Lecture Outline

• Reading: Senturia Chpt. 3, Jaeger Chpt. 11, Handout: “Surface Micromachining for Microelectromechanical Systems”
• Lecture Topics:
  - Finish diffusion
  - 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
Metallurgical Junction Depth, $x_j$

$x_j =$ point at which diffused impurity profile intersects the background concentration, $N_B$

Log[$N(x)$]

$N_0$ e.g., p-type Gaussian

$N_B$ e.g., n-type

$x = \text{distance f/ surface}$

Log[$N(x) - N_B$]

$N_0 - N_B$ Net impurity conc.

$N_B$ p-type region

$x = \text{distance f/ surface}$

$n$-type region

Expressions for $x_j$

* Assuming a Gaussian dopant profile: (the most common case)

$$N(x_j, t) = N_o \exp \left[ -\left( \frac{x_j}{2\sqrt{Dt}} \right)^2 \right] = N_B \rightarrow x_j = 2\sqrt{Dt} \ln \left( \frac{N_o}{N_B} \right)$$

* For a complementary error function profile:

$$N(x_j, t) = N_o \text{erfc} \left( \frac{x_j}{2\sqrt{Dt}} \right) = N_B \rightarrow x_j = 2\sqrt{Dt} \text{erfc}^{-1} \left( \frac{N_B}{N_o} \right)$$
Sheet Resistance

- Sheet resistance provides a simple way to determine the resistance of a given conductive trace by merely counting the number of effective squares.

  **Definition:**

  \[ R = \frac{\rho L}{A} = \frac{(\rho / t) L}{w} = R_s \left( \frac{L}{w} \right) \]

  - \( A = t \cdot w \)
  - Sheet resistance
  - Unit square of material in the resistor
  - Uniformly doped material
  - Resistivity \( \rho \)
  - Conductivity \( \sigma \) = \( q/(\mu_n + \mu_p) \)

- What if the trace is non-uniform? (e.g., a corner, contains a contact, etc.)

# Squares From Non-Uniform Traces

- Corner = 0.36 squares
- 0.64 squares
- 0.14 squares
- 0.35 squares
Sheet Resistance of a Diffused Junction

For diffused layers:

\[ R_s = \frac{\rho}{x_j} = \left[ \int_{x_j}^{x_o} \sigma(x) dx \right]^{-1} = \left[ \int_{x_j}^{x_o} q \mu N(x) dx \right]^{-1} \]

This expression neglects depletion of carriers near the junction, \( x_j \to \) thus, this gives a slightly lower value of resistance than actual

Above expression was evaluated by Irvin and is plotted in “Irvin’s curves” on next few slides

Illuminates the dependence of \( R_s \) on \( x_j \), \( N_o \) (the surface concentration), and \( N_B \) (the substrate background conc.)

Irvin’s Curves (for n-type diffusion)

Example.

Given:

- \( N_B = 3 \times 10^{16} \, \text{cm}^{-3} \)
- \( N_o = 1.1 \times 10^{18} \, \text{cm}^{-3} \)
- (n-type Gaussian)
- \( x_j = 2.77 \, \mu\text{m} \)

Can determine these given known predep. and drive conditions

Determine the \( R_s \).

Using Fig. 7.7:

\[ R_s x_j = 470 \, \Omega \cdot \mu\text{m} \]

\[ \therefore R_s = \frac{470 \, \Omega}{2.77 \, \mu\text{m}} = 170 \, \Omega/\mu\text{m} \]
Irvin's Curves (for p-type diffusion)

Example.

Given:
- $N_b = 3 \times 10^{16} \text{ cm}^{-3}$
- $N_a = 1.1 \times 10^{18} \text{ cm}^{-3}$ (p-type Gaussian)
- $x_j = 2.77 \, \mu\text{m}$

Can determine these given known predep. and drive conditions.

Determine the $R_s$.

Using Fig. 7.9:

$$R_s x_j = \frac{800 \, \text{S}}{8} = 289 \, \Omega$$

$$R_s = \frac{289 \, \Omega}{2.77}$$

Surface Micromachining
Polysilicon Surface-Micromachining

- Uses IC fabrication instrumentation exclusively
- Variations: sacrificial layer thickness, fine- vs. large-grained polysilicon, in situ vs. POCL₃-doping

Polysilicon Beam

300 kHz Folded-Beam Micromechanical Resonator
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
  - Anchor Opening
  - 2nd Polysilicon
  - 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 = 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
- RIE polysilicon interconnects:
  - CCl₄/He/O₂ @300W, 280mTorr
- Remove photoresist in PRS2000
Surface-Micromachining Process Flow

- Deposit sacrificial PSG:
  - Target = $2 \mu m$
  - 1 hr. 40 min. LPCVD @450°C
- Densify the PSG
  - Anneal @950°C for 30 min.
- Lithography to define anchors
- 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 = $2 \mu m$
  - In-situ Phosphorous-doped
  - 11 hrs. LPCVD @650°C

Surface-Micromachining Process Flow

- Deposit oxide hard mask (PSG)
  - 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)
  - 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 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

- 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)

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

<table>
<thead>
<tr>
<th>Etchant</th>
<th>Silica</th>
<th>Silicon nitride</th>
<th>Wet thermal SiO₂</th>
<th>Annealed PSG</th>
<th>Al (Si rich)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>10000</td>
<td>3000</td>
<td>1250</td>
<td>1350</td>
<td>20000</td>
</tr>
<tr>
<td>BHF</td>
<td>10000</td>
<td>3000</td>
<td>1250</td>
<td>1350</td>
<td>20000</td>
</tr>
<tr>
<td>Dry N₂</td>
<td>10000</td>
<td>3000</td>
<td>1250</td>
<td>1350</td>
<td>20000</td>
</tr>
<tr>
<td>Wet N₂</td>
<td>10000</td>
<td>3000</td>
<td>1250</td>
<td>1350</td>
<td>20000</td>
</tr>
<tr>
<td>Wet Ar</td>
<td>10000</td>
<td>3000</td>
<td>1250</td>
<td>1350</td>
<td>20000</td>
</tr>
<tr>
<td>Wet CO₂</td>
<td>10000</td>
<td>3000</td>
<td>1250</td>
<td>1350</td>
<td>20000</td>
</tr>
<tr>
<td>Wet CO</td>
<td>10000</td>
<td>3000</td>
<td>1250</td>
<td>1350</td>
<td>20000</td>
</tr>
</tbody>
</table>

**Notes:**
- Polysilicon is the material. (From K. Williams, 2007.)
- Values are approximate and may not be exact. These rates are specific to the materials and conditions described. Use caution when applying these rates to other materials or conditions.
- The table provides a general overview of etch rates for different materials and etchants. Actual rates may vary depending on the specific conditions and materials used. Always consult with a materials engineer or perform trials to determine the exact etch rates for your specific application.
### 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

• **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