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Etching

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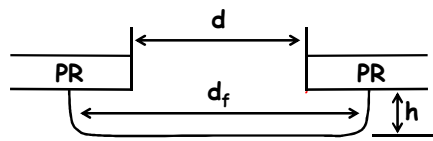
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Etching Basics

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

1. Anisotropy -

a) Isotropic Etching (most wet etches)



If 100% isotropic: $d_f = d + 2h$
 Define: $B = d_f - d$
 If $B = 2h \Rightarrow$ isotropic

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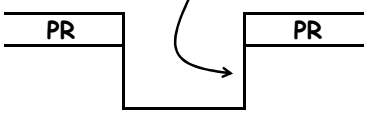
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Etching Basics (cont.)

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

Degree of Anisotropy: (definition)

$$A_f = 1 - \frac{B}{2h} = 0 \quad \text{if 100\% isotropic}$$

$$0 < A_f \leq 1 \quad \leftarrow \text{anisotropic}$$


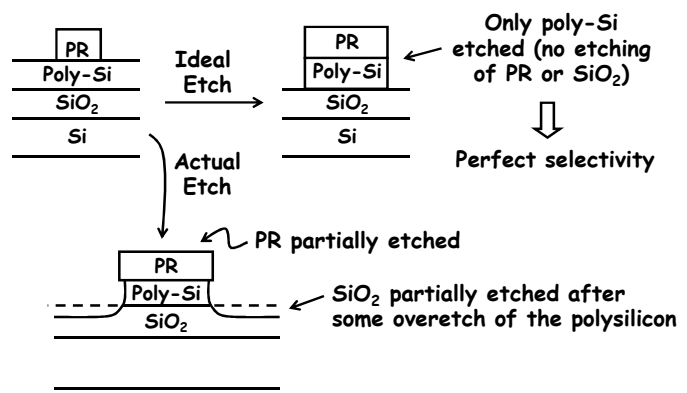
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Etching Basics (cont.)

2. Selectivity -



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Etching Basics (cont.)

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Why overetch?

$\sqrt{2}d = 1.4d = 0.56\mu\text{m}$ → Thicker spots due to topography!

$0.4\mu\text{m} = d$

10nm Gate oxide

PR

45°

0.4μm

Poly-Si → conformal if deposited by LPCVD

remaining poly-Si after etching 0.4μm → stringer

Thus, must overetch at least 40%:
40% overetch → $(0.4)(0.4) = 0.16\mu\text{m}$ poly = ??? oxide

Depends on the selectivity of poly-Si over the oxide

get rid of the stringer by overetching

This is caused by topography!

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Etching Basics (cont.)

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Define selectivity of A over B:

$$S_{ab} = \frac{E.R._a}{E.R._b}$$

← Etch rate of A
← Etch rate of B

Selectivity of A over B

e.g., wet poly etch ($\text{HNO}_3 + \text{NH}_4 + \text{H}_2\text{O}$)

$$S_{\text{poly}/\text{SiO}_2} = \frac{15}{1} \quad (\text{very good selectivity})$$

$S_{\text{poly}/\text{PR}}$ = Very high (but PR can still peel off after soaking for > 30 min., so beware)

e.g., polysilicon dry etch:

Regular RIE

$$S_{\text{poly}/\text{SiO}_2} = \frac{5-7}{1} \quad (\text{but depends on type of etcher})$$

$S_{\text{poly}/\text{PR}} = \frac{4}{1}$

ECR: 30:1
Bosch: 100:1 (or better)

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Etching Basics (cont.)

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

$$\frac{0.16}{8} = 20 \text{ nm of oxide!} \Rightarrow$$

This will etch all poly over the thin oxide, etch thru the 10nm of oxide, then start etching into the silicon substrate → needless to say, this is bad!

with better selectivity:

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

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Dry Etching

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- Physical sputtering
- Plasma etching
- Reactive ion etching

All based upon plasma processes.

(+) ions generated by inelastic collisions with energetic e^{-1} 's
Get avalanche effect because more e^{-1} 's come out as each ion is generated.

RF (also, could be μ wave)

Develop (-) bias

Plasma (partially ionized gas composed of ions, e^{-1} 's, and highly reactive neutral species)

E-field

wafer

Develops (+) charge to compensate for \therefore (+) ions will be accelerated to the wafer

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Physical Sputtering (Ion Milling)

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

ions

plasma

PR

PR

film

Si

Steep vertical wall

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Problems With Ion Milling

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PR etched down to here

Once through the film, the etch will start barreling through the Si

- PR or other masking material etched at almost the same rate as the film to be etched \rightarrow very poor selectivity!
- 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)

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Plasma Etching

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

Plasma Etching Mechanism:

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

MOST IMPORTANT STEP! (determines whether plasma etching is possible or not.)

plasma

PR

PR

Film to be etched

Si

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Ex: Polysilicon Etching w/ CF₄ and O₂

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$CF_4 \xrightarrow{\text{plasma}} CF_4^+ + CF_3^+ + CF_2^+ + CF^+ + F^+ + F^0 + CF_2^+ + \dots$

Si

Neutral radical (highly reactive!)
 $e^- + CF_4 \rightarrow CF_3 + F + e^-$

SiCF₆, SiF₄ ← both volatile ∴ dry etching is possible.

• F⁰ is the dominant reactant → but it can't be given a direction → thus, get isotropic etch!

isotropic component → F⁰

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Ex: Polysilicon Etching w/ CF₄ and O₂

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isotropic component → F⁰

• **Problems:**

1. Isotropic etching
2. Formation of polymer because of C in CF₄
↳ **Solution:** add O₂ to remove the polymer (but note that this reduces the selectivity, S_{poly/PR})

• **Solution:**
↳ Use Reactive Ion Etching (RIE)

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Reactive Ion Etching (RIE)

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- 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

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RIE: Surface Damage Mechanism

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- 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

Result: E.R. at surface >> E.R. on sidewalls

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RIE: Surface Inhibitor Mechanism

The diagram shows a cross-section of a substrate with a photoresist (PR) film on top of a silicon (Si) layer. A plasma is applied above the PR film, releasing reactive radicals (indicated by 'o' and '+' symbols). These radicals react with the PR film, breaking it up. Positive ions (+) from the plasma bombard the horizontal surface, causing the PR to be removed. However, these ions do not reach the sidewalls, so the PR remains there, acting as a surface inhibitor. This results in anisotropic etching where the etch rate at the surface is much higher than on the sidewalls.

- 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

(+) ions breakup the polymer layer
 get reaction

Result: E.R. @ surface >> E.R. on sidewalls

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Deep Reactive-Ion Etching (DRIE)

The diagram illustrates the Bosch process in three stages. 1. Etch cycle: A silicon substrate is etched by SF₆ plasma, forming SF_x⁺ ions that attack the silicon surface. 2. Deposition cycle: C₄F₈ plasma is used to deposit a protective polymer layer (CF₂)_n on the sidewalls and bottom of the trench. 3. Next etch cycle: The process repeats, with the polymer layer being removed by SF_x⁺ ions while the silicon is etched further.

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 (SF_x⁺) 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°

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DRIE Issues: Etch Rate Variance

The micrograph shows a series of etched trenches with varying widths. A 20 μm scale bar is provided. The graph plots Etch Rate (μm/min) on the y-axis (0.5 to 2.0) against Trench Width (μm) on the x-axis (0 to 80). The etch rate increases sharply from 0 to about 1.75 μm/min as trench width increases from 0 to 10 μm, then levels off. A yellow box highlights that the etch rate decreases with trench width.

- 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)

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