Problem 1 Processing Modules and Simple Process Sequence (25 points total)
The following schematic cross-section shows a MOSFET together with a tunneling ohmic contact to the substrate. The MOSFET part of the process sequence has been well described in your textbook [Jaeger, Chapter 1].

(i) (5 points) Consider the whole process sequence. There are some sacrificial layers used during the process sequence which does not end up in the final structure. Quotes one example of such a sacrificial layer.

Silicon nitride is used to mask the field oxide pattern during the LOCOS step. It is completely removed afterwards.

(ii) (5 points) Starting with a blanket p-Si wafer, consider the whole process sequence. How many thermal oxidation steps are used to fabricate this structure? List all thermal oxidation steps used, and briefly describe the purpose.

Pad Oxide thermal oxidation
Field oxide thermal oxidation
Gate oxide thermal oxidation

(iii) (12 points) Starting with a blanket p-Si wafer, consider the whole process sequence. How many etching steps are used to fabricate this structure? List all etching steps used, and briefly describe the purpose. [Do not count photoresist development as etching steps]

LOCOS: Etch silicon nitride pattern
Etch pad oxide pattern
After LOCOS: Blanket etch silicon nitride
Blanket etch pad oxide
Gate patterning: Etch poly-Si
Contact Opening: Etch CVD SiO2
Metal patterning: Etch Al

(iv) (3 points) Which doped region will be subjected to the largest thermal budget for dopant diffusion?

The p+ channel stop region underneath the field oxide
Problem 2 Thermal oxidation (25 points total)

(a) (15 points) The following structure is subjected to a steam oxidation step at 1000°C for 3 hours. Sketch a roughly proportional cross-section after this oxidation step in the same figure. Label all regions and important thicknesses. Use the attached oxidation chart to generate numerical values of the different oxide thickness.

Undercut region underneath Si3N4: completely oxidized to 0.1 µm and oxidation stops because of nitride mask. Volume change around “bird’s beak” raises the nitride.

Oxide over blanket Si area: ~0.8 µm. Si consumed ~0.4 µm

Thick oxide region: 0.5 µm initial oxide ~ 1.5 hr oxidation time at 1000°C. Total oxidation time is equivalent to ~ 4.5 hr. Total oxide thickness ~1 µm. Si consumed ~0.25 µm

(b) A Si wafer has an unknown initial oxide thickness \(x_i\). After thermal oxidation for 1 hour, the total oxide thickness is measured to be \(x\) µm. With an additional 3 hours of oxidation, the total oxide thickness becomes \(2x\) µm.

Given: Linear oxidation constant \(B/A = 1\) µm /hour and parabolic oxidation constant \(B = 0.3\) µm²/hour.

(i) (5 points) Find the numerical value of \(x\)

[Hint: The solution for the quadratic equation: \(ax^2 + bx +c = 0\) is \(x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\)]

Deal-Grove model: \(x_{ox}^2 + Ax_{ox} = B (t+\tau)\)

\[\begin{align*}
\text{x}^2 + Ax &= B (1 +\tau) & [1] \\
4x^2 + 2Ax &= B (4 +\tau) & [2]
\end{align*}\]

[2] - [1] gives \(3x^2 + Ax - 3B = 0\)

\[(i) B/A = 1\ \mu m/hour \text{ and } B = 0.3\ \mu m^2/hour \Rightarrow A = 0.3\ \mu m,\]

or \(x = \frac{-0.3 + \sqrt{(0.3)^2 + 4 \times 3 \times 0.3}}{2 \times 3} = 0.5\ \mu m\)

(ii) (5 points) Find the numerical value of initial oxide thickness \(x_i\).

We then solve for \(\tau\). Using \(4 \times [1] - [2]\) gives \(2Ax = 3B\tau\)

or \(\tau = \frac{2 \times 0.3 \times 0.5}{3 \times 0.3} = 0.33\) hours

From \(x_i^2 + Ax_i = B\tau\), we obtain

\(x_i = \frac{-0.25 + \sqrt{(0.25)^2 + 4 \times 3 \times 0.28}}{2} = 0.2\ \mu m\).
Problem 3  Ion Implantation (25 points total)

Boron implantation (using B⁺ ions) is performed to the following structure to a boron dose of $10^{13}/\text{cm}^2$. The B⁺ ion energy is chosen such that the boron concentration at Location A is a maximum. For simplicity, let us assume the ion stopping powers and ion scattering characteristics are identical for both silicon and silicon dioxide.

(a) (4 points) What is the B⁺ ion energy?

235 keV boron gives a $R_p$ of 0.6 μm. The corresponding $\Delta R_p = 0.097$ μm

(b) (4 points) Calculate the maximum boron concentration at Location A?

$$C_{\text{max}} = \frac{0.4 \times 10^{13}}{0.097 \times 10^3} = 4.12 \times 10^{17}/\text{cm}^3$$

(c) (4 points) Calculate the boron concentration at Location B?

$$C(\text{at B}) = 4.12 \times 10^{17} \exp\left[-\frac{(0.75-0.6)^2}{2(0.097)^2}\right] = 1.25 \times 10^{17}/\text{cm}^3$$

(d) (5 points) The n-type Si substrate has a uniform doping concentration $= 10^{15}/\text{cm}^3$. Calculate the junction depth $x_j$ underneath Location B.

$$4.12 \times 10^{17}\exp\left[-\frac{(x_j - 0.6)^2}{2(0.097)^2}\right] = 10^{15}$$

$$x_j = 0.936 \text{ μm from poly-Si surface}$$

or $$0.186 \text{ μm from location B}$$
Problem 3 continued

(e) (4 points) Now, let us consider ion channeling effect. Will you expect a longer channeling tail in the crystalline silicon substrate underneath Location A or Location B? Write down your reasoning.

Our assumption was the ion stopping powers and ion scattering characteristics are identical for both silicon and silicon dioxide. Since **Location A** has less random scattering centers on top (0.6 µm total thickness) compare with that of Location B (0.75 µm total thickness), the collimated ion beam is scattered less and **has a larger fraction for channeling**.

(f) (4 points) After the boron implantation, a high temperature drive-in diffusion step is performed with 

\[(D_t)_{\text{drive-in}} = (\Delta R_p)^2\]

of the boron implantation profile. Sketch qualitatively the boron concentrations (log scale) in the Si substrate versus depth x underneath **Location B** for: (i) before drive-in (dash line), and (ii) after drive-in (solid line). Pay attention to slopes of the curves.

\[C(x) \text{ log scale}\]

**SiO2 has negligible dopant diffusion**

\[x = 0\]

before drive-in  
slope=0 at x=0  
after drive-in
Problem 4 Dopant Diffusion (22 points total)

(I) Consider the following Arsenic doping profiles.

(a) (4 points) Calculate the sheet resistance of Profile A using the mobility curves.
\[
R_s = \frac{1}{q \mu_n C x_j} = \frac{1}{1.6 \times 10^{-19} \cdot 160 \cdot 4 \times 10^{18} \cdot 2 \times 10^4} = 48.8 \text{ ohm/square}
\]

(b) (3 points) Use the Irvin’s curves to find the sheet resistance of Profile B.

\[C(x=0) = 4 \times 10^{18} \text{ /cm}^3, \quad N_B = 10^{15} \text{ /cm}^3 \implies R_s x_j = 300 \text{ ohm-\mu m from n-gaussian Irvin’s curve}\]

Therefore

\[R_s = 300 \text{ ohm-\mu m /2 \mu m} = 150 \text{ ohm/square}\]

(c) Suppose Profile B is subjected to an additional drive-in diffusion step such that the (Dt) product of the half-gaussian profile is doubled.

(i) (3 points) Calculate the new surface concentration.

\[C(x=0) = \frac{Q}{\sqrt{\pi Dt}} \text{ and dose } Q \text{ is conserved with drive-in diffusion}\]

After drive-in, \[C(x=0) = \frac{4 \times 10^{18}}{\sqrt{2}} = 2.8 \times 10^{18} \text{ /cm}^3\]

(ii) (3 points) Explain concisely why the sheet resistance of profile B is lower after the additional drive-in step.

Q is conserved but concentration is lower at all depths. The corresponding carrier mobilities are all higher. Therefore sheet resistance is lower.
Problem 4 continued

(II) A microfabrication textbook use the following expression to calculate the diffusivity of Arsenic in Si at 1000°C when the arsenic concentration is equal to $10^{20}$/cm$^3$.

$$D_{As} = 0.011 \exp\left(-\frac{3.44}{k(1000 + 273)}\right) + 31.0 \exp\left(-\frac{4.15}{k(1000 + 273)}\right)\left(\frac{1 \times 10^{20}}{7.14 \times 10^{18}}\right)$$

(i) (3 points) What physical quantity does the number “$7.14 \times 10^{18}$” represent?

The intrinsic carrier concentration $n_i$ of Si at 1000°C

(ii) (3 points) What physical quantity does the expression “$31.0 \exp\left(\frac{4.15}{k(1000 + 273)}\right)$” represent?

The diffusivity of As in Silicon due to negatively charged point defects (e.g. V$^-$) at 1000°C for very lightly doped Si (i.e., intrinsic Si)

(iii) (3 points) What physical quantity does the number “3.44” represent?

The activation energy (in eV) of the diffusivity of As in Si due to neutral point defects (e.g. V$^o$)