

IV. Exposure System/Optics

Contact Printing

- Mask in contact with wafer
- Problem:** mask pattern can become damaged with each exposure → must make a new mask after x number of exposures
- 1X printing very useful for MEMS → can expose surfaces with large topography (where reduction printers cannot)

Proximity Printing

- Mask in very close proximity but not touching

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IV. Exposure System/Optics

Projection Printing

- Dominates in IC transistor fabrication
- 5X or 10X reduction typical
- Mask minimum features can be larger than the actual printed features by the focused reduction factor → less expensive mask costs
- Less susceptible to thermal variation (in the mask) than 1X printing
- Can use focusing tricks to improve yield:

Handwritten notes: must thicken them → contact like! Dust particle will be out of focus → better yield!

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Contact Lithography

Handwritten notes: w/ complete! ΔT, T0, 1µm, right temperature = T0, Wafer, 1µm

Projection Lithography

Handwritten notes: 10cm, 1µm, 10x reduction, 1cm, D10, p0, D10, T0 + ΔT, T0 (right temp)

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Etching

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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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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** -

Only poly-Si etched (no etching of PR or SiO₂)
 Perfect selectivity

Actual Etch: PR partially etched, SiO₂ partially etched after some overetch of the polysilicon

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Etching Basics (cont.)

Why overetch?

Assume anisotropic etch

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

10nm Gate oxide
 Poly-Si \rightarrow conformal if deposited by LPCVD

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

Depends on the selectivity of poly-Si over the oxide

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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

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

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

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

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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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Wet Etching

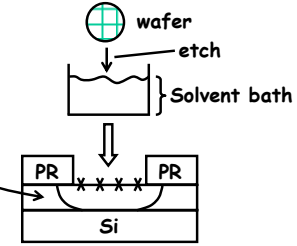
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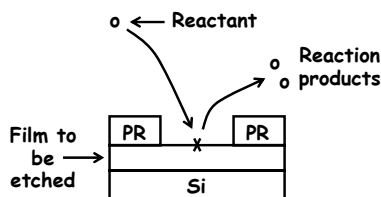
Wet Etching

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- Wet etching: dip wafer into liquid solution to etch the desired film
 - Generally isotropic, thus, inadequate for defining features < 3μm-wide



- General Mechanism -
 - Diffusion of the reactant to the film surface
 - Reaction: adsorption, reaction, desorption
 - Diffusion of reaction products from the surface



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Wet Etching (cont.)


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- There are many processes by which wet etching can occur
 - ↳ Could be as simple as dissolution of the film into the solvent solution
 - ↳ Usually, it involves one or more chemical reactions
 - Oxidation-reduction (redox) is very common:
 - (a) Form layer of oxide
 - (b) Dissolve/react away the oxide
- **Advantages:**
 1. High throughput process → can etch many wafers in a single bath
 2. Usually fast etch rates (compared to many dry etch processes)
 3. Usually excellent selectivity to the film of interest

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Wet Etching Limitations

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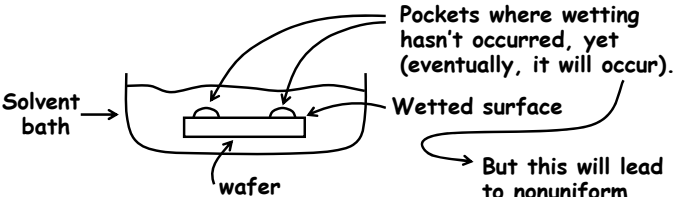
1. **Isotropic**
 - ↳ Limited to $>3\mu\text{m}$ features 
 - ↳ But this is also an advantage of wet etching, e.g., if used for undercutting for MEMS
2. Higher cost of etchants & DI water compared w/ dry etch gas expenses (in general, but not true vs. deep etchers)
3. **Safety**
 - ↳ Chemical handling is a hazard
4. Exhaust fumes and potential for explosion
 - ↳ Need to perform wet etches under hood
5. Resist adhesion problems
 - ↳ Need HMDS (but this isn't so bad)

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Wet Etch Limitations (cont.)

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6. **Incomplete wetting of the surface:**



But this will lead to nonuniform etching across the wafer.

↳ For some etches (e.g., oxide etch using HF), the solution is to dip in DI water first, then into HF solution → the DI water wets the surface better

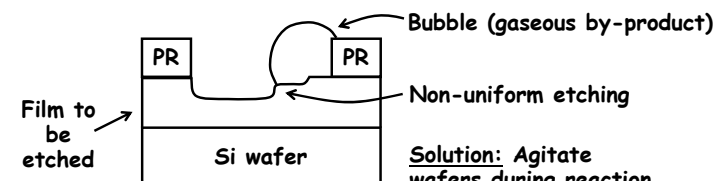
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Wet Etch Limitations (cont.)

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7. **Bubble formation (as a reaction by-product)**

↳ If bubbles cling to the surface → get nonuniform etching



Solution: Agitate wafers during reaction.

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Some Common Wet Etch Chemistries

Wet Etching Silicon:

Common: $\text{Si} + \text{HNO}_3 + 6\text{HF} \rightarrow \text{H}_2\text{SiF}_6 + \text{HNO}_2 + \text{H}_2 + \text{H}_2\text{O}$

(isotropic)

(nitric acid) (hydrofluoric acid)
 ↓ ↓
 (1) forms a layer of SiO_2 (2) etches away the SiO_2

Different mixture combinations yield different etch rates.

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Silicon Crystal Orientation

• Silicon has the basic diamond structure

- ↳ Two merged FCC cells offset by $(a/4)$ in x, y, and z axes
- ↳ From right:
 - # available bonds/cm² $\langle 111 \rangle$
 - # available bonds/cm² $\langle 110 \rangle$
 - # available bonds/cm² $\langle 100 \rangle$

↑ Increasing

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Anisotropic Wet Etching

Anisotropic etches also available for single crystal Si:

- ↳ Orientation-dependent etching: $\langle 111 \rangle$ -plane more densely packed than $\langle 100 \rangle$ -plane

↑ Faster E.R. 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% H₂O)

⇒ E.R. _{$\langle 100 \rangle$} = 100 × E.R. _{$\langle 111 \rangle$}

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Anisotropic Wet Etching (cont.)

Can get the following:

(on a $\langle 100 \rangle$ - wafer)

(on a $\langle 110 \rangle$ - wafer)

⇒ Quite anisotropic!

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Dry Etching

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Dry Etching

- 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^{-} '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)

- 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

PR etched down to here

PR

PR

PR

film

Si

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

- 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.)

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Ex: Polysilicon Etching w/ CF_4 and O_2

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

Neutral radical (highly reactive!)

$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

$SiCF_6, SiF_4$ ← both volatile ∴ dry etching is possible.

- F^0 is the dominant reactant → but it can't be given a direction → thus, get isotropic etch!

isotropic component → F^0 → PR → polySi → SiF_4

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Ex: Polysilicon Etching w/ CF_4 and O_2

isotropic component → F^0 → PR → polySi → SiF_4

- Problems:**
 - Isotropic etching
 - Formation of polymer because of C in CF_4
 - Solution:** add O_2 to remove the polymer (but note that this reduces the selectivity, $S_{\text{poly/PR}}$)
- Solution:**
 - Use Reactive Ion Etching (RIE)

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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
 - Surface damage mechanism
 - Surface inhibitor mechanism

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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

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

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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

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

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