NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 2 EXAMINATION 2021-2022

EE3013 – SEMICONDUCTOR DEVICES AND PROCESSING

Apr / May 2022 Time Allowed: 2 hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 8 pages.
2. Answer all 4 questions.
3. All questions carry equal marks.
4. This is a closed book examination.
5. Unless specifically stated, all the symbols have their usual meaning.
6. A **List of Selected Formulae** and a **Table of Physical Constants** are provided in **Appendices A** and **B** on pages 6 – 8.

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1. (a) In a photolithographic process, a photoresist layer with a desired pattern is formed on a silicon wafer surface. The photoresist is composed of three main components.

(i) What are these three main components and their roles in the photoresist?

(ii) What are the major differences between positive and negative photoresists?

(7 Marks)

(b) You are required to pattern 2 parallel metallic lines on a Si substrate. Two masks, A and B are available for use as shown in Figure 1a. Mask A has 2 parallel chromium lines on transparent silica. Mask B is the inverse of Mask A. (Ignore the effect of chromium frame during patterning).

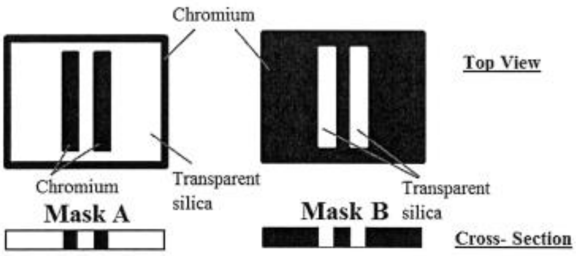

Figure 1a: Masks for patterning

Note: Question No. 1 continues on page 2

You are provided with one type of photoresist, of which its contrast curve is shown in Figure 1b.

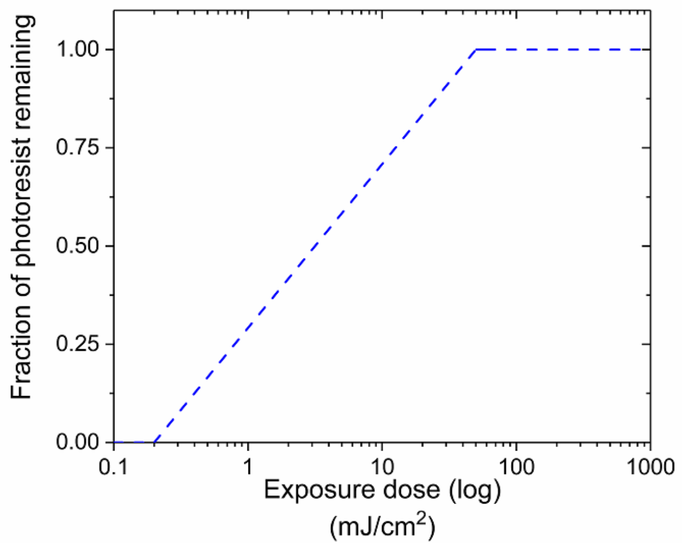

Figure 1b: Contrast curve of a photoresist

(i) Identify the type of photoresist with such contrast curve.

(ii) Calculate the contrast value of the photoresist.

(iii) Name the suitable lithography process to pattern the metal lines on the Si substrate.

(iv) Indicate which mask you need to use, Mask A or Mask B.

(8 Marks)

(c) Figure 2 on Page 3 shows the isoetch curve for silicon using the $HF:HNO_3:CH_3COOH$ etchant.

(i) Name the particular load line drawn in the figure.

(ii) The load line intersects the etch rate contour line at a particular point A shown in the figure. For point A, determine the etch rate and the respective percentage of the etchant constituents.

(iii) Explain why the etch rate is lower if the diluent is changed to H_2O?

(10 Marks)

Note: Question No. 1 continues on page 3

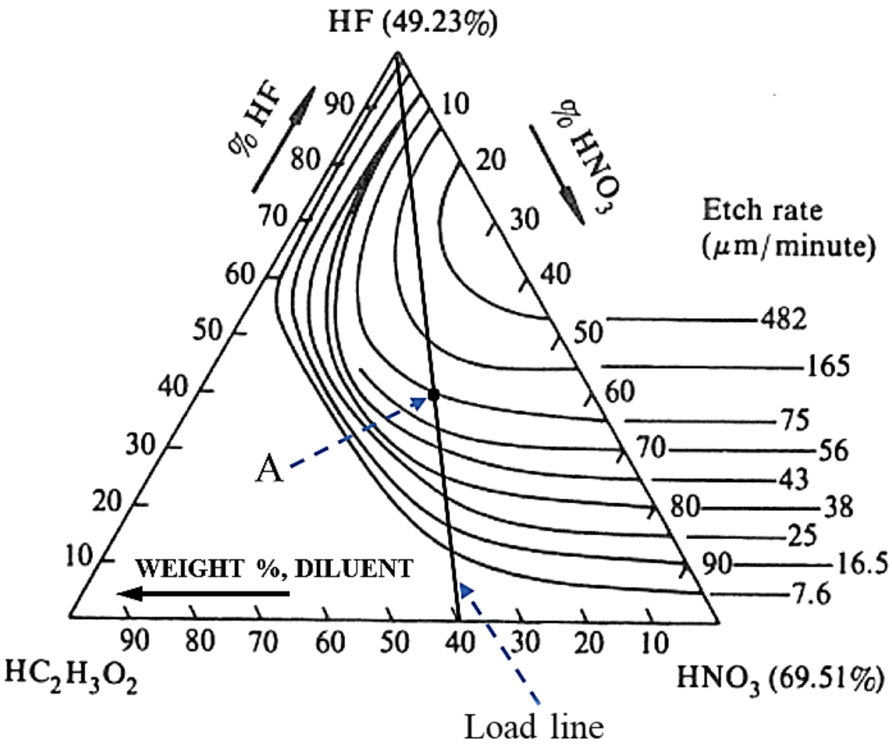

Figure 2: Isoetch curve for silicon

2. (a) In the CVD process, silicon films are formed through the reaction SiH_4 (g) → Si (s) + $2H_2$ (g). In the LPCVD process, it usually requires temperature greater than 600 °C, but it can be carried out at 200 °C in the PECVD process. Explain why the PECVD process enables Si deposition at lower temperature, and justify whether the PECVD process is limited by mass transport or surface reaction.

(10 Marks)

(b) Two common Physical Vapour Deposition (PVD) techniques for coating components are those that rely on either evaporation or sputtering.

(i) Compare PVD coating techniques by evaporation and sputtering citing some advantages and disadvantages of each technique.

(ii) In the sputtering process, the effect of ion energy on sputter yield is as shown in Figure 3 on page 4. Briefly explain the shape of the plot. Outline other key factors that affect the sputter yield.

(10 Marks)

Note: Question No. 2 continues on page 4

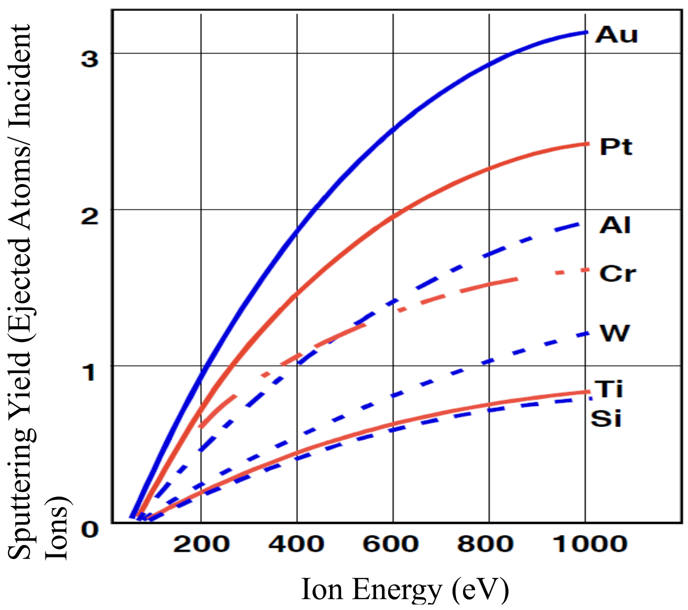

Figure 3 : Plot of sputter yield as a function of ion energy for normal incident argon ions for several materials

(c) In a sputtering deposition run, 25 sccm pure argon gas is released into the sputtering chamber and the targeted sputtering pressure is 5.0 mTorr. Given that 1 torr litre/s = 78.9 sccm, calculate the effective pumping speed needed to maintain the 5.0 mTorr sputtering process pressure.

(5 Marks)

3. (a) Consider a *pnp* transistor.

(i) How many operation modes can the transistor have and how they are defined, respectively?

(ii) If the transistor is at active mode, explain why collector current is significant and how to make the collector current even bigger without changing the biases to the two junctions?

(iii) What is I_{CEO}? State whether it is smaller or greater than I_{CBO} and explain the mechanism.

(9 Marks)

(b) For the *pnp* transistor in (a) at saturation mode,

(i) Plot the diagrams of the energy band and the minority carrier distributions in the emitter, base and collector regions. Indicate the expression of the minority carrier concentrations at all boundaries.

Note: Question No. 3 continues on page 5

(ii) What do you expect to the direction and magnitude of the collector current if the forward bias to the base-collector junction varies from 0.5 V to 1.5 V? Explain in detail.

(10 Marks)

(c) (i) What is substitutional diffusion and which type of substitutional diffusion is dominant? Give your reason(s).

(ii) What is the solid solubility limit and how it affects the thermal diffusion?

(6 Marks)

4. (a) Consider an ideal Metal-Oxide-Si(p-type) diode.

(i) If the surface potential of the p-type Si is equal to $(E_i\text{-}E_F)/q$, is the corresponding voltage applied to the metal gate positive or negative? Plot the energy band diagram of the semiconductor. Give the electron and hole concentrations at the surface of the p-type Si.

(ii) If a strong inversion occurs, what are the charges at and near the surface of the p-type Si?

(iii) If a stronger inversion occurs by adjusting the metal gate voltage, how do you expect the charges at and near the surface of the p-type Si to vary? Give your reason(s).

(iv) If the work function of the metal is greater than that of the Si, show the energy band diagram of the diode at thermal equilibrium.

(12 Marks)

(b) A (100) Si wafer is placed in a wet oxidation system to grow an oxide of 0.5 μm at 1100°C. It is then moved to a system to grow another 0.1 μm under dry condition at the same temperature. Given that A =0.09 μm and B = 0.027 μm^2/hr for dry oxidation, and A =0.11 μm and B = 0.51 μm^2/hr for wet oxidation. Find the total time used for the two oxidations.

(8 Marks)

(c) In the ion implantation process, what are R_p and ΔR_p and how do they change after an annealing? Plot the implanted dopant distribution before and after an annealing.

(5 Marks)

APPENDIX A

List of Selected Formulae

P-n junction

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

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

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

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

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

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

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

Thermal oxidation

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

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

APPENDIX A (continued)

List of Selected Formulae (continued)

Thermal diffusion

Constant source diffusion:

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

Limited source diffusion:

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

Ion implantation

Before Annealing

$$N(x) = \frac{Q}{\sqrt{2\pi}\varDelta R_p} \exp[-\frac{(x-R_p)^2}{2\varDelta R_p^2}]$$

After annealing

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

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

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} 1.38066×10^{-23}	eV/K 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	9.65×10^{9}	cm^{-3}

END OF PAPER