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)

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 = 100nm
  - 22 min. LPCVD @800°C
- Deposit interconnect polysilicon:
  - 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

- 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 CCl4/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 Mask

Silicon Substrate

Oxide Hard Mask

Silicon Substrate

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.
  - Transfer structures to methanol
- Keep structures submerged in DI water after the etch
- Supercritical CO₂ dry release

Polysilicon Surface-Micromachined Examples

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

Wet Etch Rates (f/ K. Williams)

<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)
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>HNO₂·H₂O·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>
</tr>
<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>H₃PO₄·HNO₂·CH₂COOH</td>
<td>660</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>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

- **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
  - Occurs when the contact angle \( \theta_{\text{water}} < 90^\circ \)
- **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 \( \Rightarrow \) 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

\[
F = -\Delta P_{\text{lm}} A = \frac{2\sigma_{\text{lm}} \cos \theta_C}{g}
\]