Midterm evaluations

What learning activities were found *most helpful*

Example problems, case studies (5);
graphs (good for extracting useful info) (4);
Good interaction (2);
Good lecture notes, slides (2);
Connection between different concepts (1);
Highlighting key points (1).

What learning activities were found *least helpful*

Cluttered slides (2);
Not always sure of importance of topics (1);
Poor information flow in derivation process (1);
Readings (1);
Sometimes information overload (1);
Speaking too quickly (1).

If you could implement one change, by end term, what would it be?

Clarify definitions at start of lecture (1);
Cleaner slides (1);
Final summary of key concepts at end of lec. (1);
Fewer reports, 2 would be sufficient (1);
More concepts, fewer calculations (1);
More guidance on how to handle odd results (1).
Require a textbook (1).
Review sessions and office hrs should not conflict with
with extracurricular activities (1).

Process determines product

Students like most aspects of this class… favourite tends to be labs;
students need guidance about what to do when .. get strange results.

Students like lectures in general, .. fast at times.
..need highlights of important points to get the "big picture"

- For lengthy derivations,… slides show only small portions at a time; students **like to see entire derivation at once**, possibly …on the board.
- When students ..think through a particularly difficult concept, professor **moves too quickly**, not allowing students to digest information

..graphs and example problems ..very appropriate.

Please ask questions

What I'll do

Begin with definitions, overview
Moderate the pace of speaking and info transfer
End with summary that emphasizes key points

Make more use of figures, graphs, examples
Less clutter on slides
(and post ppt slides, not pdf)
When derivations are helpful, be more methodical
(but still emphasize concepts)

Textbook will continue to be optional ($)

Etching

Etching is the selective removal of deposited films

e.g.: HF dip to remove native oxide… but not Si

More often: through mask to leave patterned film:

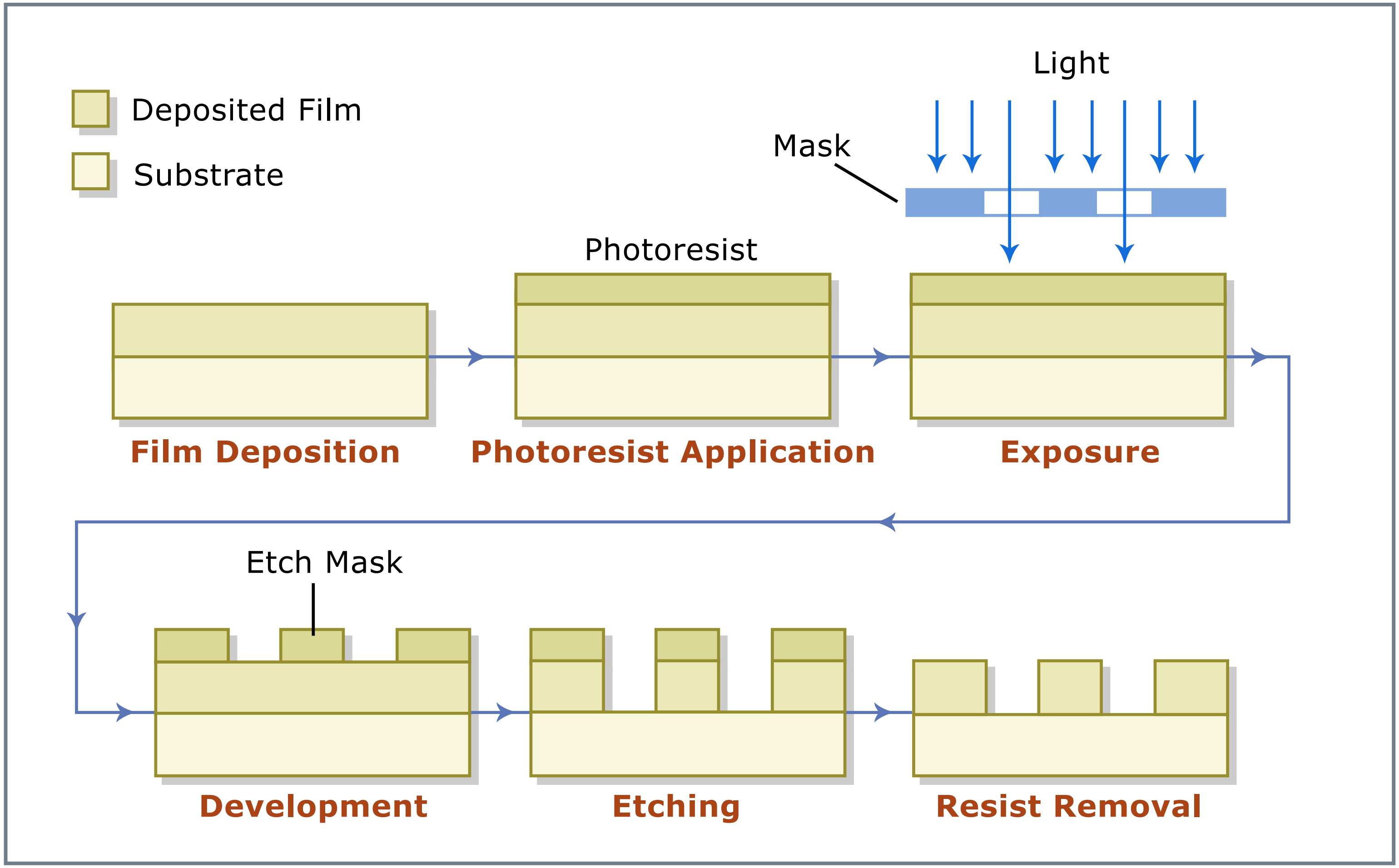


Figure by MIT OCW.

Etching

Etching usually done through a mask of

1. Photoresist (soft mask)

2. SiO_x or SiN (hard mask)

(+ Photoresist to define hard mask)

More robust than PR alone

Etching must be done with consideration of prior processes

(Material already present may inadvertently be affected by etching)

Mask, substrate

Chemical Etching

Wafer in contact with liquid, reactive gas or plasma.

Etch is from chemical reaction acting isotropically

undercut is possible

highly selective

rate is thermally activated

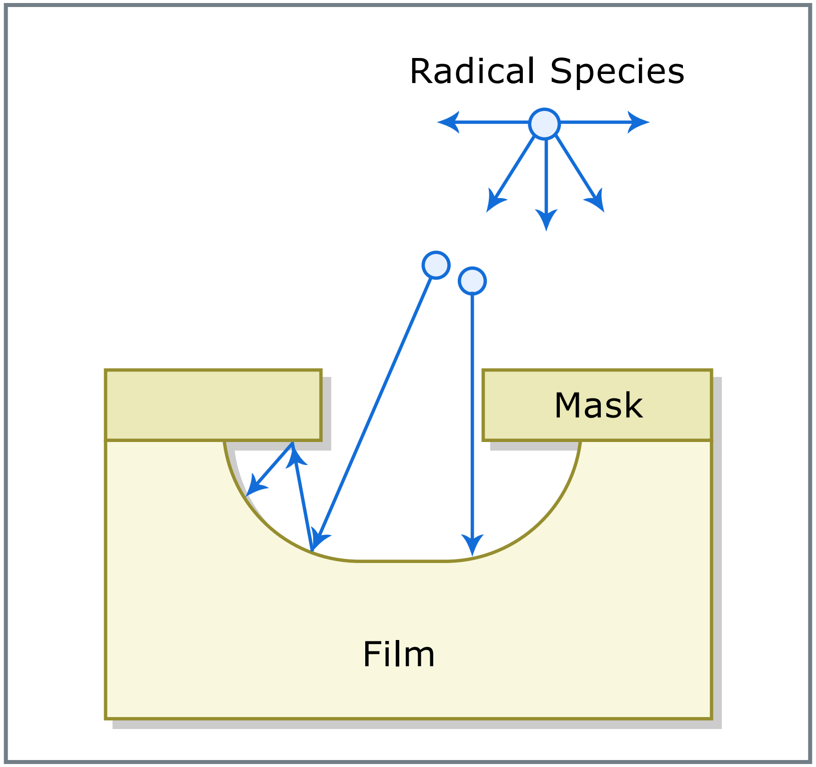


Figure by MIT OCW.

Physical Etching

Wafer exposed to inert gas and/or plasma.

Etch is from momentum transfer
- **of accelerated ions acting anisotropically**
- **good edge definition**
- **low selectivity**
- **rate is mass transport dependent (byproducts)**

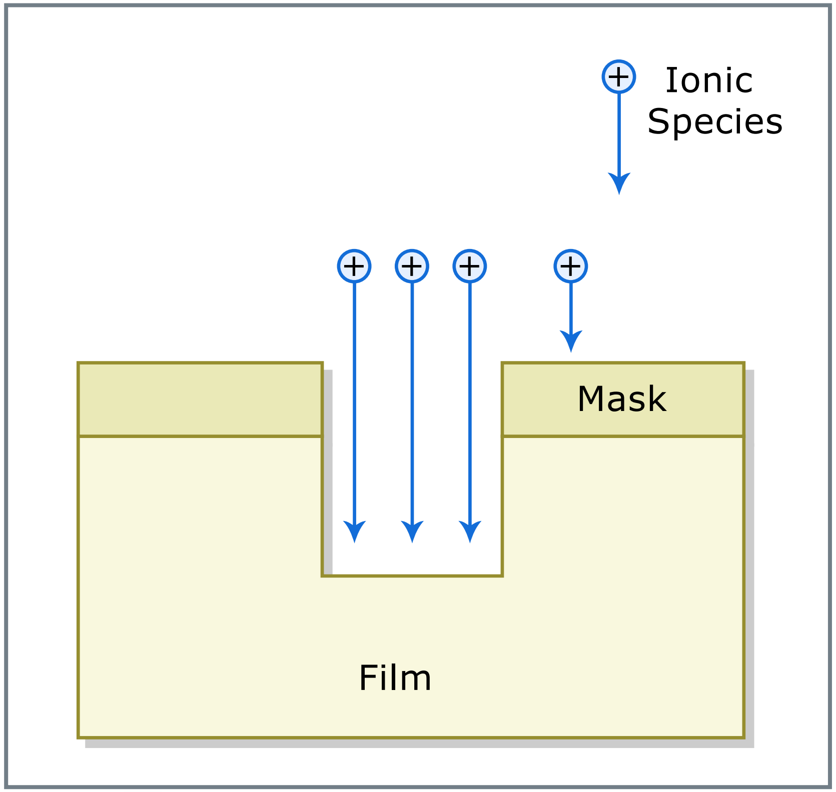


Figure by MIT OCW.

Issues in etching

1) ***Uniformity*** across wafer, and across window

2) ***Rate***; fast enough to be practical,
slow enough to be controllable

3) ***Selectivity***: rate of etching target material
relative to mask-etch rate (should be large)

4) ***Anisotropy***: directional dependence of etch rate

5) ***Byproducts***: volatile or otherwise easily removed,
and are they safe

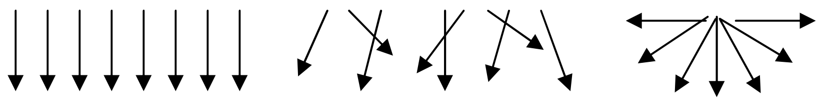
Selectivity = $\frac{\text{Etch rate of material intended to be removed}}{\text{Etch rate of mask}}$

S≈exp(-G/kT)

Sputter yield,
mM/(m+M), energy

Chemical reactions can be highly selective (20 - 50)
Physical etch processes (sputter etch) less so (1 - 5)

Directionality: From anisotropic to isotropic



	Wet etch (*Chemical*)	Dry etch (*Physical*)	Deposition techniques CVD	Sputtering
Selectivity	**25 - 50**	**1 - 5**	high	(Sputter yield)
Directionality	**low**	**high**	good step coverage	poor step coverage

Removing material *adding material*

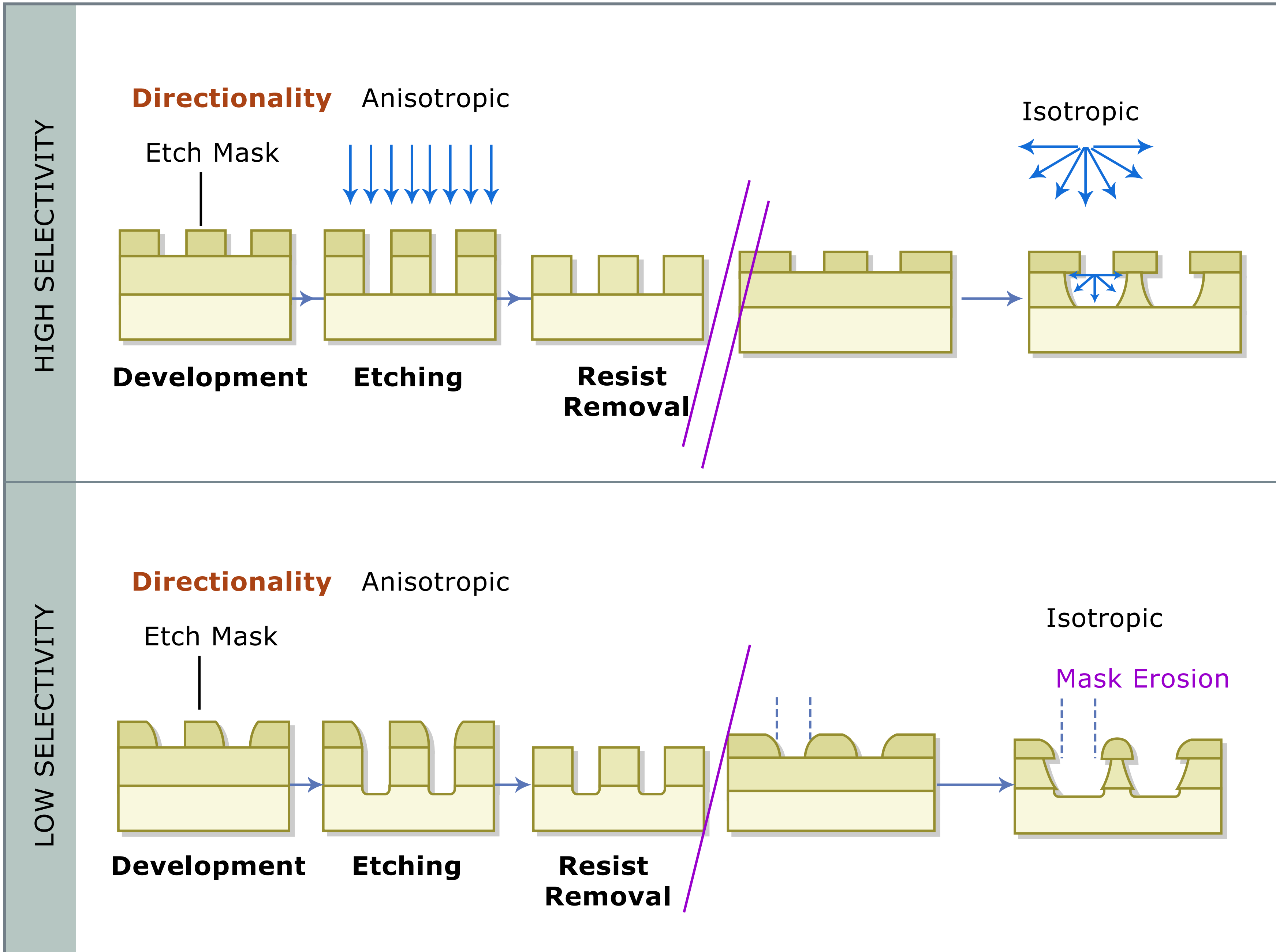
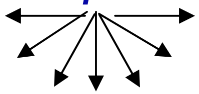


Figure by MIT OCW.

Wet etch (***Chemical***: *wet, vapor or in plasma*)

isotropic (*usually*), highly selective



HF dip:

$SiO_2 + 6HF \Rightarrow H_2SiF_6(g) + 2H_2O$

Used less for VLSI (poor feature size control)

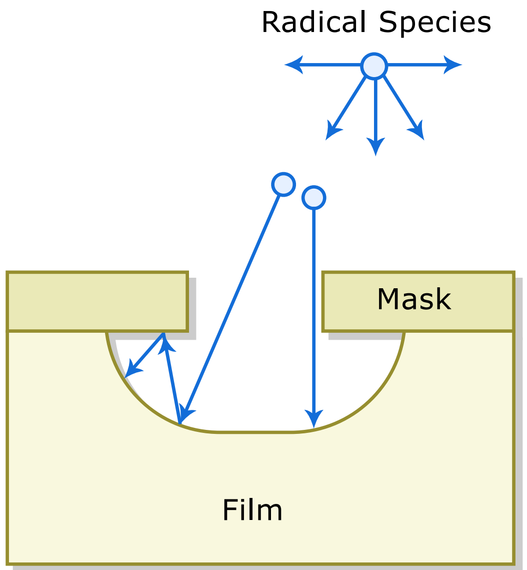
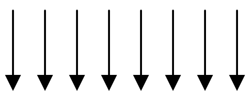


Figure by MIT OCW.

Dry etch (***Physical***: *ions, momentum transfer*)

anisotropic, not selective

Sputter etching



More widely used for small features

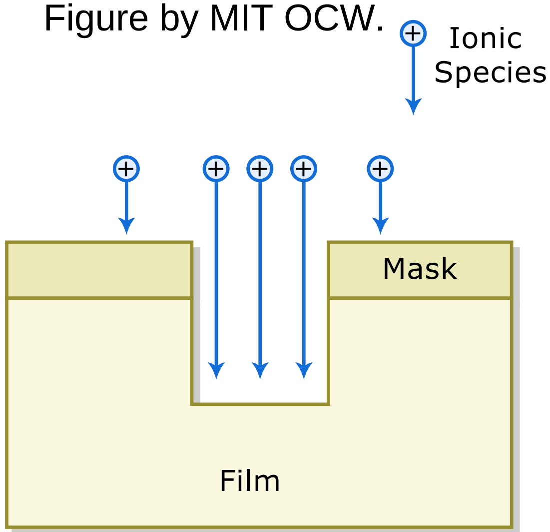
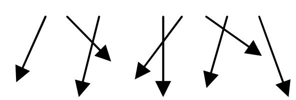


Figure by MIT OCW.

Combination (*Physical & Chemical*)

Ion-enhanced or

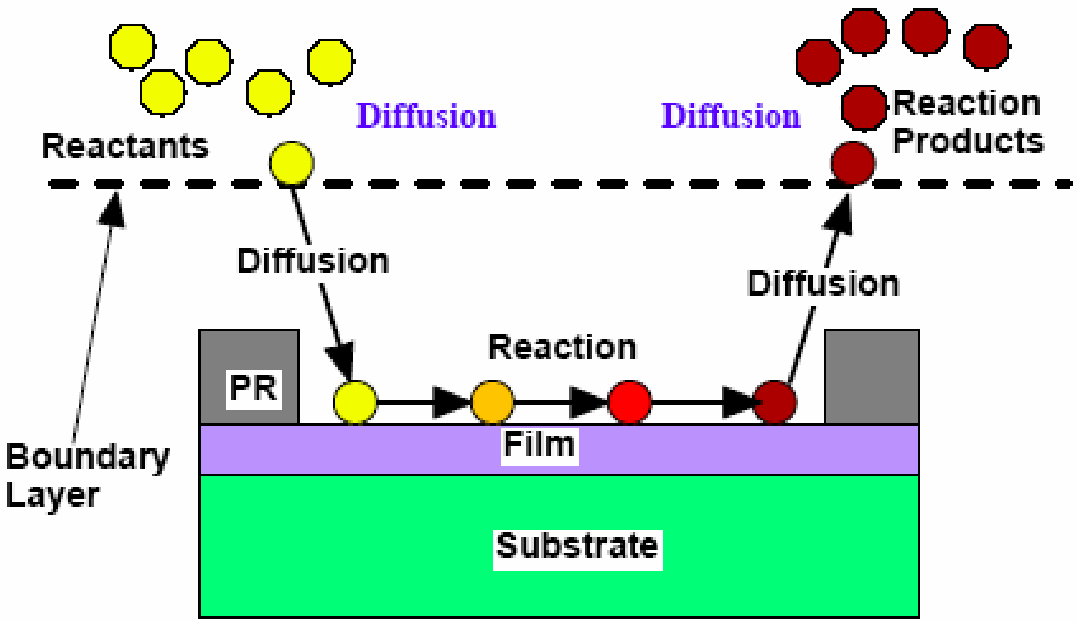
Reactive Ion Etching (RIE)



Blends best of *directionality* and *selectivity*

Wet Etching

Wafer in solution that attacks film to be etched, but not mask



Reactive species ***diffuse*** through boundary layer to surface of wafer

Thermally activated ***reaction*** at surface gives soluble species

Products ***diffuse*** through boundary layer, transported away

Advantages: high *selectivity* due to chemical reactions

Disadvantages: *Isotropic (except for Si)*, poor *process control*
(can be transport or reaction limited, just like CVD),
strong *T*-dependence

Wet etching

Wet etching controlled by:	**which affects:**
Mass transport, boundary layer	***Uniformity, Rate*** $\delta(x) \propto \sqrt{x}$
Specific chemical reaction, ΔG	***Rate, Selectivity***
Temperature exp$(-\Delta G/k_B T)$	***Rate***

(Just as in CVD, oxidation)

Wet etching

HF dip removes native oxide from shipped wafers

Silicon Dioxide

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$$

Rinse in DI water

If you want no further oxide growth,
passivate surface with hydrogen

Crystallographic selectivity used to make cantilevers

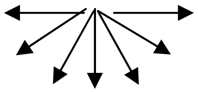
Silicon

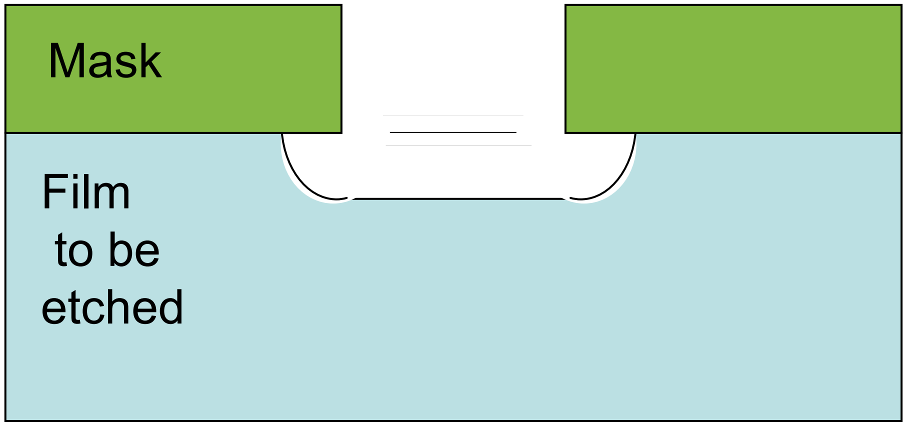
$$Si + 2HNO_3 \rightarrow SiO_2 + 2HNO_2$$

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$$

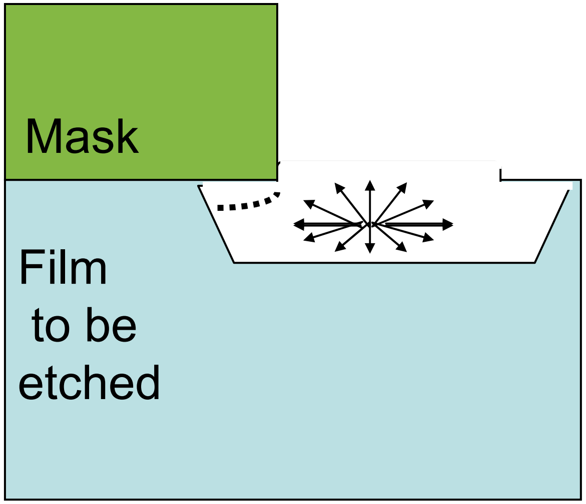
Wet etching

isotropic





Boundary layer prevents growth from being Linear like this:



Boundary layer also retards removal of by-products

Wet etching of SiO_2

Immerse wafer in bath (HF dip)

or etch SiO_2 through photoresist mask

$$SiO_2(s) + 6HF(l) \rightarrow H_2SiF_6(g) + 2H_2O(l)$$

Reaction products must be gaseous or water soluble

Slow reaction by diluting HF with H_2O

120 nm/min in 6:1::H_2O:HF

1000 nm/min in 1:1

Doped or deposited oxide etches faster

Selectivity relative to Si ≈ 100

Buffered oxide etch (BOE) (add NH_4F)

improves consistency, maintains F

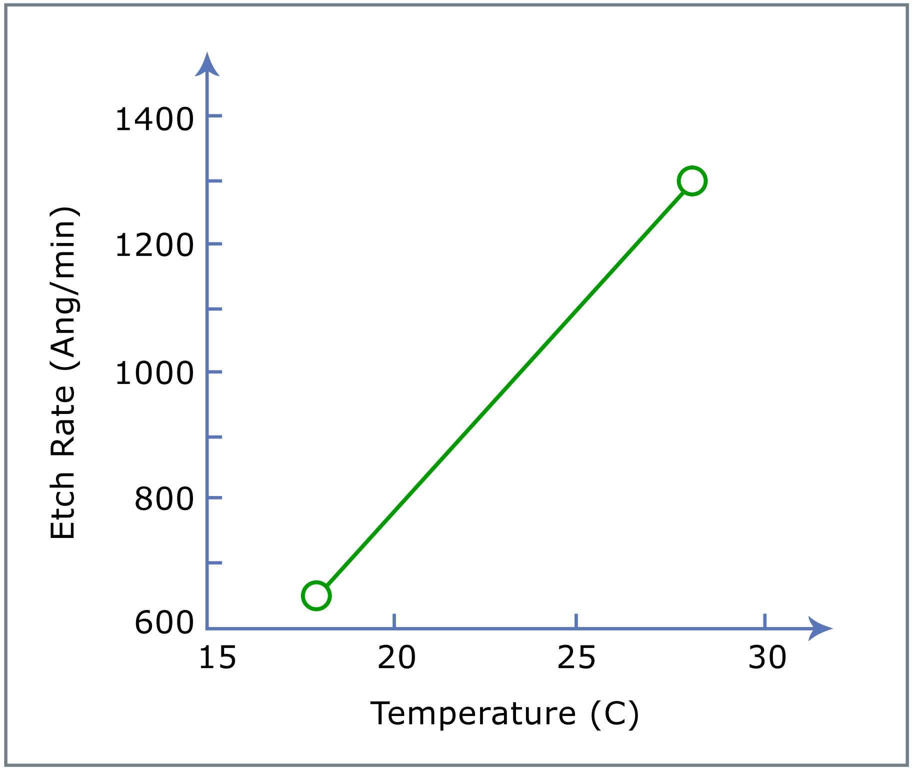


Figure by MIT OCW.

Wet etching of Si

Common silicon wet etch: nitric (=>NO_2) + hydrofluoric acid

$$Si(s) + 2NO_2(g) + 2H_2O(l) \rightarrow SiO_2(s) + H_2 + 2HNO_2(l)$$

HF dissolves SiO_2 by reaction above. Total reaction:

$$Si(s) + HNO_3(l) + 6HF(l) \rightarrow H_2SiF_6(g) + 2H_2O(l) + HNO_2(l) + H_2$$

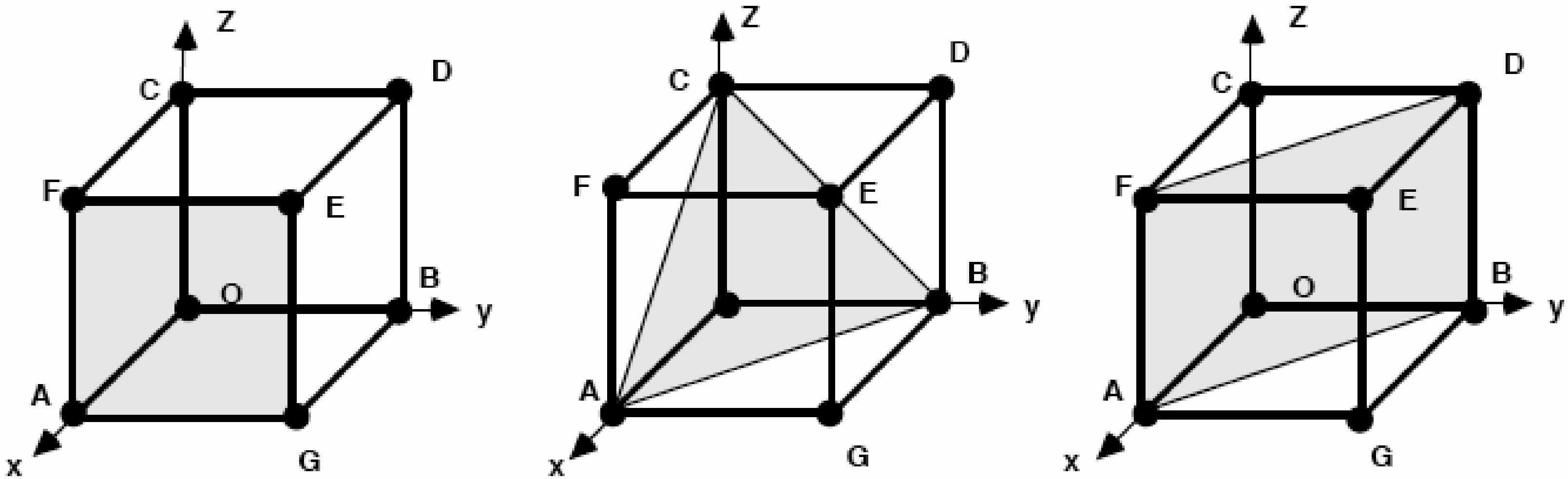
Buffered HF: Acetic acid (CH_3COOH) instead of H_2O,
NH_4F added to prevent depletion of F and retard etch of photoresist

Figure removed for copyright reasons.

Please see: Figure 11-4 in Campbell, S. ***The Science and Engineering of Microelectronic Fabrication***. 2nd ed. New York, NY: Oxford University Press, 2001. ISBN: 0195136055.

Wet etching of Si

(From Lec 7, M. Schmidt)



Bond coordination in (111) is greatest

The family of planes AFEG (1,0,0), ABC (1,1,1) and ABDF (1,1,0)

(111) planes most stable

Fall 2005 – M.A. Schmidt

3.155J/6.152J – Lecture 7 – Slide 28

Wet etching of Si
(From Lec 7, M. Schmidt)

Two graphs removed for copyright reasons.

See H. Seidel, L. Csepregi, A. Hueberger, and H. Baungärtel. *The Journal of the* Electrochemical Society 137 (1990): 3612-3626.

Wet etching of Si
(From Lec 7, M. Schmidt)

Figures removed for copyright reasons.

Figures can be found in slide 9 of Tang, W. "MEMS Programs at DARPA." Presentation, DARPA,
http://www.darpa.mil/mto/mems/presentations/memsatdarpa3.pdf

Wet etching

High selectivity of wet etch derives from chemical reaction.

$$S = \frac{r_1}{r_2}$$

r_1 is film to be etched

r_2 is mask and/or material beneath film

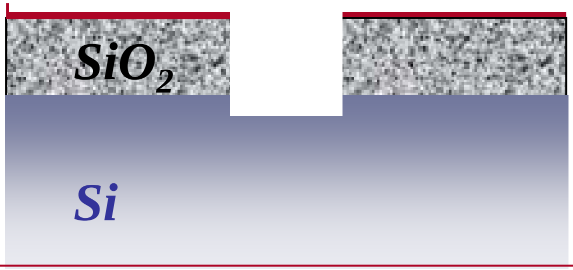
Selectivity determines mask thickness

Exercise

0.6 μm of SiO_2 is to be etched; rate is 0.2 μm/min. If etch selectivity of oxide relative to mask is 24:1 and to slightly over-etch you expose for 3.6 min, ***how thick should mask be?***

Solution

$$S = \frac{r_1}{r_2} = 24 = \frac{0.2\mu m/\min}{thickness/3.6\min}$$



Mask should be > 0.03 μm thick

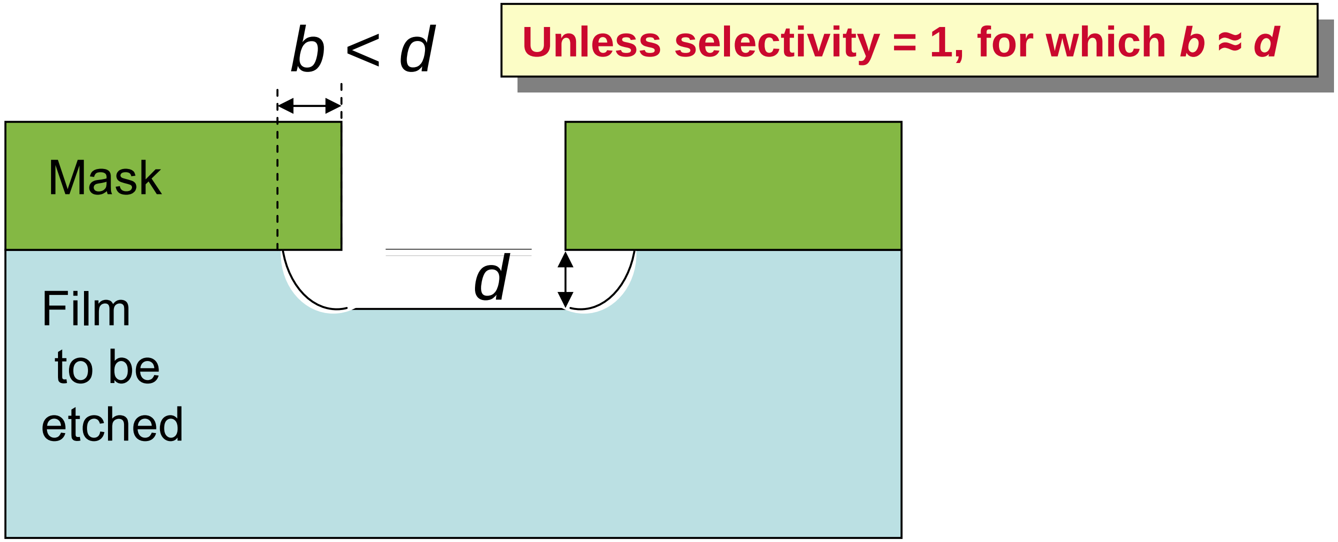
How thick is 0.035 μm mask after etch?

$$t_{\text{mask}}(3.6) = 0.035\mu m - \frac{0.2}{24} \times 3.6 = 3\ \ nm$$

$r_2 = r_1/24$

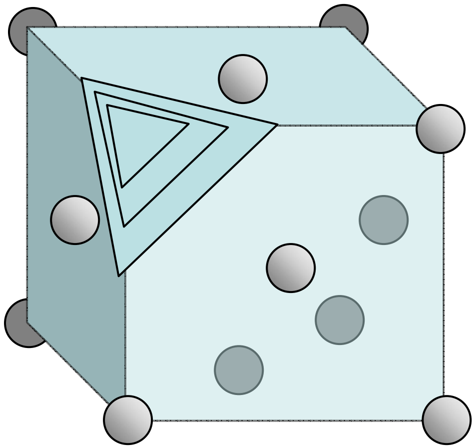
Wet etching: bias

Isotropic wet etch leads to bias, *b*:



Exception:

when etch rate depends on crystallography
as in Si etch:
fastest normal to low-in-plane-bond direction, <100>
slowest normal to high-in-plane-bond direction, <111>



Wet etching

Exercise

0.4 μm of SiO_2 is to be etched at least into Si; rate is r_{ox} (μm/min). Oxide ***thickness*** *and* ***etch rate*** *each have ± 5% variance.*

Q. What % etch time is required to be sure all oxide is etched?

Solution

Worst case time is thickest oxide, slowest rate:

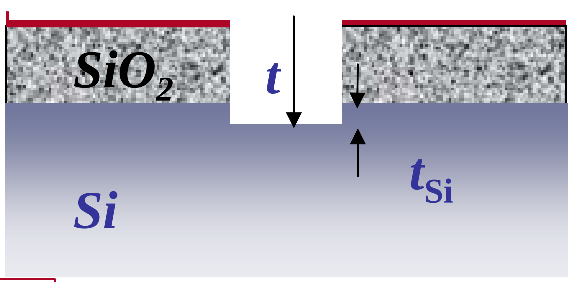
$$t = \frac{1.05 x_{ox}}{0.95 r_{ox}} = 1.105 \frac{0.4 \mu m}{r_{ox}}$$

This implies a 10.5% greater time is needed to insure fully exposed Si.

Q. What selectivity, r_{ox}/r_{Si}, is required so that no more than 5 nm of Si is etched anywhere?

Solution

Maximum Si etch is beneath thinnest SiO_2 and for fastest r_{ox} so shortest oxide-etch time is $t_{ox} = 0.95x_{ox}/1.05r_{ox} = 0.362/r_{ox}$. Use time t_{tot} from a):



$$S = \frac{r_{ox}}{x_{Si}^{max} / t_{Si}} = \frac{r_{ox}}{0.005 / (t_{tot} - 0.362 / r_{ox})} = 16:1$$

Etching: mask erosion

Prior examples assume no mask erosion $r_{ox}/r_{mask} \approx \infty$

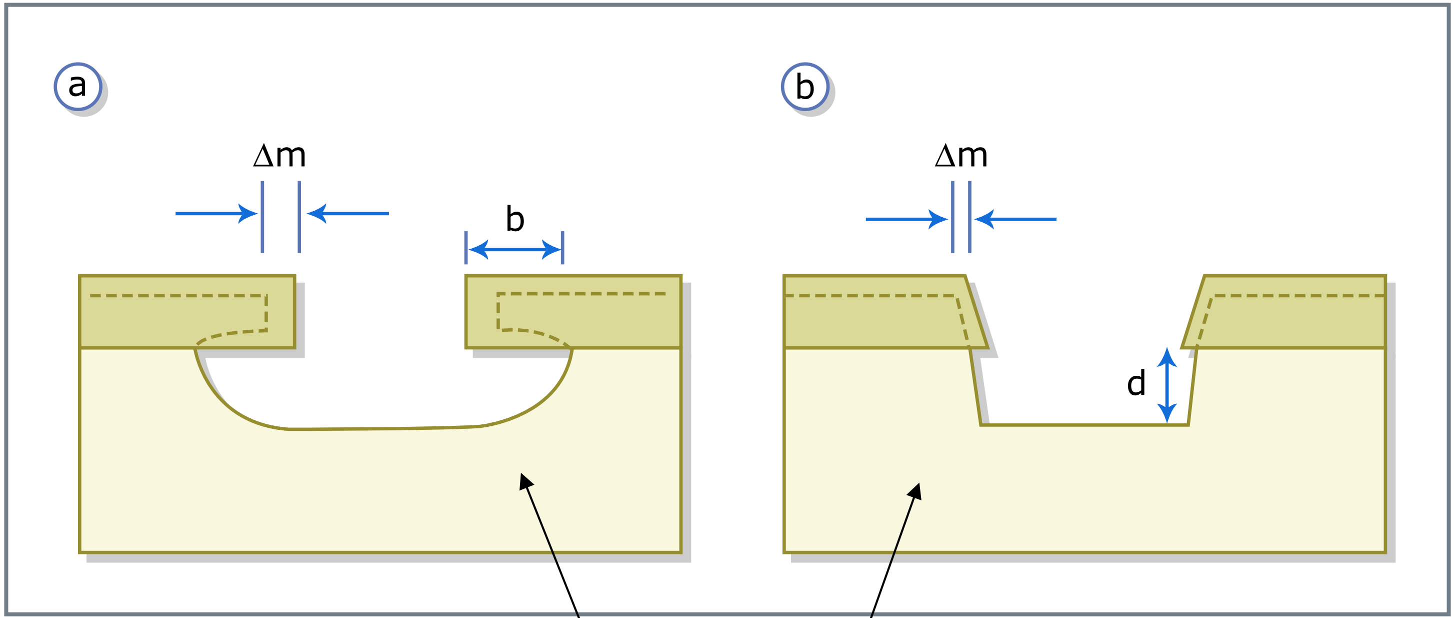


Figure by MIT OCW.

Mask erosion, Δm, depends on
whether etch is isotropic or anisotropic

Define degree of etch *isotropy*, $I_{etch} = r_{lateral}/r_{vertical}$

or degree of *anisotropy*, $A_{etch} = 1 - I_{etch} = 1 - b/d$. ($b$ is the bias).

Etching just to the bottom of the layer gives: $A_{etch} = 1 - b/x_{film}$

Etching: mask erosion

Exercise

Consider structure shown at right in which an oxide layer, $x_f = 0.3\ \mu m$, is etched to achieve equal structural widths and spacing, S_f. If the etch process is characterized by $A = 0.9$ and $x = 0.2\ \mu m$, ***find S_f.***

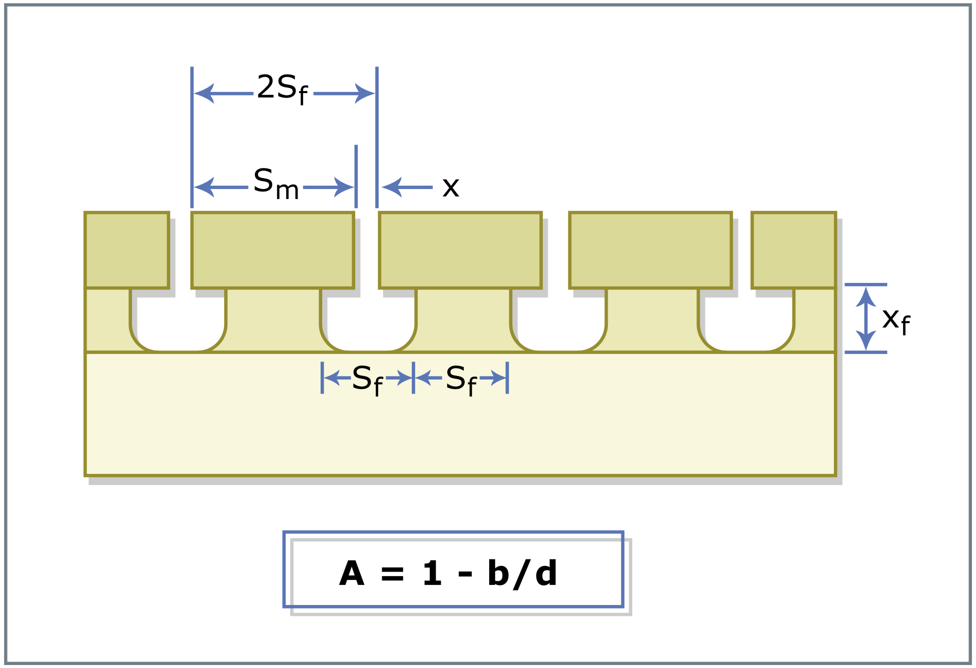


Figure by MIT OCW.

Solution

$$S_m = S_f + 2b = S_f + 2(1 - A_{etch})x_f$$ *(using result from prior page)*

Note that for anisotropic etch, $A = 1$ and $S_m = S_f$). Also from Fig., $x = 2S_f - S_m$.

Eliminate S_m to get: $x = S_f - 2(1 - A_{etch})x_f$ (typo in text), or

$$\mathbf{S_f = x + 2(1 - A_{etch})x_f} = 0.2 + 2 \times 0.1 \times 0.3\ ,\quad \boxed{\mathbf{S_f = 0.26\ \mu m}}$$

Note**: the size of the final etched feature, S_f, approaches minimum lithographic dimension only when x_f is very small or when A approaches unity.* ***Small features hard in wet etch.

Figure removed for copyright reasons.

Please see: Table 10-1 in Plummer, J., M. Deal, and P. Griffin. ***Silicon VLSI Technology: Fundamentals, Practice, and Modeling.*** Upper Saddle River, NJ: Prentice Hall, 2000. ISBN: 0130850373.

Isotropic Etches

Silicon Nitride

- Silicon Nitride is etched very slowly by HF solutions at room temperature, for example 20:1 BOE @20 C
  - Etch rate of SiO_2- 300 Å/min
  - Etch rate of Si_3N_4 – 5-15 Å/min
  - Very good selectivity of oxide to nitride
- Silicon nitride etches in 49% HF at room temperature at about 500 Å/min
- Phosphoric acid at 150 °C [140-200 °C] etches Si_3N_4 at fairly fast rate
  - Etch rate of Si_3N_4 – 100 Å/min
  - Etch SiO_2 – 10 Å/min
  - Selectivity of Si_3N_4 over SiO_2 : S = 10
  - Selectivity of Si_3N_4 over Si: S=30

Phosphoric Acid Etch Rate

Graph removed for copyright reasons.

Isotropic Etch

Aluminum

$50HNO_3 : 20H_2O : 1HNO_3 : 1CH_3COOH$

- Aluminum etches in water, phosphoric, nitric and acetic acid mixtures
- Converts Al to Al_2O_3 with nitric acid (evolves H_2)
- Dissolve Al_2O_3 in phosphoric acid
- Gas evolution leading to bubbles
- Local etch rate goes down where bubble is formed
  - Non-uniformity