Lecture Outline

- Reading: Senturia, Chpt. 3; Jaeger, Chpt. 2, 4, 5
  - Lithography
  - Etching
    - Wet etching
    - Dry etching
  - Semiconductor Doping
    - Ion implantation
    - Diffusion

Etching Basics

- Removal of material over designated areas of the wafer
- Two important metrics:
  1. Anisotropy
  2. Selectivity

1. Anisotropy -
   a) Isotopic Etching (most wet etches)

   ![Anisotropy Diagram]

   - If 100% isotropic: \( d_f = d + 2h \)
   - Define: \( B = d_f - d \)
   - If \( B = 2h \) \( \Rightarrow \) isotropic
Etching Basics (cont.)

b) Partially Isotropic: \( B < 2h \)
   (most dry etches, e.g., plasma etching)

Degree of Anisotropy: (definition)
\[
A_p = 1 - \frac{B}{2h} = 0 \quad \text{if 100% isotropic}
\]
\[
0 < A_p \leq 1 \quad \text{anisotropic}
\]

Etching Basics (cont.)

Why overetch?

\[ \sqrt{2d} = 1.4d = 0.56\mu m \quad \text{Thicker spots due to topography!} \]

Poly-Si \( \rightarrow \) conformal if deposited by LPCVD

Thus, must overetch at least 40%: 40% overetch \( \rightarrow (0.4)(0.4) = 0.16 \mu m \) poly \( \rightarrow 277\) oxide

Depends on the selectivity of poly-Si over the oxide

Etching Basics (cont.)

Define selectivity of A over B:
\[
S_{ab} = \frac{E_{R_a}}{E_{R_b}} = \text{Etch rate of A} \quad \text{Etch rate of B}
\]

Selectivity of A over B

- e.g., wet poly etch (HNO\(_3\) + NH\(_4\) + H\(_2\)O)
- e.g., polysilicon dry etch:

\[ S_{poly/SiO_2} = \frac{15}{1} \quad \text{(very good selectivity)} \]
\[ S_{poly/PR} = \text{Very high (but PR can still peel off after soaking for > 30 min., so beware)} \]

- bosch:
\[ S_{poly/SiO_2} = \frac{5 - 7}{1} \quad \text{Regular RIE} \]
\[ S_{poly/PR} = \frac{4}{1} \quad \text{ECR: 30:1} \]
\[ \text{Bosch: 100:1 (or better)} \]
Etching Basics (cont.)

If \( S_{\text{poly}/\text{SiO}_2} = \frac{8}{1} \Rightarrow 40\% \) overetch removes

\[
\frac{0.16}{8} = 20 \text{ nm of oxide!} \Rightarrow \text{This will etch all poly over the thin oxide, etch thru the 10nm of oxide, then start etching into the silicon substrate \( \rightarrow \) needless to say, this is bad!}
\]

with better selectivity:

\( \text{e.g., } S_{\text{poly}/\text{SiO}_2} = \frac{30}{1} \)

(Can attain with high density Cl plasma ECR etch!)

40% overetch removes \( \frac{0.16}{30} = 5.3 \text{nm} \) (better)

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Dry Etching

Dry Etching

- Physical sputtering
- Plasma etching
- Reactive ion etching

All based upon plasma processes.

- (+) ions generated by inelastic collisions with energetic e⁻'s
- Get avalanche effect because more e⁻'s come out as each ion is generated.

- Develops (+) charge to compensate for

- RF (also, could be microwave)
- Develop (-) bias

- Plasma (partially ionized gas composed of ions, e⁻'s, and highly reactive neutral species)
- E-field
- Wafer

- (+) ions will be accelerated to the wafer

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Physical Sputtering (Ion Milling)

- Bombard substrate w/ energetic ions \( \rightarrow \) etching via physical momentum transfer
- Give ions energy and directionality using E-fields
- Highly directional \( \rightarrow \) very anisotropic

- Steep vertical wall

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Problems With Ion Milling

1. PR or other masking material etched at almost the same rate as the film to be etched \( \rightarrow \) very poor selectivity!
2. Ejected species not inherently volatile \( \rightarrow \) get redeposition \( \rightarrow \) non-uniform etch \( \rightarrow \) grass!

* Because of these problems, ion milling is not used often (very rare)

Plasma Etching

* Plasma (gas glow discharge) creates reactive species that chemically react with the film in question
* Result: much better selectivity, but get an isotropic etch

Plasma Etching Mechanism:

1. Reactive species generated in a plasma.
2. Reactive species diffuse to the surface of material to be etched.
3. Species adsorbed on the surface.
4. Chemical reaction.
5. By-product desorbed from surface.
6. Desorbed species diffuse into the bulk of the gas

Ex: Polysilicon Etching w/ CF\(_4\) and O\(_2\)

\[
\text{CF}_4 \rightarrow \text{CF}_4^- + \text{CF}_3^- + \text{CF}_2^- + \text{CF}^- + F^+ + F^0 + \text{CF}_2^+ + \ldots
\]

Neutral radical (highly reactive!)

\[\text{e}^- + \text{CF}_4 \rightarrow \text{CF}_3 + F + \text{e}^-\]

SiCF\(_6\), SiF\(_4\) \( \leftarrow \) both volatile \( \therefore \) dry etching is possible.

* \( \text{F}^0 \) is the dominant reactant \( \rightarrow \) but it can’t be given a direction \( \rightarrow \) thus, get isotropic etch!

Ex: Polysilicon Etching w/ CF\(_4\) and O\(_2\)

\[\text{SiF}_4 \rightarrow \text{SiF}_4\]

isotropic component \( \rightarrow \)

* Problems:
  1. Isotropic etching
  2. Formation of polymer because of C in CF\(_4\)

  Solution: add O\(_2\) to remove the polymer (but note that this reduces the selectivity, \( S_{\text{poly}/\text{PR}} \))

  * Solution:
    - Use Reactive Ion Etching (RIE)
**Reactive Ion Etching (RIE)**

- Use ion bombardment to aid and enhance reactive etching in a particular direction
  - Result: directional, anisotropic etching!
- RIE is somewhat of a misnomer
  - It's not ions that react ... rather, it's still the neutral species that dominate reaction
  - Ions just enhance reaction of these neutral radicals in a specific direction

- Two principle postulated mechanisms behind RIE
  1. Surface damage mechanism
  2. Surface inhibitor mechanism

**RIE: Surface Damage Mechanism**

- Relatively high energy impinging ions (>50 eV) produce lattice damage at surface
- Reaction at these damaged sites is enhanced compared to reactions at undamaged areas

**RIE: Surface Inhibitor Mechanism**

- Non-volatile polymer layers are a product of reaction
- They are removed by high energy directional ions on the horizontal surface, but not removed from sidewalls

**Deep Reactive-Ion Etching (DRIE)**

- 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 (CFₓ)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)

Etch rate decreases with trench width