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
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

- 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 = 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: CCl₄/He/O₂ @300W,280mTorr
- Remove photoresist in PR52000

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 sacrificial PSG:**
  - Target = 2 μm
  - 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 = 2 μm
  - In-situ Phosphorous-doped
  - 11 hrs. LPCVD @650°C

**Silicon Substrate**

**Sacrificial Oxide**

**Silicon Substrate**

**Photoresist**

**Silicon Substrate**

**Structural Polysilicon**

**Silicon Substrate**

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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 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

**Silicon Substrate**

**Oxide Hard Mask**

**Silicon Substrate**

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**Surface-Micromachining Process Flow**

- **Remove PR (more difficult)**
  - Ash in O₂ 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 CO₂ dry release**

**Silicon Substrate**

**Hydrofluoric Acid**

**Silicon Substrate**

**Free-Standing Polysilicon Beam**

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**Polysilicon Surface-Micromachined Examples**

- **Below:** All surface-micromachined in polysilicon using variants of the described process flow

**Free-Free Beam Resonator**

**Folded-Beam Comb-Driven 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 μm/min
  - Annealed PSG ~ 3.6 μm/min
  - Aluminum (Si rich) ~ 4 nm/min (much faster in other Al)

**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>HNO₃, H₂O₂, NH₄F</td>
<td>120-600</td>
<td>SF₆ + He</td>
<td>170-920</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>H₃PO₄</td>
<td>5</td>
<td>SF₆</td>
<td>150-250</td>
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<tr>
<td>Silicon dioxide</td>
<td>HF</td>
<td>20-2000</td>
<td>CHF₃ + O₂</td>
<td>50-150</td>
</tr>
<tr>
<td>Aluminum</td>
<td>H₂PO₄, HNO₃, CH₃COOH</td>
<td>600</td>
<td>Cl₂ + SiCl₄</td>
<td>100-150</td>
</tr>
<tr>
<td>Photoresist</td>
<td>Acetone</td>
<td>&gt;4000</td>
<td>O₂</td>
<td>35-3500</td>
</tr>
<tr>
<td>Gold</td>
<td>I₂</td>
<td>40</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

**Wet Etch Rates (f/ K. Williams)**

**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