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, POCl₃, 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)
  - 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

Cross-sections through A-A'

- Deposit isolation LTO (or PSG):
  - Target = 2 μm
  - 1 hr. 40 min. LPCVD @450°C
- Densify the LTO (or PSG):
  - Anneal @950°C for 30 min.
- Deposit nitride:
  - Target = 100 nm
  - 22 min. LPCVD @800°C
- Deposit interconnect polySi:
  - Target = 300 nm
  - 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 CHF₃/CF₄/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 N₂

- 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 CHF₃/CF₄/He @ 350W, 2.8Torr

- Etch structural polysilicon
  - RIE using CCl₄/He/O₂ @ 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

<table>
<thead>
<tr>
<th>Structural Material</th>
<th>Sacrificial Material</th>
<th>Etchant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly-Si</td>
<td>SiO₂, PSG, LTO</td>
<td>HF, BHF</td>
</tr>
<tr>
<td>Al</td>
<td>Photoresist</td>
<td>O₂ plasma</td>
</tr>
<tr>
<td>SiO₂</td>
<td>Poly-Si</td>
<td>XeF₂</td>
</tr>
<tr>
<td>Al</td>
<td>Si</td>
<td>TMAH, XeF₂</td>
</tr>
<tr>
<td>Poly-SiGe</td>
<td>Poly-Ge</td>
<td>H₂O₂, hot H₂O</td>
</tr>
</tbody>
</table>

- 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 mm/min
  - Annealed PSG ≈ 3.6 mm/min
  - Aluminum (Si rich) ≈ 4 nm/min (much faster in other Al)
Wet Etch Rates (f/ K. Williams)

<table>
<thead>
<tr>
<th>ETCHANT</th>
<th>EQUIPMENT CONDITIONS</th>
<th>TARGET MATERIAL</th>
<th>SC Si</th>
<th>Poly e</th>
<th>Poly undep</th>
<th>Wet Ox</th>
<th>Dry Ox</th>
<th>LTO undep</th>
<th>PSG unical</th>
<th>PSG amide</th>
<th>Stoic Nitride</th>
<th>Low-η Nitride</th>
<th>Al</th>
<th>Spat Tung</th>
<th>Spat Ti/W</th>
<th>Spat Ti</th>
<th>OCU</th>
<th>Euid</th>
<th>Hid/PDR</th>
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</thead>
<tbody>
<tr>
<td>Concentrated HF (49%)</td>
<td>Wet Sink</td>
<td>Silicon oxides</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>23k</td>
<td>F</td>
<td>&gt;14k</td>
<td>F</td>
<td>36k</td>
<td>40</td>
<td>52</td>
<td>42</td>
<td>42</td>
<td>&lt;30</td>
<td>F</td>
<td>-</td>
<td>P</td>
<td>0</td>
</tr>
<tr>
<td>10:1 HF</td>
<td>Room Temperature</td>
<td>Silicon oxides</td>
<td>-</td>
<td>7</td>
<td>0</td>
<td>230</td>
<td>230</td>
<td>340</td>
<td>15k</td>
<td>4700</td>
<td>11</td>
<td>3</td>
<td>2500</td>
<td>2500</td>
<td>12k</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5:1 HF</td>
<td>Wet Sink</td>
<td>Silicon oxides</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>97</td>
<td>95</td>
<td>150</td>
<td>W</td>
<td>1500</td>
<td>6</td>
<td>1</td>
<td>W</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td></td>
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<tr>
<td>5:1 DHP</td>
<td>Wet Sink</td>
<td>Silicon oxides</td>
<td>-</td>
<td>9</td>
<td>2</td>
<td>1000</td>
<td>1000</td>
<td>1200</td>
<td>6800</td>
<td>4400</td>
<td>3500</td>
<td>4400</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>1400</td>
<td>&lt;20</td>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td>Phosphoric Acid (85%)</td>
<td>Room Temperature</td>
<td>Silicon oxides</td>
<td>-</td>
<td>7</td>
<td>0</td>
<td>0.7</td>
<td>0.8</td>
<td>&lt;1</td>
<td>31/4</td>
<td>24</td>
<td>9</td>
<td>28</td>
<td>24</td>
<td>42</td>
<td>42</td>
<td>9800</td>
<td>-</td>
<td>-</td>
<td>530</td>
</tr>
<tr>
<td>Silicon Etchant (112 HNO₃: 60 H₂O: 5 NH₄F)</td>
<td>Wet Sink</td>
<td>Silicon</td>
<td>1500</td>
<td>3100</td>
<td>1200</td>
<td>6000</td>
<td>1000</td>
<td>87</td>
<td>W</td>
<td>110</td>
<td>4000</td>
<td>1700</td>
<td>2</td>
<td>3</td>
<td>4000</td>
<td>130</td>
<td>3000</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>KOH (1 KOH : 7 H₂O by weight)</td>
<td>Room Temperature</td>
<td>&lt;100Si Silicon</td>
<td>14k</td>
<td>&gt;10k</td>
<td>F</td>
<td>77</td>
<td>-</td>
<td>94</td>
<td>W</td>
<td>380</td>
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<td>0</td>
<td>F</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>F</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>Aluminum Etchant Type A (16 H₂PO₄: 1 HNO₃: 1 HAc : 2 H₂O)</td>
<td>Heated Bath</td>
<td>Aluminium</td>
<td>-</td>
<td>&lt;10</td>
<td>&lt;9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>&lt;10</td>
<td>0</td>
<td>2</td>
<td>6600</td>
<td>2600</td>
<td>6600</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Titanium Etchant (20 H₂O : 1 H₂O₂ : 1 HF)</td>
<td>Wet Sink</td>
<td>Titanium</td>
<td>-</td>
<td>12</td>
<td>12</td>
<td>W</td>
<td>W</td>
<td>W</td>
<td>2100</td>
<td>8</td>
<td>4</td>
<td>W</td>
<td>0</td>
<td>0</td>
<td>&lt;10</td>
<td>8300</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>H₂O₂ (30%)</td>
<td>Room Temperature</td>
<td>Tungsten</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>&lt;20</td>
<td>190</td>
<td>190</td>
<td>190</td>
<td>1000</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>Piranha (~30 H₂SO₄: 1 H₂O₂)</td>
<td>Heated Bath</td>
<td>Cleaning off metals and organics</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1800</td>
<td>-</td>
<td>2400</td>
<td>F</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>Acetone</td>
<td>Wet Sink</td>
<td>Photorezist</td>
<td>-</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>&gt;44k</td>
<td>&gt;35k</td>
<td></td>
</tr>
</tbody>
</table>

Notation: - Test not performed; W=not performed, but known to work (≥ 10 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. Each area is an 8 inch wafer for the transparent thin films and haf of the wafer for single-crystal silicon and the metals. Each rate will vary with temperature and prior use of solution, area of exposure of film, other materials present (e.g., photorezist), film impurities and microstructure, etc. Some variation should be expected.
## Film Etch Chemistries

For some popular films:

<table>
<thead>
<tr>
<th>Material</th>
<th>Wet etchant</th>
<th>Etch rate [nm/min]</th>
<th>Dry etchant</th>
<th>Etch rate [nm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polysilicon</td>
<td>HNO$_3$·H$_2$O·NH$_4$F</td>
<td>120-600</td>
<td>SF$_6$ + He</td>
<td>170-920</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>H$_3$PO$_4$</td>
<td>5</td>
<td>SF$_6$</td>
<td>150-250</td>
</tr>
<tr>
<td>Silicon dioxide</td>
<td>HF</td>
<td>20-2000</td>
<td>CHF$_3$ + O$_2$</td>
<td>50-150</td>
</tr>
<tr>
<td>Aluminum</td>
<td>H$_3$PO$_4$·HNO$_3$·CH$_3$COOH</td>
<td>660</td>
<td>Cl$_2$ + SiCl$_4$</td>
<td>100-150</td>
</tr>
<tr>
<td>Photoresist</td>
<td>Acetone</td>
<td>&gt;4000</td>
<td>O$_2$</td>
<td>35-3500</td>
</tr>
<tr>
<td>Gold</td>
<td>KI</td>
<td>40</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
**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 $\theta_{\text{water}} < 90^\circ$

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

Microstructures

Wetted Area

Force Applied to Maintain Equilibrium

F

A

Contact Angle

Liquid Layer Thickness

Laplace Equation: Surface Tension @ the Liquid-Air Interface

\[ \Delta P_{la} = \frac{\gamma_{la}}{r} \]

Pressure Difference @ the Meniscus (− if concave)

\[ r = -\frac{(g/2)}{\cos \theta_c} \]

\[ F = -\Delta P_{la} A = \frac{2A \gamma_{la} \cos \theta_c}{g} \]

Force needed to keep the plates apart

\[ (\text{force means a } \times \text{ Laplace pressure}) \]
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