

NANYANG TECHNOLOGICAL UNIVERSITY**SEMESTER 1 EXAMINATION 2020-2021****EE3013 – SEMICONDUCTOR DEVICES AND PROCESSING**

November / December 2020

Time Allowed: 2 hours

INSTRUCTIONS

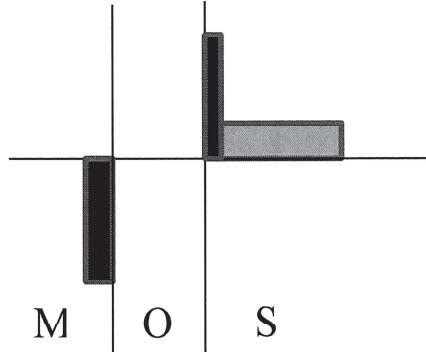
1. This paper contains 4 questions and comprises 8 pages.
 2. Answer ALL 4 questions.
 3. All questions carry equal marks.
 4. This is a closed book examination.
 5. Unless specifically stated, all symbols have their usual meanings.
 6. A **List of Formulae** is provided in Appendix A on pages 6 and 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 $n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$, $D_n = 25 \text{ cm}^2/\text{s}$, $D_p = 10 \text{ cm}^2/\text{s}$, $\tau_{p0} = \tau_{n0} = 5 \times 10^{-7} \text{ s}$, $\varepsilon_r = 11.7$, and $kT = 0.0259 \text{ eV}$.
 - (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.

**Figure 1**

(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 $N_C = 7 \times 10^{15}$ cm $^{-3}$. The transistor is operating in the **inverse-active mode** with $V_{BE} = -2$ V and $V_{BC} = 0.565$ V. Assume $n_i = 1.5 \times 10^{10}$ cm $^{-3}$, $\epsilon_{Si} = 11.7$, $\epsilon_0 = 8.85 \times 10^{-14}$ F/cm and $kT = 0.0259$ eV.
- (i) If the metallurgical base width is 1.2 μ m, determine the neutral base width.
 - (ii) Explain the disadvantages of the inverse-active mode versus forward-active mode.

(9 Marks)

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

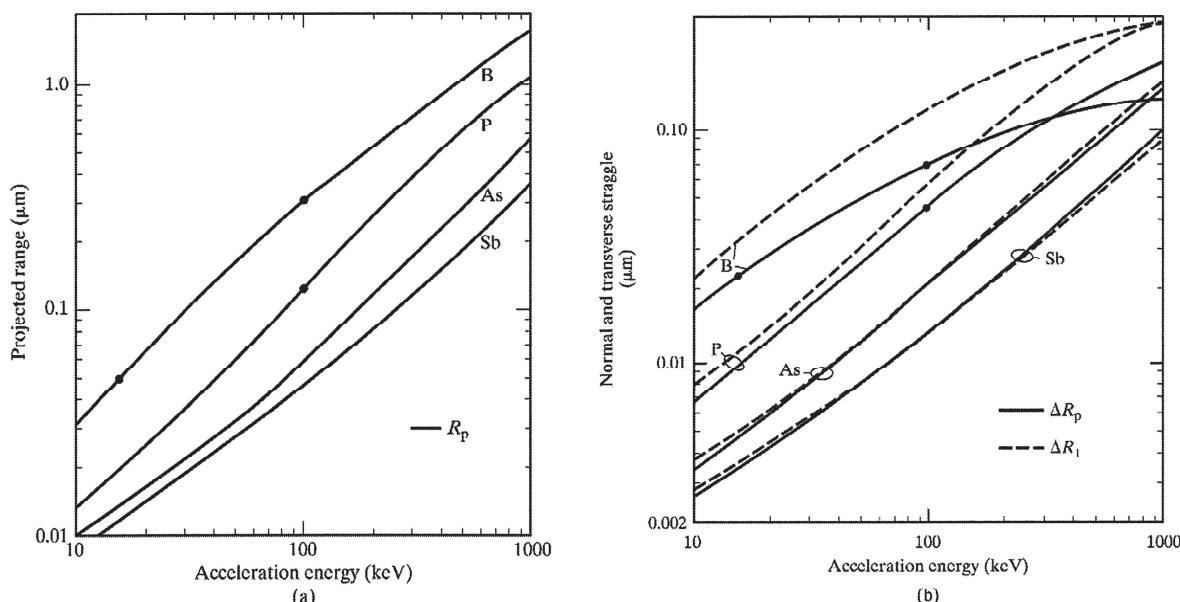
- (b) A limited-source boron diffusion is carried out on a n-type silicon wafer with a background concentration of $4.0 \times 10^{15} \text{ cm}^{-3}$ at 1100°C . Given the surface concentration of $5.0 \times 10^{18} \text{ cm}^{-3}$, $D_0 = 10.5 \text{ cm}^2/\text{s}$ and $E_a = 3.69 \text{ eV}$.

- (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-SiO₂ interface.

- (i) The projected range and straggles 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 $1.0 \times 10^{13} \text{ cm}^{-2}$?
- (iii) How thick should the SiO₂ layer be in areas that are not to be implanted if the background concentration is $1.0 \times 10^{16} \text{ cm}^{-3}$?

(9 Marks)

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

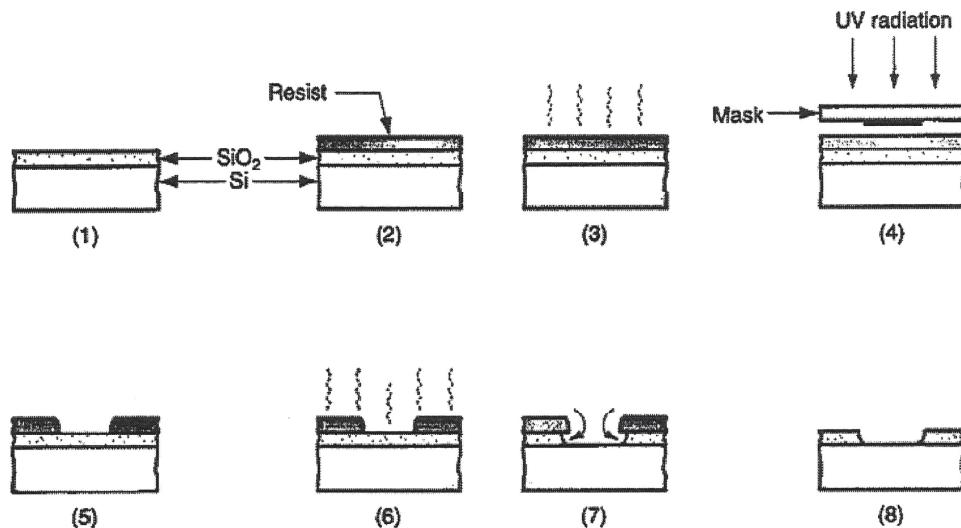
(5 Marks)

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**

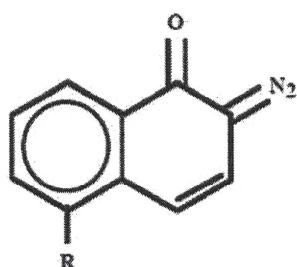
(5 Marks)

- (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)

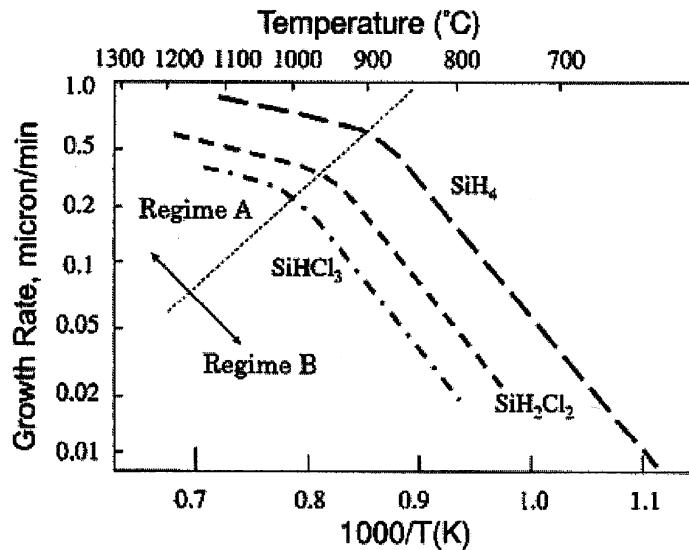
- (e) Explain how diazo-naphtho-quinone (DNQ), which is a photoactive compound (PAC) in a positive photoresist, promotes dissolution of the resin after light exposure. Figure 4 shows the molecular structure of DNQ, in which R, O and N stand for radical, oxygen and nitrogen, respectively.

(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,
- Identify the limiting mechanisms in Regime A and Regime B.
 - 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**

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

$$W = \sqrt{\frac{2\varepsilon_s}{q} \left[\frac{1}{N_A} + \frac{1}{N_D} \right] (V_{bi} - V)}; \quad L_p = \sqrt{D_p \tau_p}.$$

Bipolar junction transistors

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

$$I_{CEO} = (1 + \beta_0) I_{CBO}; \quad p_n(x) = p_{n0} e^{qV_{EB}/kT} \left(1 - \frac{x}{W}\right); \quad \gamma = \frac{1}{1 + \frac{D_E}{D_p} \cdot \frac{N_B}{N_E} \cdot \frac{W}{L_E}};$$

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

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

MOS devices

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

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

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

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

Thermal oxidation

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

Thermal diffusion

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

APPENDIX A (Continued)**Constant source diffusion:**

$$N(z,t) = N_s \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}\right)$$

Limited source diffusion:

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

Ion implantation

Before Annealing

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

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

After annealing

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

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

1.) a.) $J = 20 \text{ A/cm}^2$, $V_{FB} = 0.65 \text{ V}$, $n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$, $D_n = 25 \text{ cm}^2/\text{s}$, $D_p = 10 \text{ cm}^2/\text{s}$
 $T_{po} = T_{no} = 5 \times 10^{-7} \text{ s}$, $\epsilon_r = 11.7$, $kT = 0.0259 \text{ eV}$

i.) Total current density $J = J_n(-x_p) + J_p(x_n) = \left[\frac{qD_p P_{no}}{L_p} + \frac{qD_n n_{po}}{L_n} \right] (e^{qV_{FB}/kT} - 1)$ (R)

$$20 = J_s \cdot (e^{0.65 \text{ V} / 0.0259 \text{ eV}} - 1)$$

$$J_s = \frac{2.522 \times 10^{-10} \text{ A/cm}^2}{11}$$

ii.) $\frac{J_n(-x_p)}{J} = 0.1 = \frac{1}{10}$, $\frac{J_p(x_n)}{J} = 0.9$

$$J_n(-x_p) = 0.1 J$$

$$\frac{qD_n n_{po}}{L_n} (e^{qV_{FB}/kT} - 1) = \frac{J_s}{10} (e^{qV_{FB}/kT} - 1)$$

$$(L_n = \sqrt{D_n T_n})$$

$$\frac{q n_{po} \sqrt{\frac{D_n}{T_n}}}{L_n} = \frac{J_s}{10} = 2.522 \times 10^{-11}$$

$$1.133 \times 10^{-15} n_{po} = 2.522 \times 10^{-11}$$

$$n_{po} = 22259.488$$

$$\frac{n_{po}}{N_A} = \frac{(1.5 \times 10^{10})^2}{N_A} = 22259.488$$

$$N_A = 1.011 \times 10^{16} \text{ cm}^{-3}$$

$$J_p(x_n) = 0.9 J$$

$$\frac{qD_p P_{no}}{L_p} (e^{qV_{FB}/kT} - 1) = 0.9 J_s (e^{qV_{FB}/kT} - 1)$$

$$(L_p = \sqrt{D_p T_p})$$

$$q P_{no} \sqrt{\frac{D_p}{T_p}} = 0.9 J_s = 2.2698 \times 10^{-10}$$

$$7.165 \times 10^{-16} P_{no} = 2.2698 \times 10^{-10}$$

$$P_{no} = 316789.951$$

$$\frac{n_i^2}{N_D} = \frac{(1.5 \times 10^{10})^2}{N_D} = 316789.951$$

$$N_D = 7.102 \times 10^{15} \text{ cm}^{-3}$$

#Note that equation (R) is not given in the formula sheet, need to memorize some of the formulas!

b.) i.) the equation $f_T = \frac{1}{2\pi T_B}$ & $T_B = \frac{W^2}{2D}$ for BJT holds for FET too.

- If the gate oxide is reduced, capacitance becomes larger. This will increase the propagation delay & reduce the frequency.
- Add capacitive load to cancel the limitations or only reduce the gate length.
→ (#not sure)

ii.) n type → the p-channel is created (n-type semiconductor for pMOS)

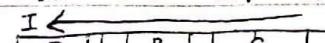
Inversion mode → EF in metal moves up further, there's +positive Qn at the semiconductor - oxide interface, higher negative Qm.

c.) $T = 300K$, $N_E = 10^{19} \text{ cm}^{-3}$, $N_B = 10^{17} \text{ cm}^{-3}$, $N_c = 7 \times 10^{15} \text{ cm}^{-3}$

inverse-active mode $V_{BE} = -2 \text{ V}$, $V_{BC} = 0.565 \text{ V}$, $n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$, $\epsilon_s = 11.7$

i.) $W_B = 1.2 \mu\text{m}$, W_{Bn} ?

$$W_{Bn} = W_B - W_1 - W_2$$



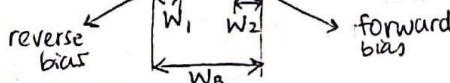
$$W_1 = \sqrt{\frac{2\epsilon}{q} \left(\frac{N_E}{N_B} \right) \left(\frac{1}{N_E + N_B} \right) (V_{bi} - V_{BE})} = 0.194 \mu\text{m} = 0.933 \mu\text{m}$$

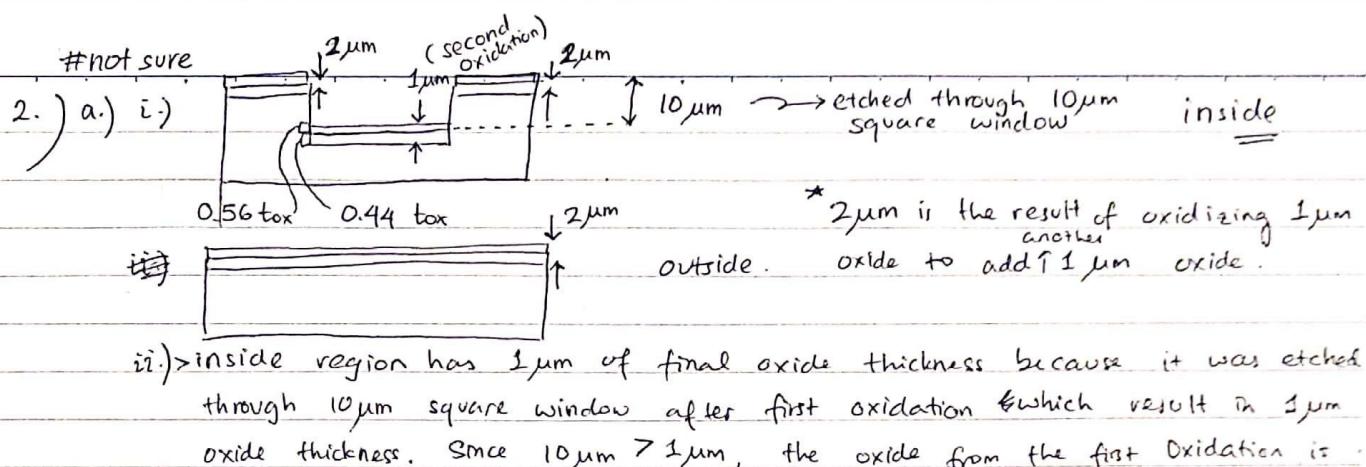
$$W_2 = \sqrt{\frac{2\epsilon}{q} \left(\frac{N_c}{N_B} \right) \left(\frac{1}{N_c + N_B} \right) (V_{bi} - V_{BC})} = 0.012 \mu\text{m}$$

$$V_{bi} = \frac{kT}{q} \ln \left(\frac{N_c N_B}{n_i^2} \right) = 0.745 \text{ V}$$

$$W_{Bn} = 1.2 - 0.194 - 0.012$$

$$= 0.994 \mu\text{m}$$





> inside region has 1 μm of final oxide thickness because it was etched through 10 μm square window after first oxidation which result in 1 μm oxide thickness. Since 10 μm > 1 μm, the oxide from the first oxidation is 100% etched through. (with 0.44 μm of oxide thickness in semiconductor)

> outside region has 2 μm of final oxide thickness since the first oxidation's oxide layer is kept (= 1 μm) & second oxidation adds another 1 μm (= 2 μm)

b.) $N_B = 4 \times 10^{15} \text{ cm}^{-3}$, $N_s = 5 \times 10^{18} \text{ cm}^{-3}$, $D_0 = 10.5 \text{ cm}^2/\text{s}$, $E_a = 3.69 \text{ eV}$, $T = 1100^\circ\text{C}$

i.) $D = D_0 \exp\left(-\frac{E_a}{kT}\right) = 3.025 \times 10^{-13} \text{ cm}^2/\text{s}$
(note that $T = 1373 \text{ K}$)

$$N_B = N_s \exp\left(-\frac{z^2}{4Dt}\right) \text{ where } t = 2 \text{ hours} = 7200 \text{ s}$$

$$\sqrt{-4Dt \ln\left(\frac{N_B}{N_s}\right)} = z \rightarrow z = 2.492 \times 10^{-4} \text{ cm} = 2.492 \mu\text{m}$$

ii.) I.) Constant - source diffusion

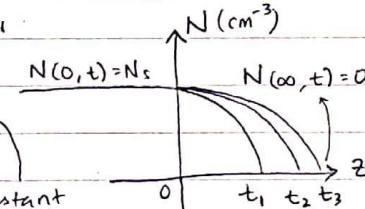
Boundary Conditions:

1.) $N(z, 0) = 0$

2.) $N(0, t) = N_s$

3.) $N(\infty, t) = 0$

Constant peak @ $z = 0$.



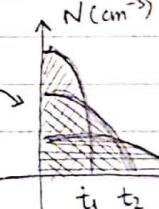
2.) Limited - source diffusion

Boundary conditions:

1.) $N(z, 0) = 0$

2.) $\frac{dN(0, t)}{dz} = 0$

3.) $N(\infty, t) = 0$



where $t_1 < t_2 < t_3$

* Area below curve will always be same.

c.) i.) projected range = 50 nm requires energy of $\sim 16 \text{ keV}$ (x-axis)

L refer to Figure 2(a) with y-axis being 0.5 μm using the Boron (B) curve

ii.) $Q = 1 \times 10^{13} \text{ cm}^{-2}$, $N_p = \frac{Q}{\sqrt{2\pi} \Delta R_p}$ where ΔR_p can be obtained from Figure 2(b)

$$N_p = \frac{1 \times 10^{13}}{\sqrt{2\pi} (0.023 \mu\text{m})} = 1.735 \times 10^{18} \text{ cm}^{-3}$$

by projecting 16 keV (x-axis) to the y-axis through B curve. $\Delta R_p = \sim 0.023 \mu\text{m}$

iii.) $N_B = 1 \times 10^{16} \text{ cm}^{-3}$.

$$N_B = N_p \exp\left[-\frac{(x - R_p)^2}{2\Delta R_p^2}\right]$$

$$\ln\left(\frac{N_B}{N_p}\right) = -\frac{(x - R_p)^2}{2\Delta R_p^2}$$

$$\sqrt{-2\Delta R_p^2 \ln\left(\frac{N_B}{N_p}\right)} + R_p = x$$

$$x = R_p + \Delta R_p \sqrt{2 \ln\left(\frac{N_B}{N_p}\right)}$$

$$= 50 \text{ nm} + 7.386 \times 10^{-6} \text{ cm}$$

$$= 123.860 \text{ nm}$$

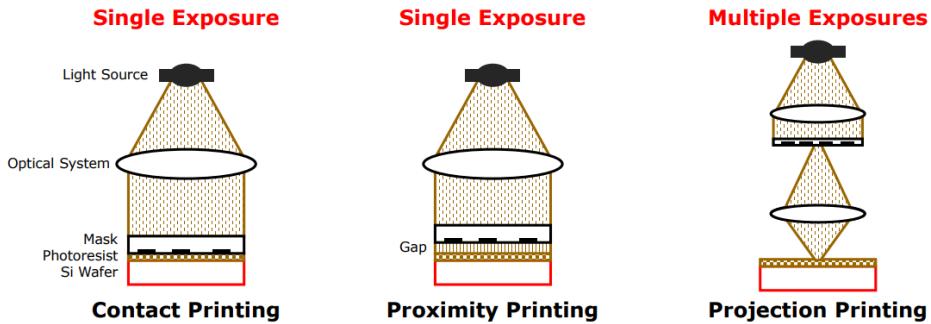
3. Answers:

a. **Contact** – mask and wafer in direct contact, high resolution of the order of $1\mu\text{m}$, the problem with dust particles.

Proximity – mask and wafer in close proximity (a small gap of $10\text{-}50\mu\text{m}$ between mask and wafer), less damage by dust particles, the low resolution of the order of $2\text{-}5\mu\text{m}$ due to the fringe.

Projection – (also called step-and-repeat aligners), the gap between mask and wafer is very large (in the range of cm).

Three Basic UV Exposure Methods



b. For projection lithography,

$$W_{\min} \approx k_1 \frac{\lambda}{NA}$$

$$\sigma = \frac{k_2 \lambda}{(NA)^2}$$

The resolution W_{\min} is **178.154 nm**

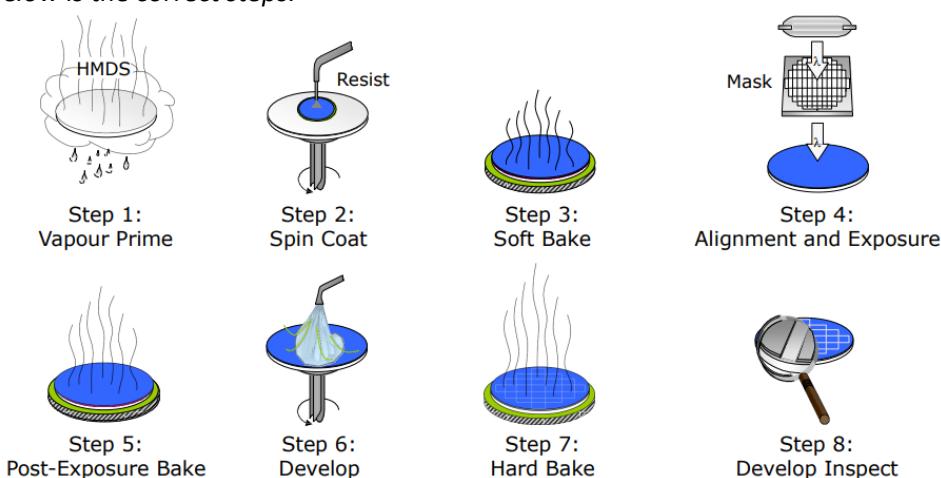
The DOF (σ) is **228.402 nm**

Resolution enhancement method (improve k) – Optical enhanced techniques

- Phase-Shift Mask (PSM) – overcome problems associated with light diffraction through small openings patterned on the reticle, reticle is modified with an additional transparent layer.
- Optical Proximity Correction (OPC) – ends and bows of narrow lines are not ideal.
- Off-Axis Illumination (OAI) – the incident exposure light that strikes the mask at an angle in order to align diffraction fringes with the lens.

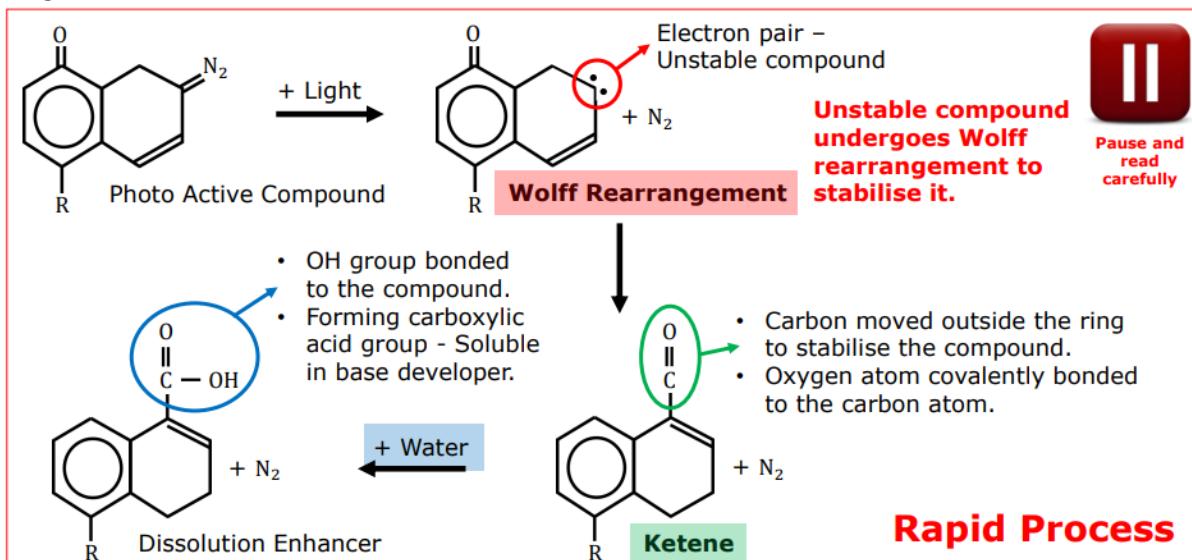
c. (1) = vapour prime, (2) = spin coat, (3) = soft bake, (4) = alignment and exposure, (5) = dissolved exposure parts, (6) = post-exposure bake/hard bake, (7) = wet etching, (8) = develop inspect

*The photolithography process steps shown in Figure 3 in question 3c is not the same as the notes. Below is the correct steps.



- d. - Purpose of applying a primer layer: removal of water molecules on the wafer surface. Dehydration baking will ensure that any H₂O on the sample evaporates out. This is especially important for samples that oxidize easily, for example like silicon.
- Hotplate for soft bake step malfunctioned:
- Prebaking or Soft Bake makes the photoresist (PR) sensitive to UV light by removing the solvent component of the PR.
 - A short prebake will prevent UV light from reaching the PAC (photoactive compound) due to an excess of solvent remaining in the PR.
 - Over-baking the sample will increase the sensitivity to UV light and, in severe cases, may destroy the PAC and reduce the solubility of the PR in the developer

- e. Diagram below is from lecture notes.



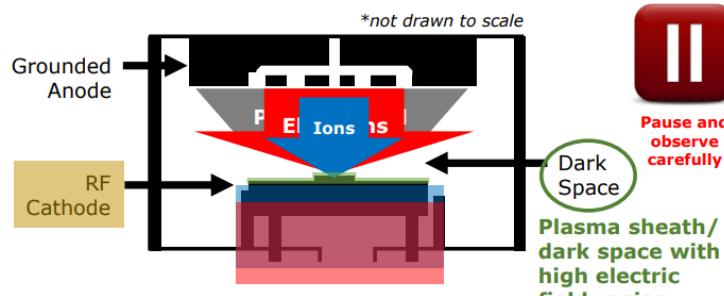
4. Answers:

- a. Explain by comparing dry etching and wet etching, showing **dry is better**:

| Wet Etching | Dry Etching |
|--|--|
| No proper etchant for specific materials (Si ₃ N ₄) | Anisotropic etching (High downwards etching) |
| Minimum etching dimension is relatively large | Minimum etching dimension is small |
| Undercutting in isotropic etching | Less lateral etching, less undercutting |

- b. Diagram below is from lecture notes.

1. Electrons in chamber gained energy by applied RF power.
2. When the bottom electrode is positive, many highly mobile electrons are accelerated towards the electrode, causing a significant accumulation of negative charge.
3. When the bottom electrode is negative and heavy, immobile ions accelerate towards it. However, only relatively few of these ions strike the electrode as compared to the number of electrons in the previous cycle. Hence, in a steady state, this electrode is negative biased, and therefore is called a cathode.



4. A high electric field region is then formed around the cathode. This region is known as the plasma sheath, or the dark space, where ion acceleration takes place before bombarding the substrate.
5. **Ions are accelerated** in dark space before bombarding the electrode.

c. - Due to the vertical bombardment of ions onto the target surface, good anisotropy can be achieved, but it has poor selectivity (no differentiation between different target elements). It also gives damage to the surface.

- Sputter yield depends on ion energy (also with ion mass, and the incident angle of the ion):

- The yield increases with the ion energy.
- For higher ion energies, the yield approaches saturation, which occurs at higher energies for heavier bombarding particles.
- Sometimes, at very high energies, the yield decreases as argon ions penetrate into sputter target (i.e. atoms beneath the target surface are unable to reach the surface to escape).

d. Given: $V = 50$ liters, $p = 0.5$ mTorr

i. $S = 1200$ liter/s, t_r ?

$$t_r = \frac{V}{S}$$

$$t_r = 50/1200 = \mathbf{0.0417 \text{ s}}$$

ii. 1 torr liter/s = 78.9 sccm, throughput (Q) y in sccm?

$$Q = pS$$

$$Q = 0.5 \text{ m} * 1200 = 0.6 \text{ torr liter/s} = \mathbf{47.34 \text{ sccm}}$$

e. Refer to Figure 5:

- i. Regime A: Mass transport-limited
Regime B: Surface reaction-limited

- ii. Regime A: Occurs at high temperature (temperature is needed to decompose the gases and move the species easily to the substrate).
Regime B: Occurs at low temperature but sensitive to temperature change. A small change in temperature can greatly affect the chemical reaction rate.

