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

Microstructure Stiction

Microstructures

Contact Angle

Stiction

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

Avoiding Stiction

Reduce droplet area via mechanical design approaches

Avoid liquid–vapor meniscus formation

Use solvents that sublime

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 CO₂ Drying

- A method for stictionless drying of released microstructures by immersing them in CO₂ 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 CO₂
  - Apply heat & pressure to take the CO₂ past its critical pt.
  - Vent to lower pressure and allow the supercritical CO₂ to revert to gas → liquid-to-gas Xstion in supercritical region means no capillary forces to cause stiction

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

Tailoring Contact Angle Via SAM's

- Can reduce stiction by tailoring surfaces so that they induce a water contact angle > 90°
- Self-Assembled Monolayers (SAM's):
  - Monolayers of “stringy” molecules covalently bonded to the surface that then raise the contact angle
- Beneficial characteristics:
  - Conformal, ultrathin
  - Low surface energy
  - Covalent bonding makes them wear resistant
  - Thermally stable (to a point)

Dry Release

- Another way to avoid stiction is to use a dry sacrificial layer etch
- For an oxide sacrificial layer:
  - Use HF vapor phase etching
  - Additional advantage: gas can more easily get into tiny gaps
  - Issue: not always completely dry
  - Moisture can still condense → stiction → soln: add alcohol
- For a polymer sacrificial layer:
  - Use an O₂ plasma etch (isotropic, so it can undercut well)
  - Issues:
    - Cannot be used when structural material requires high temperature for deposition
    - If all the polymer is not removed, polymer under the suspended structure can still promote stiction
Residual Stress

After release, poorly designed microstructures might buckle, bend, or warp → often caused by residual film stress

Origins of residual stress, \( \sigma \)
- Non-equilibrium deposition
- Grain morphology change
- Gas entrapment
- Doping
- Thermal stresses

- Thermal expansion mismatch of materials → introduce stress during cool-down after deposition
- Annealing

Residual Stress in Thin Films

Need to Control Film Stress

- Resonance frequency expression for a lateral resonator:

\[
f_0 = \frac{1}{2\pi} \sqrt{\frac{4E_y t W^3}{ML^4}} + \frac{24\sigma r W}{5ML}
\]

Since \( W \ll L \), the stress term will dominate if \( \sigma_r \sim E_y \)

E_y = Young’s modulus
\( \sigma_r \) = stress
\( t \) = thickness
\( W \) = beam width
\( L \) = beam length
\( M \) = mass

Tensile Versus Compressive Stress

- Under tensile stress, a film wants to shrink w/r to its substrate
  - Caused, e.g., by differences in film vs. substrate thermal expansion coefficients
  - If suspended above a substrate and anchored to it at two points, the film will be “stretched” by the substrate

- Under compressive stress, a film wants to expand w/r to its substrate
  - If suspended above a substrate and anchored to it at two points, the film will buckle over the substrate
**Vertical Stress Gradients**

- Variation of residual stress in the direction of film growth
- Can warp released structures in z-direction

**Stress in Polysilicon Films**

- Stress depends on crystal structure, which in turn depends upon the deposition temperature
  - Temperature \( \leq 600^\circ C \)
    - Films are initially amorphous, then crystallize
    - Get equiaxed crystals, largely isotropic
    - Crystals have higher density \( \rightarrow \) tensile stress
    - Small stress gradient
  - Temperature \( \geq 600^\circ C \)
    - Columnar crystals grow during deposition
    - As crystals grow vertically and in-plane they push on neighbors \( \rightarrow \) compressive stress
    - Positive stress gradient

**Annealing Out Polysilicon Stress**

- Control polySi stress by annealing at high temperatures
  - Typical anneal temperatures: 900-1150°C
  - Grain boundaries move, relax
  - Can dope while annealing by sandwiching the polysilicon between similarly doped oxides (symmetric dopant drive-in), e.g., using 10-15 wt. % PSG
  - Rapid thermal anneal (RTA) also effective (surprisingly)

**Topography Issues**

- Degradation of lithographic resolution
  - PR step coverage, streaking
- Stringers
  - Problematic when using anisotropic etching, e.g., RIE
  - Thickness differences pose problems for reduction steppers
Nickel Surface-Micromachining

**Process Flow**

- **Electroplating:** Metal MEMS
  - Use electroplating to obtain metal structures
  - **Pros:** fast low temp deposition, very conductive
  - **Cons:** drift, low mech. Q, but may be solvable?

**Nickel Metal Surface-Micromachining**

- Deposit isolation LTO:
  - Target = 2μm
  - 1 hr. 40 min. LPCVD @450°C
- Densify the LTO:
  - Anneal @950°C for 30 min.
- Define metal interconnect via lift-off:
  - Spin photoresist and pattern lithographically to open areas where interconnect will stay
  - Evaporate a Ti/Au layer:
    - Target = 30nm Ti
    - Target = 270nm Au
- Wet etch the aluminum to form anchor vias:
  - Use solution of \( \text{H}_3\text{PO}_4/\text{HNO}_3/\text{H}_2\text{O} \)
- Remove photoresist in PRS2000
- Electroplate nickel to fill the anchor vias:
  - Use solution of nickel sulfamate @ 50°C
  - Time the electroplating to planarize the surface
Nickel Metal Surface-Micromachining

- Evaporate a thin film of nickel to serve as a seed layer for subsequent Ni electroplating
  - Target = 20nm
- Form a photoresist mold for subsequent electroplating
  - Spin 6 um-thick AZ 9260 photoresist
  - Lithographically pattern the photoresist to delineate areas where nickel structures are to be formed
- Electroplate nickel structural material through the PR mold
  - Use a solution of nickel sulfamate @ 50°C
  - Cathode-to-anode current density ~ 2.5 mA/cm²

Nickel Surface-Micromachining Example

- Below: Surface-micromachined in nickel using the described process flow

3D “Pop-up” MEMS

Nickel Metal Surface-Micromachining

- Strip the PR in PRS2000
- Remove the Ni seed layer in Ni wet etchant

- Release the structures
  - Use a K₄Fe(CN)₆/NaOH etchant that attacks Al while leaving Ni and Au intact
  - Etch selectivity > 100:1 for Al:Ni and Al:Au
EE 245: Introduction to MEMS
Lecture 10m: Surface Micromachining

Pop-Up MEMS

First MEMS hinge
[K. Pister, et al., 1992]

Corner Cube Reflector
[v. Hsu, 1999]

3D Direct-Assembled Tunable L

[Ming Wu, UCLA]

Hinge Process Flow

Deposit first sacrificial
Deposit and pattern first poly

Deposit and pattern second sacrificial

Pattern contacts
Deposit and pattern second poly

Etch sacrificial
Assemble part