**Lecture Module 6: Bulk Micromachining**

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### Mechanical Properties of Silicon

- Crystalline silicon is a hard and brittle material that deforms elastically until it reaches its yield strength, at which point it breaks.
- Tensile yield strength = 7 GPa (~1500 lb suspended from 1 mm²)
- Young’s Modulus near that of stainless steel
- \{100\} = 130 GPa; \{110\} = 169 GPa; \{111\} = 188 GPa
- Mechanical properties uniform, no intrinsic stress
- Mechanical integrity up to 500°C
- Good thermal conductor
- Low thermal expansion coefficient
- High piezoresistivity
Anisotropic Wet Etching

Anisotropic etches are available for single crystal Si:

- Orientation-dependent etching: <111> plane more densely packed than <100> plane

  \[ \text{Faster E.R.} \quad \text{Slower E.R.} \]

  ...in some solvents

One such solvent: KOH + isopropyl alcohol
(e.g., 23.4 wt% KOH, 13.3 wt% isopropyl alcohol, 63 wt% H$_2$O)

\[ \text{E.R.}_{100} = 100 \times \text{E.R.}_{111} \]

Anisotropic Wet Etching (cont.)

Can get the following:

- (on a <100> - wafer)

  SiO$_2$

  54.7°

  <100>

  Si

- (on a <110> - wafer)

  SiO$_2$

  <110>

  <111>

  Si

Anisotropic Etching of Silicon

- Etching of Si w/ KOH
  
  \[ \text{Si} + 2\text{OH}^- \rightarrow \text{Si(OH)}_2^{2+} + 4e^- \]
  
  \[ 4\text{H}_2\text{O} + 4e^- \rightarrow 4\text{OH}^- + 2\text{H}_2 \]

- Crystal orientation dependent etch rates
  
  \[ \{110\} : \{100\} : \{111\} = 600 : 400 : 1 \]

  \{100\} and \{110\} have 2 bonds below the surface & 2 dangling bonds that can react
  
  \{111\} plane has three of its bonds below the surface & only one dangling bond to react \( \rightarrow \) much slower E.R.

  \{111\} forms protective oxide

  \{111\} smoother than other crystal planes \( \rightarrow \) good for optical MEMS (mirrors)

Self-limiting etches

- Membrane

  Front side mask

  Back side mask

- Nitride Mask

  Photoresist

  Silicon Substrate

.pattern nitride mask

  RIE using SF$_6$

  Remove PR in PRS2000

  Etch the silicon

  \( \times \) 1:2 KOH:H$_2$O (wt.), stirred bath \( \times 80^\circ\text{C} \)

  \( \times \) Etch Rates:

  - (100) Si \( \rightarrow \) 1.4 μm/min
  - Si$_3$N$_4$ \( \rightarrow \) 0 nm/min
  - SiO$_2$ \( \rightarrow \) 1-10 nm/min

  - Photoresist, Al \( \rightarrow \) fast

  - Micromasking by H$_2$ bubbles leads to roughness

  - Stir well to displace bubbles

  - Can also use oxidizer for (111) surfaces

  - Or surfactant additives to suppress bubble formation
Silicon Wafers

Silicon Crystallography

Miller Indices \((h k l)\):
- Planes
  - Reciprocal of plane intercepts with axes
  - e.g., for \((110)\), intercepts: \((x, y, z) = (1, 1, \infty)\); reciprocals: \((1, 1, 0)\)
  - (unique), \(\{\text{family}\}\)
- Directions
  - One endpoint of vector @ origin
  - \([\text{unique}], \langle\text{family}\rangle\)

Silicon Crystal Orientation

Determining Angles Between Planes

- The angle between vectors \([abc]\) and \([xyz]\) is given by:
  \[\theta_{(a,b,c)}(x,y,z) = \cos^{-1}\left(\frac{ax + by + cz}{\sqrt{(a,b,c) \cdot (x,y,z)}}\right)\]
- For \((100)\) and \((110)\) \(\rightarrow 45^\circ\)
- For \((100)\) and \((111)\) \(\rightarrow 54.74^\circ\)
- For \((110)\) and \((111)\) \(\rightarrow 35.26^\circ, 90^\circ, \text{and } 144.74^\circ\)
Silicon Crystal Origami

- Silicon fold-up cube
- Adapted from Profs. Kris Pister and Jack Judy
- Print onto transparency
- Assemble inside out
- Visualize crystal plane orientations, intersections, and directions

Undercutting Via Anisotropic Si Etching

- Concave corners bounded by \{111\} are not attacked
- ... but convex corners bounded by \{111\} are attacked
- Two \{111\} planes intersecting now present two dangling bonds → no longer have just one dangling bond → etch rate fast
- Result: can undercut regions around convex corners

Corner Compensation

- Protect corners with “compensation” areas in layout
- Below: Mesa array for self-assembly structures [Smith 1995]

Other Anisotropic Silicon Etchants

- TMAH, Tetramethyl ammonium hydroxide, 10–40 wt.% (90°C)
  - Etch rate (100) = 0.5–1.5 μm/min
  - Attacks Al
  - Si-doped Al safe & IC compatible
  - Etch ratio (100)/(111) = 10–35
  - Etch masks: SiO₂, Si₃N₄ ~ 0.05–0.25 nm/min
  - Boron doped etch stop, up to 40× slower
- EDP (115°C)
  - Carcinogenic, corrosive
  - Etch rate (100) = 0.75 μm/min
  - Al may be etched
  - R(100) > R(110) > R(111)
  - Etch ratio (100)/(111) = 35
  - Etch masks: SiO₂ ~ 0.2 nm/min, Si₃N₄ ~ 0.1 nm/min
  - Boron doped etch stop, 50× slower
Boron-Doped Etch Stop

- Control etch depth precisely with boron doping (p++)
  - \([\text{B}] > 10^{20} \text{ cm}^{-3}\) reduces KOH etch rate by 20-100×
  - Can use gaseous or solid boron diffusion
- Recall etch chemistry:
  - \(\text{Si} + 2\text{OH}^- \rightarrow \text{Si(OH)}_2^{2-} + 4\text{e}^-\)
  - \(4\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^- + 2\text{H}_2\)
- At high dopant levels, injected electrons recombine with holes in valence band and are unavailable for reactions to give OH⁻
- Result:
  - Beams, suspended films
  - 1-20 μm layers possible

Ex: Micronozzle

- Micronozzle using anisotropic etch-based fabrication
- Used for inkjet printer heads

Ex: Microneedle

- Below: micro-neurostimulator
  - Used to access central nervous system tissue (e.g., brain) and record electrical signals on a cellular scale
- Wise Group, Univ. of Michigan
  - Selectively diffuse p++ into substrate
  - Deposit interconnect pattern and insulate conductors
  - Pattern dielectric and metallize recording sites
  - Dissolve away the wafer (no mask needed)
**Ex: Microneedles (cont.)**

- Micromachined with on-chip CMOS electronics
- Both stimulation and recording modes
- 400 μm site separations, extendable to 3D arrays
- Could be key to neural prosthesis systems focusing on the central nervous system

**Electrochemical Etch Stop**

- When silicon is biased with a sufficiently large anodic potential relative to the etchant $\rightarrow$ get oxidation (i.e., electrochemical passivation), which then prevents etching
- For passivation to occur, current flow is required
- If current flow can be prevented $\rightarrow$ no oxide growth, and etching can proceed
- Can prevent current flow by adding a reverse-biased diode structure

**Electrochemical etch stop**

- $n$-type epitaxial layer grown on $p$-type wafer forms $p$-$n$ junction diode
- $V_p > V_n$ $\rightarrow$ electrical conduction (current flow)
- $V_p < V_n$ $\rightarrow$ reverse bias current (very little current flow)

**Passivation potential:** potential at which thin SiO$_2$ film forms different for $p$-Si and $n$-Si, but basically need the Si to be the anode in an electrolytic setup

**Setup:**
- $p$-$n$ diode in reverse bias
- $p$-substrate floating $\rightarrow$ etched
- $n$-layer above passivation potential $\rightarrow$ not etched
**Electrochemical Etching of CMOS**

- N-type Si well with circuits suspended from SiO₂ support beam
- Thermally and electrically isolated
- If use TMAH etchant, doped (w/Si) Al bond pads safe

[Reay, et al. (1994)]
[Kovacs Group, Stanford]

**Ex: Bulk Micromachined Pressure Sensors**

- Piezoresistivity: change in electrical resistance due to mechanical stress
- In response to pressure load on thin Si film, piezoresistive elements change resistance
- Membrane deflection < 1 μm

[Maluf]

**Ex: Pressure Sensors**

- Below: catheter tip pressure sensor [Lucas NovaSensor]
  - Only 150×400×900 μm³