EE C245 – ME C218 Introduction to MEMS Design Fall 2012

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Lecture Module 4: Lithography, Etching, & Doping

Lecture Outline

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

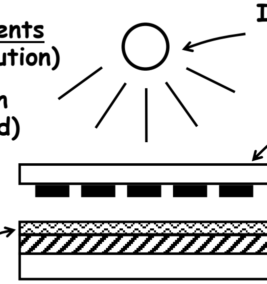
Lithography

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)

I. Radiation Source



Designated pattern
(clear or dark field)
emulsion chrome

- Generated from layout

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
optics ⟶ this is where the real art is!

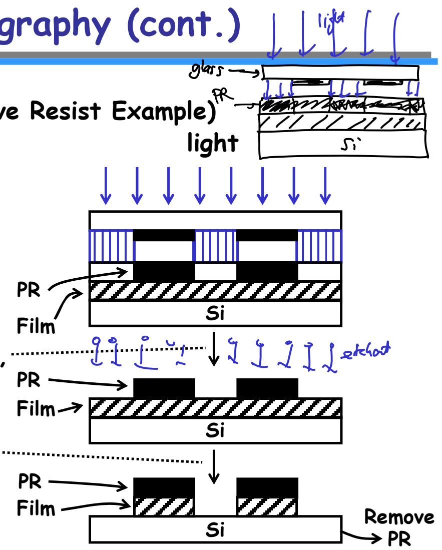
Lithography (cont.)

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



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

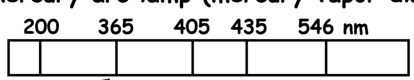
Comb-Drive Resonator: 3 masks
GHz Disk: 4 masks

Now, take a closer look at the 4 components:

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 $\underbrace{\text{throughput}}_{\text{Can expose billions of devices at once!}}$.

Optical Sources:
- Mercury arc lamp (mercury vapor discharge)



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

II. Mask

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

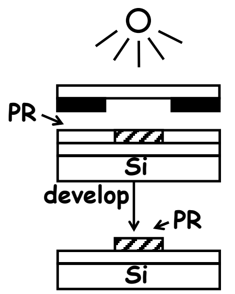
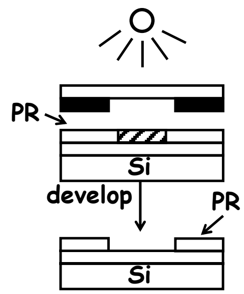
Electronic computer representation of layout (e.g., CIF, GDSII) ⟹ A single file contains all layers

↓ 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.

III. Photoresist (optical)

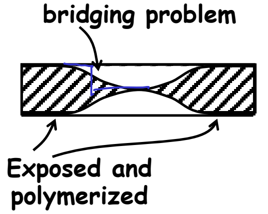
	Negative	Positive
Pictorial Description:		
Exposed Area:	remains	removed

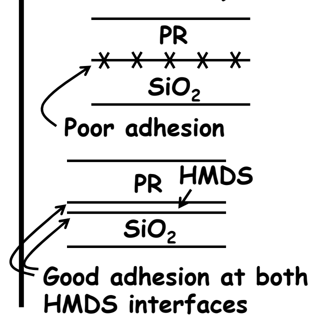
III. Photoresist (optical)

	Negative	Positive
Mechanism:	photoactivation ↓ Polymerization (long, linked Carbon chains) ↓ Developer solvent removes unexposed PR	photoactivation ↓ Converts exposed PR to organic acid ↓ Alkaline developer (e.g.,kOH) removes acid

III. Photoresist (optical)

	Negative	Positive
Issues:	Polymerized PR swells in solvent → bridging problem	Doesn't adhere well to SiO_2 Need primer: HMDS (hexamethyl disilazane)



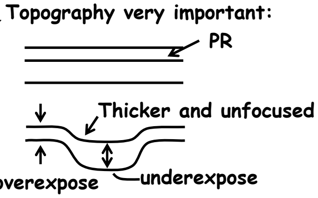


Typical Procedure for Lithography

- 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
- ↓ Develop → Descum → Post Bake

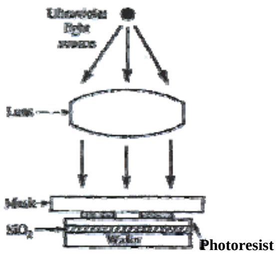
Oxygen plasma (low power ~ 50W)

Topography very important:



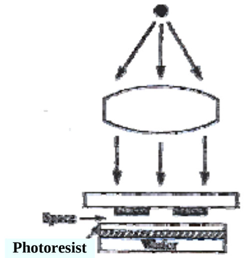
IV. Exposure System/Optics

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

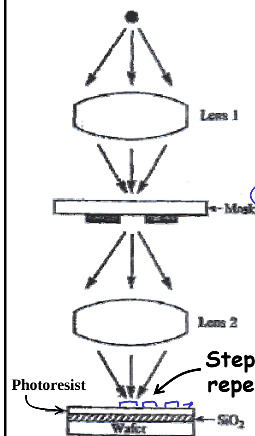


- Mask in very close proximity but not touching

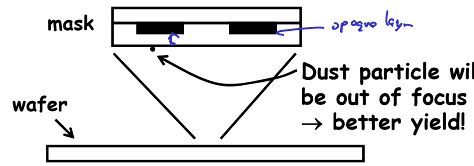
- 1X printing very useful for MEMS → can expose surfaces with large topography (where reduction printers cannot)

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:

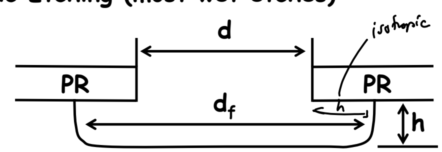


Etching

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 $B = 2h$ ⇨ isotropic

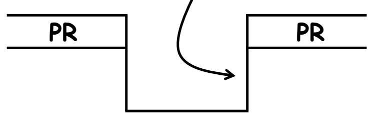
Etching Basics (cont.)

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

Degree of Anisotropy: (definition)

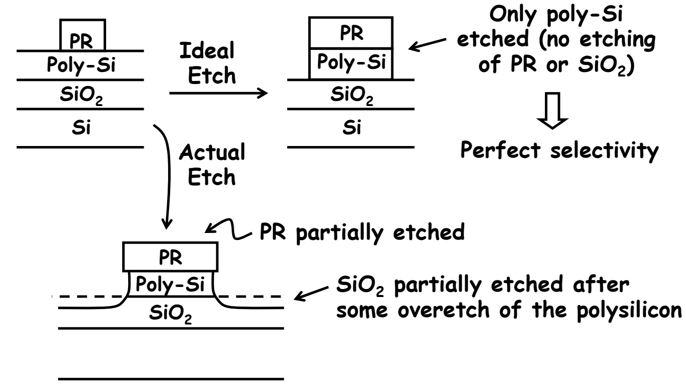
$$A_f = 1 - \frac{B}{2h} = 0 \quad \text{if 100\% isotropic}$$

$0 < A_f \le 1$ ← anisotropic



Etching Basics (cont.)

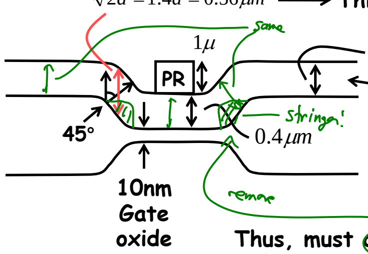
2. Selectivity -



Etching Basics (cont.)

Why overetch?

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



Poly-Si → conformal if deposited by LPCVD

Thus, must overetch at least 40%:
40% overetch → (0.4)(0.4) = 0.16 μm poly
= ??? oxide

Depends on the selectivity of poly-Si over the oxide

Etching Basics (cont.)

Define selectivity of A over B:

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

$E.R._a$ ⟵ Etch rate of A
$E.R._b$ ⟵ Etch rate of B
S_{ab}: Selectivity of A over B

e.g., wet poly etch (HNO_3 + NH_4 + H_2O)

$S_{poly/SiO_2} = \frac{15}{1}$ (very good selectivity)

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

e.g., polysilicon dry etch:

$S_{poly/SiO_2} = \frac{5-7}{1}$ ← Regular RIE (but depends on type of etcher)

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

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

Etching Basics (cont.)

If $S_{poly/SiO_2} = \frac{8}{1}$ $\Longrightarrow$ 40% overetch removes

$\frac{0.16}{8} = 20 \text{ nm of oxide!}$ $\Longrightarrow$ 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., $S_{poly/SiO_2} = \frac{30}{1}$

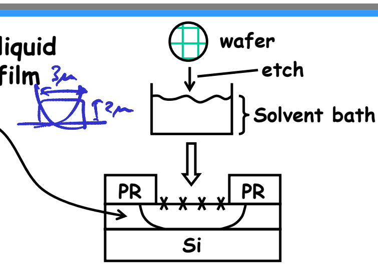
(Can attain with high density Cl plasma ECR etch!)

40% overetch removes $\frac{0.16}{30} = 5.3nm$ (better)

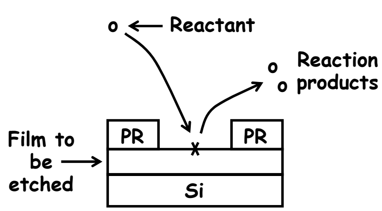
Wet Etching

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

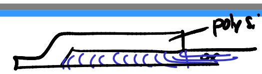
Wet Etching (cont.)

- 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

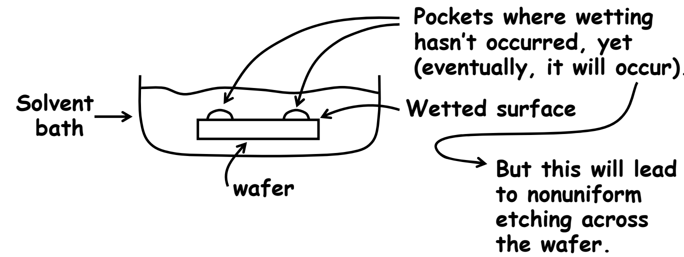
1. Isotropic
   - Limited to >3μm features
   - But this is also an advantage of wet etching, e.g., if used for undercutting for MEMS



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)

Wet Etch Limitations (cont.)

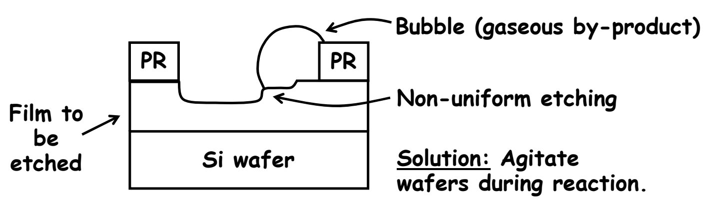
6. Incomplete wetting of the surface:



- 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

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.

Some Common Wet Etch Chemistries

Wet Etching Silicon:

Common: $Si + HNO_3 + 6HF \longrightarrow H_2SiF_6 + HNO_2 + H_2 + H_2O$

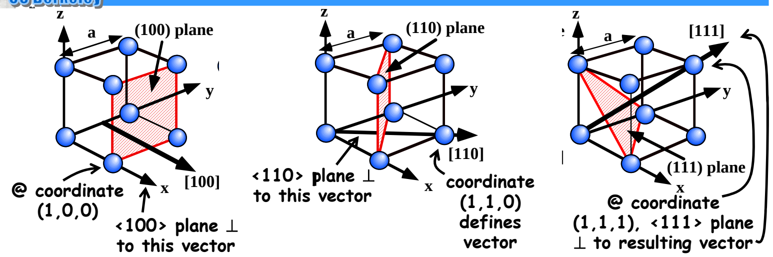
(isotropic)

HNO_3 (nitric acid) → (1) forms a layer of SiO_2

HF (hydrofluoric acid) → (2) etches away the SiO_2

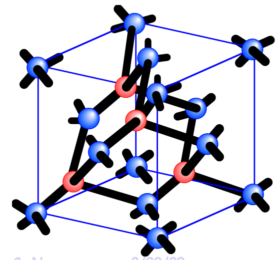
Different mixture combinations yield different etch rates.

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/cm^2 <111>
    - # available bonds/cm^2 <110>
    - # available bonds/cm^2 <100>

Increasing ↑



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

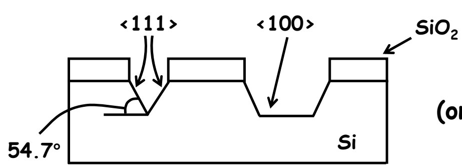
One such solvent: KOH + isopropyl alcohol

(e.g., 23.4 wt% KOH, 13.3 wt% isopropyl alcohol, 63 wt% H_2O)

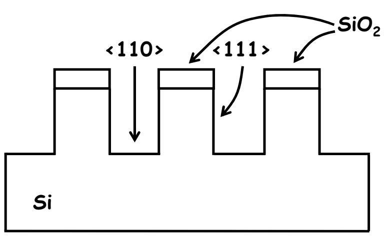
$\Longrightarrow$ E.R.$_{<100>}$ = 100 x E.R.$_{<111>}$

Anisotropic Wet Etching (cont.)

Can get the following:



(on a <100> - wafer)



(on a <110> - wafer)

$\Longrightarrow$ Quite anisotropic!