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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)

Note: Question No. 1 continues on page 2.

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

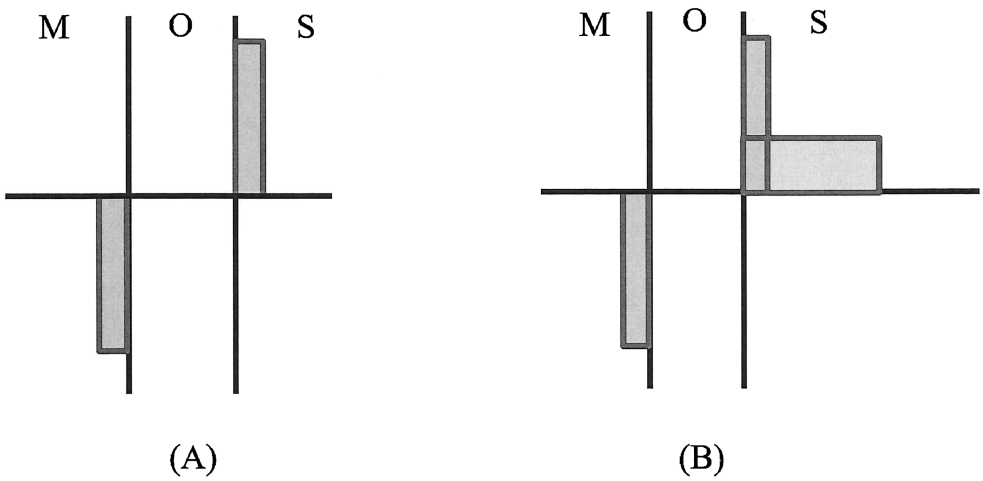

Figure 1

(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)

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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)

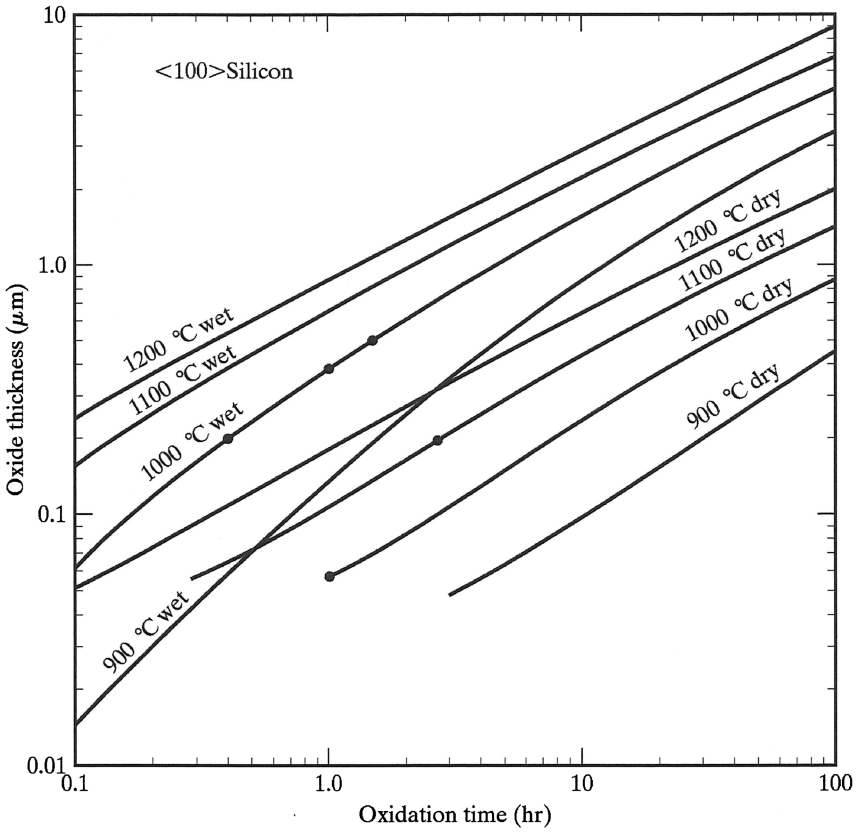

Figure 2

(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)

Note: Question No. 2 continues on page 4.

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(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)

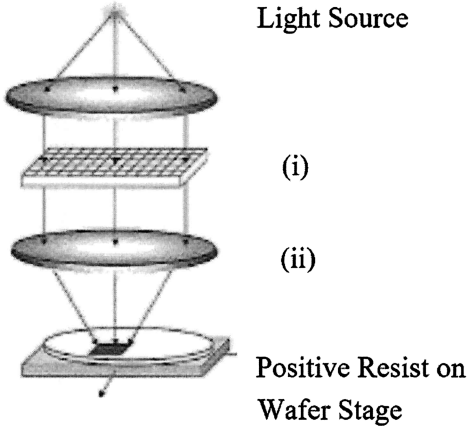

Figure 3

(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.

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(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 $HF:HNO_3:CH_3COOH$ 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)

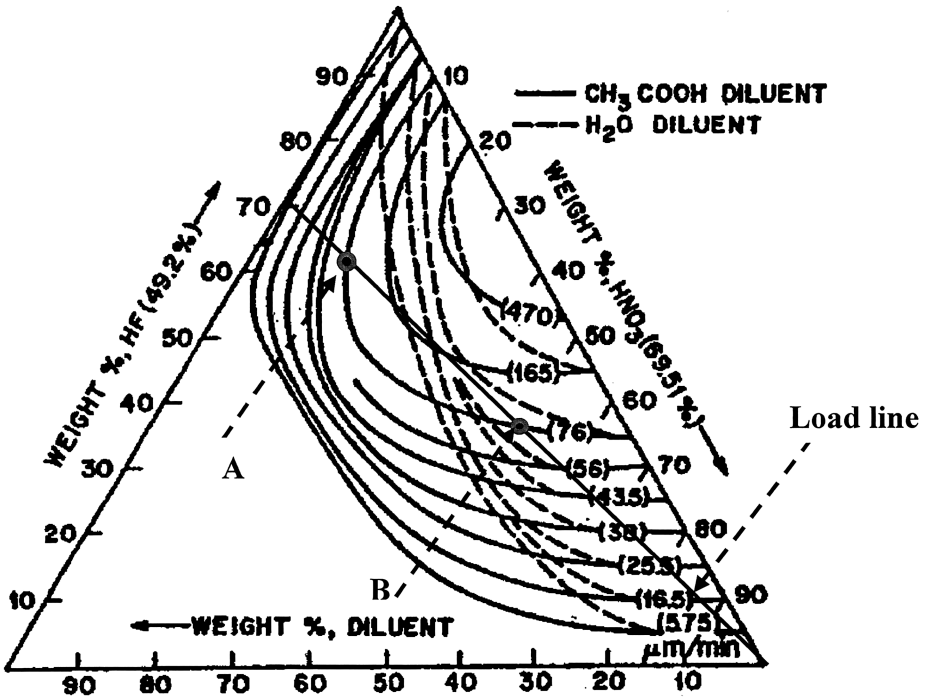

Figure 4

(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.

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(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)

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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

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

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

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

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

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Thermal oxidation

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

Thermal diffusion

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

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

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

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

After annealing

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

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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	1×10^{10}	cm^{-3}

END OF PAPER

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2. You are not allowed to leave the examination hall unless accompanied by an invigilator. You may raise your hand if you need to communicate with the invigilator.

3. Please write your Matriculation Number on the front of the answer book.

4. Please indicate clearly in the answer book (at the appropriate place) if you are continuing the answer to a question elsewhere in the book.