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EE C245 - ME C218 Introduction to MEMS Design Fall 2010

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Lecture Module 4: Lithography, Etching, & Doping

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Lecture Outline

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

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Lithography

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Lithography

Lithography
 ↳ Method for massive patterning of features on a wafer → pattern billions of devices in just a few steps

Four Main Components (that affect resolution)

Designated pattern (clear or dark field)

emulsion chrome

↳ Generated from layout

III. Photoresist

IV. Exposure System → contact, step and repeat
 ↳ optics → this is where the real art is!

I. Radiation Source

II. Mask

Mask (glass/quartz)

Photoresist (~1 μm-thick)

Film to be patterned (e.g., poly-Si)

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Lithography (cont.)

The basic Process - (Positive Resist Example)

Exposed PR → converts to another form after reaction with light (e.g., (+)-resist: polymer → organic acid)

Dip or spray wafer with developer → if (+) resist, developer is often a base

Etch → PR protects film; open areas of film get etched

Remove PR

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Lithography (cont.)

With each masking step usually comes a film deposition, implantation and/or etch. Thus, the complexity of a process is often measured by # masks required.

- NMOS: 4-6 masks
- Bipolar: 8-15 masks
- BICMOS: ~20 masks
- CMOS: 8-28 masks

↖ Multi-level metallization

- Comb-Drive Resonator: 3 masks
- GHz Disk: 4 masks

Now, take a closer look at the 4 components:

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I. Radiation Source

I. Radiation Source

Several types: optical (visible, UV, deep UV light), e-beam, X-ray, ion beam

The shorter the wavelength → Better the resolution

Today's prime choice due to cost and throughput.

Can expose billions of devices at once!

Optical Sources:

- Mercury arc lamp (mercury vapor discharge)

we have all of these in our μlab

| | | | | | |
|--|-----|--------|-----|--------|--------|
| | 200 | 365 | 405 | 435 | 546 nm |
| | | I-line | | G-line | |

For deep UV, need Excimer laser (very expensive)

Glass opaque, so must use quartz mask and lens

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II. Mask

II. Mask → has become one of today's biggest bottlenecks!

Electronic computer representation of layout (e.g., CIF, GDSII)

⇒ A single file contains all layers

tape → mask generator

Masks for each layer

Mask Material:

- Fused silica (glass) → inexpensive, but larger thermal expansion coeff.
- Quartz → expensive, but smaller thermal expansion coeff.

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III. Photoresist (optical)

Pictorial Description:

Negative

Exposed Area: **remains**

Positive

Exposed Area: **removed**

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III. Photoresist (optical)

Mechanism:

Negative

photoactivation

↓

Polymerization
(long, linked Carbon chains)

↓

Developer solvent
removes
unexposed PR

Positive

photoactivation

↓

Converts exposed PR
to organic acid

↓

Alkaline developer
(e.g., KOH) removes
acid

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III. Photoresist (optical)

Issues:

Negative

Polymerized PR swells in solvent → bridging problem

Exposed and polymerized

Positive

Doesn't adhere well to SiO₂

Need primer: HMDS (hexamethyl disilazane)

Poor adhesion

Good adhesion at both HMDS interfaces

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Typical Procedure for Lithography

```

graph TD
    A[Clean Wafer] --> B[Dry Wafer]
    B --> C[Deposit HMDS]
    C --> D[Spin-on PR]
    D --> E[Soft Bake]
    E --> F[Align & Expose]
    F --> G[Develop]
    G --> H[Descum]
    H --> I[Post Bake]
    
```

Clean Wafer Very important step

Dry Wafer 30 min. @ 120°C pre-bake

Deposit HMDS (for oxide on wafer surface)

Spin-on PR 30-60 sec @ 1000-5000 rpm

Soft Bake 2 min @ 90°C Improve adhesion and remove solvent from PR

Align & Expose Oxygen plasma (low power ~ 50W)

Develop → **Descum** → **Post Bake**

Topography very important:

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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:

Dust particle will be out of focus → better yield!

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Etching

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Etching Basics

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

PR partially etched
SiO₂ partially etched after some overetch of the polysilicon

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Etching Basics (cont.)

Why overetch?

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

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

Poly-Si \rightarrow conformal if deposited by LPCVD

10nm Gate oxide

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

Depends on the selectivity of poly-Si over the oxide

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Etching Basics (cont.)

Define selectivity of A over B:

$$S_{ab} = \frac{E.R._a}{E.R._b} \quad \leftarrow \begin{array}{l} \text{Etch rate of A} \\ \text{Etch rate of B} \end{array}$$

Selectivity of A over B

e.g., wet poly etch (HNO₃ + NH₄ + H₂O)

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

$S_{\text{poly}/\text{PR}} =$ 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 $S_{poly/SiO_2} = \frac{8}{1} \Rightarrow$ 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 \rightarrow needless to say, this is bad!

with better selectivity:

e.g., $S_{poly/SiO_2} = \frac{30}{1}$

(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

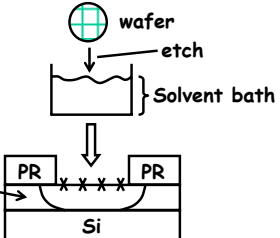
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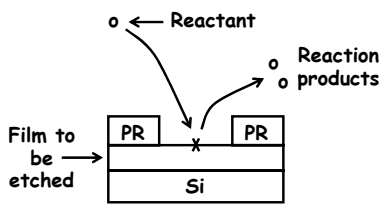
Wet Etching

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- Wet etching: dip wafer into liquid solution to etch the desired film
 - Generally isotropic, thus, inadequate for defining features $< 3\mu\text{m}$ -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:
 - Form layer of oxide
 - Dissolve/react away the oxide
- Advantages:
 - High throughput process \rightarrow can etch many wafers in a single bath
 - Usually fast etch rates (compared to many dry etch processes)
 - Usually excellent selectivity to the film of interest

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Wet Etching Limitations

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.)

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.)

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 $\langle 111 \rangle$ - wafer)

⇒ Quite anisotropic!

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Wet Etching SiO₂

$\text{SiO}_2 + 6\text{HF} \rightarrow \text{H}_2 + \text{SiF}_6 + 2\text{H}_2\text{O}$

Generally used to clear out residual oxides from contacts

Problem: Contact hole is so thin that surface tensions don't allow the HF to get into the contact
→ Generally the case for VLSI circuits

bubble → oxide → native oxide
can get this just by exposing Si to air → 1-2nm-thick

300nm → nt

Solution: add a surfactant (e.g., Triton X) to the BHF before the contact clear etch

1. Improves the ability of HF to wet the surface (hence, get into the contact)
2. Suppresses the formation of etch by-products, which otherwise can block further reaction if by-products get caught in the contact

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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.

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

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

film

Si

Steep vertical wall

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Problems With Ion Milling

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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Problems With Ion Milling (continued)

Reasonably thick PR $\sim 1.1\mu\text{m}$

open to etch

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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.)

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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 PR F⁰ SiF₄
polySi

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Ex: Polysilicon Etching w/ CF₄ and O₂

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isotropic component → F⁰ PR F⁰ SiF₄
polySi

- Problems:**
 - Isotropic etching
 - 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
 - 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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Deep Reactive-Ion Etching (DRIE)

The Bosch process:

- Inductively-coupled plasma
- Etch Rate: 1.5-4 $\mu\text{m}/\text{min}$
- Two main cycles in the etch:
 - Etch cycle (5-15 s): SF_6 (SF_x^+) etches Si
 - Deposition cycle: (5-15 s): C_4F_8 deposits fluorocarbon protective polymer (CF_2^-)_n
- Etch mask selectivity:
 - $\text{SiO}_2 \sim 200:1$
 - Photoresist $\sim 100:1$
- Issue: finite sidewall roughness
 - scalloping < 50 nm
- Sidewall angle: $90^\circ \pm 2^\circ$

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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

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