EE C247B – ME C218
Introduction to MEMS Design
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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

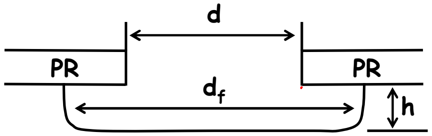
Etching

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 $B = 2h$ ⇨ isotropic

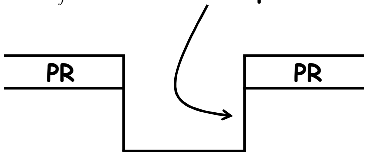
Etching Basics (cont.)

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

Degree of Anisotropy: (definition)

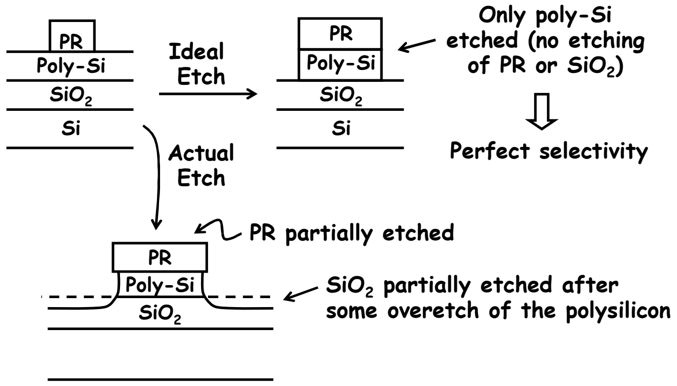
$$A_f = 1 - \frac{B}{2h} = 0$$ if 100% isotropic

$$0 < A_f \le 1$$ ← anisotropic



Etching Basics (cont.)

2. Selectivity -



Only poly-Si etched (no etching of PR or SiO_2)

⇩

Perfect selectivity

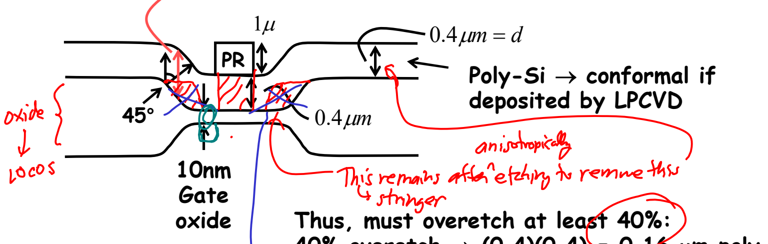
PR partially etched

SiO_2 partially etched after some overetch of the polysilicon

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

This remains after anisotropically etching to remove this
↳ stringer

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 $S_{poly/SiO_2} = \frac{8}{1}$ ⟹ 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 → 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!)

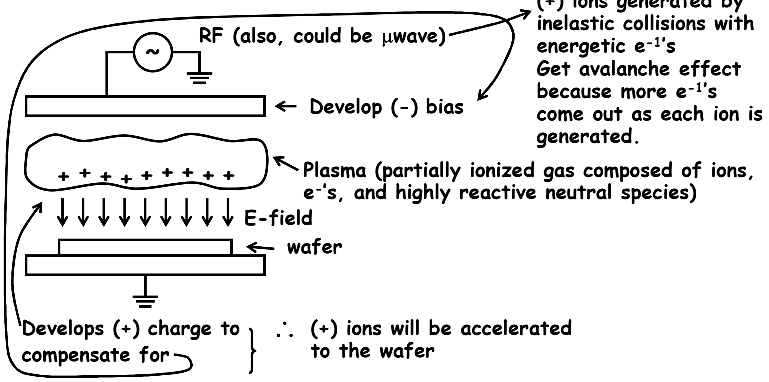
40% overetch removes $\frac{0.16}{30} = 5.3nm$ (better)

Dry Etching

Dry Etching

- Physical sputtering
- Plasma etching
- Reactive ion etching

} All based upon plasma processes.



RF (also, could be µwave)

(+) 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.

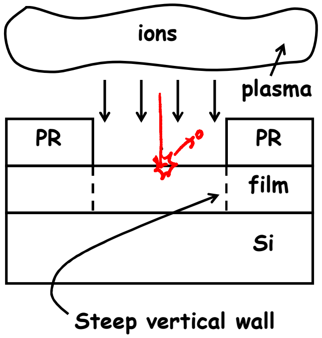
← Develop (-) bias

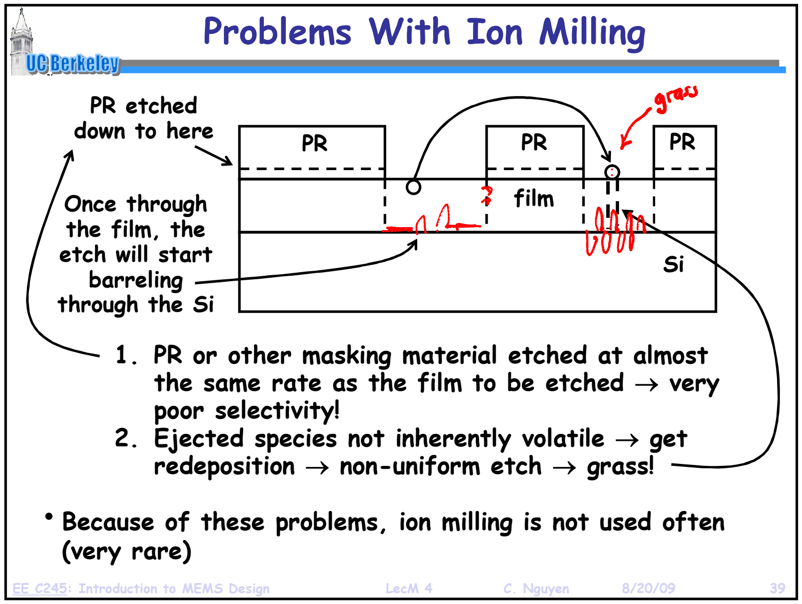
Plasma (partially ionized gas composed of ions, e^-'s, and highly reactive neutral species)

Develops (+) charge to compensate for } ∴ (+) ions will be accelerated to the wafer

Physical Sputtering (Ion Milling)

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

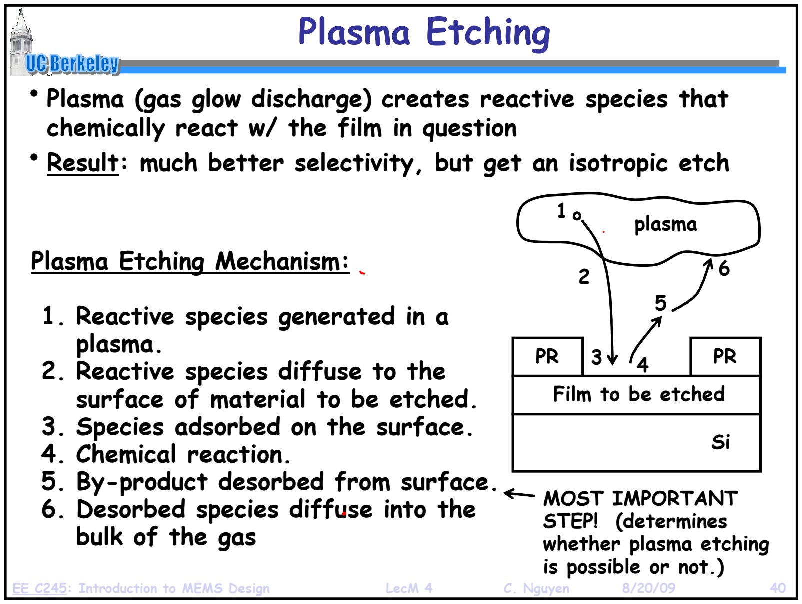




Problems With Ion Milling

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)

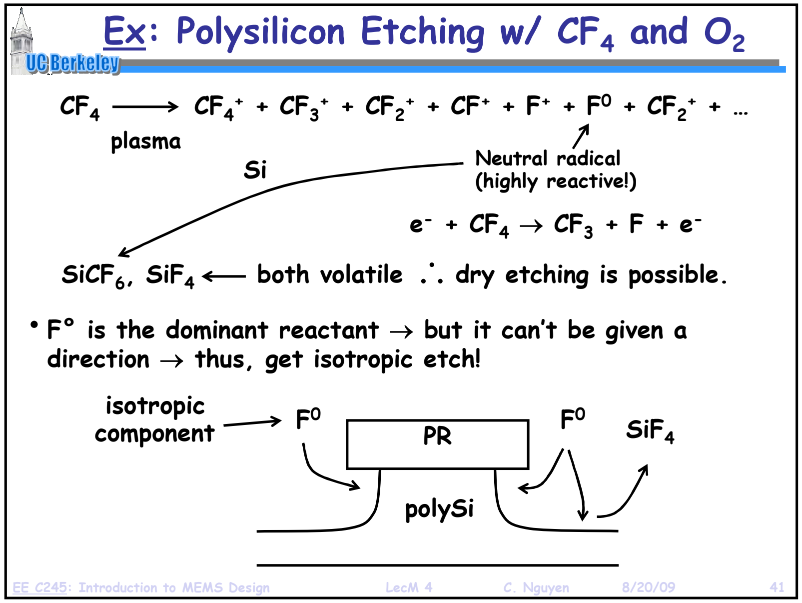


Plasma Etching

- 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:

1. Reactive species generated in a plasma.
2. Reactive species diffuse to the surface of material to be etched.
3. Species adsorbed on the surface.
4. Chemical reaction.
5. By-product desorbed from surface. ← MOST IMPORTANT STEP! (determines whether plasma etching is possible or not.)
6. Desorbed species diffuse into the bulk of the gas



Ex: Polysilicon Etching w/ CF_4 and O_2

$$CF_4 \xrightarrow[\text{plasma}]{} CF_4^+ + CF_3^+ + CF_2^+ + CF^+ + F^+ + F^0 + CF_2^+ + \ldots$$

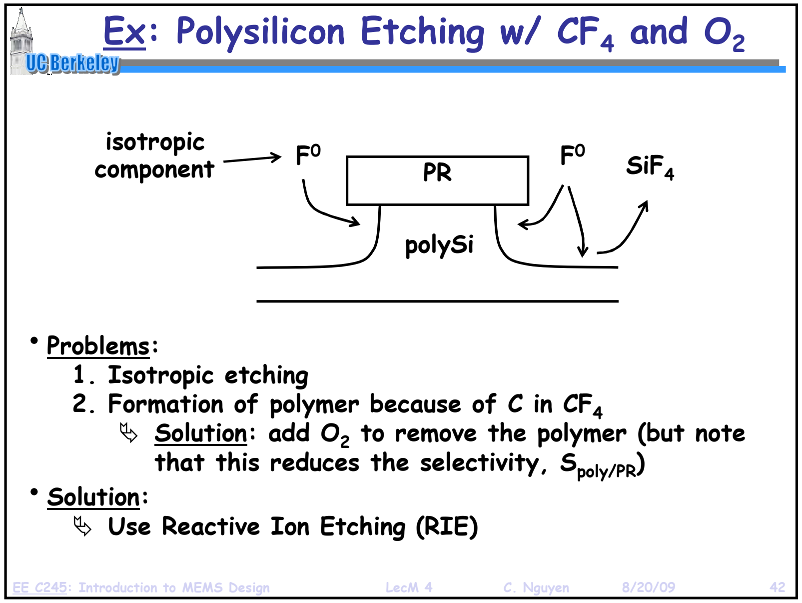
Neutral radical (highly reactive!)

Si

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

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

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



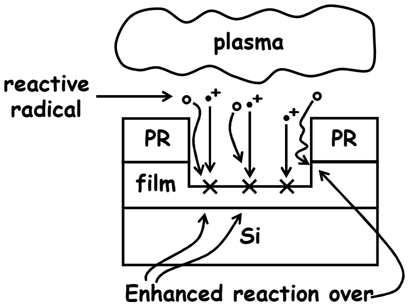
Ex: Polysilicon Etching w/ CF_4 and O_2

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

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
  1. Surface damage mechanism
  2. Surface inhibitor mechanism

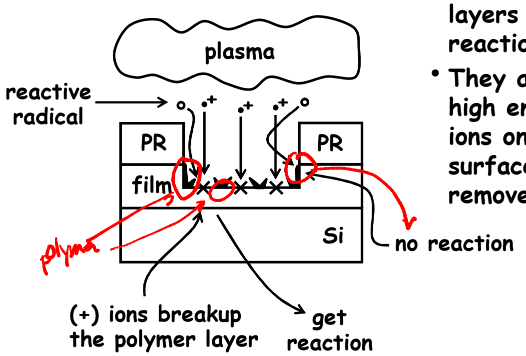
RIE: Surface Damage Mechanism



- 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

RIE: Surface Inhibitor Mechanism



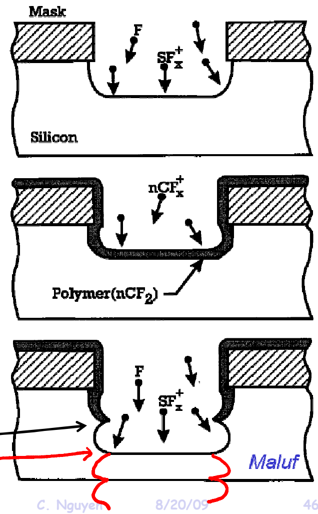
- Non-volatile polymer layers are a product of reaction
- They are removed by high energy directional ions on the horizontal surface, but not removed from sidewalls

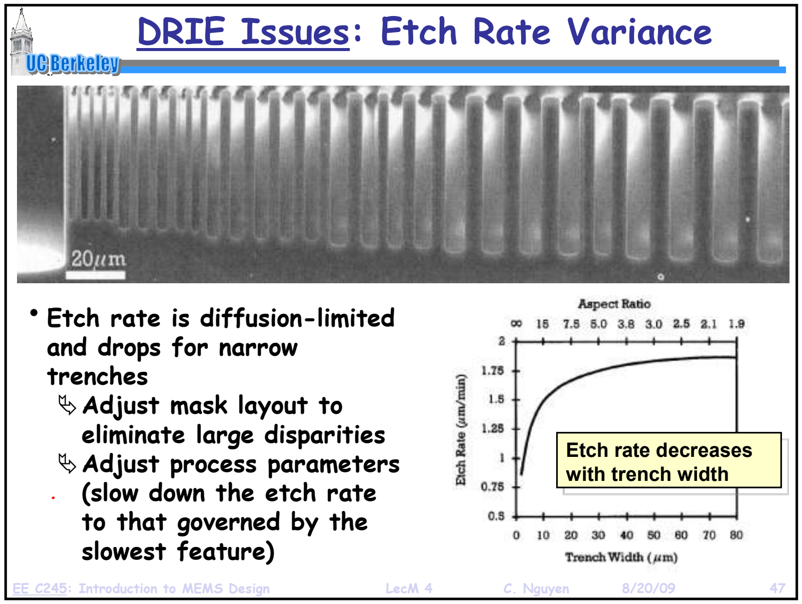
Result: E.R. @ surface >> E.R. on sidewalls

Deep Reactive-Ion Etching (DRIE)

The Bosch process:

- Inductively-coupled plasma
- Etch Rate: 1.5-4 μm/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:
  - SiO_2 ~ 200:1
  - Photoresist ~ 100:1
- **Issue**: finite sidewall roughness
  - scalloping < 50 nm
- Sidewall angle: 90° ± 2°





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