Problem 1 of 3 (Answer each question briefly and clearly. (35 points)

What is the mass-action law? (5pts)

It states that \( np = n_i^2(T) \), or that the product of concentrations of free holes and electrons is a function of temperature.

What is the concentration of holes, electrons and ions if Si is doped with \( 10^{16} \) As atoms/cm\(^3\), at room temperature? (5pts)

As is in group VI, it has five valence electrons, so it creates free electrons, while As atoms become positive ions. The concentration of positive ions is \( 10^{16} \), the concentration of electrons is also \( 10^{16} \), while the concentration of holes, at room temp is \( 10^4 \).

What are the four types of currents you can find across a p-n junction at equilibrium? (6pts)

electron drift, electron diffusion, hole drift and hole diffusion currents.

Find the resistance of the following structure (drawn to scale), if the Rs is 10 Ohms/square. Assume corner squares account for 0.56 Rs, while “dogbone” contact areas amount to 0.65 squares. (8pts)

0.65+1.5+0.56+5.5+0.56+1+0.56+3+0.56+1+0.56+5.5+0.56+1.5+0.65=1.3+6x0.56+19=23.44, so the total resistance is about 234.4 Ohms.
At what gate-to-bulk bias do you obtain the minimum possible capacitance of an MOS structure on top of a p-type substrate? (5pts)

This happens exactly before the point of inversion, when we have the maximum depletion region, but no inversion layer.

\[ \sqrt{\frac{1}{T_n}} \]

Consider an MOS structure on top of a n-type substrate, while using n+ type gate. Mark the type of charges (i.e. positive ions / negative ions / free electrons / free holes) on the gate and the substrate as a function of the biasing conditions on the following table (6pts):

<table>
<thead>
<tr>
<th>Bias</th>
<th>Gate Charges</th>
<th>Substrate Charges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulation</td>
<td>positive ions</td>
<td>free electrons</td>
</tr>
<tr>
<td>Depletion</td>
<td>free electrons</td>
<td>positive ions</td>
</tr>
<tr>
<td>Inversion</td>
<td>free electrons</td>
<td>free holes and positive ions</td>
</tr>
</tbody>
</table>
Problem 2 of 3 (40 points)

Sometimes, a special "Vt-adjust" implant is being used in order to set the threshold voltage of a device at a specific value. The process sequence described next is an example of this. Please follow the steps and draw the two cross sections at the steps indicated (10 points):

Step 0: start with $10^{15}$ atoms/cm$^3$ p-type wafer and 0.5μm of isolation oxide.

Step 1: use mask shown to create active area (i.e. remove the thick gate oxide in shaded region.)

Step 2: implant a dose of $10^{12}$ atoms of Boron per cm$^2$, so that the annealed profile has a uniform concentration of $10^{17}$/cm$^3$ from the surface down to a finite depth. (draw the two cross sections marked on the graph and calculate and mark the depth of the annealed Boron profile.)

Step 3: grow 100 Angstroms of gate oxide

Step 4: deposit and pattern gate

Step 5: Implant n+ source/drain and gate, to a depth of 0.5μm. (draw the two cross sections marked on the graph)
On a different example of using the Vt adjust implant, make the assumption that the implant is very shallow, so all its charge can be approximated by a delta function at the surface of the channel. Now consider the specific case where we have n+ poly (assume $\phi_m = 0.55\text{V}$), p-type substrate with $10^{15}/\text{cm}^3$ concentration of Boron, and a Tox of 100 Angstroms ($10^{-6}\text{cm}$). The unknown in this problem is the dose $D$ and the polarity of the implanted material, in # of atoms / cm$^2$.

Sketch the charge density ($\rho$), electric field ($E$) and potential ($\phi$) diagrams (15 points).

Label all values with the proper units.

Here I assume $D$ is negative, i.e. the expansion implant is made of donors, (this assumption will be resolved in the numerical solution next).

Find the dose and type (donor or acceptor) of the channel implant so that the depletion depth $X_d$ is exactly 0.1 $\mu$m when $V_{GS} = V_{BS} = 0\text{V}$ ($\varepsilon_0 = 8.85 \times 10^{-14}\text{F/cm}$, $\varepsilon_{ox} = 3.9\varepsilon_0$, $\varepsilon_{si} = 11.7\varepsilon_0$, elementary charge is $1.6 \times 10^{-19}\text{Cb}$) (15 points)

I write the equation that describes the potential function:

$$0.55\text{V} - \frac{(-\rho_0 X_d - D)}{E_{ox}} - (-0.36\text{V}) = -\frac{\rho_0 X_d^2}{2\varepsilon_s}$$

the only unknown is $D$!

$$0.55\text{V} + \frac{105 \times 1.6 \times 10^{-19}\text{Cb} \cdot 10^{16}/\text{cm}^3 + D_0^2}{3.9 \times 8.85 \times 10^{-14}\text{F/cm}} - 10^{-6}\text{cm} + 0.36\text{V} = \frac{1.6 \times 10^{-19}/\text{cm}^3 \cdot (10^{-5}\text{cm})^2}{2 \times 11.7 \times 8.85 \times 10^{-14}\text{F/cm}}$$

$$\Rightarrow 0.55\text{V} \cdot 0.0464 + 0.36 - 0.0773 = -\frac{D_0^2}{3.45 \times 10^{-6}} \Rightarrow \frac{D_0}{3.45 \times 10^{-7}} = -0.786 \cdot 3.45 \cdot 10^{-7} = -2.713 \cdot 10^{-7}\text{Cb}$$

so, the implanted dose is $-2.713 \cdot 10^{-7} \text{/cm}^3 \Rightarrow D = 1.43 \cdot 10^{12} \text{atom/cm}^2$ (acceptor)
Problem 3 of 3 (3 points)

You just found in your basement a batch of old, n-type wafers from the 70s. You decide to make some cheap inverters on them, just by using p-channel transistors and diffusion resistors. This is the design of the inverter you come up with:

![Diagram of inverter circuit]

Now, assume that W/L is 10/2, \( V_{DD} = 5V \), \( V_{TP} = -1V \), \( \mu_p \cdot \text{Cox} \) is \( 25 \mu A/V^2 \) and \( \lambda_p = 0V^1 \). Sketch the load line diagrams for the resistor and the transistor, and mark the approximate values of Vout for Vin taking the values 0V, 1V, 2V, 3V 4V and 5V.

\[
I_{DS} = -\frac{1}{2} K_P \left( V_{SG} + V_{TP} \right)^2
\]

<table>
<thead>
<tr>
<th>( V_{in} )</th>
<th>( V_{SG} )</th>
<th>( I_{DS} )</th>
<th>( V_{ou} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-5</td>
<td>-1mA</td>
<td>~3.5</td>
</tr>
<tr>
<td>1</td>
<td>-4</td>
<td>-0.5625mA</td>
<td>~2.5</td>
</tr>
<tr>
<td>2</td>
<td>-3</td>
<td>-0.25mA</td>
<td>~1.5</td>
</tr>
<tr>
<td>3</td>
<td>-2</td>
<td>-0.0625mA</td>
<td>~0.5</td>
</tr>
<tr>
<td>4</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(Vol = 0V, Voh = )

(over)
Draw the small signal equivalent circuit and calculate $A_v$ when $V_{in} = 2V$. (10 points)

\[ g_{mp} = K_p \left( V_{dd} - 2V + V_{ce} \right) = 125 \mu A/V^2 \cdot 2V = 250 \mu A/V^* \]

\[ \eta_{op} = \infty \quad \text{since} \quad \eta_c = 0 \quad V^{-1} \]

\[ A_v = \frac{V_{out}}{V_{in}} = -g_{mp} \cdot R = -250 \mu A/V^* \cdot 5000 \cdot \frac{V}{A} = -1.25 \quad \text{(not too good!)} \]