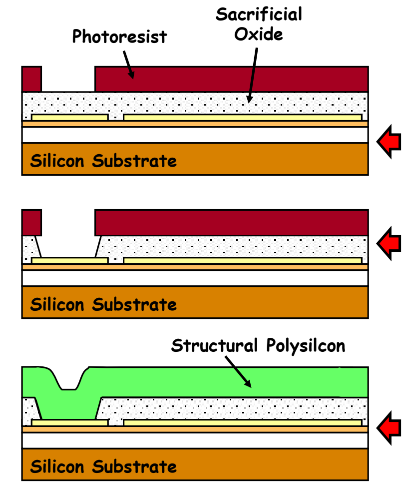
Surface-Micromachining Process Flow

Cross-sections through A-A'



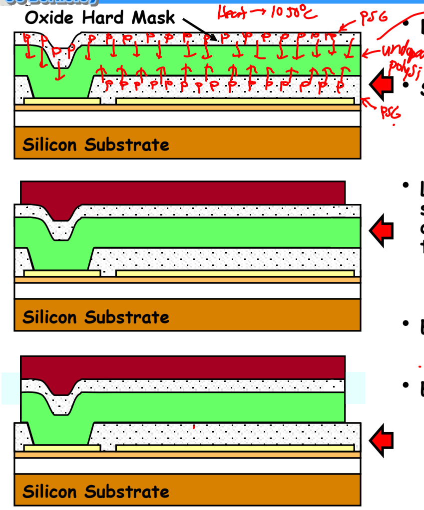
- Deposit isolation LTO (or PSG):
  - Target = 2μm
  - 1 hr. 40 min. LPCVD @450°C
- Densify the LTO (or PSG)
  - Anneal @950°C for 30 min.
- Deposit nitride:
  - Target = 100nm
  - 22 min. LPCVD @800°C
- Deposit interconnect polySi:
  - Target = 300nm
  - In-situ Phosphorous-doped
  - 1 hr. 30 min. LPCVD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

Surface-Micromachining Process Flow

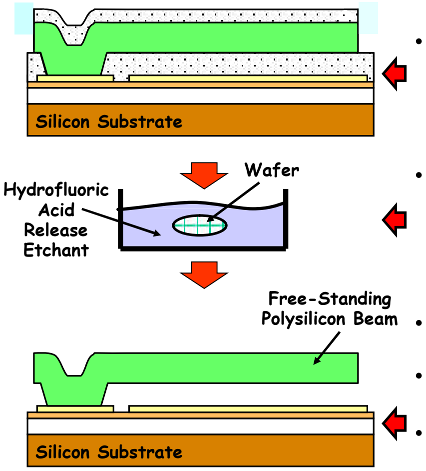


- Deposit oxide hard mask
  - Target = 500nm
  - 25 min. LPCVD @450°C
- Stress Anneal
  - 1 hr. @ 1050°C
  - Or RTA for 1 min. @ 1100°C in 50 sccm N_2

Symmetrical doping top&bottom reduces stress!

- 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

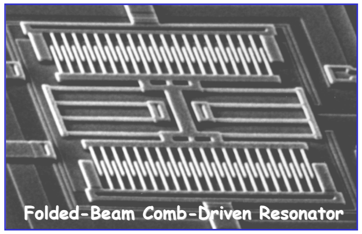
Surface-Micromachining Process Flow

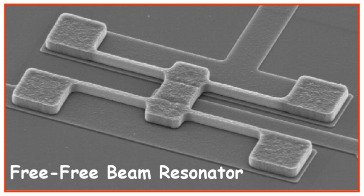


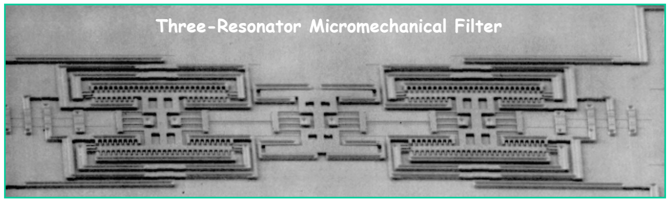
- Remove PR (more difficult)
  - Ash in O_2 plasma
  - Soak in PRS2000
- Release the structures
  - Wet etch in HF for a calculated time that insures complete undercutting
  - If 5:1 BHF, then ~ 30 min.
  - If 48.8 wt. % HF, ~ 1 min.
- Keep structures submerged in DI water after the etch
- Transfer structures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

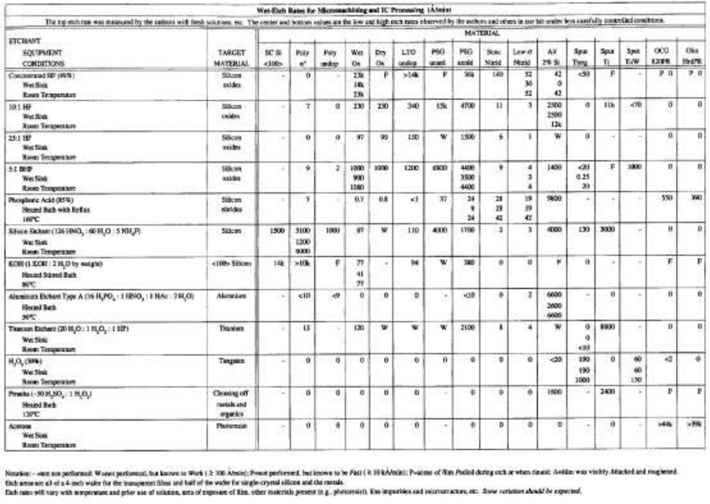

Three-Resonator Micromechanical Filter

Structural/Sacrificial 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)



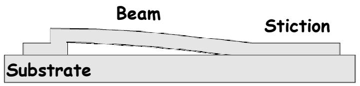
Wet-Etch Rates for Micromachining and IC Processing (Å/min)

Film Etch Chemistries

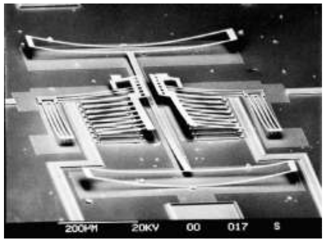
- For some popular films:

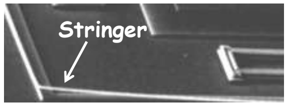
Material	Wet etchant	Etch rate [nm/min]	Dry etchant	Etch rate [nm/min]
Polysilicon	HNO_3:H_2O: NH_4F	120-600	SF_6 + He	170-920
Silicon nitride	H_3PO_4	5	SF_6	150-250
Silicon dioxide	HF	20-2000	CHF_3 + O_2	50-150
Aluminum	H_3PO_4:HNO_3: CH_3COOH	660	Cl_2 + $SiCl_4$	100-150
Photoresist	Acetone	>4000	O_2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

Issues in Surface Micromachining

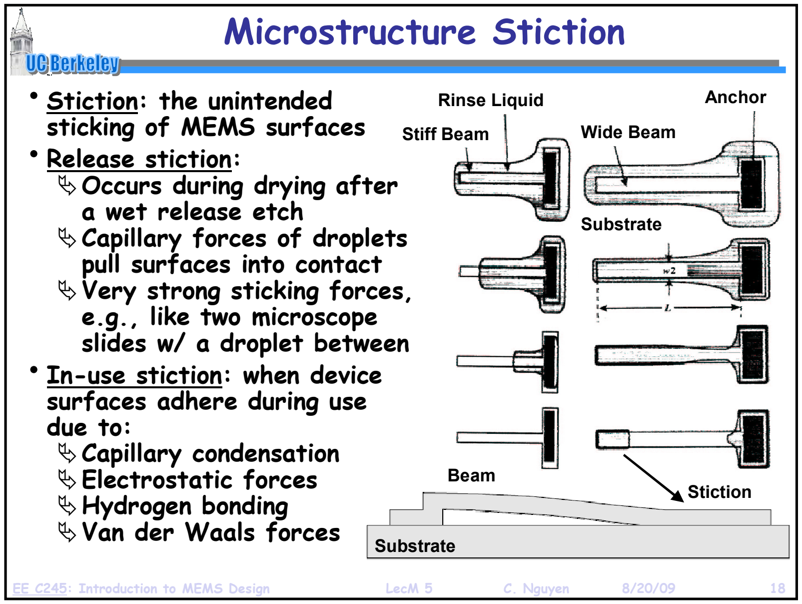


- **Stiction**: sticking of released devices to the substrate or to other on-chip structures
  - Difficult to tell if a structure is stuck to substrate by just looking through a microscope
- Residual Stress in Thin Films
  - Causes bending or warping of microstructures
  - Limits the sizes (and sometimes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



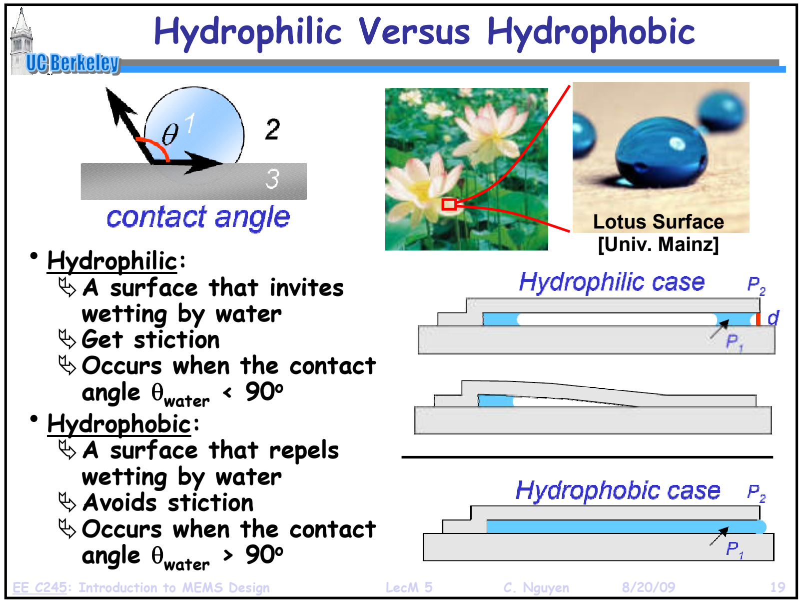


Microstructure Stiction



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

- **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 $\theta_{water} > 90°$