EE C245 – ME C218
Introduction to MEMS Design
Fall 2012

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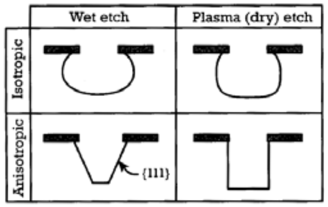
Lecture Module 6: Bulk Micromachining

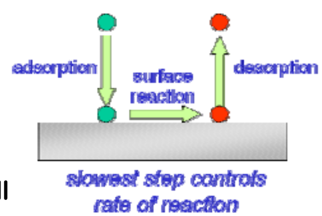
Lecture Outline

- Reading: Senturia Chpt. 3, Jaeger Chpt. 11, Handouts: "Bulk Micromachining of Silicon"
- Lecture Topics:
  - Bulk Micromachining
  - Anisotropic Etching of Silicon
  - Boron-Doped Etch Stop
  - Electrochemical Etch Stop
  - Isotropic Etching of Silicon
  - Deep Reactive Ion Etching (DRIE)

Bulk Micromachining

- Basically, etching the substrate (usually silicon) to achieve microstructures
- Etching modes:
  - Isotropic vs. anisotropic
  - Reaction-limited
    - Etch rate dep. on temp.
  - Diffusion-limited
    - Etch rate dep. on mixing
    - Also dependent on layout & geometry, i.e., on loading
- Choose etch mode based on
  - Desired shape
  - Etch depth and uniformity
  - Surface roughness (e.g., sidewall roughness after etching)
  - Process compatiblity (w/ existing layers)
  - Safety, cost, availability, environmental impact



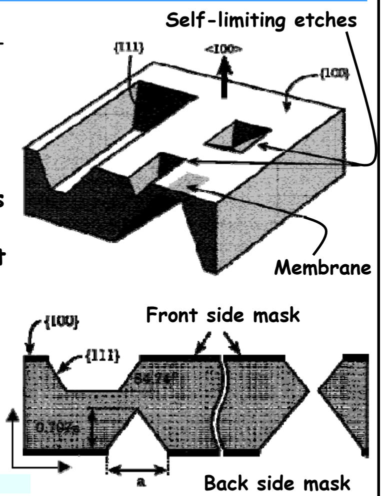


Mechanical Properties of Silicon

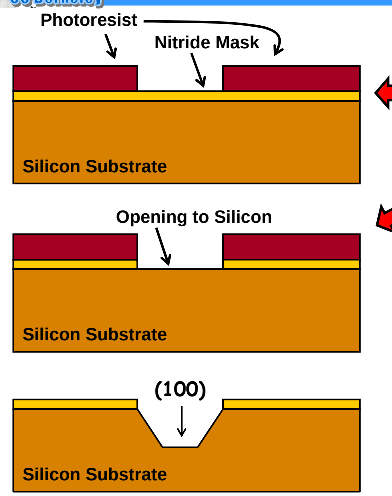
- Crystalline silicon is a hard and brittle material that deforms elastically until it reaches its yield strength,at which point it breaks.
  - Tensile yield strength = 7 GPa (~1500 lb suspended from 1 mm^2)
  - Young's Modulus near that of stainless steel
  - {100} = 130 GPa; {110} = 169 GPa; {111} = 188 GPa
  - Mechanical properties uniform, no intrinsic stress
  - Mechanical integrity up to 500°C
  - Good thermal conductor
  - Low thermal expansion coefficient
  - High piezoresistivity

Anisotropic Etching of Silicon

- Etching of Si w/ KOH
  $Si + 2OH^- \rightarrow Si(OH)_2^{2+} + 4e^-$
  $4H_2O + 4e^- \rightarrow 4(OH)^- + 2H_2$
- 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 → much slower E.R.
  - {111} forms protective oxide
  - {111} smoother than other crystal planes → good for optical MEMS (mirrors)

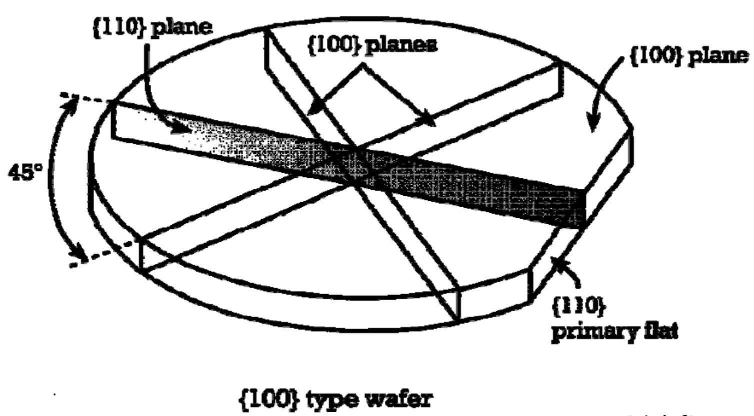


Anisotropic Etching of Silicon



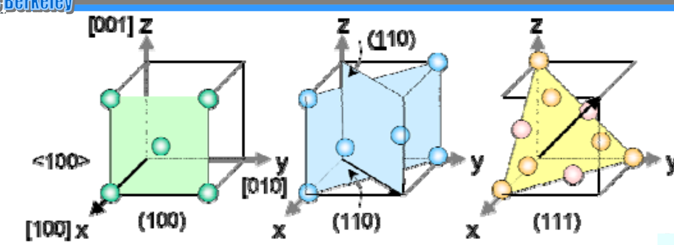
- Deposit nitride:
  - Target = 100nm
  - 22 min. LPCVD @800°C
- Lithography to define areas of silicon to be etched
- Etch/pattern nitride mask
  - RIE using SF_6
  - Remove PR in PRS2000
- Etch the silicon
  - Use 1:2 KOH:H_2O (wt.), stirred bath @ 80°C
  - Etch Rates:
    - (100) Si → 1.4 μm/min
    - Si_3N_4 → ~ 0 nm/min
    - SiO_2 → 1-10 nm/min
    - Photoresist, Al → 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

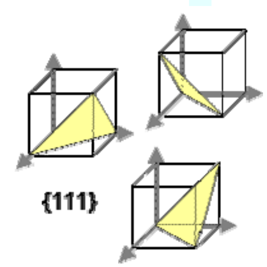


[Maluf]

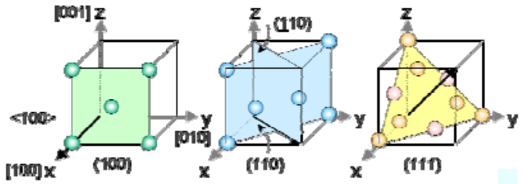
Silicon Crystallography



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



Determining Angles Between Planes



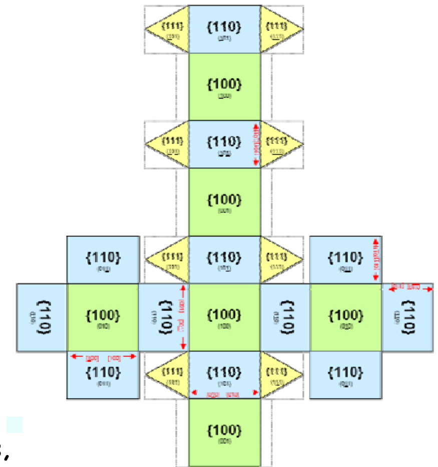
- The angle between vectors [abc] and [xyz] is given by:

$$ax + by + cz = |(a,b,c)| \cdot |(x,y,z)| \cdot \cos\theta$$

$$\theta_{(a,b,c),(x,y,z)} = \cos^{-1}\left[\frac{ax + by + cz}{|(a,b,c)| \cdot |(x,y,z)|}\right]$$

- For {100} and {110} → 45°
- For {100} and {111} → 54.74°
- For {110} and {111} → 35.26°, 90°, and 144.74°

Silicon Crystal Origami

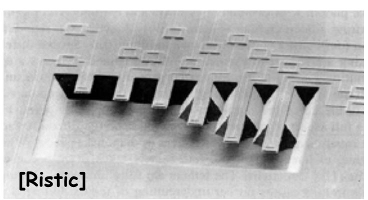


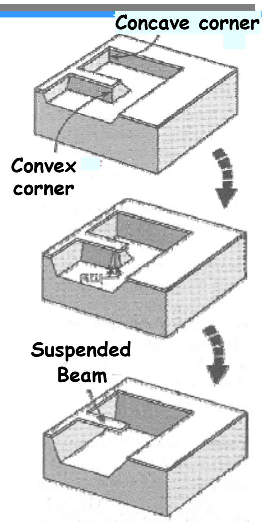
- Silicon fold-up cube
- Adapted from Profs. Kris Pister and Jack Judy
- Print onto transparency
- Assemble inside out
- Visualize crystal plane orientations, intersections, and directions

[Judy, UCLA]

Undercutting Via Anisotropic Si Etching

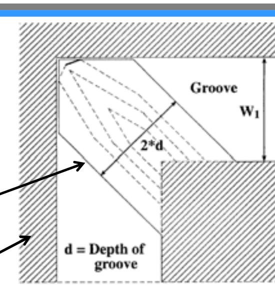
- Concave corners bounded by {111} are not attacked
- … but convex corners bounded by {111} are attacked
  - Two {111} planes intersecting now present two dangling bonds → no longer have just one dangling bond → etch rate fast
  - Result: can undercut regions around convex corners





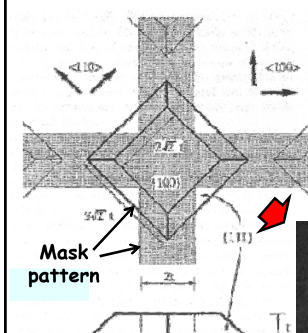
Corner Compensation

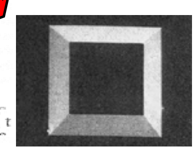
- Protect corners with "compensation" areas in layout
- Below: Mesa array for self-assembly structures [Smith 1995]

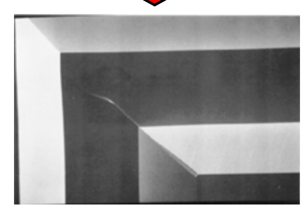


Mask pattern

Shaded regions are the desired result







Other Anisotropic Silicon Etchants

- TMAH, Tetramethyl ammonium hydroxide, 10-40 wt.% (90°C)
  - Etch rate (100) = 0.5-1.5 μm/min
  - Al safe, IC compatible
  - Etch ratio (100)/(111) = 10-35
  - Etch masks: SiO_2 , $Si3N_4$ ~ 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: SiO_2 ~ 0.2 nm/min, Si_3N_4 ~ 0.1 nm/min
  - Boron doped etch stop, 50× slower