NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 1 EXAMINATION 2021-2022

EE3013 – SEMICONDUCTOR DEVICES AND PROCESSING

November / December 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) The Rayleigh criterion is used to derive the minimum feature size in projection lithography. In each of the following parameters affecting the Rayleigh equation, describe how one will implement the physical change on the lithography system to improve its resolution.

   (i) Change of wavelength, λ
   (ii) Change of resist constant, k
   (iii) Change of numerical aperture, NA

   (4 Marks)

   (b) A photoresist is a light-sensitive material used in several processes in the electronic industry.

   (i) List some functions of a photoresist.
   (ii) Name the various process steps before the Soft Bake process.
   (iii) How does a resist adhesion promotor work?

   (8 Marks)

Note: Question No. 1 continues on page 2.

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(c) Briefly describe two approaches to mask engineering that can be utilized to improve resolution in optical lithography.

(6 Marks)

(d) An exposure is performed using a step-and-repeat aligner printing system. The light source has a wavelength of 365 nm. If its depth of focus of the image is 1 μm, determine the resolution of the system. Assume $k_1 = 1$ and $k_2 = 0.8$.

(7 Marks)

2. (a) In a parallel plate plasma etching system, two electrodes ***E*1** (powered) and ***E*2** (grounded) are used.

(i) Schematically sketch the voltage distribution in the plasma between the two non-symmetrical electrodes in which area size of ***E*1** < ***E*2**.

(ii) If the size area of ***E*2** is 8 times larger than ***E*1**, determine the cathode potential if the anode potential with respective to the plasma potential is – 50mV.

(iii) The etched surface becomes relatively rough when the stainless-steel cathode is replaced by an aluminum one. Comment on this observation.

(iv) What changes in the etch rate would one expect to observe and why, if
- the radio frequency (rf) power is decreased?
- the process temperature is increased?

(12 Marks)

(b) Figure 1 shows the transport of film particles to a substrate in a Physical Vapour Deposition (PVD) System.

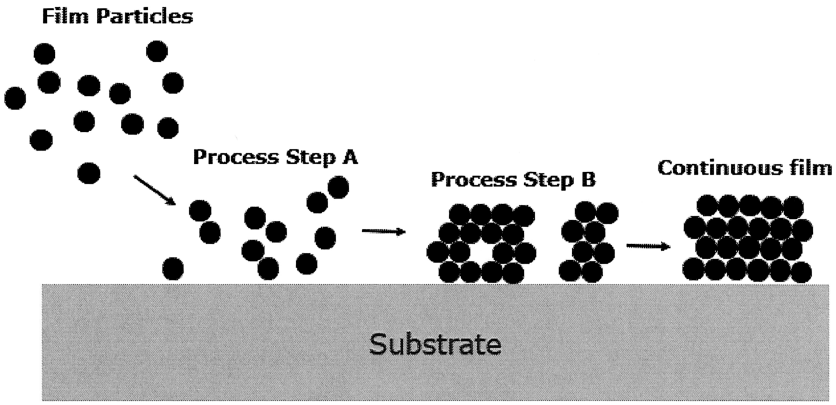

Figure 1: Typical PVD Deposition Mechanism

Note: Question No. 2 continues on page 3.

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(i) Name the process steps Step A and B shown in Figure 1.
(ii) List some differences between the thermal and electron beam evaporation.

(7 Marks)

(c) Figure 2 shows a schematic diagram of a magnetron sputtering system.

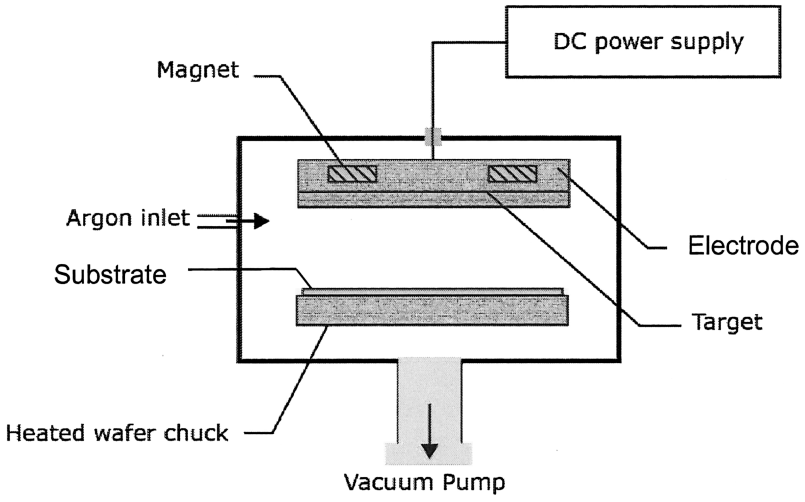

Figure 2: A Magnetron Sputtering System

(i) Name the electrode on which the target is mounted.

(ii) Explain why magnets are deployed in the electrode.

(iii) What is/are the advantage(s) of replacing the DC power supply with a radio frequency (rf) power supply?

(6 Marks)

3. (a) A <100> silicon wafer with an initial oxide thickness of 0.025 μm has gone through a 30 min of dry oxidation followed by a 120 min wet oxidation cycle at 1100°C. Assume the following parameters:

For Dry oxidation: A = 0.140 μm and B = 0.024 μm^2/hr

For Wet oxidation: A = 0.183 μm and B = 0.529 μm^2/hr

(i) Determine the final total oxide thickness.

(6 Marks)

(ii) What are the advantages of dry oxidation versus wet oxidation?

(3 Marks)

Note: Question No. 3 continues on page 4.

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(b) (i) When a diffusion process should be used in semiconductor wafer fabrication?

(3 Marks)

(ii) A p-n junction is formed by diffusing pre-deposited boron atoms into the n-type silicon substrate at 1150°C. Assuming that the diffusion is Gaussian and the doping concentration of the silicon substrate is $2 \times 10^{16}\text{cm}^{-3}$, what is the diffusion time required to form a junction depth at 2μm? Given the surface concentration $N_s = 2 \times 10^{17}\text{cm}^{-3}$ and $D = 1 \times 10^{-12}\text{cm}^2/s$ at 1150°C.

(6 Marks)

(c) (i) What is ion channeling in an ion-implantation process? How to avoid it?

(4 Marks)

(ii) When is ion-implantation process preferred over thermal diffusion in the doping of semiconductor devices?

(3 Marks)

4 (a) Calculate the applied reverse-biased voltage at which the ideal reverse current in a p-n junction diode at $T = 300\text{K}$ reaches 90 percent of its reverse-saturation current value.

(5 Marks)

(b) For a p-n-p bipolar junction transistor (BJT),

(i) Explain why the base width (W_B) needs to be smaller than the hole diffusion length (L_p).

(ii) Give one advantage and one disadvantage for a narrow base width BJT.

(6 Marks)

(c) An ideal MOS capacitor with an n^+ polysilicon gate has a silicon dioxide thickness of t_{ox} = 12 nm on a p-type silicon substrate doped at $N_d = 10^{16}\text{cm}^{-3}$. At a frequency of 1 MHz, determine:

(i) The maximum capacitance per unit area.

(ii) The minimum capacitance per unit area under strong inversion if the depletion width is $1.182 \times 10^{-4}\text{cm}$.

(8 Marks)

Note: Question No. 4 continues on page 5.

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(d) An n-channel MOSFET has a threshold voltage $V_T = 4.5$V. The gate terminal is connected to the drain terminal.

(i) Is the MOSFET in linear or saturation mode? Explain your answer.

(ii) If $K_n = 1.111$ mA/V^2, what is the drain current at $V_{DS} = 3$V?

(6 Marks)

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List of Selected Formulae

(1) P-N junction

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

$$W = \sqrt{\frac{2\varepsilon_s}{q}[\frac{1}{N_A}+\frac{1}{N_D}](V_{bi}-V)};\quad J = J_n(-\boldsymbol{x_p}) + J_p(\boldsymbol{x_n}) = \left(\frac{qD_p p_{no}}{L_p} + \frac{qD_p n_{po}}{L_n}\right)\left[e^{qV/kT} - 1\right]$$

(2) Bipolar junction transistors

$$\gamma \equiv \frac{I_{Ep}}{I_E} = \frac{I_{Ep}}{I_{Ep}+I_{En}};\quad \alpha_T \equiv \frac{I_{Cp}}{I_{Ep}};\quad \alpha_0 = \gamma\alpha_T;\quad \beta_0 = \frac{\alpha_0}{1-\alpha_0};\quad I_C = \alpha_0 I_E + I_{CBO};$$

$$I_{CEO} = (1+\beta_0)I_{CBO};\quad p_n(x) = p_{no}e^{qV_{EB}/kT}(1-\frac{x}{W});\quad \gamma = \frac{1}{1+\frac{D_E}{D_p}\cdot\frac{N_B}{N_E}\cdot\frac{W}{L_E}};$$

$$I_{Ep} = qA\frac{D_p p_{n0}}{W}e^{(qV_{EB}/kT)};\quad I_{En} = qA\frac{D_E n_{E0}}{L_E}(e^{qV_{EB}/kT}-1);\quad I_{Cn} = qA\frac{D_C n_{C0}}{L_C};$$

$$p_{n0}\cdot N_B = n_{E0}\cdot N_E = n_{C0}\cdot N_C = n_i^2;\quad \tau_B = \frac{W^2}{2D_p};\quad f_T = \frac{1}{2\pi\tau_B}.$$

(3) 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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(4) Thermal oxidation

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

(5) 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:

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

(6) 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

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

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

Silicon oxide for masking

$$N(t_{ox}) = N_p \exp\left[-\frac{(t_{ox}-R_p)^2}{2\Delta R_p^2}\right] < \frac{N_B}{10}$$

$$t_{ox} \geq R_p + \Delta R_p \sqrt{2\ln\left(\frac{10N_p}{N_B}\right)}$$

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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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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.

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