Lecture 6: Process Modules III: Lithography, Etching
Lecture Outline

• Reading: Senturia, Chpt. 3; Jaeger, Chpt. 2, 3, 5, 6

Film Deposition
- Evaporation
- Sputter deposition
- Chemical vapor deposition (CVD)
- Plasma enhanced chemical vapor deposition (PECVD)
- Epitaxy
- Atomic layer deposition (ALD)
- Electroplating

Lithography
Etching
Ion implantation
Diffusion
Atomic Layer Deposition (ALD)
Atomic Layer Deposition (ALD)

- **Fundamental Components:**
  - Self-limiting surface reactions of suitable precursor compounds A & B
  - A & B then form the desired product S in a binary reaction cycle consisting of two sequential half-reactions
• Run the ALD video
ALD Capability

Excellent conformity, even at the bottom of the trench! (aspect ratio ~60:1)

Figure 3. ALD features superb step coverage performance. The SEM images show close to 100% conformity for an 18nm thick Al₂O₃ film which was deposited by ALD into high aspect ratio trenches with a minimum lateral dimension of 80nm and a final aspect ratio of ~60.
# ALD Versus CVD

<table>
<thead>
<tr>
<th></th>
<th>ALD</th>
<th>CVD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly reactive precursors</td>
<td>Less reactive precursors</td>
<td></td>
</tr>
<tr>
<td>Precursors react separately on the substrate</td>
<td>Precursors react at the same time on the substrate</td>
<td></td>
</tr>
<tr>
<td>Precursors must not decompose at process temperature</td>
<td>Precursors can decompose at process temperature</td>
<td></td>
</tr>
<tr>
<td>Uniformity ensured by the saturation mechanism</td>
<td>Uniformity requires uniform flux of reactant and temperature</td>
<td></td>
</tr>
<tr>
<td>Thickness control by counting the number of reaction cycles</td>
<td>Thickness control by precise process control and monitoring</td>
<td></td>
</tr>
<tr>
<td>Surplus precursor dosing acceptable</td>
<td>Precursor dosing important</td>
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</table>
# ALD Versus Other Deposition Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>ALD</th>
<th>MBE</th>
<th>CVD</th>
<th>Sputter</th>
<th>Evapor</th>
<th>PLD</th>
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<tbody>
<tr>
<td>Thickness Uniformity</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
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<tr>
<td>Film Density</td>
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<td>Good</td>
<td>Good</td>
<td>Poor</td>
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<tr>
<td>Step Coverage</td>
<td>Good</td>
<td>Poor</td>
<td>Varies</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
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<tr>
<td>Interface Quality</td>
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<td>Good</td>
<td>Varies</td>
<td>Poor</td>
<td>Good</td>
<td>Varies</td>
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<tr>
<td>Number of Materials</td>
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<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Fair</td>
<td>Poor</td>
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<tr>
<td>Low Temp. Deposition</td>
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<td>Varies</td>
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<td>Good</td>
<td>Good</td>
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<tr>
<td>Deposition Rate</td>
<td>Fair</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
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<tr>
<td>Industrial Apps.</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
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</table>
Electroplating
**Metal Electroplating**

- **Electroplating**: the process using electrical current to coat an electrically conductive object with a thin layer of metal
  - Useful when very thick (>1 μm) metal films are needed
  - Evaporation and sputtering generally suffer from excessive stress when films get too thick → get peeling

1. Switch on external supply of direct current
2. Metal at anode is oxidized to form cations with a (+) charge
3. Cations are attracted to the (-) charge on the cathode
4. Cations get reduced by e⁻’s at the cathode, depositing the metal (in this case, Cu)
Wafer-Level Implementation

- **Wafer Preparation**: areas where plating is to occur must have electrical access to the DC voltage source
  - Often use a seed layer that accesses all plating locations

- Need not be the metal to be electroplated
  - Often just a platinum electrode
  - In this case, must replenish electrolytic solution after time
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

I. Radiation Source

II. Mask

- Mask (glass/quartz)
- Photoresist (~1μm-thick)
- Film to be patterned (e.g., poly-Si)

III. Photoresist

IV. Exposure System

contact, step and repeat

this is where the real art is!
The basic Process - (Positive Resist Example)

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

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

Etch $\rightarrow$ PR protects film; open areas of film get etched
With each masking step usually comes a film deposition, implantation and/or etch. Thus, the complexity of a process is often measured by 

- **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:
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.

Optical Sources:

- Mercury arc lamp (mercury vapor discharge)
  - 200 365 405 435 546 nm
  - we have all of these in our µlab

- I-line
- G-line (we have both in our µlab)

For deep UV, need Excimer laser (very expensive)

Glass opaque, so must use quartz mask and lens

Can expose billions of devices at once!
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.
III. Photoresist (optical)

Pictorial Description:

Negative

Exposed Area: remains

Positive

Exposed Area: removed
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
III. Photoresist (optical)

**Issues:**

**Negative**

- Polymerized PR swells in solvent → bridging problem

**Positive**

- Doesn't adhere well to SiO₂
- Need primer: HMDS (hexamethyldisilazane)

Good adhesion at both HMDS interfaces
Typical Procedure for Lithography

1. **Clean Wafer**
   - Very important step

2. **Dry Wafer**
   - 30 min. @ 120°C pre-bake
   - (for oxide on wafer surface)

3. **Deposit HMDS**
   - 30-60 sec @ 1000-5000 rpm

4. **Spin-on PR**
   - 2 min @ 90°C
   - Improve adhesion and remove solvent from PR
   - Oxygen plasma (low power ~ 50W)

5. **Soft Bake**

6. **Align & Expose**

7. **Develop**

8. **Descum**

9. **Post Bake**

Topography very important:

- PR
- Thicker and unfocused
- Overexpose
- Underexpose

EE C245: Introduction to MEMS Design
Lecture 6
C. Nguyen
9/16/08
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

Proximity Printing

- Mask in very close proximity but not touching

- **1X** printing very useful for MEMS → can expose surfaces with large topography (where reduction printers cannot)
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!
  - Step & repeat
  - Photoresist
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)

If 100% isotropic: \( d_f = d + 2h \)

Define: \( B = d_f - d \)

If \( B = 2h \) \( \Rightarrow \) isotopic
Etching Basics (cont.)

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

Degree of Anisotropy: (definition)

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

$$0 < A_f \leq 1 \quad \text{anisotropic}$$
2. Selectivity -

Ideal Etch:
- PR
- Poly-Si
- SiO₂
- Si

- 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
Why overetch?

\[ \sqrt{2d} = 1.4d = 0.56 \mu m \]

Thicker spots due to topography!

Poly-Si → conformal if deposited by LPCVD

Thus, must overetch at least 40%:

40% overetch \( \rightarrow (0.4)(0.4) = 0.16 \mu m \) poly

Depends on the selectivity of poly-Si over the oxide
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 (HNO₃ + NH₄ + H₂O)

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

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

e.g., polysilicon dry etch:

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

\[ S_{poly/PR} = \frac{4}{1} \]

Regular RIE

ECR: 30:1

Bosch: 100:1 (or better)
If \( S_{poly/SiO_2} = \frac{8}{1} \) \( \Rightarrow \) 40% overetch removes

\[
\frac{0.16}{8} = 20 \text{ nm of oxide!}
\]

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)
Wet Etching

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

• **General Mechanism** -

  1. Diffusion of the reactant to the film surface
  2. Reaction: adsorption, reaction, desorption
  3. Diffusion of reaction products from the surface
Wet Etching (cont.)

• 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
Wet Etching Limitations

1. Isotropic
   - Limited to <3μm 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)
6. Incomplete wetting of the surface:

- Pockets where wetting hasn’t occurred, yet (eventually, it will occur).
- Wetted surface
- Solvent bath
- Wafer

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.
7. Bubble formation (as a reaction by-product)
   - If bubbles cling to the surface → get nonuniform etching

Solution: Agitate wafers during reaction.
Some Common Wet Etch Chemistries

Wet Etching Silicon:

**Common**: Si + HNO$_3$ + 6HF $\rightarrow$ H$_2$SiF$_6$ + HNO$_2$ + H$_2$ + H$_2$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.
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 <111>
  - # available bonds/cm² <110>
  - # available bonds/cm² <100>
Anisotropic Wet Etching

Anisotropic etches also available for single crystal Si:

- Orientation-dependent etching: \(<111>-plane more densely packed than \(<100>-plane\)
  - 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% H_2O)

\[ \text{E.R.}_{<100>} = 100 \times \text{E.R.}_{<111>} \]
Anisotropic Wet Etching (cont.)

Can get the following:

(on a \(<100\) - wafer)

(on a \(<110\) - wafer)

\[ \text{SiO}_2 \]

\[ \text{Si} \]

\[ 54.7^\circ \]

Quite anisotropic!
**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

![Diagram of SiO₂ etch process](image)

**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

**300nm**

**Native oxide**

**Bubble**
More Wet Etch Chemistries

- Wet etching silicon nitride
  - Use hot phosphoric acid: 85% phosphoric acid @ 180°C
  - Etch rate ~ 10 nm/min (quite slow)
  - **Problem**: PR lifted during such etching
  - **Solution**: use SiO₂ as an etch mask (E.R. ~2.5 nm/min)
    - A hassle → dry etch processes more common than wet

- Wet etching aluminum
  - Typical etch solution composition:
    - 80% phosphoric acid, 5% nitric acid, 5% acetic acid, 10% water
    - \((H₂PO₄)\) \((HNO₃)\) \((CH₃COOH)\) \((H₂O)\)
    - (1) Forms \(Al₂O₃\) (aluminum oxide)
    - (2) Dissolves the \(Al₂O₃\)
  - **Problem**: \(H₂\) gas bubbles adhere firmly to the surface → delay the etch → need a 10-50% overetch time
  - **Solution**: mechanical agitation, periodic removal of wafers from etching solution
### Wet Etch Rates for Micromachining and IC Processing (Å/min)

The top etch rate was measured by the authors with fresh solutions. The center and bottom values are the low and high etch rates observed by the authors and others in our lab under less carefully controlled conditions.

<table>
<thead>
<tr>
<th>ETCHANT</th>
<th>EQUIPMENT</th>
<th>CONDITION</th>
<th>TARGET MATERIAL</th>
<th>SC Si</th>
<th>Poly n+</th>
<th>Poly undep</th>
<th>Wet Ox</th>
<th>Dry Ox</th>
<th>LTO undep</th>
<th>PSG unapid</th>
<th>PSG amidal</th>
<th>Stoic Nitrid</th>
<th>Low-K Nitrid</th>
<th>Al/2% Si</th>
<th>Spat Tung</th>
<th>Spat Ti</th>
<th>Spat Fe/W</th>
<th>Spat Ni/Fe</th>
<th>OCU</th>
<th>Off</th>
<th>HfO2/Pt</th>
<th>Pt/Ag</th>
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</thead>
<tbody>
<tr>
<td>Concentrated HF (49%)</td>
<td>Wet Sink</td>
<td>Room Temperature</td>
<td>Silicon oxides</td>
<td>-</td>
<td>0</td>
<td>- 23k</td>
<td>F</td>
<td>&gt;14k</td>
<td>F</td>
<td>36k</td>
<td>(40)</td>
<td>S2</td>
<td>42</td>
<td>20/20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>7</td>
<td>0 230</td>
<td>230</td>
<td>340</td>
<td>15k</td>
<td>4700</td>
<td>11</td>
<td>3</td>
<td>2500</td>
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<td>11k</td>
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<td>3:1 HF</td>
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<td>0 97</td>
<td>95</td>
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<td>Phosphoric Acid (85%)</td>
<td>Heated Bath with Reflux at 164°C</td>
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<td>7</td>
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<tr>
<td>Silicon Enchant (160 HNO₃ : 60 H₂O : 5 NH₄F)</td>
<td>Wet Sink</td>
<td>Room Temperature</td>
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<td>3100</td>
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<td>KOH (1 KOH : 7 H₂O by weight)</td>
<td>Heated Stirred Bath at 80°C</td>
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<td>Aluminum Enchant Type A (16 H₃PO₄ : 1 HNO₃ : 1 H₂O : 2 H₂O)</td>
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<td>Piranha (30 H₂SO₄ : 1 H₂O₂)</td>
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<td>Cleaning off metals and organics</td>
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<td>&gt;44k</td>
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</tr>
</tbody>
</table>

**Notation:** - = test not performed; W = not performed, but known to Work (≥ 100 Å/min); F = not performed, but known to be Fast (≥ 10 kÅ/min); P = some of film Peled during etch or when rinsed; A = film was visibly Attacked and roughened. Each area is all of a 4-inch wafer for the transparent films and half of the wafer for single-crystal silicon and the metals. Each rate will vary with temperature and prior use of solution, area of exposure of film, other materials present (e.g., photoresist), film impurities and microstructure, etc. Some variation should be expected.
Film Etch Chemistries

- For some popular films:

<table>
<thead>
<tr>
<th>Material</th>
<th>Wet etchant</th>
<th>Etch rate [nm/min]</th>
<th>Dry etchant</th>
<th>Etch rate [nm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polysilicon</td>
<td>HNO$_3$:H$_2$O: NH$_4$F</td>
<td>120-600</td>
<td>SF$_6$ + He</td>
<td>170-920</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>H$_3$PO$_4$</td>
<td>5</td>
<td>SF$_6$</td>
<td>150-250</td>
</tr>
<tr>
<td>Silicon dioxide</td>
<td>HF</td>
<td>20-2000</td>
<td>CHF$_3$ + O$_2$</td>
<td>50-150</td>
</tr>
<tr>
<td>Aluminum</td>
<td>H$_3$PO$_4$:HNO$_3$: CH$_3$COOH</td>
<td>660</td>
<td>Cl$_2$ + SiCl$_4$</td>
<td>100-150</td>
</tr>
<tr>
<td>Photoresist</td>
<td>Acetone</td>
<td>&gt;4000</td>
<td>O$_2$</td>
<td>35-3500</td>
</tr>
<tr>
<td>Gold</td>
<td>KI</td>
<td>40</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
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)

RF (also, could be µwave)

Develop (-) bias)

E-field

Develops (+) charge to compensate for

∴ (+) ions will be accelerated to the wafer

EE C245: Introduction to MEMS Design

Lecture 6

C. Nguyen

9/16/08
Physical Sputtering (Ion Milling)

- Bombard substrate with energetic ions → etching via physical momentum transfer
- Give ions energy and directionality using E-fields
- Highly directional → very anisotropic

Steep vertical wall
Problems With Ion Milling

1. PR or other masking material etched at almost the same rate as the film to be etched → very poor selectivity!

2. Ejected species not inherently volatile → get redeposition → non-uniform etch → grass!

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