NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 1 EXAMINATION 2019-2020

EE3013 – SEMICONDUCTOR DEVICES AND PROCESSING

November / December 2019   Time Allowed: 2 hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 9 pages.

2. Answer all 4 questions.

3. All questions carry equal marks.

4. This is a closed book examination.

5. Unless specifically stated, all symbols have their usual meanings.

6. A List of Formulae is provided in Appendix A on pages 7 and 8. The Table of Physical Constants is provided in Appendix B on page 9.

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1. (a) An ideal one-sided silicon p^+n junction at $T = 300$ K is uniformly doped on both sides of the metallurgical junction. Given that the doping relation $N_A = 80\ N_D$, the built-in potential barrier $V_{bi} = 0.74$ V and $n_i = 1.5 \times 10^{10}$ cm^{-3}. When a reverse-biased of $V_R = 10$ V is applied, determine:

    (i) N_A and N_D.

    (5 Marks)

    (ii) Junction capacitance (C_j) in unit of F/cm^2

    (4 Marks)

1

(b)   The dc charge distribution of two ideal MOS capacitors are shown in Figure 1. For each case, determine:
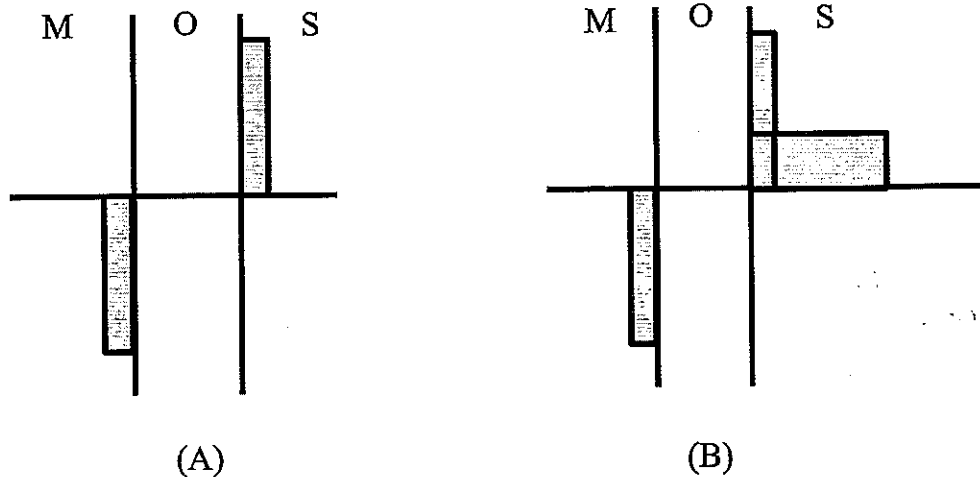

(A)   (B)

Figure 1

(i)   Whether the semiconductor is n or p type. Explain your answer.

(4 Marks)

(ii) Whether the device is biased in the accumulation, depletion, or inversion mode. Explain your answer.

(4 Marks)

(c)   Consider a uniformly doped silicon npn bipolar junction transistor at $T = 300$ K. The device is biased in the forward-active mode with $V_{CB} = 2.5$ V. The metallurgical base width is 1.0 μm. The doping concentrations in the emitter, base and collector are 8×10^{17} cm^{-3}, 2×10^{16} cm^{-3} and 1×10^{15} cm^{-3}, respectively. The intrinsic concentration of silicon (n_i) is 1.5×10^{10} cm^{-3}.

(i)   Sketch the minority carrier distributions across the transistor.

(4 Marks)

(ii) Determine the base-emitter voltage such that the minority carrier concentration at the edge of the emitter-base depletion region is 10% of the majority carrier hole concentration.

(4 Marks)

2. (a) (i) An one-hour dry oxidation at 1000 °C is followed by a 5-hour wet oxidation at 1100 °C. Estimate the final oxide thickness graphically using Figure 2.

(4 Marks)
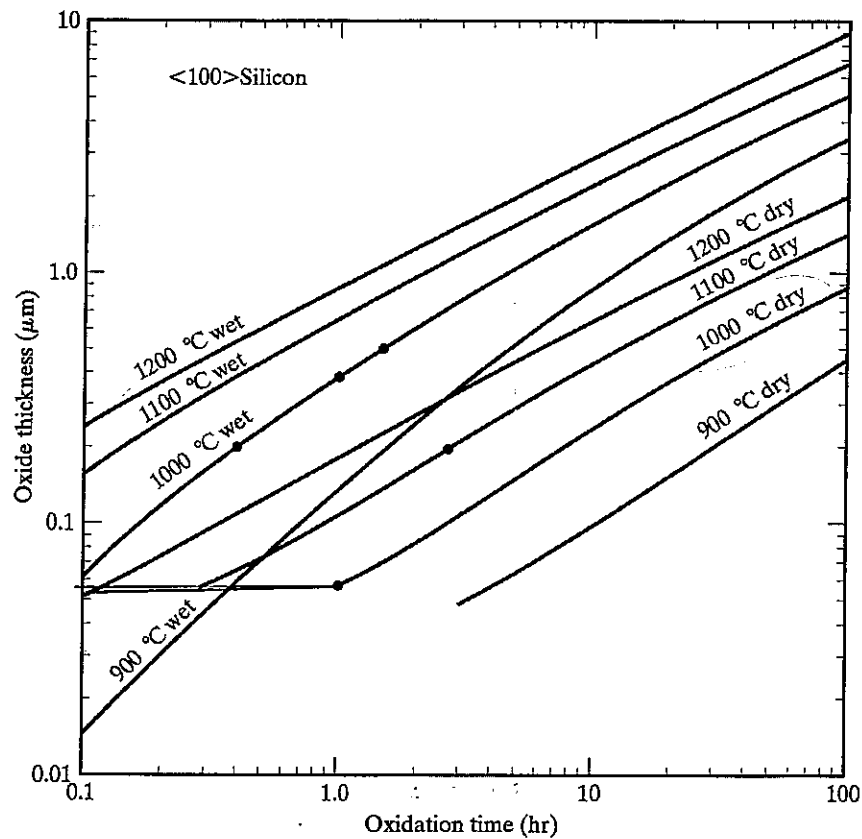
Figure 2

(ii) Sketch the oxide thickness versus time diagram, and indicate the regions for linear and parabolic growth rates. For each region, explain the limiting factors for these two growth rate regions.
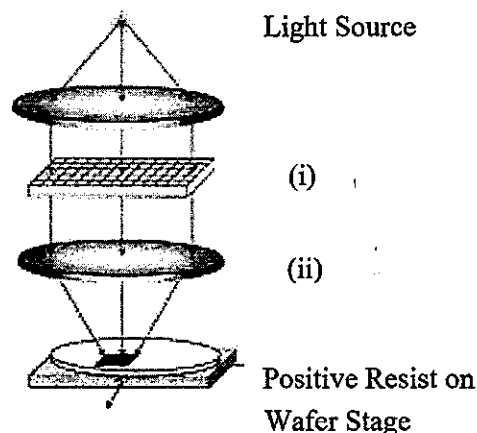
(5 Marks)

(b) (i) A p-n junction with a junction depth of 2 μm is formed by diffusing pre-deposited boron atoms into the n-type silicon substrate at 1150 °C for 1 hr. The dose for the pre-deposited boron atoms is 3×10^{13} boron atoms/cm^2. Assuming that the diffusion is Gaussian, find the doping concentration of the n-type silicon substrate. Given that $D_B = 9.2 \times 10^{-13}$ cm^2/s at 1150 °C.

(4 Marks)

(ii) Name two types of devices which use diffusion, and name two advantages of diffusion process.

(4 Marks)

(c) (i) Boron is implanted into silicon with an energy of 60 keV through a 0.25 μm layer of silicon dioxide. Given that the implanted dose is 1×10^{14} cm^{-2}, the straggle range ΔR_p is 0.09 μm and the projected range R_p is 0.19 μm, find the junction depth from the silicon-silicon dioxide interface if the background concentration of silicon is 3×10^{15} cm^{-3}.

(5 Marks)

(ii) Name three advantages of using ion-implantation for doping in wafer processing.

(3 Marks)

3. (a) Identify the optical lithographic system as shown in Figure 3 and name the labelled parts (i) and (ii).

(3 Marks)

Light Source

(i)

(ii)

Positive Resist on
Wafer Stage

Figure 3

(b) Suggest possible types of light source that can be deployed in the system.

(2 Marks)

(c) 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. Determine the depth of focus of the system which uses a wavelength $\lambda = 248$ nm and numerical aperture (NA) of 0.45. Assume the constant $k_2 = 1$.

(8 Marks)

(d) The system was used to define a T-shaped metallization in a lift-off process. Draw the mask used, identifying the transparent section of the mask.

(5 Marks)

Note: Question No. 3 continues on page 5.

4

(e) Define resist contrast, γ. Given that γ is 1.05 and the lowest energy dose of 90 mJ/cm^2 for which all of the resist is removed, draw the contrast curve of the resist. Discuss the performance of a resist with infinite-contrast value.

(7 Marks)

4. (a) Figure 4 shows the isoetch curve for silicon using HF:HNO$_3$:CH$_3$COOH etchant. Identify the particular load line drawn in the figure. The load line intersects the etch rate contour line of 76 μm/min at two points, A and B as shown in the figure. For point A, name the controlling etching agent, and for point B, determine the respective percentage of the etchant constituents.
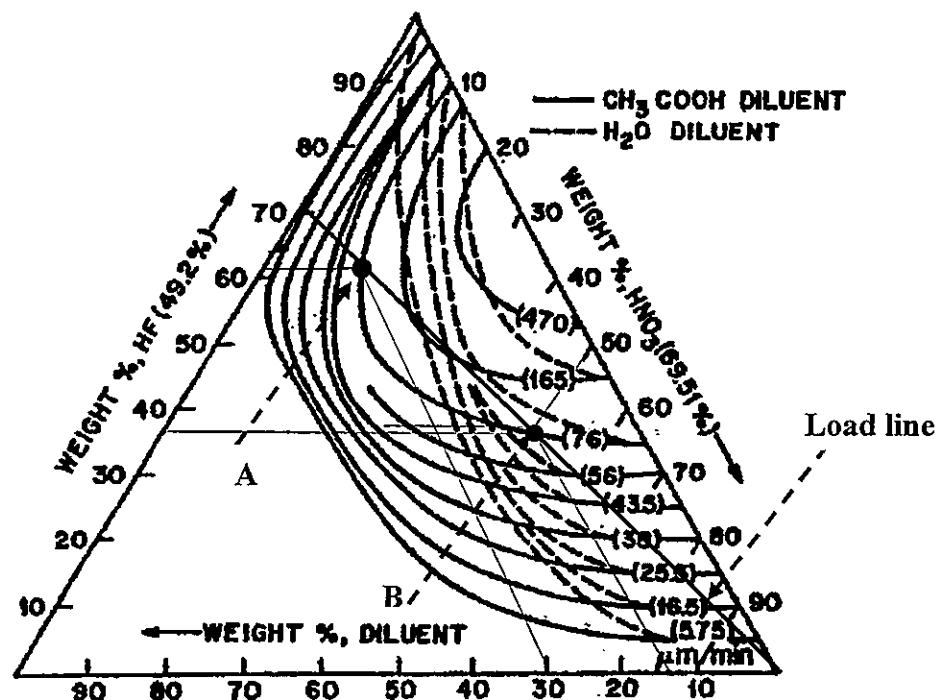
(6 Marks)

Figure 4

(b) The engineer realized that the etch rate is faster when acetic acid (instead of water) is used as a diluent. Explain why this is so.

(3 Marks)

(c) Explain why the etch rate will decrease with time. What steps should be taken to maintain a constant etch rate?

(3 Marks)

Note: Question No. 4 continues on page 6.

5

(d) What are the advantages and disadvantages of reactive ion etching (RIE) versus sputter etching? Cite an example of when you might want to use sputter etching rather than RIE?

(5 Marks)

(e) In a PECVD process, a reactive gas is metered into a 30 litre chamber at a flow rate of 40 sccm. The resulting steady-state pressure is 50 mtorr with the throttle valve 100% open. Assume that 1 torr litre per second = 79 sccm.

(i) Calculate the gas residence time.

(ii) If the throttle valve is 50% open during the process, what changes in the deposition rate would you expect, and why?

(iii) Identify the rate limiting mechanism and name the various component parts of this system configuration.

(8 Marks)

APPENDIX A

List of Selected Formulae

P-N junction

$$V_{bi} = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2}; \quad N_A x_p = N_D x_n; \quad W = x_p + x_n; \quad C_j = \frac{\varepsilon_s}{W};$$

$$W = \sqrt{\frac{2\varepsilon_s}{q}[\frac{1}{N_A} + \frac{1}{N_D}](V_{bi} - V)}; \quad L_p = \sqrt{D_p \tau_p}.$$

Bipolar junction transistors

$$\gamma \equiv \frac{I_{Ep}}{I_E} = \frac{I_{Ep}}{I_{Ep} + I_{En}}; \quad \alpha_T \equiv \frac{I_{Cp}}{I_{Ep}}; \quad \alpha_0 = \gamma\alpha_T; \quad \beta_0 = \frac{\alpha_0}{1-\alpha_0}; \quad I_C = \alpha_0 I_E + I_{CBO};$$

$$I_{CEO} = (1+\beta_0)I_{CBO}; \quad p_n(x) = p_{no}e^{qV_{EB}/kT}(1-\frac{x}{W}); \quad \gamma = \frac{1}{1 + \frac{D_E}{D_p}\cdot\frac{N_B}{N_E}\cdot\frac{W}{L_E}};$$

$$I_{Ep} = qA\frac{D_p p_{n0}}{W}e^{(qV_{EB}/kT)}; \quad I_{En} = qA\frac{D_E n_{E0}}{L_E}(e^{qV_{EB}/kT} - 1); \quad I_{Cn} = qA\frac{D_C n_{C0}}{L_C};$$

$$p_{n0}\cdot N_B = n_{E0}\cdot N_E = n_{C0}\cdot N_C = n_i^2; \quad \tau_B = \frac{W^2}{2D_p}; \quad f_T = \frac{1}{2\pi\tau_B}.$$

MOS devices

$$\psi_s = 2\psi_B = \frac{2kT}{q}\ln(\frac{N_A}{n_i}); \quad W_m^2 = \frac{2\varepsilon_s(2\psi_B)}{qN_A} = \frac{4\varepsilon_s kT}{q^2 N_A}\ln(\frac{N_A}{n_i}); \quad V_T = \frac{qN_A W_m}{C_o} + 2\psi_B;$$

$$\frac{C}{C_0} = \frac{1}{\sqrt{1 + \frac{2\varepsilon_{ox}^2 V}{qN_A\varepsilon_s d^2}}}; \quad \frac{1}{C_{min}} = \frac{d}{\varepsilon_{ox}} + \frac{W_m}{\varepsilon_s}; \quad V_{FB} = \phi_{ms} - \frac{(Q_f + Q_m + Q_{ot})}{C_0}.$$

$$I_D = K_n[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}] \text{ for } V_{DS} < V_{GS} - V_T; \quad V_T = \frac{qN_A W_m}{C_0} + 2\psi_B \text{ when } V_{FB} = 0;$$

$$I_D = \frac{K_n}{2}(V_{GS} - V_T)^2 \text{ for } V_{DS} \geq V_{GS} - V_T; \quad K_n = \mu_n C_{ox}\frac{W}{L}.$$

Thermal oxidation

$$t_{ox}^2 + At_{ox} = B(t+\tau) \; ; \quad \tau = \frac{t_{oxi}^2}{B} + \frac{t_{oxi}}{B/A} \; . \; t_{ox} = \frac{-A + \sqrt{A^2 + 4B(t+\tau)}}{2}$$

Thermal diffusion

$$D = D_o \exp(-\frac{E_a}{kT})$$

Constant source diffusion: Limited source diffusion:

$$N(z,t) = N_s erfc(\frac{z}{2\sqrt{Dt}})$$

$$N(z,t) = \frac{Q}{\sqrt{\pi Dt}} \exp[-\frac{z^2}{4Dt}], \quad Q = \frac{2}{\sqrt{\pi}} N_s \sqrt{Dt} .$$

Ion implantation

Before Annealing   After annealing

$$N(x) = \frac{Q}{\sqrt{2\pi}\Delta R_p} \exp[-\frac{(x-R_p)^2}{2\Delta R_p^2}]$$ $$N(x) = \frac{Q}{\sqrt{2\pi}(\Delta R_p^2 + 2Dt)^{1/2}} \exp[-\frac{(x-R_p)^2}{2(\Delta R_p^2 + 2Dt)}]$$

$$Q = \int_0^\infty N(x)\,dx = \sqrt{2\pi} N_p \Delta R_p$$

APPENDIX B

Table of Physical Constants

Physical Constant	Symbol	Value	Units
Electronic charge	q	1.6×10^{-19}	C
Boltzmann's constant	k	8.62×10^{-5}	eV/K
		1.38066×10^{-23}	J/K
Planck's constant	h	6.626×10^{-34}	J·s
Permittivity of free space	ε_0	8.85×10^{-14}	F/cm
Dielectric constant of Si	ε_{Si}	11.7	-
Dielectric constant of SiO$_2$	ε_{ox}	3.9	-
Electron Mass	m	9.11×10^{-31}	kg
Speed of Light	c	3×10^8	m/s
Bandgap of Si at 300 K	E_g	1.12	eV
Intrinsic carrier concentration in Si at 300 K	n_i	1×10^{10}	cm^{-3}

END OF PAPER

1a) i. By substituting $N_A = 80 N_D$ into the equation below, we get

$$V_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

N_D = 2.68e15, and $N_A = 80 N_D$ = 2.15e17.

ii. First, find W using this equation: (V = -10 V)

$$W = \sqrt{\frac{2\varepsilon_s}{q}[\frac{1}{N_A} + \frac{1}{N_D}](V_{bi} - V)}$$

W = 2.29e-4 cm

$$C_j = \frac{\varepsilon_s}{W}$$

C_j = 4.52 F/cm^2

1b) A: p type biased in accumulation mode. The semiconductor contains positive charges from majority carrier (holes) which accumulates near the surface of oxide.

B: n type biased in inversion mode. Inversion can be seen from the 2 different charges in semiconductor. Because the semiconductor is inverted to have positive charges, therefore the device is n type.

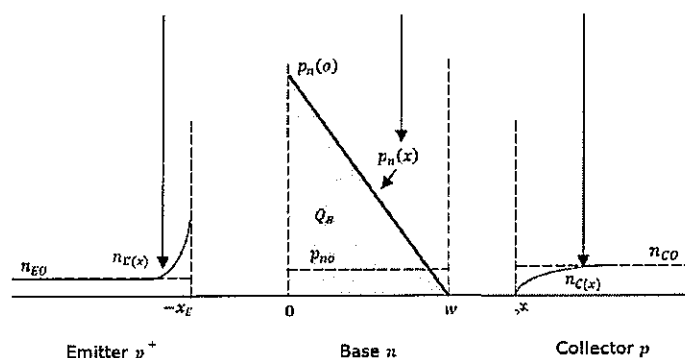**1c) i.** Minority carrier distributions across forward-biased BJT:

Figure 2.20

ii. We have the equation for pnp BJT as below.

$$p_n(x) = p_{no} e^{qV_{EB}/kT} (1 - \frac{x}{W})$$

We can use this equation for npn BJT by substituting p_n with n_p and p_{no} with n_{po}.

We know that $n_{po} = n_i^2/N_B = 11250$.

We need to find V_{EB} at x = 0 such that n_p is 10% of N_B (n_p = 2e15 /cm³).

By substituting all the values, we get

$$V_{EB} = 0.67 \text{ V}$$

2a) i. From one-hour dry oxidation at 1000 °C, we have oxide thickness of around 0.05 μm. This thickness is insignificant for wet oxidation at 1100 °C, as the lowest thickness that we get by 0.1 hour of oxidation time is more than 0.1 μm. So, we can ignore this process and directly see the result of 5-hour wet oxidation at 1100 °C from the graph: 1.5 μm.

ii. Oxide thickness vs. time diagram:
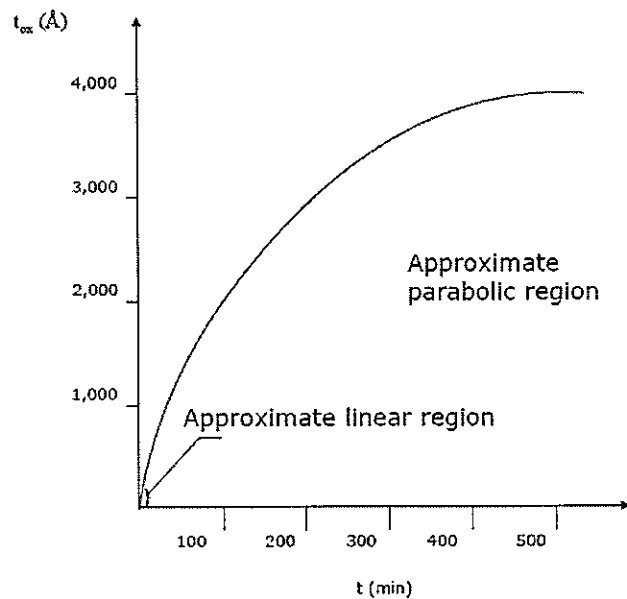
Linear growth rate is limited by the reaction at the silicon interface (depends on Si-Si bond strength), while parabolic growth rate is limited by the diffusion rate.

2b) i. Using limited source diffusion equation,

$$N(z,t) = \frac{Q}{\sqrt{\pi Dt}} \exp[-\frac{z^2}{4Dt}]$$

With z = 2 μm, Q = 3e13 atoms/cm², and t = 3600 s, we get N_D = 1.44e16 /cm³.

ii. 2 types of devices which use diffusion: BJT, MOS.

2 advantages of diffusion process: no damage from ion implantation, cheap and easy.

2c) i. We can use the equation below with N(x) = 3e15 /cm³ to find x as the junction depth.

$$N(x) = \frac{Q}{\sqrt{2\pi \Delta R_p}} \exp\left[-\frac{(x-R_p)^2}{2\Delta R_p^2}\right]$$
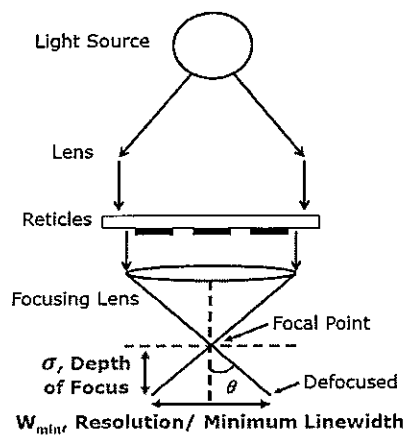
$$X_j = 0.53 \ \mu m$$

ii. 3 advantages of using ion-implantation for doping: very fast, can achieve complex profiles, and wide selection of masking materials.

3a) Projection lithographic system, (i) reticle, (ii) projection lens

3b) Possible light source: excimer laser, mercury lamp

3c) Proof:

$$\sigma = \pm \frac{W_{min}/2}{\tan\theta} \cong \pm \frac{k\lambda/2NA}{\sin\theta}$$

$$\sigma = \pm \frac{k\lambda/2NA}{NA/n} \cong \pm \left(\frac{k_2\lambda}{(NA)^2}\right)$$

$tan\ \theta \sim sin\ \theta$ for θ < 12°

k and k_2 are constant , n = 1 (for air)

It is proven that for a given resolution, the use of light with the longest wavelength and lens with the smallest NA gives the greates DOF.

Using the proven equation above, DOF = 1224.7 nm.

3d) To define a T-shaped metallization in a lift-off process, we need to cover the region outside T with resist and leave the T region empty for the metal. Because we are using positive resist, the resist pattern formed on substrate is the same as the mask. Hence, the T region is the transparent section of the mask.
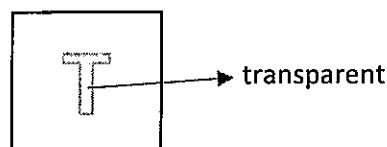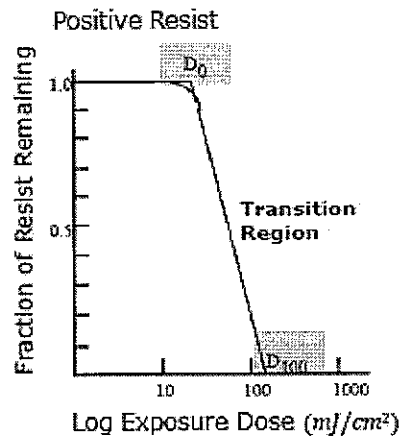

3e) Resist contrast is ability to distinguish between transparent and opaque regions of the mask.

Resist contrast curve:

$D_{100} = 90$ mJ/cm^2

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

Hence, $D_0 = 10.04$ mJ/cm^2

Positive Resist

Log Exposure Dose (mJ/cm^2)

A resist with infinite-contrast value is an ideal resist, as it can completely distinguish transparent and opaque regions of the mask used. There is no transition region (where there is a fraction of resist remaining on the surface) resulting in sharper edge, hence better resolution.

4a) For point A, the controlling etching agent is HNO$_3$ (refer to the image below).
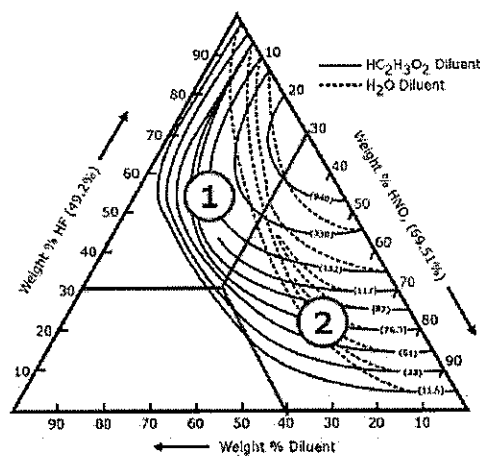
For point B, HF : HNO$_3$: CH$_3$COOH = 37 : 50 : 13.

4b) The etch rate is faster when acetic acid is used because acetic acid has a lower dielectric constant than water, resulting in less dissociation of HNO$_3$.

4c) The etch rate decreases over time possibly because the concentrations of HF and HNO$_3$ are decreasing as they are converted to another compound as by-products. To maintain a constant etch rate, we can constantly add HF and HNO$_3$.

4d) Advantage: more selectivity due to the chemical reaction; disadvantage: requires more sophisticated tool as it require vacuum chamber, RF generator. We might want to use sputter

etching for etching a multilayer stack of different materials on the substrate and when etching substrate a little does not matter.

4e) i. By substituting the known values into equation below while being careful of the units used,

$$t_r = \frac{V.p}{760.F}$$

We get t_r = 3.9 ms.

ii. If the throttle valve is half open, the flow rate will decrease hence increasing the residence time. With increased residence time, the deposition rate becomes faster as there is more time for the plasma to react with the surface.

iii. PECVD is limited by surface reaction rate. The components of this system configuration are shown below.
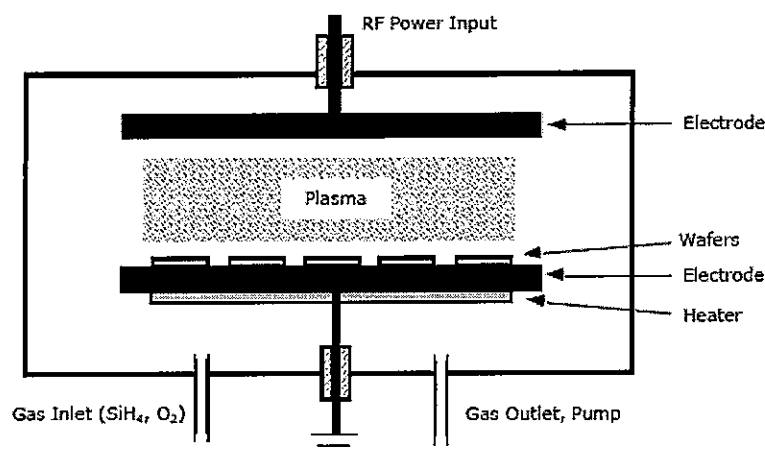
Tips and tricks:

- This semester's paper is comparably easier than previous ones. The calculations are straightforward and the rest are memorization. During the tutorial, the prof did say that the paper would be easy, so do listen to the prof.
- If you feel like you might forget some things as you do the paper, read through the questions first and jot down whatever memory you have to answer memorization questions. Then you can do the calculations and fill in the gap for memorization questions after you have finished the calculations.
- Come to **tutorial class** (if it's not too late already), especially during the second part of the course. The prof will give out hints of what will come out in quiz/exam. **Take note** of what he says is important and focus on those parts when studying (but still, study other parts).
- **Memorize equations** from the second part of the course. They won't be in appendix.
- Be careful of **units**, especially μm and cm.
- Several questions are recycled from previous papers/tutorial questions.

All the best! ☺