NANYANG TECHNOLOGICAL UNIVERSITY

Course: EE3013 Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

Revision

Lithography – Summary

Lithography processing:

- UV light is used as the exposure source in optical lithography. Smaller UV wavelength enables printing of smaller features.
- For a positive resist, regions exposed to UV light will be washed away by the developer, whereas for a negative resist, regions shaded from UV light will be washed away by the developer.
- The eight basic steps of lithography include vapour prime, spin coat, soft bake, alignment and exposure, post-exposure bake, develop, hard bake, and develop inspect, sequentially.

Lithography – Summary

Lithography technology:

- Lithography aligners can be single exposure or multiple exposures.
- The resolution of lithography determines the smallest feature size it can print, whereas the depth of focus determines the range of tolerable focus error.
- Masks are used in single exposure aligners, whereas reticles are used in multiple exposure aligners.

Resist technology:

- Positive resist forms carboxylic groups after photochemical reaction with UV light, enabling it to be dissolved in the base developer.
- Negative resist forms polymer cross-linking after photochemical reaction with UV light, preventing it from dissolving in the organic developer.
- The important metrics of resist include resolution, contrast, and viscosity.

Lithography – Summary

Advanced lithography:

- Optical enhancement techniques in UV lithography include phase shift mask, optical proximity correction, and off-axis illumination.
- Immersion lithography improves the resolution and depth of focus by performing UV light exposure in an immersion liquid.
- X-ray lithography uses X-ray as its exposure source, whereas e-beam lithography uses an electron beam as its exposure source.
- SCALPEL combines all the benefits of step-and-repeat imaging, size reduction, and the narrow beam resolution of e-beam lithography to improve resolution and decrease exposure time.

Practice Question 1

Prove that for a given resolution, the use of a lens with the longest wavelength and the smallest numerical aperture gives the greatest depth of focus.

Pause and try out this question

$NA = n \sin \alpha$ --- (1)

$W_{\min} \approx k \dfrac{\lambda}{NA}$ --- (2)

$\tan \alpha \cong \sin \alpha = (W/2) / \sigma$ --- (3)

From (1), (2), and (3), we can derive: $\boldsymbol{\sigma} = \pm \dfrac{k_1\lambda / 2NA}{NA/n} \cong \pm \dfrac{k_2\lambda}{(NA)^2}$

i.e. longest wavelength and the smallest aperture gives the greatest depth of focus.

Practice Question 2

a) The figure shows the light intensity profiles incident on a substrate for exposure of a small circular feature through different lithography systems.

- Identify the types of lithography systems associated with the profile (i) and (ii).
- List the advantages or disadvantages of the two systems.

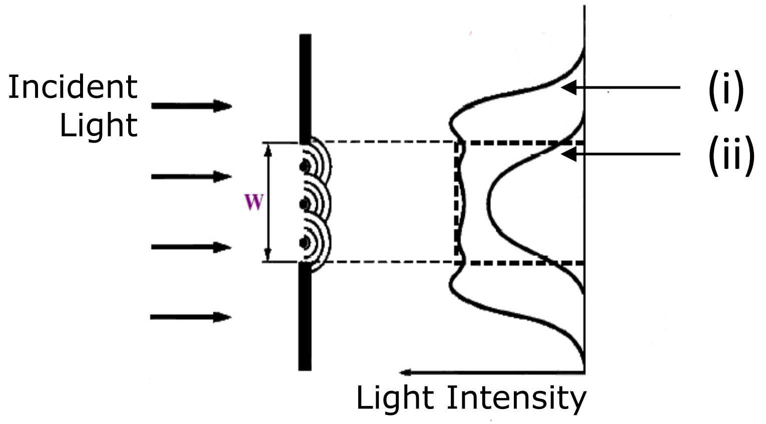


Figure: Light Intensity Profiles

Pause and try out this question

b) Determine the resolution W of the optical lithographic system using a KrF stepper (λ: 248nm) for the two cases:

i. Proximity printing with a gap of 0.6μm;

ii. Projection printing using a numerical aperture (NA) of 0.45.

Comment on your result. Assume the resist constant k = 1.

Practice Question 2

Pause and read carefully

a) i. Proximity Printer

ii. Projection Printer

Proximity Printer: High resolution of the order of 1μm, the problem with dust particles.

Projection Printer: Less damage by dust particles, the low resolution of the order of 2-5μm due to the fringe.

b) i. $$W_{min} = \sqrt{k\lambda g} = \sqrt{248x10^{-9} \times 0.6x10^{-6}}$$
$$= 3.86x10^{-7}\, m$$

ii. $$W_{min} \approx k\frac{\lambda}{NA} = \frac{1x\ 248\ x10^{-9}}{0.45} = 5.55 \text{ x } 10^{-7} \text{ m}$$

Slightly better resolution from the proximity printer.

Practice Question 3

a) Which type of resists requires shorter exposure time with higher throughput? What are the disadvantages of using such resists?

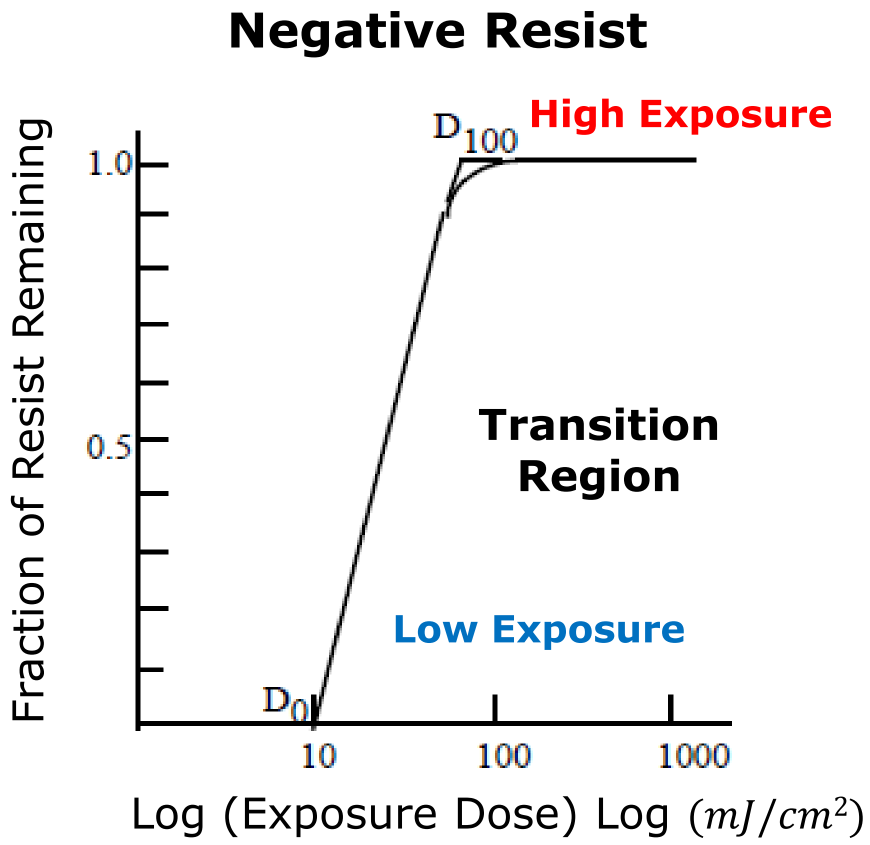
b) Define resist contrast. Explain with the aid of a diagram, how can the contrast of a negative photoresist be determined?

Pause and try out this question

Practice Question 3

a) Negative resist. Negative resist suffers from swelling. Broadening of the linewidth during the development phase causes the lines to be distorted and hence not suitable for features less than 2µm.

Pause and read carefully



b) Negative resist: The curve has three regions;
high exposure where almost all of the resist remains,
low exposure where all of the resist is removed,
and the transition region between these two extremes.

To derive a numerical value for the contrast of a photoresist, first approximate the steeply sloped portion of the curve by a straight line. The lowest energy needed to begin to drive the photochemistry is called D_0. The line extends from the lowest energy dose to D_{100} for which all of the resist remains on the wafer. The contrast is defined as

$$\gamma = \left[\log_{10}\frac{D_{100}}{D_0}\right]^{-1}$$

which is simply the slope of the line.

Practice Question 4

a) One future possibility for lithography systems beyond conventional optical projection tools is an optical projection system using a 157-nm F_2 excimer laser. If its resolution is 22nm, what is the expected numerical aperture of such a system? Assume k = 0.75.

b) Actual projections for the system mentioned above suggest that it might be capable of resolving features beyond 22nm node technology. Suggest three approaches to achieving higher resolution with this system.

c) An X-ray exposure system uses photons with an energy of 1 keV. Due to some mistake, or a dust particle, the separation between the mask and wafer is increased to 20 μm. What is the effect of the increased gap on the image and estimate the wavelength deployed by this system? Assume k = 1.

Pause and try out this question

Practice Question 4

a) The formula for resolution is $R = k_1 \frac{\lambda}{NA}$

$$0.22\mu m = 0.75\,\frac{0.157\mu m}{NA}$$

$$NA = 0.54$$

Pause and read carefully

b) The calculated resolution in part (a) is more than a factor of two larger than required for the 0.07μm generation. Therefore some “tricks” will have to be used actually to achieve such resolution. There are a number of possibilities:

   i. Use of phase-shift masks. This technique works by designing a more sophisticated mask. Simple masks are digital - black or white. Phase shifting adds a second material to the mask features, usually at the edges which shifts the optical phase and sharpens up the aerial image. Sophisticated computer programs are required to design such masks.

Practice Question 4

b) ii. Use of optical proximity correction in the mask design. This is another approach to designing a better mask and can also improve the resolution significantly. The approach involves adding extra features to the mask, usually at corners where features are sharp, to compensate for the high-frequency information lost to diffraction effects.

iii. Off-axis illumination. This allows the optical system to capture some of the higher-order diffracted light and hence can improve resolution.

c) Increased gap --- Min resolution ↑ (worse off)

The equivalent wavelength of 1 keV x-rays is given by

$$\mathrm{E} = hv = \frac{hc}{\lambda} \qquad \lambda = \frac{hc}{E} = \frac{(6.626 * 10^{-34})(3 * 10^{8})}{10^{3} * 1.6 * 10^{-19}} m = 1.24nm$$

Pause and read carefully

Revision Part 2

Etching – Summary

Comparison:

- Wet etching usually yields an isotropic etching profile; whereas dry etching usually yields an anisotropic etching profile.
- Wet etching uses wet chemical etchant; whereas dry etching uses ionic/ plasma etchant.

Wet Etching:

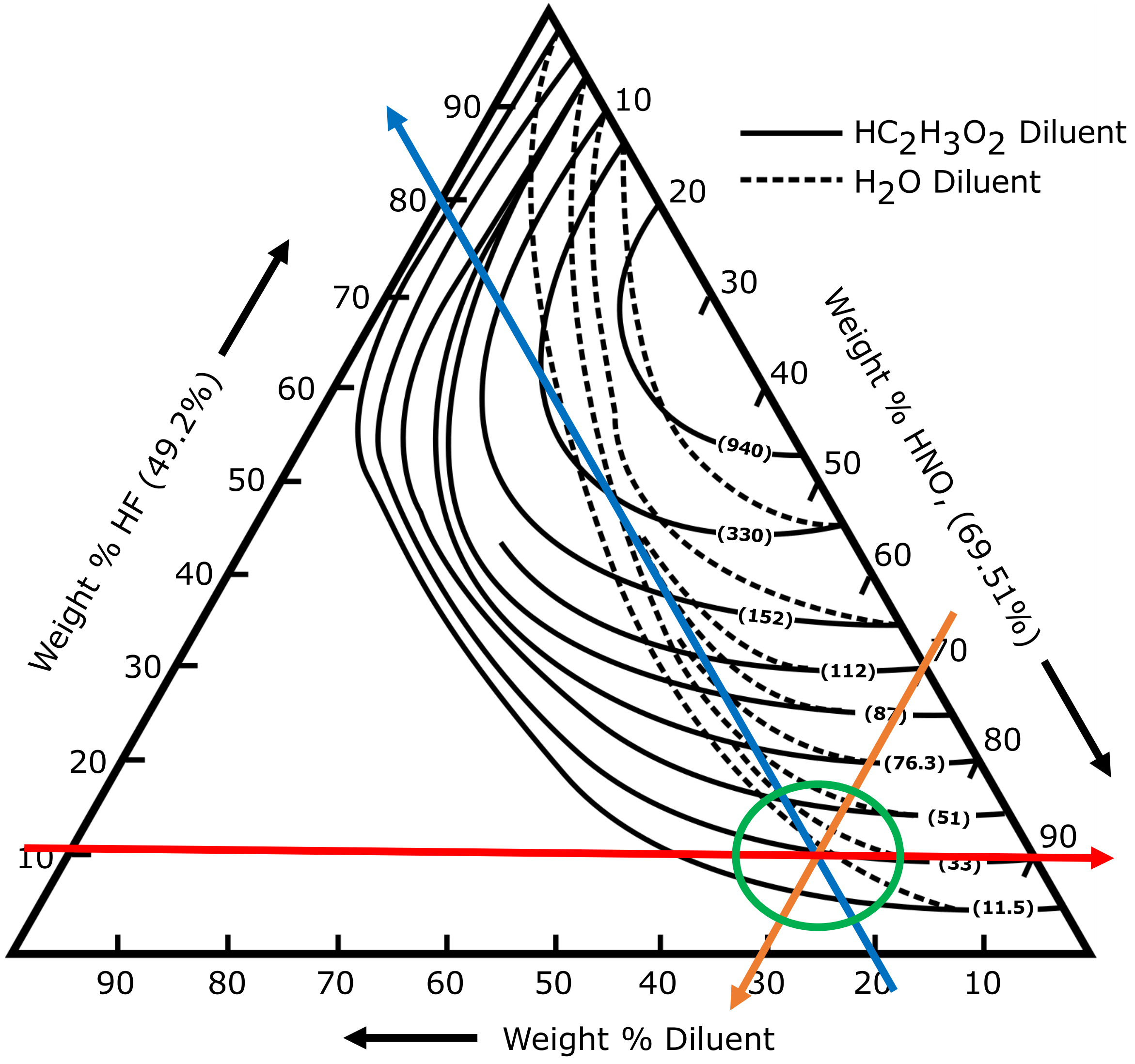
- Wet etching uses chemical etchants to etch away the target materials.
- In wet etching of Si, HNO_3 is used to oxidise Si into SiO_2; and HF is used to etch away the formed SiO_2.
- The etching rate of Si depends on its crystal orientation for certain etchants.

Etching – Summary

Dry Etching:

- Dry etching uses ionic (plasma) etchants to etch away the target materials.
- Plasma generation involves ionisation, recombination, excitation, relaxation and dissociation processes.
- Sputter etching uses inert ions (argon), whereas reactive ion etching uses reactive ions (C_2F_6).
- The operation of an RIE system is governed by the plasma potential and the area of the electrodes.
- Important parameters in dry etching include etchant gas flow rate, the average residence time of the etchant gas, steady state pressure of the system chamber, and pumping speed of the etching system’s pump.
- Plasma etching may cause sidewall damage, surface damage, and edge damage on the substrate.

Determining the Si Etch Rate From Iso-Etch Curve



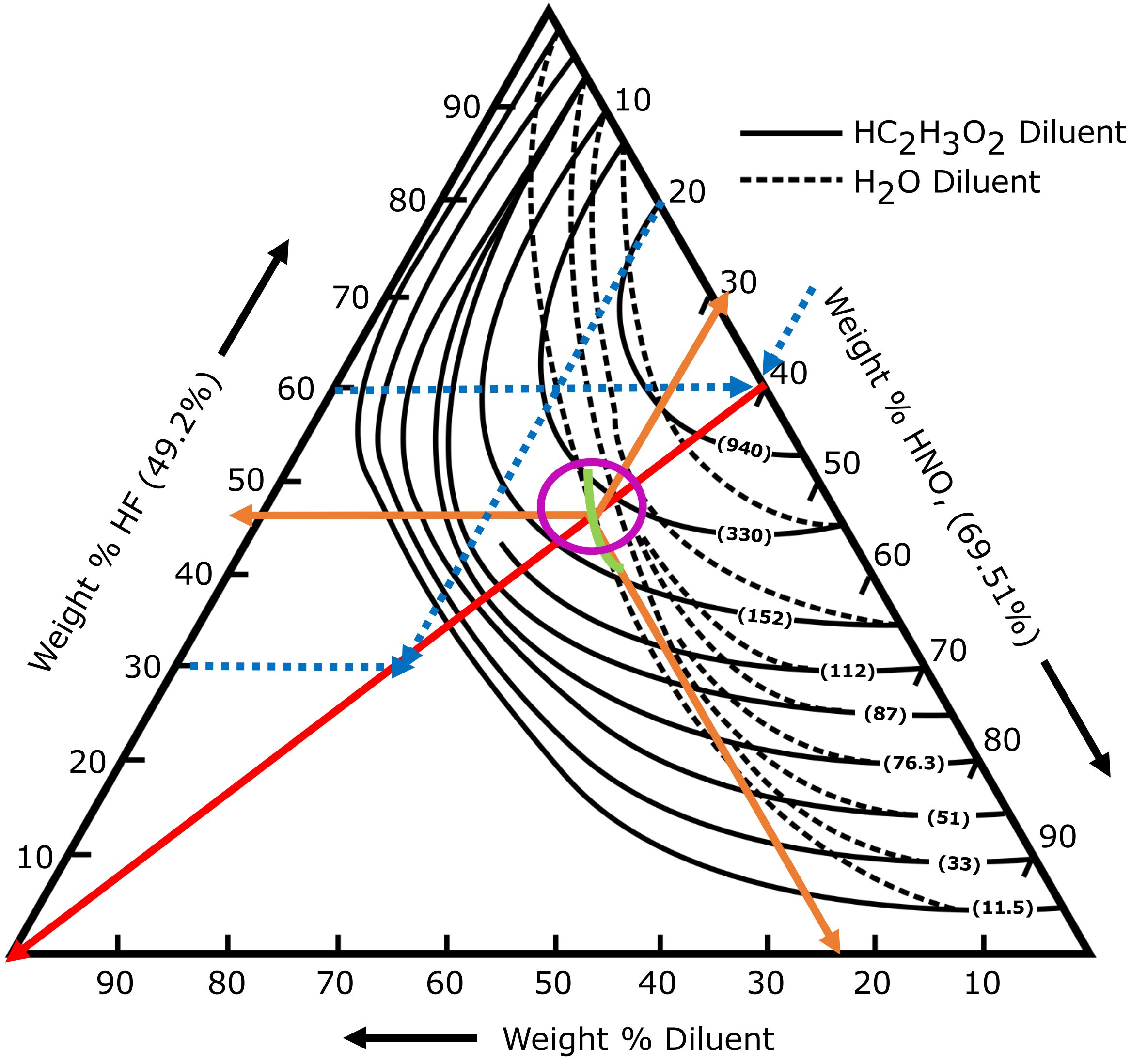
How to determine the Si etch rate using the iso-etch curve?

For example, if a mixture of 10% HF, 70% HNO_3, and 20% water diluent is used as Si etchant:

1. Draw a line of such from 10% HF axis.
2. Draw a line of such from 70% HNO_3 axis.
3. Draw a line of such from 20% diluent axis.
4. The intersection point of these three lines falls at 11.5 μm/min curve of the dashed line (water diluent). Therefore, the Si etch rate is 11.5 μm/min.

Pause and observe carefully

Determining the % Constituent From Iso-Etch Curve

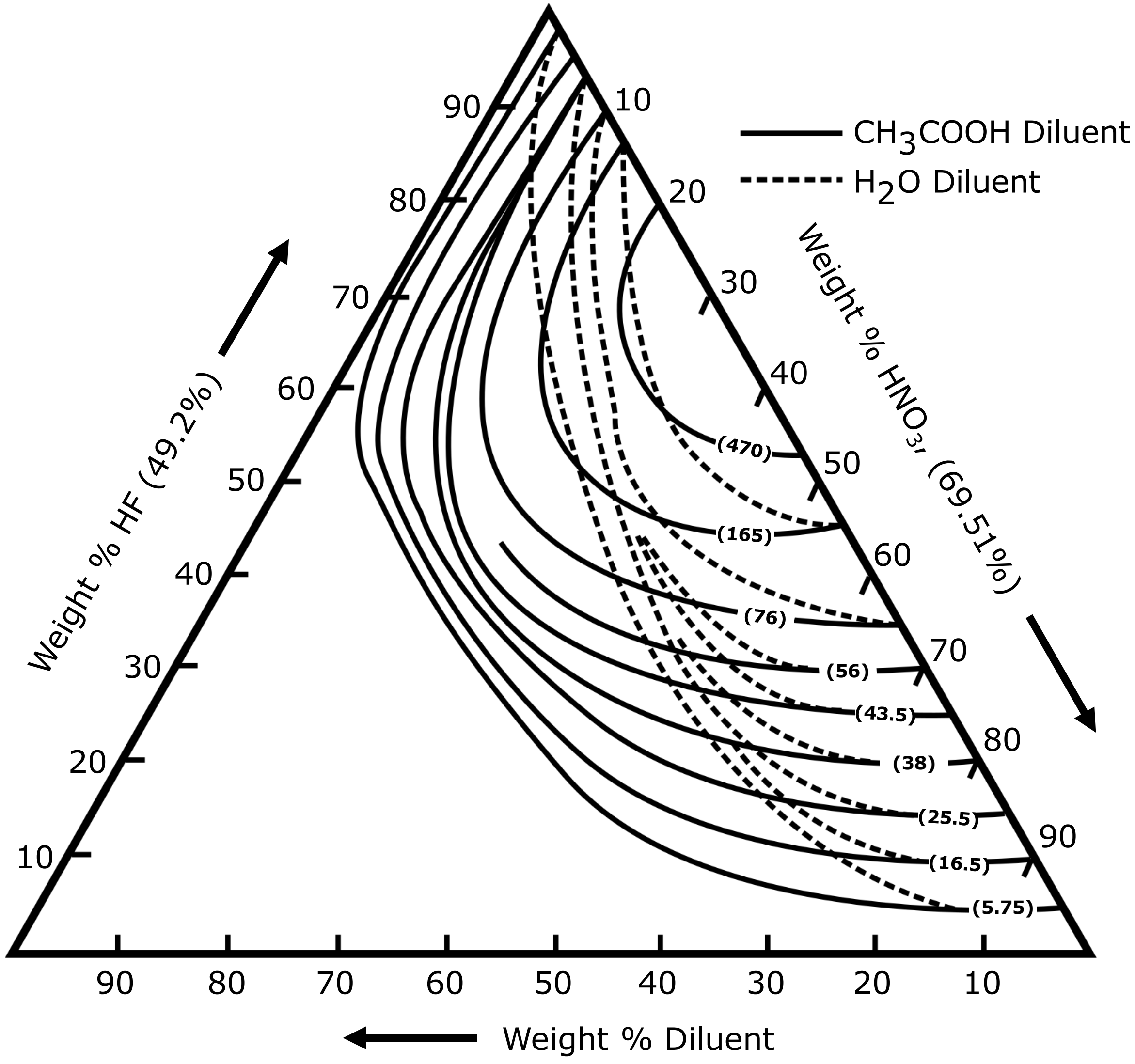


Assuming an etch rate of 11.5 um/min and the ratio of HF: HNO_3 is maintained at 3:2, what is the weight % of H_2O used in the etchant.

1. Draw the 3:2 load line by first identifying two coordinates: (30%, 20%) and (60%, 40%) of HF – HNO_3.
2. Identify the point of intersection of this load line with the contour line 11.5 um/min.
3. Project from the intersection point to the three respective axes.
4. Determine the % constituent from the three axes: (1) 46% HF (2) 31% HNO_3 (3) 23% H_2O

Pause and observe carefully

Practice Question 1

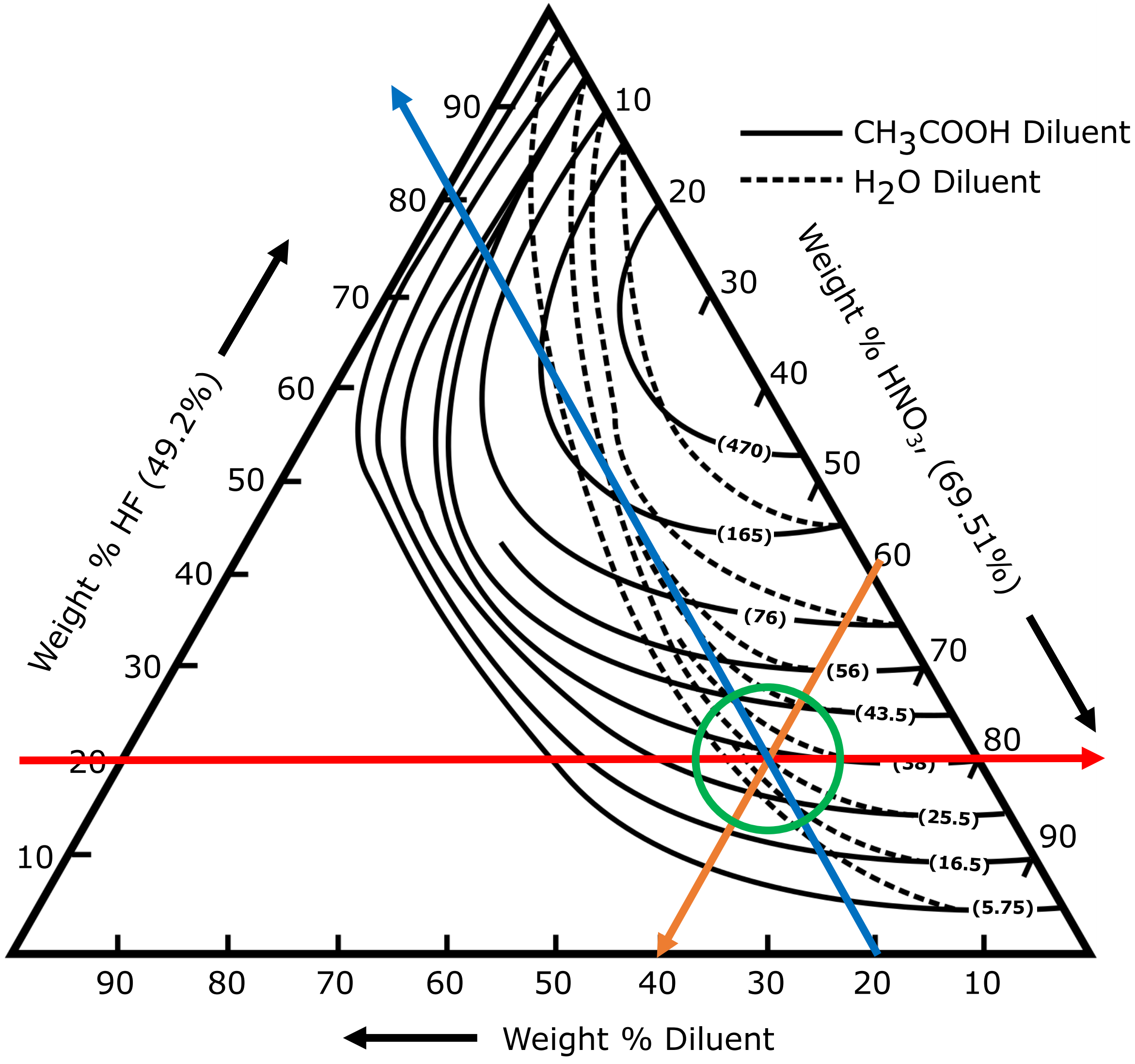


a) The figure shows the iso-etch curve for silicon using the HF: HNO_3: diluent system. A hole must be wet etched through a silicon wafer that is 700μm thick. A mixture of two parts of H_2O, two parts of HF and six parts of HNO_3 is mixed together to perform the etch. How long should the etch take?

b) If the diluent is to now be changed to CH_3COOH and its ratio is maintained the same as HF, what will be the new composition(s) of HNO_3 assuming an etch rate of 36μm/min? Why the etch rate is usually higher with use of CH_3COOH as a diluent?

Pause and try out this question

Practice Question 1

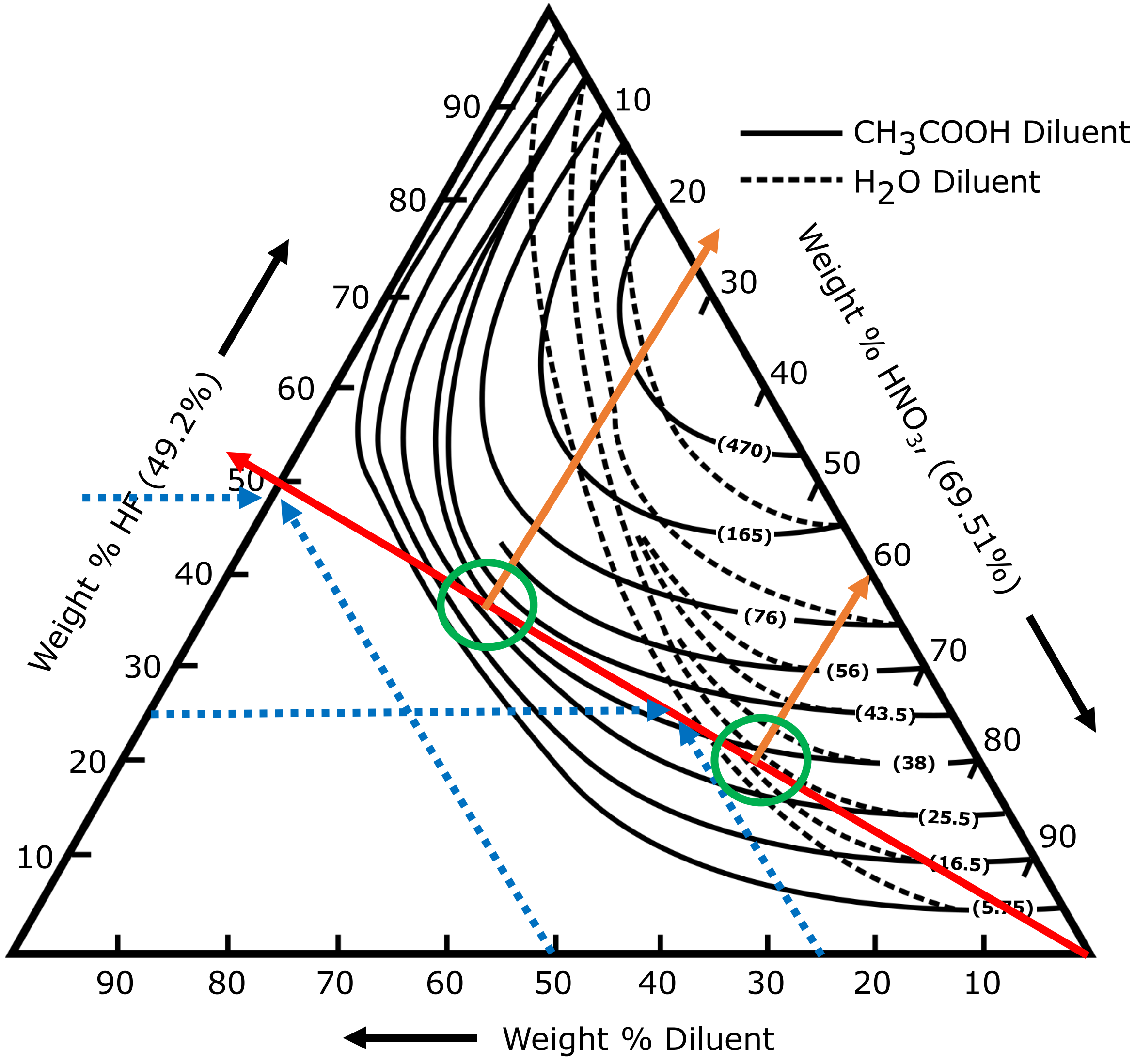


Answer a):

1. Draw a line of such from 20% HF axis.
2. Draw a line of such from 60% HNO_3 axis.
3. Draw a line of such from 20% diluent axis.
4. Intersection point of these three lines falls at 25.5 μm/min curve of the dash line (water diluent). Therefore, the etch time is 700/25.5 = 27.5 mins.

Pause and read carefully

Practice Question 1



Answer b):

1. Draw the 1:1 load line by first identifying two coordinates: (50%, 50%) and (25%, 25%) of HF-CH_3COOH.
2. Identify the point of intersection of this load line with the contour line 36 um/min. There is two possible points of intersections as seen.
3. Project from these intersection points to the HNO_3 axis.
4. Determine the % constituent of HNO_3: Can either be 28% or 60%.

Use of CH_3COOH – It also produces less dissociation of the HNO_3, which yields a higher oxidation power for the etching process.

Pause and read carefully

Practice Question 2

a) The figure shows the schematic layout of an RF discharge system. Gases available in this system are CF_4, O_2, and H_2. Name this system.

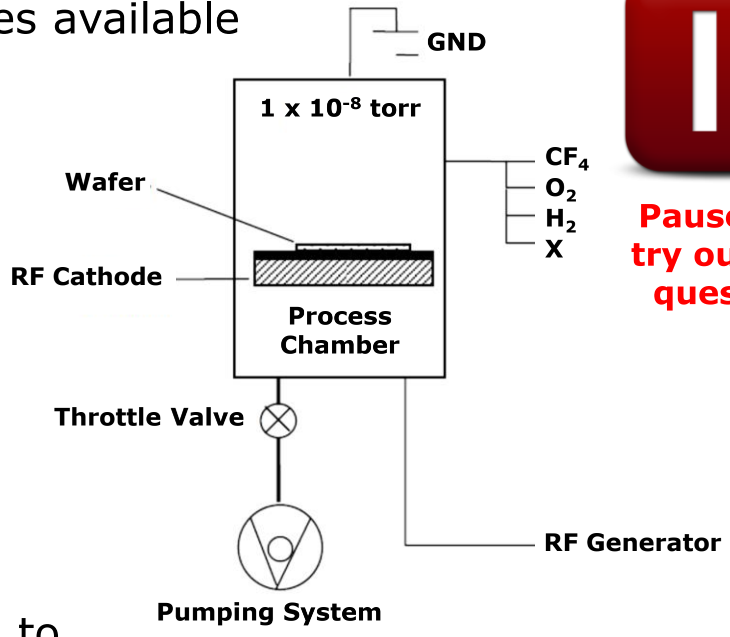
b) Explain why the RF cathode is negatively biased?

c) Gas mixtures are often used to control etch processes. Discuss how one would inhibit a CF_4 etch with the addition of O gas?

d) Given the chamber volume of the above system is 10 litres, the pressure is stabilized at 5 torr and the residence time of the process gas is 1 second, determine the speed of the pumping system and the flow rate of the gas feed. Discuss whether it is possible to increase etching rate of the system just by increasing the flow rate of the gas feed.

e) As seen in Figure 1, there is a spare outlet for an unknown gas, X. An engineer intends to reconfigure the above system for RF sputtering of Silicon Dioxide (SiO_2) onto a Si wafer. Name the gas X to be deployed and what modifications he needs to carry out on the system.

f) What are the advantages of an RF sputtering system in comparison to a thermal evaporator?



Pause and try out this question

Practice Question 2

a) RIE System

b) Answer:

- When the electrode (which is connected to the RF generator) is positive, many highly mobile electrons are accelerated towards the electrode causing a significant accumulation of negative charge.
- When the electrode (the cathode) is negative, heavy, immobile ions are accelerated towards. However, only relatively few of these ions strike the electrode compared to the number of electrons on the previous cycle.
- Hence the RF cathode is negatively biased.

Pause and read carefully

Practice Question 2

Pause and read carefully

c) Inhibiting a CF_4 etch:

Adjusting C, O balance by adding small amounts of O_2:

- Etching is mostly done by reactive neutral species – Free radicals such as F.
- Additives like O_2 can be used that react with CF_3 (and CF_2, form CO and CO_2) and reduce CF_3 + F recombination, thus higher F concentration and higher etch rate.
- However, too much O_2 reduces etch rate due to a dilution effect, the competition of O with F for surface sites.

d) $t_r = \frac{V}{S} = 1\ s$

Therefore S = *10 litre/s*

$S = \frac{F\ x\ 760}{P}$, hence F = *65ml/s*

It is not possible to increase the etching rate of the system just by increasing the flow rate of the gas feed, because the residence time (which is dependent on both *V* and *S*) remains unchanged due to fixed value of *V* and *S*.

Practice Question 2

e) Answer:

- Gas X: Ar gas
- Add an anode electrode.
- Place a SiO_2 target on the cathode.
- Place the Si wafer on the anode.

f) Advantages of Sputtering:

- Able to deposit a wide variety of metals, insulators, alloys, and composites.
- Able to deposit compound/ alloy thin film – The film has the same composition as the sputter target.
- Better film quality (densified) and step coverage than evaporation. This is partly because adatoms are more energetic.
- More reproducible deposition control – Same deposition rate for same process parameters (not true for evaporation), so easy film thickness control via time.
- Can use large area targets for uniform thickness over large substrates.
- Sufficient target material for many depositions.
- No x-ray damage.

Pause and read carefully

Revision Part 3

PVD – Summary

- Step coverage and trench filling are important figure of merit in a thin film deposition, where trench filling is highly dependent on the aspect ratio of the trench.
- PVD can be carried out using evaporation technique or a sputtering technique.
- Evaporation technique can either be carried out using thermal evaporation or electron beam evaporation.
- For the sputtering process, high energetic argon ions are used to dislodge atoms from target materials for deposition.
- Sputter yield depends on ion energy, ion mass, and the incident angle of the ion.
- RF sputtering can prevent charge accumulation on the substrate, hence, making dielectric deposition possible. However, magnetron sputtering induces spiral motion on ions, which increases the sputter yield.

CVD – Summary

- CVD is a thin film deposition technique based on chemical reactions that are supplied through the use of gaseous compounds.
- CVD is usually used to deposit dielectric films, such as silicon oxide and silicon nitride films.
- CVD process can be summarised as transportation of gas reactants onto substrate, chemisorption and reaction of the gas reactants onto the substrate, transportation of by-product away from the substrate, and purging of the by-product from the chamber.
- CVD deposition rate is limited by the gas reactant transportation-limited regime and surface reaction-limited regime.
- To maximise the film deposition, various types of CVD techniques can be used, such as Atmospheric-Pressure CVD, Low-Pressure CVD, and Plasma-Enhanced CVD.

Practice Question 1

You want to increase your sputter deposition rate for silver (Ag) electrical contact.

You had been using Ar sputtering gas. Discuss how the following changes would help to **increase the Ag deposition rate**:

a) Switch sputtering gas to Kr (with a much heavier atomic mass unit than Ar).

b) Increase the anode-cathode potential difference.

c) Reduce the pressure in the chamber.

Pause and try out this question

a) Switching to Kr (better mass match to Ag) will increase the sputtering yield of Ag at the target

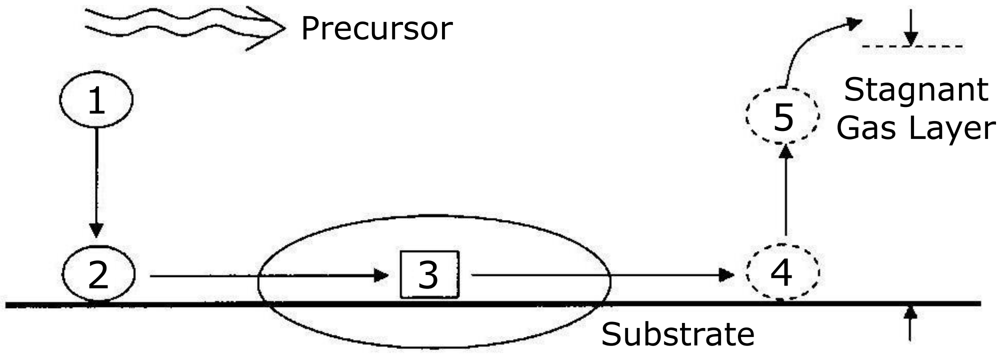
b) Increasing the anode-cathode potential difference will increase the rate of sputtering from the target and increase the deposition rate.

c) Reduced pressure (higher vacuum) in the chamber increases the deposition rate because there are fewer collisions for Ag between the target and substrate.

Practice Question 2

a) The figure below shows the mechanisms for Chemical Vapour Deposition.

Identify the mechanisms associated with the numbers.



b) Compare the advantages of APCVD, LPCVD, and PECVD.

Pause and try out this question

Practice Question 2

a) Answer:

1. Diffusion of precursor to the surface
2. Absorption of precursor to the surface
3. Chemical reaction
4. Desorption of gaseous by-products
5. Transportation of gaseous by-products

b) Answer:

Type	Advantage	Disadvantage
APCVD	Simple and fast	Poor step coverage
LPCVD	Excellent purity, conformity, and uniformity	Low deposition rate
PECVD	Low deposition temperature	Plasma damage, more maintenance intensive, and requires RF generator

Pause and read carefully

Practice Question 3

Pause and try out this question

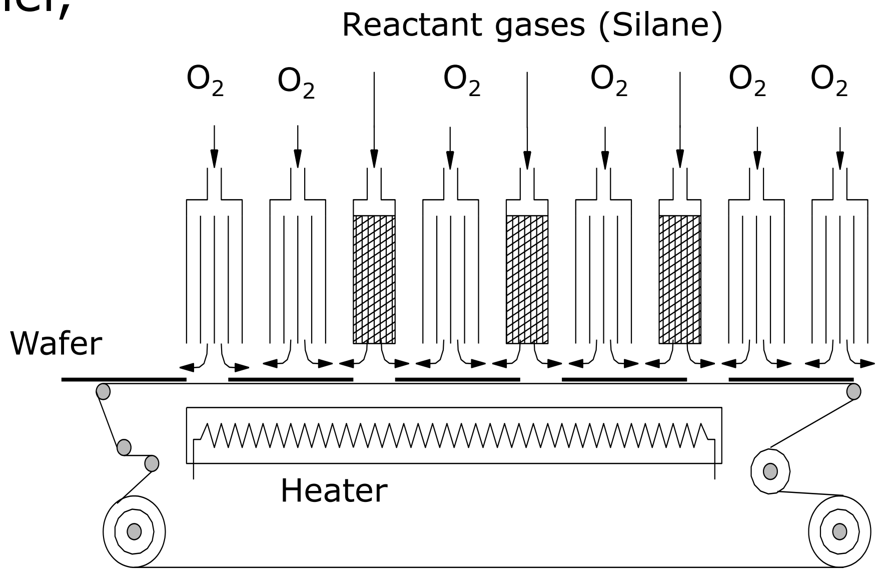
The figure below shows a typical CVD process system which deployed horizontal stacking of wafers for film growth.

a) Identify the type of CVD system.

b) Explain, giving reasons, whether the film growth in this CVD system is reaction-rate or gas transport limited.

c) If the wafers are to be stacked vertically and closed together, explain with reasons, what modifications need to be implemented to the system?

d) From the gases available, identify the materials developed by this system and write the overall chemical reaction for the deposition process.



Practice Question 3

a) APCVD

b) Gas Transport limited (collision of gas molecules with air molecules)

c) Change the system from APCVD to LPCVD to operate under reaction rate limited. Incorporate vacuum pumps, vacuum chamber, mass flow controller. Operated at low pressure (diffusivity of gas species is increased), increase in the transport of reactants to the substrate surface. Since there is no issue with gas transport, one can afford to stack the wafers vertically close to each other.

d) $\mathrm{SiH_4 + 2O_2 \rightarrow SiO_2 + 2H_20}$

Pause and read carefully

Practice Question 4

You are using a CVD system for which the data shown below has been proven reliable for the growth of poly Si.

a) Write the chemical reaction for silane pyrolysis to grow Si at 650°C.

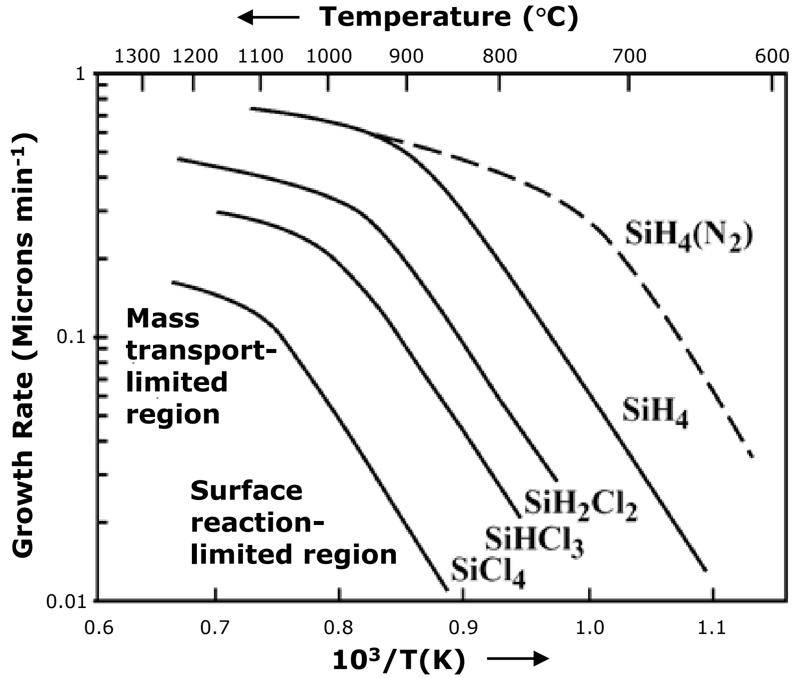
b) Is this film growth *reaction-rate limited* or *gas transport limited*?

c) How would you calculate the activation energy for this reaction?

d) You want to grow your Si film more smoothly with lower deposition rate. To achieve this, how would you do the following:

- Increase or decrease processing temperature, T?
- Increase or decrease the gas flow rate?

Pause and try out this question



Practice Question 4

a) SiH_4 (g) => Si (s) + $2H_2$ (g)

b) From the figure above, it is reaction-rate limited (strong linear ln(v) vs 1/T).

c) It is given by the slope of these ln(v) vs 1/T curves in the reaction-limited regime.

d) Answer:

   i. Decrease *T* to slow down the reaction-limited growth rate.

   ii. The reaction-limited process is not affected by the gas flow rate.

Pause and read carefully

Conclusions

- Able to explain the basic concepts for photolithography, determine the resolution of printers and describe the types of photoresists used in wafer manufacturing.
- Able to discuss the optical enhancement techniques for sub-wavelength lithography, describe the alternatives for advanced lithography, including the challenges for introducing each alternative into production.
- Able to explain wet and dry etch including their advantages and how etching action takes place.
- Able to provide an overview of the different PVD and CVD film deposition techniques.