NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 2 EXAMINATION 2020-2021

EE3013 – SEMICONDUCTOR DEVICES AND PROCESSING

April / May 2021 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. 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 photolithography when people say their photoresist has "opposite polarity" to the pattern obtained, what does that mean? Sketch and explain the process.

(6 Marks)

(b) Explain why hexa-methyl-di-silazane (HMDS) primer coated on Si surface can make the Si surface more hydrophobic. The molecular structure of HMDS is shown in Figure 1.

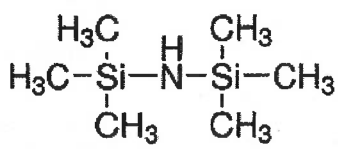

Figure 1

(6 Marks)

Note: Question No. 1 continues on page 2.

(c) A dry Step-and-Scan Exposure system designed to use in air was fitted with an ArF 193 nm DUV excimer laser as the light source. The Numerical Aperture of the exposure lens was $NA_{dry} = 0.68$. Note : $NA = n \sin\theta$, where θ is the exit angle of the lens.

The exposure system was then retrofitted with a Deionized Water Immersion stage without changing the lens column. Assume that the NA in the immersion system did not change, $NA_{wet} = 0.68$. The refractive index of Deionized water $n = 1.437$ for the ArF 193 nm DUV laser light. The final wet process parameters were: k_1 (wet) = 0.45 and k_2 (wet) = 0.65.

Calculate the Exit Angle for the wet immersion system. Calculate the Resolution W_{min} and Depth of Focus DOF for the wet operation of the exposure system.

(8 Marks)

(d) In order to obtain high quality uniform thin films in cases (i), (ii) and (iii) below, choose the appropriate deposition methods: thermal evaporation, DC sputtering, Low Pressure Chemical Vapour Deposition (LPCVD). Specify the reasons for your answers.

(i) 50 nm SiO_2 film on a silicon wafer.

(ii) 500 nm tungsten film on a quartz side.

(iii) 200 nm titanium film on a stainless steel cylinder.

(5 Marks)

2. (a) Briefly discuss wet etching process on Si (100) according to Figure 2. In the figure, $\delta = 2$ μm and $D = 350$ μm when the etching process is stopped after 5 minutes. What are the etch rates in the <100> and <111> directions?

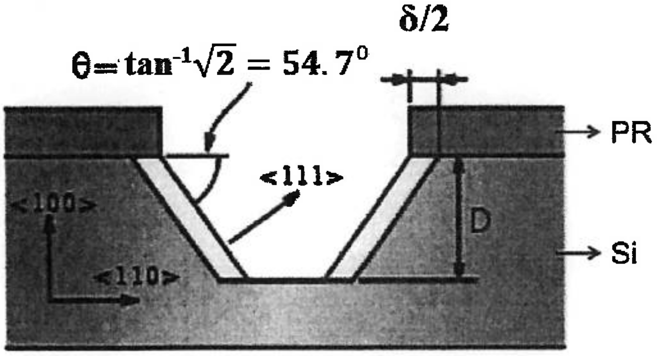

Figure 2

(7 Marks)

Note: Question No. 2 continues on page 3.

(b) Figure 3 below illustrates a Reactive Ion Etching (RIE) system. Identify places numbered 1 through 8 and explain how the etching is done.

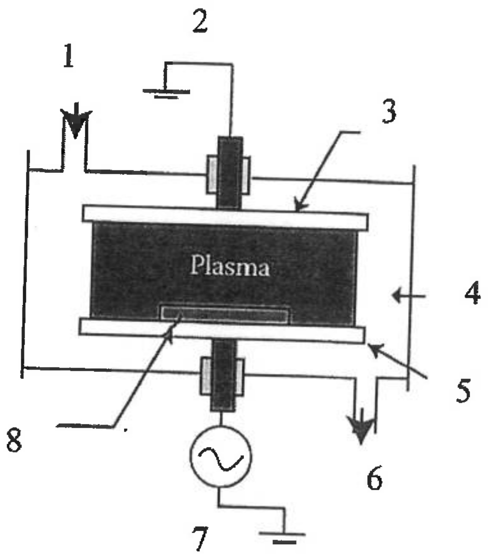

Figure 3

(6 Marks)

(c) The high ion bombardment energy of the RIE causes damages to the material, and considerable degradation to the electrical and optical properties of devices.

(i) What are factors affecting the degree of the damages?

(ii) What are the types of the RIE plasma damages that can be inflicted on a material surface with patterned edges?

(iii) How could one overcome the device degradation caused by the damages?

(6 Marks)

(d) In a sputtering deposition run, 20 sccm pure argon gas is released into the sputter chamber and the resulting sputtering pressure is 2.0 mTorr. Given the volume of the chamber is 30 litres, calculate the effective pumping needed to maintain the 2.0 mTorr sputtering pressure. Given 1 torr litre / s = 78.9 sccm.

(6 Marks)

3. (a) A Si (100) wafer has two oxide layers. The first oxide layer of 500 nm was grown by the wet oxidation process at 1000°C while the second oxide layer was grown by the dry oxidation process at 1200°C for 30 minutes. Table 1 shows the data of the oxidation processes.

(i) Find the time required for the growth of the first oxide layer.

(ii) Calculate the total thickness of the two oxide layers.

Temperature (°C)	Dry Oxidation		Wet Oxidation	
	A(μm)	B(μm²/hr)	A(μm)	B(μm²/hr)
1000	0.165	0.0117	0.226	0.287
1100	0.090	0.0270	0.110	0.510
1200	0.040	0.0450	0.050	0.720

Table 1. Data of oxidation

(10 Marks)

(b) A *p*-Si wafer is used to form a *p-n* junction by the thermal diffusion.

(i) What impurity atoms should be used and how to determine the junction position?

(ii) What are the electron and hole concentrations at the junction position? Sketch the carrier concentration profile as a function of position.

(6 Marks)

(c) Consider a *npn* transistor at common emitter configuration. The biased voltage between the emitter and the base is V_{be} and the biased voltage between the emitter and the collector is V_{ce}.

(i) If the transistor is at active mode, explain why the collector current increases with the bias voltage V_{ce}. Describe the breakdown mechanism of the *npn* transistor.

(ii) If the transistor is at saturation mode, plot the energy band diagram and the minority carrier distributions of the device. Show the expression of the minority carrier concentrations at all boundaries.

(9 Marks)

4. (a) A p-Si wafer has a doping concentration of 1×10^{15} cm^{-3} covered by a 300 nm thick oxide. Arsenic was implanted with a dose of 1×10^{13} atoms/cm^2. Given $R_p = 550$ nm and $\Delta R_p = 120$ nm.

(i) Find the implanted dopant concentration at the Si/oxide interface.

(ii) Calculate the junction position.

(iii) Explain how many junctions can be formed.

(11 Marks)

(b) (i) For an ideal metal-oxide-Semiconductor (MOS) diode on n-Si substrate, state the polarity of voltage which should be applied to the metal gate to make it in accumulation condition. Sketch the energy band diagram.

(ii) For a real MOS diode fabricated on a p-Si substrate, if the work function of metal is 0.5 eV less than that of Si, sketch the energy band diagram of the diode when it is at thermal equilibrium.

(iii) For a real MOS diode fabricated on a p-Si substrate, if there are negative charges in the oxide, will the threshold voltage increase or decrease? Explain why.

(iv) Taking a MOS diode on p-Si as an example, describe how the threshold voltage is defined and what are the factors that will affect the value of threshold voltage?

(14 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

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

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	9.65×10^9	cm^{-3}

END OF PAPER