Problem 1 Simple Process Sequence (25 points total)

The cross-section of a pn diode is sketched in the above figure.

(a) (10 points) Starting with a p-type Si wafer, describe the process sequence (in the left column) and sketch the cross-sections of the structure after each lithography step (in the right column)

<table>
<thead>
<tr>
<th>Process Description</th>
<th>Cross-section</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Starting material : p-type wafer</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Mask 1 : Pattern n+ region with photoresist</strong></td>
<td>n-dopant implant (e.g. As+)</td>
</tr>
<tr>
<td>As implantation</td>
<td>![Process Diagram]</td>
</tr>
<tr>
<td>Grow thermal oxide</td>
<td>SiO2 SiO2 SiO2</td>
</tr>
<tr>
<td><strong>Mask 2: Pattern openings for Al contacts</strong></td>
<td>n+</td>
</tr>
<tr>
<td></td>
<td>p-Si</td>
</tr>
<tr>
<td>Deposit Al film by evaporation or sputtering deposition</td>
<td>Al</td>
</tr>
<tr>
<td><strong>Mask 3: Pattern Al lines</strong></td>
<td>SiO2 SiO2 SiO2</td>
</tr>
<tr>
<td></td>
<td>p-Si</td>
</tr>
</tbody>
</table>
Problem 1 continued

(b) (5 points) How many etching steps are used in this process sequence? List each one and describe their purpose. [DO NOT count photoresist development as etching step]

For the process described in part (a), there are two etching steps:
Etch 1: Etch SiO2 contact holes
Etch 2: Etch Al lines

[Note: Depending on your process flow, your answer will be different from above]

(c) (4 points) Circle the correct answer
The Al/n+ Si interface forms:
(1) a tunneling ohmic contact (2) a Schottky ohmic contact
The Al/p- Si interface forms:
(1) a tunneling ohmic contact (2) a Schottky ohmic contact

(d) (6 points) You probably recognize that the pn diode structure of part (a) has no electrical isolation with neighboring devices. Electrical isolation can be implemented by fabricating the diode with a p-well.

Describe the changes to your process sequence of part (a) such that you can implement this new structure. Note that the starting Si wafer now is n-type.

The key change is to form the p-well before diode processing. The depth of the well (large Dt product) can be controlled by a diffusion step before n+ doping.
Problem 2 Thermal oxidation (25 points total)

The following Dry Oxidation and Wet Oxidation data are available for thermal oxidation of <100> Si wafers

Rate constants for Dry Oxidation <100> Si

<table>
<thead>
<tr>
<th>Oxidation Temp (°C)</th>
<th>B (µm²/hr)</th>
<th>B/A (µm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>0.045</td>
<td>0.667</td>
</tr>
<tr>
<td>1100</td>
<td>0.027</td>
<td>0.178</td>
</tr>
<tr>
<td>1000</td>
<td>0.0117</td>
<td>0.042</td>
</tr>
</tbody>
</table>

(a) (6 points) A Si wafer has an initial oxide thickness of 0.5 µm. With Wet-Oxidation at 1000°C, what is the required oxidation time to obtain a total thickness of 1 µm?

Starting with a bare wafer and using the wet-oxidation curves:
1.0 µm oxide takes 4.5 hours with wet oxidation at 1000°C
0.5 µm initial oxide is equivalent to ~1.4 hr of wet oxidation at 1000°C

Therefore, it takes ~3.1 hours from 0.5 µm to 1.0 µm of oxide.

(b) (6 points) The oxidized wafer of part (a) is further subjected to Dry-Oxidation at 1000°C. What is the oxidation rate (in µm/hr) when the oxide has a total thickness = 2 µm?

\[
\frac{d x_{ox}}{d t} = \frac{B}{A+2x_{ox}} = \frac{0.0117}{0.279 + 2 \times 2} = 0.00273 \text{ µm/hr}
\]

\[
B = 0.0117 \text{ µm}^2/\text{hr} \quad \text{and} \quad B/A = 0.042 \text{ µm/hr. Therefore} \quad A = 0.0117/0.042 = 0.279 \text{ µm}
\]
Problem 2 continued

(c ) Heavily doped Si has more charged point defects near the oxide/Si interface. The linear rate constant 
(B/A) increases for heavily doped Si but the parabolic rate constant (B) remains the same. The following 
oxide window has an initial oxide thickness = 0.3 µm. After oxidation for a certain time t , the final oxide 
thickness \( X_{\text{ox}} \) is found to be equal over both \( n^+ \) and \( p \) regions .

Given : \( (B/A)_{n^+} = 4 \) \( (B/A)_p = 0.4 \) µm/hour ; \( (B)_{n^+} = (B)_p = 0.15 \) µm²/ hour

(i) (4 points) Calculate the Si substrate step height \( \Delta \).

\[
\text{Si consumed in } n^+ \text{ region} = X_{\text{ox}}/2.17 \\
\text{Si consumed under original oxide region} = (X_{\text{ox}}-0.3)/2.17 \\
\text{Step height} \Delta = X_{\text{ox}}/2.17 - (X_{\text{ox}}-0.3)/2.17 = 0.138 \text{ µm}
\]

(ii) (4 points) Do you expect the boron concentration at point A (see figure) has a higher or lower 
concentration than the original substrate? Briefly explain.

Lower. During oxidation, the segregation coefficient \( m \) is < 1 at the Si/SiO\(_2\) interface and boron prefers to 
stay inside the SiO\(_2\).

(iii ) (7 points) Calculate this final oxide thickness \( X_{\text{ox}} \).

\[
B_{n^+} = B_p = 0.15 \text{ µm}^2/ \text{hr} \\
A_{n^+} = 0.375 \text{ µm} \\
A_p = 4A_{n^+} = 1.5 \text{ µm}
\]

Over \( n^+ \) region : \( X_{\text{ox}}^2 + A_{n^+}X_{\text{ox}} = B_{n^+}t \) (1)

Over \( p \) region : \( X_{\text{ox}}^2 + A_pX_{\text{ox}} = B_p(t + \tau) \) where \( \tau = \frac{X_i^2 + A_pX_i}{B_p} \) (2)

Equations (2) - (1) \( \Rightarrow X_{\text{ox}} = \frac{B_{n^+} \tau}{3A_{n^+}} = \frac{1}{3} \times \frac{0.15 \times (0.3)^2 + 1.5 \times 0.3}{0.15} = 0.48 \text{ µm} \)
Problem 3 Ion Implantation (25 points total)

(A) Boron ions (B⁺) are implanted into an n-type Si wafer with background doping concentration of 10¹⁶/cm³.
Regions I of the wafer is covered with SiO₂ with thickness t_{SiO₂} and Region II has no oxide. The boron concentration C(x) versus depth x for Region I is sketched in the figure below. For simplicity, let us assume the SiO₂ and Si have identical energy stopping powers.

(a) (6 points) What is the kinetic energy of the B⁺ ions (in keV) ?

\[ 10^{18} \text{cm}^3 \times \exp \left[ -(0.2)^2 / 2 \Delta R_p^2 \right] = 10^{16} \text{cm}^3 \]

\[ \Delta R_p = 0.066 \mu m \]

The corresponding B⁺ energy is 90 keV (from B¹¹ into Si curve)

(b) (2 points) What is the boron implantation dose (in /cm²) ?

\[ 10^{19} \text{cm}^3 = 0.4 \times \text{dose} / \Delta R_p \]

\[ \text{implant dose} = 10^{18} \times 0.066 \times 10^{-4} / 0.4 = 1.65 \times 10^{13} / \text{cm}^2 \]

(c) (2 points) What is the thickness of the SiO₂ (t_{SiO₂}) ?

For 90 keV B⁺ ions, \( R_p = 0.26 \mu m \)

Therefore \( t_{SiO₂} = 0.26 - 0.1 = 0.16 \mu m \)

(d) Calculate the sheet resistance \( R_S \) of Region II (i.e., the no oxide region) using the following two different methods:

(i) (3 points) The approximate expression \( R_S \sim 1/(q \cdot \mu_{\text{effective}} \cdot \text{dose}) \)

\( \mu_{\text{effective}} \) (holes at doping conc =10¹⁵) = 160 cm²/V-sec

\[ R_S \sim 1/(1.6 \times 10^{-19} \cdot 160 \cdot 1.65 \times 10^{13}) = 2367 \text{ ohm/square} \]

(ii) (4 points) The Irvins curves

Using No=10¹⁸ /cm³ and N_B=10¹⁶ /cm³ with the p-gaussian curves, \( R_S \cdot x_j \sim 1000 \text{ ohm-\mu m} \)

Each half-gaussian will give \( R_S = 1000/0.2 = 5000 \text{ ohm/sq} \)

(Note: “\( x_j \)” is only 0.2 \( \mu m \) from the peak position)

Since there are two \( R_S \) in parallel for the full Gaussian, the overall \( R_S \) is \( \sim 2500 \text{ ohm/sq} \)
(B) (4 points) Explain in your own words what is solid phase epitaxial growth (SPEG) of Si after the Si crystal is subjected to a high dose implantation step. Use sketches to illustrate your ideas if necessary.

After an amorphous surface layer is formed by high dose implantation, the substrate underneath is still monocrystalline. Upon annealing (500°C and above), **the Si atoms in the amorphous layer will aligned themselves with the monocrystalline template at the amorphous/crystalline interface** (crystalline Si is the most energetically favorable state). The regrowth will form a new amorphous/crystalline interface. This recrystallization process will continue until the whole amorphous layer has recovered to the monocrystalline state.

![Diagram showing amorphous and monocrystalline Si before and after SPEG](image)

[Comment: Unlike vapor phase epitaxial growth where the Si crystalline overlayer is fed by external Si-containing gas, SPEG has the amorphous Si as a supply of Si atoms. Hence, the name “solid-state” epitaxial growth]  

(c ) (4 points) Explain in your own words why a higher dose of boron ions is needed to transform crystalline Si into amorphous Si as compared with arsenic ions.

Energetic particles traveling solids have two energy loss components:

1) **Nuclear stopping**- collision with substrate atoms and dislocatr them from original crystalline sites. Point facets such as interstitials and vacancies will be formed.
2) **Electronic stopping**- excitation of electrons to higher energy orbitals. Subsequent electron transition back to ground state will generate photons and phonons which eventually contribute to substrate heating. No substrate point defects are created.

For the same kinetic energy, lighter ions (e.g. boron) will be dominated by electronic stopping while heavier ions (e.g. As) will be dominated by nuclear stopping. Hence, a larger dose of boron is required to generate the threshold point defects concentration to transform the crystalline substrate into an amorphous substrate.
Problem 4 Diffusion (25 points total)
(a) 
A boron predeposition step is performed with an n-type Si substrate at 1000°C with an incorporated boron dose \( Q \) of \( 3 \times 10^{15} \text{cm}^{-2} \).
Boron solid solubility at 1000°C is known to be \( 3.5 \times 10^{20} \text{cm}^{-3} \).

(i) (5 points) What is the \( Dt \) product of the predeposition process?

\[
Q = \frac{2C_S\sqrt{Dt}}{\sqrt{\pi}}
\]

\[
Dt = \pi \left( \frac{Q}{2C_S} \right)^2 = 3.14159 \times \left( \frac{3 \times 10^{15}}{2 \times 3.5 \times 10^{20}} \right)^2 = 5.8 \times 10^{-11} \text{cm}^2/\text{sec}
\]

ii) (5 points) What is the junction depth \( x_j \) of the predeposition profile if the n-type substrate has a background concentration of \( 10^{15} \text{cm}^{-3} \). 

\[
3.5 \times 10^{20} \text{erfc}\left[ \frac{x_j}{2\sqrt{Dt}} \right] = 10^{15} \Rightarrow \frac{x_j}{2\sqrt{Dt}} = \text{erfc}^{-1} (2.9 \times 10^{-6}) = 3.3
\]

\( x_j = 3.3 \times 2 \times 7.62 \times 10^{-6} \text{cm} = 5 \times 10^{-5} \text{cm} = 0.5 \mu\text{m} \)

(b) Three doping processes are proposed to form the source and drain of a MOS transistor.

(P)rocess A) Shallow diffusion predeposition dose of \( Q \) phosphorus atoms/unit area, followed by a drive-in at 1100°C for 60 minutes.

(P)rocess B) Shallow diffusion predeposition dose of \( Q \) phosphorus atoms/unit area, followed by a drive-in at 1150°C for 30 minutes.

(P)rocess C) Shallow implantation dose of \( Q \) phosphorus atoms/unit area, followed by a drive-in at 950°C for 10 minutes.

Use the following diffusivity values and neglect high-concentration diffusion effects:

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>D (Phosphorus)</th>
</tr>
</thead>
<tbody>
<tr>
<td>950°C</td>
<td>( 5 \times 10^{-5} \mu\text{m}^2/\text{min} )</td>
</tr>
<tr>
<td>1100°C</td>
<td>( 2 \times 10^{-3} \mu\text{m}^2/\text{min} )</td>
</tr>
<tr>
<td>1150°C</td>
<td>( 5 \times 10^{-3} \mu\text{m}^2/\text{min} )</td>
</tr>
</tbody>
</table>
Problem 4 continued

(i) (5 points) Which process will give the shortest MOSFET channel length \( L \) ? Explain your reasoning. The larger the lateral junction depth \( y_j \), the shorter will the channel length \( L \). The lateral junction depth \( y_j \) from masking edge is \( \sim 0.7 \) of the vertical junction depth \( x_j \).

(A) \( D_t = 2 \times 10^{-3} \ \mu m^2 / min \times 60 \ min = 1.2 \times 10^{-1} \ \mu m^2 \)
(B) \( D_t = 5 \times 10^{-3} \ \mu m^2 / min \times 30 \ min = 1.5 \times 10^{-1} \ \mu m^2 \)
(C) \( D_t = 5 \times 10^{-5} \ \mu m^2 / min \times 10 \ min = 5 \times 10^{-4} \ \mu m^2 \)

Process B has the largest \( D_t \) product and hence the largest vertical and lateral diffusion. ∴ Process B gives the shortest MOSFET channel.

(ii) (4 points) If the substrate doping \( N_a \) is increased, which of the three processes will exhibit the biggest change in channel length \( L \) ? Use a qualitative sketch to illustrate your reasoning.

Dose Q is same for all three processes. Profile with the largest diffusion distance will have the most gentle slope (i.e. Process B). If substrate concentration is altered, Process B will have the largest change in \( x_j \) (and hence \( y_j \) and \( L \)).

(iii) (6 points) Doping concentration of source and drain regions are typically larger than \( 10^{20} / cm^3 \). Indicate with an “X” in the following table for those effects which will increase the dopant diffusivity.

<table>
<thead>
<tr>
<th></th>
<th>E-field Enhancement</th>
<th>Charge Point Defects</th>
<th>Transient Enhanced Diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process A</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Process B</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Process C</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>