Lecture Outline

* Reading: Senturia Chpt. 3, 8, Jaeger Chpt. 11, Handouts: “Bulk Micromachining of Silicon”, “Wafer-to-Wafer Bonding for Microstructure Formation”

* Lecture Topics:  
  - Vapor Phase Etching of Silicon  
  - Laser Assisted Silicon Etching  
  - Wafer Bonding  
  - Mechanics of Materials  
    - Stress  
    - Strain  
    - Poisson Ratio  
  - Material Properties
Deep Reactive-Ion Etching (DRIE)

The Bosch process:

- Inductively-coupled plasma
- Etch Rate: 1.5-4 μm/min
- Two main cycles in the etch:
  - Etch cycle (5-15 s): SF₆ (SFₓ⁺) etches Si
  - Deposition cycle (5-15 s): C₄F₈ deposits fluorocarbon protective polymer (CF₂⁻)ₙ
- Etch mask selectivity:
  - SiO₂ ~ 200:1
  - Photoresist ~ 100:1
- Issue: finite sidewall roughness
  - scalloping < 50 nm
- Sidewall angle: 90° ± 2°

DRIE Issues: Etch Rate Variance

- Etch rate is diffusion-limited and drops for narrow trenches
  - Adjust mask layout to eliminate large disparities
  - Adjust process parameters (slow down the etch rate to that governed by the slowest feature)
**DRIE Issues: “Footing”**

- Etch depth precision
  - Etch stop: buried layer of SiO₂
  - Due to 200:1 selectivity, the (vertical) etch practically just stops when it reaches SiO₂
- Problem: Lateral undercut at Si/SiO₂ interface → “footing”
  - Caused by charge accumulation at the insulator

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**Metal Interlayer to Prevent “Footing”**

- Pre-defined metal interlayer grounded to substrate supplies e’s to neutralize (+) charge and prevent charge accumulation at the Si-insulator interface

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Footing Prevention (cont.)

- Below: DRIE footing over an oxide stop layer
- Right: efficacy of the metal interlayer footing prevention approach

[Footings Diagram]

DRIE Examples

- High aspect-ratio gear [Yao, Rockwell]
- Tunable Capacitor [Yao, Rockwell]
- Microgripper [Keller, MEMS Precision Instruments]
### Vapor Phase Etching of Silicon

**• Vapor phase Xenon Difluoride (XeF$_2$)**

\[ 2\text{XeF}_2(g) + \text{Si}(s) \rightarrow 2\text{Xe}(g) + \text{SiF}_4(g) \]

**• Set-up:**
- Xe sublimes at room T
- Closed chamber, 1-4 Torr
- Pulsed to control exothermic heat of reaction

**• Etch rate:** 1-3 μm/min, isotropic

**• Etch masks:** photoresist, SiO$_2$, Si$_3$N$_4$, Al, other metals

**• Issues:**
- Etched surfaces have granular structure, 10 μm roughness
- Hazard: XeF$_2$ reacts with H$_2$O in air to form Xe and HF

### Laser-Assisted Chemical Etching

**• Laser creates Cl radicals from Cl$_2$ → reaction forms SiCl$_2$**

**• Etch rate:** 100,000 μm$^3$/s
- Takes 3 min. to etch 500×500×125 μm$^3$ trench

**• Surface roughness:** 30 nm rms

**• Serial process:** patterned directly from CAD file

**• At right:**
- Laser assisted etching of a 500x500 μm$^2$ terraced silicon well
- Each step is 6 μm-deep
Wafer Bonding

Fusion Bonding

- Two ultra-smooth (<1 nm roughness) wafers are bonded without adhesives or applied external forces
- Procedure:
  - Prepare surfaces: must be smooth and particle-free
    - Clean & hydrate: O₂ plasma, hydration, or HF dip
  - When wafers are brought in contact at room temperature, get hydrogen bonding and/or van der Waals forces to hold them together
  - Anneal at 600-1200°C to bring the bond to full strength
- Result: a bond as strong as the silicon itself!

Works for Si-to-Si bonding and Si-to-SiO₂ bonding
Fusion Bonding Example

- Below: capacitive pressure sensor w/ fusion-bonded features

Anodic Bonding

- Bonds an electron conducting material (e.g., Si) to an ion conducting material (e.g., sodium glass = Pyrex)

- Procedure/Mechanism:
  - Press Si and glass together
  - Elevate temperature: 180-500°C
  - Apply (+) voltage to Si: 200-1500V
    - (+) voltage repels Na⁺ ions from the glass surface
    - Get net (-) charge at glass surface
    - Attractive force between (+) Si and (-) glass → intimate contact allows fusing at elevated temp.
  - Current drops to zero when bonding is complete
Anodic Bonding (cont.)

- **Advantage**: high pressure of electrostatic attraction smooths out defects
- **Below**: 100 mm wafers, Pyrex glass 500 μm-thick, 430°C, 800V, N₂ @ 1000 mbar

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Metal Layer Bonding

- **Pattern seal rings and bond pads photolithographically**
- **Eutectic bonding**
  - Uses eutectic point in metal-Si phase diagrams to form silicides
  - Au and Si have eutectic point at 363°C
  - Low temperature process
  - Can bond slightly rough surfaces
  - **Issue**: Au contamination of CMOS
- **Solder bonding**
  - PbSn (183°C), AuSn (280°C)
  - Lower-T process
  - Can bond very rough surfaces
  - **Issue**: outgassing (not good for encapsulation)
- **Thermocompression**
  - Commonly done with electroplated Au or other soft metals
  - Room temperature to 300°C
  - Lowest-T process
  - Can bond rough surfaces with topography
Thermocompression Bonding

- Below: Transfer of hexsil actuator onto CMOS wafer

Hexsil MEMS

- Achieves high aspect ratio structures using conformal thin films in mold trenches
- Parts are demolded (and transferred to another wafer)
- Mold can be reused
- Design with honeycomb structure for strength
Hexsil MEMS Actuator

- Below: Transfer of hexsil actuator onto CMOS wafer

[Singh, et al., Transducers'97]

Silicon-on-Insulator (SOI) MEMS

- No bonding required
- Si mechanical structures anchored by oxide pedestals
- Rest of the silicon can be used for transistors (i.e., CMOS compatible)
SOI MEMS Examples

Micromirror
[Analog Devices]

[Brosnihan]

The SCREAM Process

SCREAM: Single Crystal Reactive Etching and Metallization process

1. Deposit oxide and photoresist
2. Etch oxide and oxide etch
3. Silicon etch
4. Coat sidewalls with PECVD oxide
5. Remove oxide at bottom and each silicon
6. Plasma etch in Si, to release structure
Elasticity

Normal Stress (1D)

If the force acts normal to a surface, then the stress is called a normal stress.

\[
\sigma = \frac{F}{A} \quad \text{[N/m}^2 \times \text{Pa]} \quad \text{standard units: N/m}^2
\]

Differential volume element

Microscopic definition: force per unit area acting on a surface of a differential volume element of a solid body.

Note: force acts uniformly over each face.
Strain (1D)

\[ \varepsilon = \frac{\Delta L}{L} \]

\[ \text{Strain} = \left\{ \begin{array}{l}
\text{Fractional Change in } \frac{\Delta L}{L} \text{ per part in } 10^6 \\
[\text{Unitless}] \end{array} \right. \]

\[ \frac{\Delta L}{L} \times 10^6 = \mu \varepsilon \]

In the elastic regime (i.e., for "small" strains),

\[ \sigma = \varepsilon E \]

\[ \varepsilon = \frac{\Delta L}{L} \]

The Poisson Ratio

\[ \varepsilon_y = \frac{W' - W}{W} = \frac{\Delta L}{L} \]

\[ \nu : \text{Poisson ratio (unitless)} \]

Typical values:
- 0 \rightarrow 0.5
- Inorganic solids: 0.2 \rightarrow 0.3
- Elastomers (e.g., rubber): \sim 0.5

\[ \text{Contractions create a } \varepsilon_y \text{ strain:} \]

\[ \varepsilon_y = \frac{W' - W}{W} = \frac{\Delta L}{L} \]
Shear Stress & Strain (2D)

Note: Assume compensating forces are applied to the vertical faces to avoid a net torque. (This by convention)

Shear Stress: \( \tau \)
- Force per unit area
- Parallel to the surface
- \( \tau = \frac{F}{A} \) [Pa]

Generates a shear strain:

Shear Strain, \( \gamma \): \( \gamma = \frac{\tau}{G} \leq \frac{E}{2G} \) (shear modulus)

\( G = \frac{E}{2(1+\nu)} \)