NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 1 EXAMINATION 2018-2019

EE3013 – SEMICONDUCTOR DEVICES AND PROCESSING

November / December 2018 Time Allowed: 2 hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 9 pages.
2. Answer ALL 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) The total junction capacitance of a GaAs p-n junction at T = 300 K is found to be 1.10 pF at a reversed bias voltage of 1 V. The doping concentration in one region is found to be 8×10^{16} cm^{-3}, and the built-in potential is found to be $V_{bi} = 1.20$ V. Given the intrinsic carrier concentration (n_i) and relative permittivity (ε_r) of GaAs are 1.8×10^6 cm^{-3} and 13.1, respectively, determine:

   (i) The doping concentration in the other region of the p-n junction.

   (3 Marks)

   (ii) The cross-sectional area of the p-n junction diode.

   (3 Marks)

   (iii) What will happen to the junction capacitance value if the reverse-biased voltage is increased.

   (3 Marks)

Note: Question No. 1 continues on page 2.

(b) Figure 1 shows the high-frequency *C-V* characteristic curve of a silicon MOS capacitor. The area of the device is 2×10^{-3} cm^2. The metal-semiconductor work function difference $\phi_{ms} = -0.50$ V, the relative permittivity of the oxide $\varepsilon_r = 3.9$, and the semiconductor doping concentration is 2×10^{16} cm^{-3}.

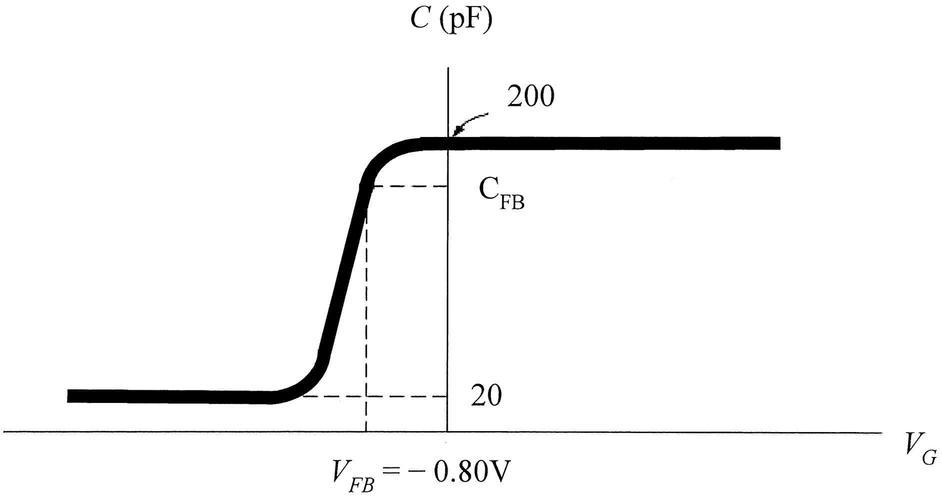

Figure 1

(i) Is the semiconductor n-or p-type?

(2 Marks)

(ii) What is the oxide thickness?

(3 Marks)

(iii) What is the equivalent trapped oxide charge density (Q_o) where ($Q_o = Q_f + Q_m + Q_{ot}$)?

(3 Marks)

(c) (i) Explain why the base-emitter should be forward biased and the base-collector reversed biased for a p$^+$-n-p BJT under forward active mode.

(4 Marks)

(ii) State two ways to increase the cutoff frequency (f_T) of a BJT.

(4 Marks)

2. (a) (i) A silicon dioxide layer was grown at 1050 °C under wet oxidation on (100) silicon for 120 minutes. Assume that A = 0.226 μm and B = 0.287 μm^2/hr. If the final thickness of the oxide is found to be 0.67 μm, what is the thickness of the initial oxide?

(4 Marks)

(ii) Name two applications of oxide in semiconductor devices. Explain if wet or dry oxidation is preferred in growing this oxide.

(4 Marks)

(b) (i) A p-n junction is formed by diffusing pre-deposited boron atoms into the n-type silicon substrate at 1100 °C for 1 hour. The dose for the pre-deposition is 2×10^{13} atoms/cm^2. Assume that the diffusion is Gaussian, the doping concentration of the silicon substrate is 1.5×10^{16} cm^{-3}, and $D_B = 9.2 \times 10^{-13}$ cm^2/s at 1100 °C, what is the junction depth?

(5 Marks)

(ii) Name two advantages of thermal diffusion over implantation.

(4 Marks)

(c) (i) A silicon wafer with a diameter of 20 cm is implanted with phosphorus ions at an implant energy of 150 keV to form a p-n junction. The implantation time is 10 seconds and the average current used is 5 μA. Under these implant conditions, the values of the projected range (R_p) is 0.14 μm and the straggle range (ΔR_p) is 0.045 μm. If the background concentration of the silicon wafer is found to be 1.6×10^{14} cm^{-3}, what is the junction depth?

(5 Marks)

(ii) Explain how a mass spectrometer in an ion-implantation system is used to select the desired ions for implant.

(3 Marks)

3. (a) Figure 2 shows the schematic of a lithography system used in many research labs to prototype new devices.

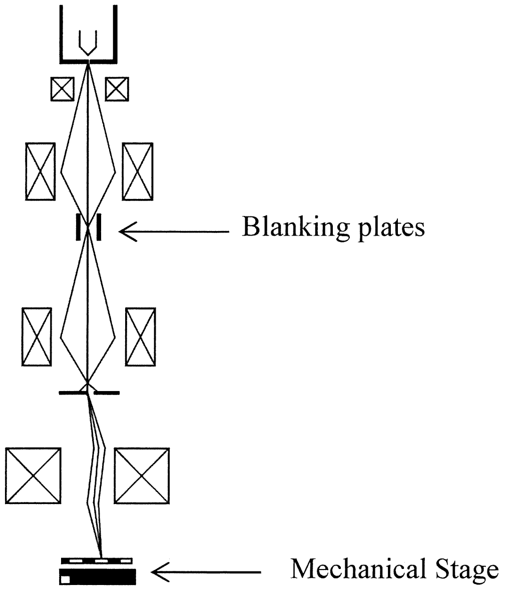

Figure 2

(i) Name the lithography system. List the advantages and disadvantages of such a system as compared to optical lithography.

(5 Marks)

(ii) State, giving reasons, the type of resist that is usually preferred for the above lithography system.

(3 Marks)

(iii) An engineer deploys such a lithography system with step and repeat imaging features to print a submicron pattern. Given that the resists used have a k_1 value of 0.7, and that the minimum line-width is 8 nm, while the gap between the mask and the wafer is 10 μm, determine the energy required for the system.

(4 Marks)

(b) Define in a few sentences the differences between the following:

(i) Hard and soft bake deployed in lithography processing steps.

(ii) Mask and reticle used for lithography.

(iii) X-ray and E-beam lithography .

(6 Marks)

Note: Question No. 3 continues on page 5.

(c) Figure 3 shows the objective lens of a projection lithography system.

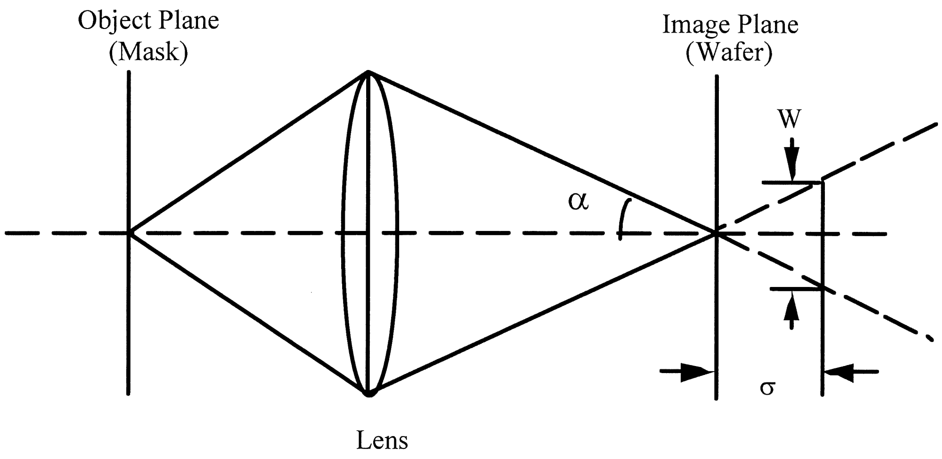

Figure 3

(i) Assuming $tan\ \alpha \sim sin\ \alpha$, determine the Numerical Aperture (NA), given that the diameter of the objective lens and its focal length are 1.5 cm and 1 cm, respectively.

(ii) Hence, determine the depth of focus of the system given that k_2 value is 0.85 and the wavelength of the optical source is 193 nm.

(7 Marks)

4. (a) In the plasma of a RIE system, consider an argon atom that is ionized during a collision in the plasma. Over a given mean free path, one of the particles will achieve a much higher speed. Explain, with a diagram, how that will affect the potential (voltage) of the plasma relative to that of either electrode.

(3 Marks)

(b) What are the etch rate results and selectivity of a RIE system if the following parameters are changed?

(i) RF frequency is decreased.

(ii) RF power is decreased.

(iii) DC bias is increased.

(iv) Cathode size is decreased.

(4 Marks)

Note: Question No. 4 continues on page 6.

(c) The mixture of SF_6 and O_2 is commonly employed in the Si dry etching process. List the main volatile etch-product of this etching process and explain the roles played by the O_2 plasma. List two other types of commonly used gases for the Si dry etching process. Explain why an effective dry etching process for SiO_2 and Si_3N_4 cannot be developed using SF_6 and O_2 mixture.

(5 Marks)

(d) Define the residence time of a gas molecule in a plasma system. Discuss what factors can affect the average residence time of the gas molecule of the plasma.

(3 Marks)

(e) In a LPCVD process system, reaction gas is metered into a 100 litter reactor at a flow of 10 ml/sec. The resulting steady state pressure is 0.2 torr. Assume that 1 torr litre per second = 79 sccm.

(i) Determine the pumping speed of the pump.

(ii) Determine the residence time of a gas molecule in the reactor.

(iii) If the flow is increased to 20 ml/sec, find the pressure and residence time.

(iv) If a throttle valve is placed on the pump to cut the pumping speed to half, find the pressure and the residence time.

(v) What possible modifications to the above system need to be made if a PECVD process is to be developed?

(10 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

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

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

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

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

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

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

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.