EE6601, Semester 2, 2016/17
School of Electrical and Electronic Engineering, NTU

Problem Set #1 (Etching) - Solutions

Problem 1

(a) Explain why selectivity is an important consideration during etching of a film with respect to mask and underlying materials;

- to ensure there is minimal mask erosion, hence minimal undercutting
- to ensure no excessive over-etch to the underlying film

(b) Give example of silicon etchants that have different etching rate in the <100> and <111> orientations. What causes this difference and how it is utilized?

- Example of etchants: TMAH, KOH
- Cause: since (111) surface has higher number of atom per unit area, the etch rate is lower
- This method is widely used by the MEMS community for silicon micro-machining

(c) Explain why over-etching is always used in a manufacturing environment;

- to ensure complete removal of film as a result of variation in film thickness and etching rate

(d) You are an etch engineer in a wafer fab and you are developing a recipe to etch a 1.0 µm new material deposited on Si wafer. This new film is known to have excellent selectivity with respect to photo-resist. However, the deposited film has a ±5% thickness variation and a ±4% etch rate variation. Determine the minimum required over-etch time for complete removal of the film and the selectivity to ensure that only a maximum of 2.5 nm of Si is removed;

<u>Over-etch time:</u>

Thickest film = 1.05 µm, Slowest rate = $0.96R_{film}$

→ Time required = $1.05/0.96R_{film}$

Nominal time = $1/ R_{film}$

Therefore, over-etch = (Time required) / (Nominal time) = 1.094 or 9.4%

<u>Silicon etch depth:</u>

Thinnest film = 0.95 µm, Fastest rate = $1.04R_{film}$

→ Time required = $0.95/1.04R_{film}$

Time Si area is exposed = $1.05/0.96R_{film} - 0.95/1.04R_{film} = 0.18/R_{film}$

Therefore, $T_{Si} = R_{Si} \times (0.18/R_{film})$ => 2.5 nm or 0.0025 μm = $R_{Si} \times 0.18/R_{film}$

$$R_{Si} / R_{film} = 1:72$$

(e) Refer to Figure 1. You are using 10:1 HF @ 20 °C to etch an MOS capacitor as shown. The etching rates are 1.0 nm/min and 30 nm/min for Poly-Si and SiO2 respectively. The as-printed mask line-width is 1 μm and you can only tolerate a maximum of 5% undercut on the poly-Si. Determine the maximum thickness of the poly-Si gate and the total etching time needed. State all assumptions in your calculation.

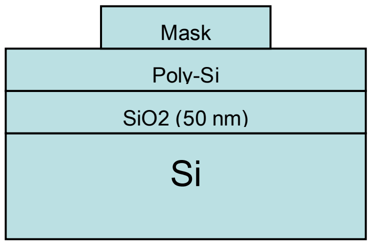


Figure 1

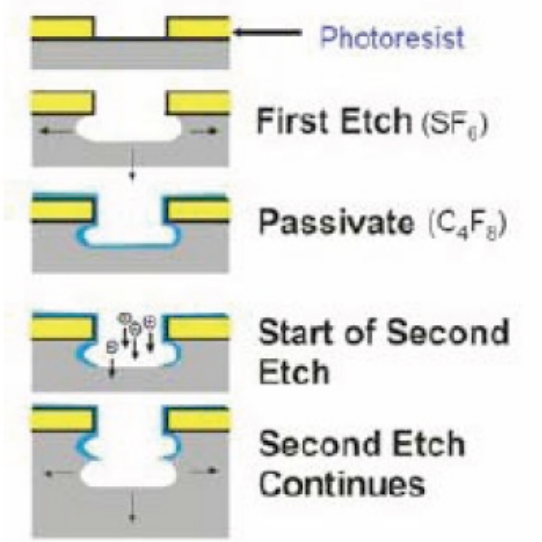
- assume that the photo-resist is not attacked and the etch is completely isotropic
- note that poly-Si will continue to be etched during SiO2 etching
- time to etch SiO2 = (50 nm)/(30 nm/min) = 1.7 min
- in 1.7 min, amount of poly-Si etched = (1.7 min) x (1.0 nm/min) = 1.7 nm
- maximum undercut of poly-Si = 5% x 1 μm = 0.05 μm
- therefore maximum poly-Si thickness is = 0.05 μm – 1.7 nm = 48.3 nm
- total etch time = (48.3 nm poly-Si)/(1.0 nm/min) + (50 nm SiO2)/(30 nm/min) = 50 min
- Note: In reality this is a bad choice of wet etchant for poly-Si etch, the sole purpose of this question is to demonstrate the idea of selectivity and under-cutting, it is not used in real life.

(2)

(a) Would it be possible to maintain a plasma using DC voltage? Explain the difficulties that might arise and how to overcome them in a plasma etch system;

- It is possible to maintain a plasma with DC voltage
- However, if the sample is not conducting, then the samples will begin to accumulate charge and prevent further discharge
- Solution: Using RF bias

(b) Do a study on a plasma etching method known as the Bosch Process that is used to etch very high aspect ratio profile;



Bosch process is a cyclical dry etch process consists of repetitive etch and passivation steps. It is widely used for silicon micro-machining for MEMS related works.

(c) Chlorine-based chemistry is widely used to etch Al. Can a similar dry approach be used on Cu?

- In principle is can be used, however the by-product is not versatile at back-end temperature of ~ 450C (unless high temperature step is used). Therefore it is Cl-based chemistry is not a practical choice for Cu etch.

(d) A plasma etch process is found to produce an etch rate of 30 nm/min when etching a single wafer. When a second wafer is added to the reactor the etch rate falls to 24 nm/min. What etch rate would you expect for three and four wafers?

- use macro-loading equation from pg 50 of Lecture notes on etching
- R = Ro/(1 + kA)
- (1) 30 nm/min = Ro/(1 + kA)
- (2) 24 nm/min = Ro/(1 + k.2A)
- Solve (1) and (2) and you will get: kA = 1/3 and Ro=40 nm/min
- Therefore: R(3 wafers) = 20 nm/min and R(4 wafers) = 17 nm/min

(e) For a particular plasma etch process in which the linear etch model is applicable, a degree of anisotropy of 0.8 or better is desired. If the unobstructed ionic flux on a flat surface is 3 x 10^{16} atoms cm^{-2} sec^{-1} (with K_i equal to 1), what unobstructed chemical flux would result in an anisotropy of 0.8. For this process S_C is 0.01 and K_f is 0.1.

Answer:

The degree of anisotropy is given as: $A_f = 1 - \frac{r_{lat}}{r_{ver}}$. For an A_f value of 0.8, $\frac{r_{lat}}{r_{ver}} = 0.2$. Using linear etch model, the etch rate in the lateral direction is given by equation in pg 55 of lecture slides with only the chemical flux term. The etch rate in the vertical direction is given by the same equation with both the chemical flux and ionic flux terms. Assuming no shadowing by the mask of the ion species in the center of the etch window (usually a reasonable assumption for the very directed ion species), we can let F_i equal the unobstructed flux of the ion species for the vertical etch rate. We also let F_c equal the unobstructed flux of the chemical species for both the vertical and lateral etch rates. This assumes completely isotropic behavior of the chemical species giving equal flux everywhere on the surface, even for narrow etch features, due to a low S_c.

Thus:

$$\frac{r_{lat}}{r_{ver}} = \frac{\left(\frac{S_c K_f F_c}{N}\right)}{\left(\frac{S_c K_f F_c + K_i F_i}{N}\right)} = \frac{S_c K_f F_c}{S_c K_f F_c + K_i F_i} = 0.2$$

Rearranging gives:

$$\frac{S_c K_f F_c}{S_c K_f F_c + K_i F_i} = 0.2 \;\Rightarrow\; S_c K_f F_c = 0.2\left(S_c K_f F_c + K_i F_i\right)$$

$$\Rightarrow 0.8\left(S_c K_f F_c\right) = 0.2\left(K_i F_i\right) \;\Rightarrow\; S_c K_f F_c = 0.25\left(K_i F_i\right)$$

$$\Rightarrow F_c = \frac{0.25\left(K_i F_i\right)}{S_c K_f}$$

Plugging in the numbers gives:

$$F_c = \frac{0.25\left(K_i F_i\right)}{S_c K_f}$$

$$= \frac{0.25\left(1 * 3x10^{16} cm^2 \sec^{-1}\right)}{0.01 * 0.1}$$

$$= 7.5\ x\ 10^{18} cm^2 \sec^{-1}$$

Any higher chemical flux would give a lower anisotropy.

(f) We want to see how the etch rate in the vertical direction might depend on pressure assuming that the etch follows the saturation/adsorption model. Assume that for a particular etch system that the chemical flux is directly proportional to the pressure, while the ion flux is inversely proportional to the pressure. That is $F_c = F_c' * P$ and $F_i = F_i'/P$. (P is normalized to 1 atm and unitless.) Also assume that density = 1 atom/nm^3, and that $K_i F_i' = S_c F_c' =$ 1 atom/nm^2/sec.

a. Plot the vertical etch rate versus pressure, P, from P = 0 to 10.

b. Repeat with $K_i F_i'$ = 40 atoms nm^{-2} sec^{-1} and $S_c F_c'$ = 1 atom nm^{-2} sec^{-1}.

Answer:

In the vertical direction, the etch rate will have contributions from both the chemical and ionic etch components, but acting an a synergistic fashion. For the saturation/adsorption etch model (ion enhanced etching):

$$\text{Etch Rate} = \frac{1}{\text{density}} \frac{1}{\left(\frac{1}{K_i F_i} + \frac{1}{S_c F_c}\right)} \text{ (pg 57 of lecture slides)}$$

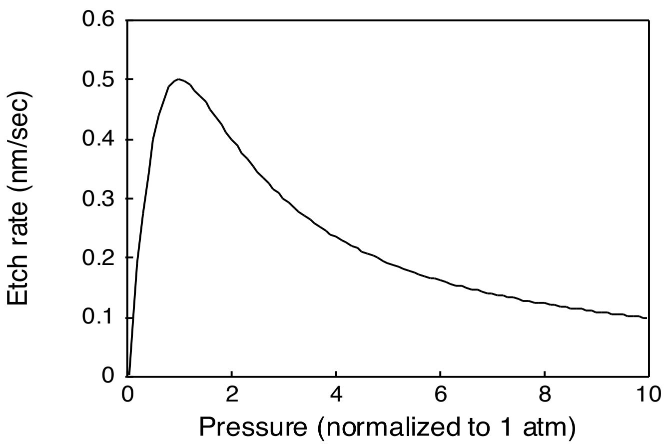
Plugging in $F_i = F_i'/P$ and $F_c = F_c'*P$, the density = 1 atom/nm^3, and that $K_i F_i'$ = $S_c F_c'$ = 1 atom/nm^2/sec gives:

Etch rate

$$= \frac{1}{\text{density}} \frac{1}{\left(\frac{1}{K_i F_i'/P} + \frac{1}{S_c F_c' * P}\right)}$$

$$= \frac{1}{1 \ \text{atom}/\text{nm}^3} \frac{1 \ \text{atom}/\text{nm}^2/\text{sec}}{\left(\frac{1}{1/P} + \frac{1}{1 * P}\right)}$$

$$= \frac{1}{\left(P + \frac{1}{P}\right)} \text{nm}/\text{sec}$$



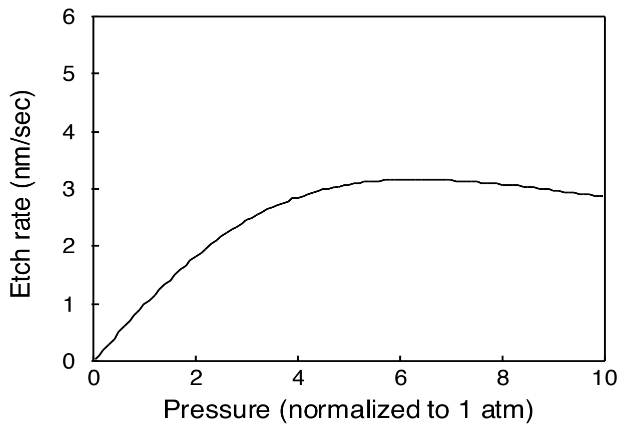
b. For $K_i F_i'$ = 40 atoms/nm^2/sec and $S_c F_c'$ = 1 atom/nm^2/sec:

Etch rate

$$= \frac{1}{\text{density}} \frac{1}{\left(\frac{1}{K_i F_i'/P} + \frac{1}{S_c F_c' * P} \right)}$$

$$= \frac{1}{1 \ \text{atom/nm}^3} \frac{1 \ \text{atom/nm}^2/\text{sec}}{\left(\frac{1}{40/P} + \frac{1}{1 * P} \right)}$$

$$= \frac{1}{\left(\frac{P}{40} + \frac{1}{P} \right)} \text{nm/sec}$$



(3)

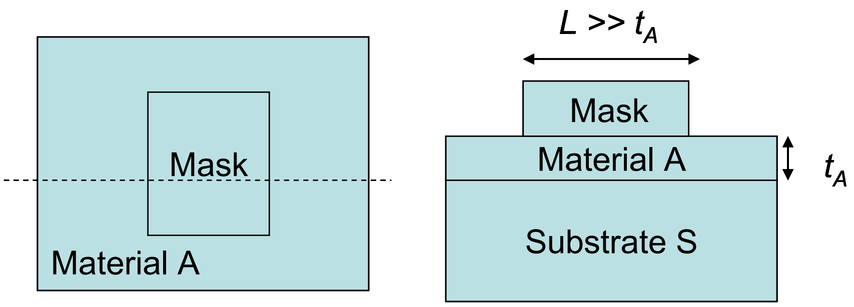
(a) One way to measure etch rate is to weigh the sample before and after etching, and translating that into the etch rate. If you use this method to determine silicon etch rate of a 8” wafer with 50% etching area, what is the resolution of the weighing scale that you need if you intend to etch at least 500nm of silicon with 1% error at the most? You can use silicon density as 2.65 g/cm^3. State any assumption you use;

- Assumption: Mask is not etched, at least 1% accuracy is targeted.
- 8” → 200 mm
- For the above etching, total silicon etch area, $A = \pi r^2$ = 50%.(3.14)(100e-1)^2 cm^2
- For 500 nm of silicon thickness (t),
  - total silicon etched = $A.t.\rho$
    = 50%. (3.14) (100e-1)^2(500e-7) (2.65)
    = 0.0208 g

- Weighing scale must be able to pick up change in 1% of 0.0208g = 0.000208g, hence a weighing scale with resolution of 0.0002g or 0.2 mg would be sufficient.

(b) Draw cross sectional schematics of the following structure under the etching conditions listed in Table, for two etching times: (i) right at end point, and (ii) 50% over-etch. State any assumption.

Profile	**A: S Selectivity**
Anisotropic	$\rightarrow \infty$
Anisotropic	5:1
Isotropic	$\rightarrow \infty$
Isotropic	5:1



Solution: Assume mask is intact.

Profile	**A: S Selectivity**	t_S	*Ua*	*Us*
Anisotropic	$\rightarrow \infty$	(i) 0 (ii) 0	0 0	0 0
Anisotropic	5:1	(i) 0 (ii) 0.2 x 0.5 x *ta*	0 0	0 0
Isotropic	$\rightarrow \infty$	(i) 0 (ii) 0	*ta* *1.5 x ta*	0 0
Isotropic	5:1	(i) 0 (ii) 0.2 x 0.5 x *ta*	*ta* *1.5 x ta*	0 0.2 x 0.5 x *ta*