Lithography and Etching

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Chapters 8.1, 8.4, 9, 11
Previous lecture

• Microdevices

• Main processes:
  – Thin film deposition
  – Patterning (lithography)
  – Doping

• Materials:
  – Single crystal (monocrystal)
  – Polycrystals
  – Thin film

• Process flow

• Cleanroom

• Yield
Outline

• Optical lithography

• Beam lithography:
  – e-beam writing
  – laser writing
  – focused ion beam

• Etching:
  – wet etching
  – plasma etching
How do we create images?

Direct writing

Drawing

Photolithography

Offset printing

Nanoimprint

Embossing

Shadow mask

Stencil process

2016 Willson Research Group, The University of Texas at Austin
Photolithography results

Microfluidic chip

Critical dimension – 50 μm
Chip size – 50 x 50 mm
Glass substrate

Intel 80286, a 16-bit microcontroller

Critical dimension – 1.5 μm
Chip size – 7 x 7 mm
Silicon substrate
The photolithography patterning

Three parts in one:
- **Optics** - exposure
- **Chemistry** - development
- **Mechanics** - alignment
PR mask after etching
Patterning terminology

**Photolithography** - photoresist pattern

**Etching** - transfer of photoresist pattern into solid material

**Stripping** - removal of photoresist after etching the pattern

**Photomask** – fabricated image on transparent holder in 1x scale

**Patterning** – lithography + etching
Lithography steps

Baking 30 minutes, 150 °C, HMDS

Spin-on, spray, dip, roller. 1.5 µm

90 °C, 1 min - hotplate, 20 min – convection furnace

Maskaligner, 1-2 seconds, UV

105 °C, 20 min – convection furnace

1 min – wetbench, 5 min – spin rinse drier

120 °C, 1 min - hotplate, 20 min – convection furnace

Possible rework

Humidity 40%, temp. 22±0.5 °C
Spin-on

Static dispense, 1-10ml

Spread cycle

Ramp-up

Final spin coat speed

Film thickness 100 nm – 500 µm

Photoresist
Wafer
Chuck
Skinning
Liquid resist

Liquid resist expelled from beneath the surface skin

Evaporation of residual solvent
Spin coating thickness of PR

Figure 2. Spin coating curves for AZ 4562 and ma-P 100.
Three types of lithography

![Diagram showing contact printing, proximity printing, and projection printing.](http://www.lithoguru.com/scientist/lithobasics.html)

- **Contact Printing**
  - Intact mask
  - Low resolution
  - Mask contamination, Mask damage

- **Proximity Printing**
  - Intact mask
  - Low resolution

- **Projection Printing**
  - High resolution
  - Exposure of small area
  - Stepper

[Link to more information on lithography](http://www.lithoguru.com/scientist/lithobasics.html)
Proximity lithography

Valid for \[ \lambda < g < \frac{b^2}{\lambda} \]

\( \lambda = 365 \text{ nm, } i\text{-line} \)
\( d = 1.4 \mu\text{m} \) (standard resist)

\( b \approx 0.6 \mu\text{m} \quad g = 0 \) (contact)

\( b \approx 2.3 \mu\text{m} \quad g = 10 \mu\text{m} \) (proximity)

\( b \) is half-pitch

Can be improved by phase-shift mask

Resolution in proximity lithography

\[ 2b_{\text{min}} = 3 \sqrt{\left(\frac{\lambda}{n_r}\right) \cdot (g + (d/2))} \]

\( 2b_{\text{min}} \) = minimum period
\( \lambda \) = vacuum wavelength
\( n_r \) = refractive index of resist
\( g\) = gap between mask and resist
\( d \) = resist thickness
Alignment and overlay

CMOS inverter

Active area mask (dark field)

Polysilicon gate mask (light field) aligned to active area

Contact hole mask (DF) aligned to active area

Polygate and contact hole layers aligned to active area layer

Si

Doped Si

Al

Features on wafer

Features on mask

Mask over wafer

Features on wafer

Alignment marks

$P \sim \frac{C}{3}$

$P \sim \frac{C}{3}$

$P = \frac{C}{2}$
MICRONOVA maskaligner

365 nm, i-line, Hg
Summary I

• **Photolithography provides:**
  – required CD
  – exact control over shape and size
  – easy alignment
  – parallel processing, i.e., patterns over an entire surface at the same time

• **Limitations of photolithography**
  – works only on flat surface
  – only 2D shapes can be generated
Photomask fabrication

- Cr deposition and resist application
- Pattern writing by e-beam or laser
- PR development, Cr etching, PR stripping
- CD control
- Inspection of defects and fidelity
- Soft error reduction (particle removal)
- Repairing by ion beam (etching or deposition)
- Final inspection
Pattern generation by e-beam tool

A pattern generation tool transcribes the circuit design data into a physical structure.

Raster scan vs. vector scanning.

Variable shaped beam vs. Gaussian beam.

Global alignment vs. chip-alignment.

Applying of e-beam resist

Shaped beam  Raster scan  Vector scan
Laser beam sweep and a laser writer

Laser beam sweep and a laser writer

Laser beam

Four laser beams

Stage movement

CD – 500 nm
Area 1x1 cm²
Time 2 hours

MICRONOVA laser writer

Beam wavelength 405 nm

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Focused ion beam (FIB)

Fabricated by FIB – 3D patterning!

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Summary II

- **Direct writing pros:**
  - extremely small patterns
  - photomask is not required

- **Direct writing cons:**
  - serial processing, i.e., one element after another
  - alignment is problematic
Lithography and etching

1) photoresist patterning

2) Etching with reactive chemicals (acids, bases, plasmas)

Same procedure applies both to etching thin films and to etching silicon wafer itself. Thicknesses and etch stop vary!

Photolithography can be redone if problems detected, but after etching no repair is available.
Etching terminology

**Etching mask** – patterned protective layer on the top of etched material

**Undercut** – lateral erosion of etched material below protective layer

**Selectivity** – ratio of etching rates for two etched materials

**Aspect ration** – ratio of height to width for a microstructure

**Anisotropy** – different etching rate in different directions
Etch mask

- Protective layer that is very slowly attacked by etchant
- Resist is the simplest etch mask to use → always consider resist mask first
- Aggressive etchants (KOH) will prevent use of resist → hard mask required

• Quiz: what is a photomask? How does it relate to etch mask?
Isotropic etching

- Proceeds as a spherical wave
- Undercuts structures (proceeds under mask)
- Most wet etching processes are isotropic, e.g., HF etching of oxide, $\text{H}_3\text{PO}_4$ etching of Al
- Some of dry etchings are isotropic, e.g., photoresist stripping

5 µm deep, isotropic etch
**Selectivity** is defined as etch rate ratio:

\[ S = \frac{\text{rate film}}{\text{rate mask}} = \frac{y}{x} \]

Silicon etch rate 500 nm/min  
Oxide etch rate 15 nm/min  
Selectivity 33:1  

Silicon etch rate 500 nm/min  
Resist etch rate 200 nm/min  
Selectivity 2.5:1  

\[ S \neq \infty \rightarrow \text{There is always some unintentional loss of material} \]
Aspect ratio

AR is the ratio of height to width

Si pillar array AR 5:1
Si nanopillar AR 15:1
Main methods of etching

Wet etching (usually, isotropic)
	solid + liquid etchant \( \rightarrow \) soluble products

\[
\text{Si (s)} + 2 \text{OH}^- + 2 \text{H}_2\text{O} \rightarrow \text{Si(OH)}_2(\text{O}^-)_2 \text{(aq)} + 2 \text{H}_2 \text{(g)}
\]

Plasma (dry) etching (usually, anisotropic)
	solid + gaseous etchant \( \rightarrow \) volatile products

\[
\text{SiO}_2 \text{(s)} + \text{CF}_4 \text{(g)} \rightarrow \text{SiF}_4 \text{(g)} + \text{CO}_2 \text{(g)}
\]

Typical etching rate 100 – 1000 nm/min in both cases
Wet etchants for common materials

- \( \text{SiO}_2 \) HF
- \(<\text{Si}>\) KOH (10-50%) anisotropic etch
- \(<\text{Si}>\) HNO\(_3\):HF:CH\(_3\)COOH isotropic etch
- poly-Si HNO\(_3\):HF: H\(_2\)O
- Al H\(_3\)PO\(_4\):HNO\(_3\):H\(_2\)O
- W, TiW H\(_2\)O\(_2\):H\(_2\)O
- Cu HNO\(_3\):H\(_2\)O (1:1)
- Ni HNO\(_3\):CH\(_3\)COOH:H\(_2\)SO\(_4\)
- Au KI:I\(_2\):H\(_2\)O
- Pt, Au HNO\(_3\):HCl (1:3) “aqua regia”

Everywhere, exclude Si etching, photoresist mask can be used
Undercutting in action: dome resonator

1) RIE etching of a small hole in polysilicon

2) Isotropic HF wet etching of oxide under polysilicon

→ Membrane can move
Anisotropic wet etching (only for crystals)

Anisotropic etching

Accurate, but limited in shape;
Excellent surface finish

Isotropic etching

Max depth is limited by lateral dimension

54.7°
Wet etching

• Usually isotropic, but can be anisotropic for crystals, e.g., for $c$-Si
• Perfect selectivity
• Special etchant for each material
• Surface finish smooth
• Fast, because batch process
• Cheap equipment
Dry etching

RIE - Reactive Ion Etching

PE - Plasma Etching, also PECVD

Ion density $10^{10}$ ions/cm$^{-3}$

Reactive neutrals or active radicals density $10^{15}$ ions/cm$^{-3}$
Plasma – surface interaction in RIE

https://scorec.rpi.edu/research_plasmaetchmodeling.php
## Chemistry of dry etching

<table>
<thead>
<tr>
<th>Material</th>
<th>Etch gas</th>
<th>Product gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>SF$_6$ (or Cl$_2$)</td>
<td>SiF$_4$, SiCl$_4$</td>
</tr>
<tr>
<td>Oxide</td>
<td>CHF$_3$ (or C$_4$F$_8$)</td>
<td>SiF$_4$, CO$_2$</td>
</tr>
<tr>
<td>Nitride</td>
<td>SF$_6$ (or CF$_4$)</td>
<td>SiF$_4$, N$_2$</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Cl$_2$</td>
<td>AlCl$_3$</td>
</tr>
<tr>
<td>Tungsten</td>
<td>SF$_6$</td>
<td>WF$_6$</td>
</tr>
</tbody>
</table>

- Copper: no practical plasma etching (Ar)
Plasma etched (anisotropic) profiles
Plasma etching

- Usually anisotropic, but can be isotropic
- Near vertical walls
- Low selectivity
- Surface finish rough
- Slow, because single wafer process?
- Expensive equipment
Wet etching vs. plasma etch

Wet etching: chemical reaction; simple wet bench and acids or bases needed

Plasma etching: chemical and physical processes; requires RF-generator, vacuum system and gas lines
Wet etch vs. plasma etch II

Oxide wet etch in HF
- Undercut, isotropic
  - Film removed from backside

Oxide plasma etch in CHF$_3$
- Vertical walls, no undercut
  - Film remains on backside
Photoresist as an etch mask

- Most simple to use
- Tolerates RIE: selectivity 10:1 at best
- Does not tolerate long RIE
- Does not tolerate most wet etchants such as KOH

Lithography:
- Photoresist spinning
- UV-exposure
- Photoresist development
- Etching with resist mask

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Hard mask

1. Cleaned silicon wafer
2. Thermal oxidation @ 1100 °C
3. Lithography: Photoresist spinning
4. Lithography: UV-exposure
5. Photoresist development
6. HF etching of SiO₂
7. Photoresist removal
8. Plasma etching

SiO₂ hard mask

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If two layers are perfectly aligned, they were made in the same etch step. Otherwise alignment error would be visible.
Etchback

One layer surface planarization

- Step 7: Au Electrode layer deposition.

Two layers surface planarization

- SiO₂ etching
- PR removal
- Planarization
- Etchback

Requirement: etching rates of glass and PR must be equal !!!