NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 1 EXAMINATION 2020-2021

EE3013 – SEMICONDUCTOR DEVICES AND PROCESSING

November / December 2020 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 symbols have their usual meanings.
6. A **List of Formulae** is provided in Appendix **A** on pages 6 and 7. The **Table of Physical Constants** is provided in Appendix **B** on page 8.

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1. (a) A silicon p-n junction diode has a diode current density of 20 A/cm^2 at a forward bias voltage of 0.65 V. Assuming $n_i = 1.5 \times 10^{10}$ cm^{-3}, $D_n = 25$ cm^2/s, $D_p = 10$ cm^2/s, $\tau_{p0} = \tau_{n0} = 5 \times 10^{-7}$ s, $\varepsilon_r = 11.7$, and kT = 0.0259 eV.

(i) Find the reverse saturation current density (J_s) in unit of A/cm^2.

(ii) If the ratio of the electron current to the total current is to be 0.10, determine the doping concentrations N_a and N_d in unit of cm^{-3}.

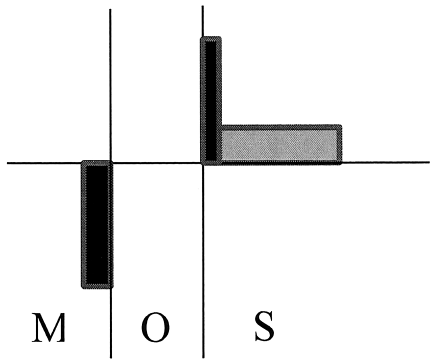
(9 Marks)

(b) (i) To increase the cutoff frequency of a Field Effect Transistor, it is necessary to reduce its gate length. However, for the gate to maintain good control of the channel, the gate oxide will need to be reduced.

- State and explain the limitations of this approach.
- Provide your recommendation to overcome this constraint.

Note: Question No. 1 continues on page 2.

(ii) The dc charge distribution of an ideal MOS capacitors is shown in Figure 1. Is the semiconductor *n* or *p* type? Is the device biased in the accumulation, depletion, or inversion mode? Explain your answers.



<u>Figure 1</u>

(7 Marks)

(c) An npn silicon bipolar transistor at T = 300 k has uniform doping concentrations of $N_E = 10^{19}$ cm^{-3}, $N_B = 10^{17}$ cm^{-3}, and $N_C = 7\times10^{15}$ cm^{-3}. The transistor is operating in the **<u>inverse-active mode</u>** with $V_{BE} = -2$ V and $V_{BC} = 0.565$ V. Assume $n_i = 1.5\times10^{10}$ cm^{-3}, $\varepsilon_{Si} = 11.7$, $\varepsilon_0 = 8.85\times10^{-14}$ F/cm and $kT = 0.0259$ eV.

(i) If the metallurgical base width is 1.2 μm, determine the neutral base width.

(ii) Explain the disadvantages of the inverse-active mode versus forward-active mode.

(9 Marks)

2. (a) A 10 μm square window is etched through a 1 μm thick oxide on a <111> silicon wafer. The wafer is re-oxidized at 1100 °C in wet oxygen to grow a new 1 μm thick oxide in the window. Given that $(B/A) = 2.895$ μm/hr, $B = 0.529$ μm^2/hr and $A = 0.183$ μm.

(i) Draw a cross section of the wafer after the second oxidation and **indicate the thickness** of the oxide layer inside and outside of the square window. (Show your workings).

(ii) Explain why there is a difference in the thickness for the final oxide layer in the two regions.

(8 Marks)

Note: Question No. 2 continues on page 3.

(b) A limited-source boron diffusion is carried out on a n-type silicon wafer with a background concentration of 4.0×10^{15} cm^{-3} at 1100 °C. Given the surface concentration of 5.0×10^{18} cm^{-3}, $D_0 = 10.5$ cm^2/s and $E_a = 3.69$ eV.

(i) Calculate the junction depth if the time taken for the diffusion is 2 hours.

(ii) Name the two types of boundary conditions for diffusion and briefly explain the differences.

(8 Marks)

(c) A boron implantation is to be performed through a 50 nm gate oxide so that the peak of the distribution is at the Si-SiO$_2$ interface.

(i) The projected range and straggle range versus acceleration energy for boron implantation is shown in Figure 2. What is the energy of the implant?

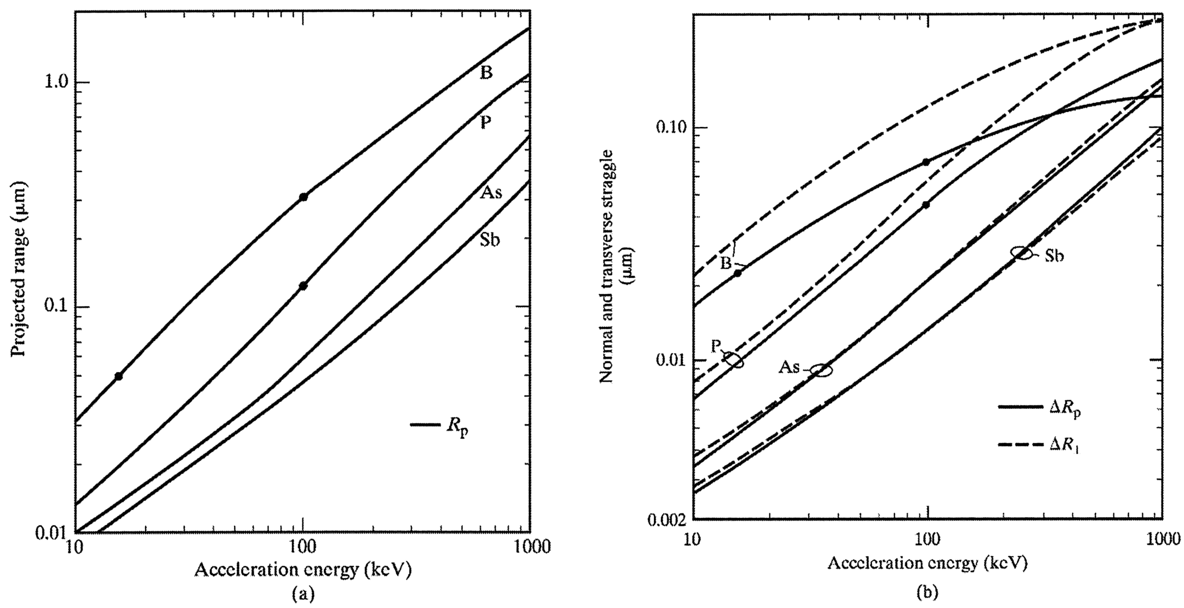


Figure 2

(ii) What is the peak concentration at the interface if the dose of the implant in silicon is to be 1.0×10^{13} cm^{-2}?

(iii) How thick should the SiO$_2$ layer be in areas that are not to be implanted if the background concentration is 1.0×10^{16} cm^{-3}?

(9 Marks)

3. (a) Briefly compare the THREE printing methods used in lithography, namely contact printing, proximity printing and projection printing.

(5 Marks)

Note: Question No. 3 continues on page 4.

(b) Estimate the resolution and the depth of focus of a projection lithography system with an ArF excimer laser of 193 nm, NA =0.65, k_1 =0.60 and k_2 = 0.50. Suggest a resolution enhancement method where the factor k can be improved.

(5 Marks)

(c) Name the fabrication steps numbered in the photolithography process show in Figure 3.

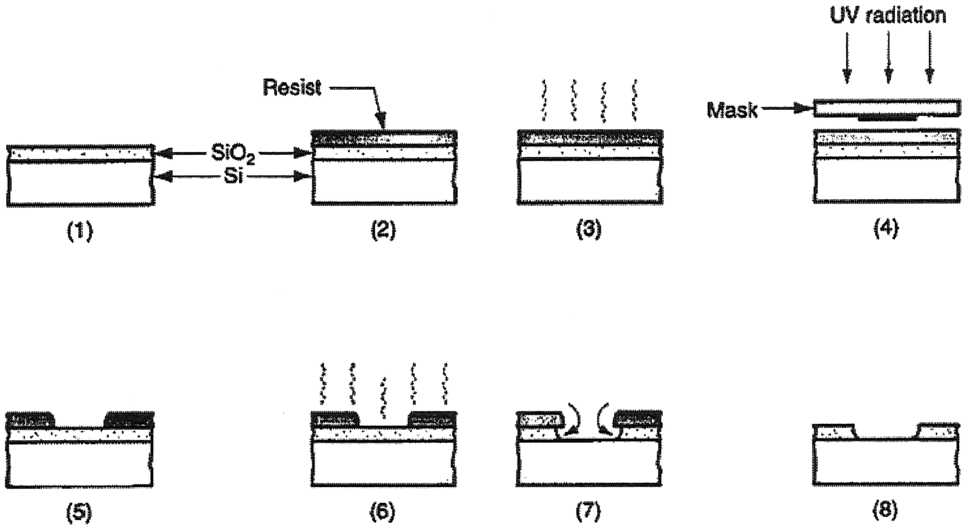


Figure 3

(5 Marks)

(d) What is the purpose of applying a primer layer on a silicon wafer surface before applying a photoresist coating? If the hotplate for the Soft Bake step is malfunctioned and remained at room temperature, what would be the effect on the exposed patterns after the wafers go through the development process?

(5 Marks)

(e) Explain how diazo-naphtho-quinone (DNQ), which is a photoactive compound (PAC) in a positive photoresist, promotes dissolution of the resin after light exposure. Figure 4 shows the molecular structure of DNQ, in which R, O and N stand for radical, oxygen and nitrogen, respectively.

(5 marks)

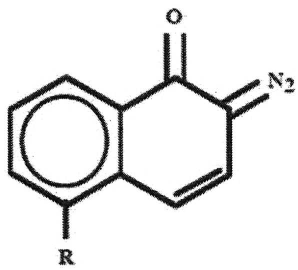


Figure 4

4. (a) Even though wet etching was widely used in the beginning, dry etching has become the dominant etching process today. Explain the shortcomings of wet etching and why dry etching is a better option.

(4 Marks)

(b) How is etching achieved in a reactive-ion etching (RIE) process? Outline the operative mechanisms in the RIE process.

(6 Marks)

(c) Outline the possible outcome when an ion bombards the surface of a target in a sputtering process. Explain how this depends on the ion energy.

(5 Marks)

(d) In a sputtering deposition run, ***y*** sccm pure argon is released into the sputter chamber of 50 litres and the resulting sputtering pressure is 0.5 mTorr. (i) Given the pumping speed of the turbomolecular pump is 1200 litre/second, calculate the effective residence time needed to maintain the sputtering pressure. (ii) Given 1 torr litre/second = 78.9 sccm, determine the value of *y*.

(5 Marks)

(e) Figure 5 shows the characteristics of vapor phase silicon growth,

(i) Identify the limiting mechanisms in Regime A and Regime B.

(ii) Briefly explain the reasons for the different slopes in Regime A and Regime B.

(5 Marks)

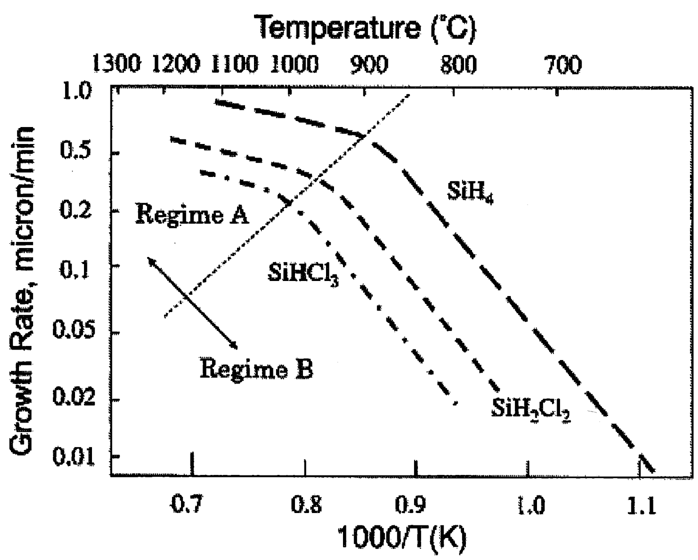


Figure 5

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

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

Thermal diffusion

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

APPENDIX A (Continued)

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

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

After annealing

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

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

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	1×10^{10}	cm^{-3}

END OF PAPER

EE3013 SEMICONDUCTOR DEVICES & PROCESSING

Please read the following instructions carefully:

1. **Please do not turn over the question paper until you are told to do so. Disciplinary action may be taken against you if you do so.**

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.