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. POCl₃-doping

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

* 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:
  • CCl₄/He/O₂ @300W, 280mTorr
* Remove photoresist in PRS2000
### 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

### Surface-Micromachining Process Flow (continued)

**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

**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

### 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 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)

<table>
<thead>
<tr>
<th>Material</th>
<th>Wet etch rate [nm/min]</th>
<th>Dry etch rate</th>
<th>Etch rate [μm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polysilicon</td>
<td>HNO₂:H₂O:NH₄F</td>
<td>SF₆ + He</td>
<td>170-920</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>H₃PO₄</td>
<td>SF₆</td>
<td>150-250</td>
</tr>
<tr>
<td>Silicon dioxide</td>
<td>HF</td>
<td>CHF₃ + O₂</td>
<td>50-150</td>
</tr>
<tr>
<td>Aluminum</td>
<td>H₂PO₄:HNO₃:CH₃COOH</td>
<td>Cl₂ + SiCl₄</td>
<td>100-150</td>
</tr>
<tr>
<td>Photoresist</td>
<td>Acetone &gt;4000</td>
<td>O₂</td>
<td>35-3500</td>
</tr>
<tr>
<td>Gold</td>
<td>KI</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

### Film Etch Chemistries

* For some popular films:

### 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

- **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
  - Gets 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 \( \theta_{\text{water}} > 90^\circ \)