Problem 1 of 3 Answer each question briefly and clearly. (36 points)

What is the concentration of holes, electrons and ions if Si is doped with $10^{17}$ Boron atoms/cm$^3$, at room temperature? ($n = 10^{17}$, $p = 10^{-3}$)

Boron is an acceptor, so we have $P:10^{17}$, $N_e = \frac{N_A}{10^{17}} = 10^{-3}$ and we also have $10^{17}$ negative ions/cm$^3$.

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

\[ J_{diff}, J_{therm}, J_{drift}, J_{diffusion} \]

All of them add up to 0.

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)

At what gate-to-bulk bias potentials do you obtain the maximum possible capacitance of an MOS structure on top of a p-type substrate? (mention all the bias regions that apply in this case). (5pts)

\[ V_{GB} > V_{fn} \quad \text{or} \quad V_{GB} < V_{fr} \]
Consider an MOS structure on top of a $n$-type substrate, while using $p$-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></td>
<td>- ions</td>
<td>+ ions</td>
</tr>
<tr>
<td></td>
<td>electrons</td>
<td>holes</td>
</tr>
<tr>
<td></td>
<td>- ions</td>
<td>+ ions</td>
</tr>
<tr>
<td></td>
<td>electrons</td>
<td>holes</td>
</tr>
<tr>
<td></td>
<td>- ions</td>
<td>+ ions</td>
</tr>
<tr>
<td></td>
<td>electrons</td>
<td>holes</td>
</tr>
<tr>
<td></td>
<td>- ions</td>
<td>+ ions</td>
</tr>
<tr>
<td></td>
<td>electrons</td>
<td>holes</td>
</tr>
<tr>
<td></td>
<td>- ions</td>
<td>+ ions</td>
</tr>
<tr>
<td></td>
<td>electrons</td>
<td>holes</td>
</tr>
</tbody>
</table>

The following signal shows up on your oscilloscope. Is the vertical input to the oscilloscope on AC mode or DC mode? Why? (2pts)

The signal would be 0V. If the AC mode is used, the signal would be 125V.

We want to draw the I-V characteristics for a 1K-ohm resistor using a curve tracer (HP4155). We would like to plot the curve for voltage values from 0 to 5 V. What's wrong with the following setting for the curve tracer (3pts)

Setting: SMU 1: 9 V
SMU 2: start: 0 V, step: 100 mV, stop: 5 V, linear, compliance current: 2 mA

If SMU 2 is 5V, the SMU should draw 5mA, which is more than the 2mA current. Therefore, the setting is incorrect.

Problem 2 of 3 (40 points)

2.1 You are given the following circuit, that includes both large signal and small signal voltage sources. (\(V_D < 0\))

\[
\begin{align*}
    V_D & \leq 0 \\
    V_{out} & = \frac{V_D}{R + \frac{1}{C_1}} \\
    C_{eq} & = \frac{C_3}{1 - V_D V_b} \\
    \frac{v_o}{V_{out}} & = \frac{1 - V_D / V_b}{1 - V_D / V_b} \\
    \end{align*}
\]

a) write the transfer function expression of \(v_{out}/V_{in}\) as a function of \(j\omega\). (5pts)

\[
\frac{v_o}{V_{in}} = \frac{1}{R + \frac{1}{C_1} + j\omega R C_1}
\]

b) write the expression that links the 3db frequency \(\omega_{3db}\) to \(V_D\). (5pts)

\[
\omega_{3db} = \frac{1}{RC_1} \frac{1 - V_D / V_b}{1 - V_D / V_b}
\]

C) complete the calculations on the table below, given that \(C_1 = 1.63pF\), \(\phi_B = 0.6V\) and \(R = 1\Omega\). (6pts)

<table>
<thead>
<tr>
<th>(V_D)</th>
<th>(C_{eq})</th>
<th>(\omega_{3db})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0V</td>
<td>1.63 pF</td>
<td>1 kHz</td>
</tr>
<tr>
<td>-1V</td>
<td>1.64 pF</td>
<td>9 kHz</td>
</tr>
<tr>
<td>-3V</td>
<td>70 kHz</td>
<td>1.4 kHz</td>
</tr>
</tbody>
</table>
2.2 The following circuit consists of three components connected in a "cascade". Assume that the connection of component B to circuits A and C does not affect their individual transfer functions. Further, assume that the total transfer function of this circuit, is simply the product of the three individual transfer functions.

![Circuit Diagram]

2.2a. Write the expressions for \( H_A(j\omega) \) and \( H_C(j\omega) \) (10pts)

\[
H_A(j\omega) = \frac{V_x}{V_A} = \frac{R_A}{R_A + \frac{1}{j\omega C_A}} = \frac{j\omega R_A C_A}{1 + j\omega R_A C_A}
\]

\[
H_C(j\omega) = \frac{V_{out}}{V_y} = \frac{1}{\frac{1}{j\omega C_C} + R_C} = \frac{1}{1 + j\omega R_C C_C}
\]

2.2b. The Bode plot below already has the \( |H_B(j\omega)| \) drawn. Assume \( R_A C_A = 10^{-3} \) sec, and \( R_C C_C = 10^6 \) sec, and draw the \( |H_A(j\omega)| \) and \( |H_C(j\omega)| \) on the same plot, and also draw the total transfer function on the same plot. Mark each of the three plots that you will draw. (10pts)

![Bode Plot]

2.2c. What is the approximate value of the total transfer function at the 3db break frequencies of \( H_B \)? (I need an answer within +/- 0.5dB). (3pts)

\[
= 40 dB - 3 dB - 3 dB
\]

\[
= 34 dB
\]
Problem 3 of 3 (26 points)

You are given an nmos transistor with \( W=20 \mu m \), \( L=1.5 \mu m \), \( V_{DS0}=1 V \), \( \mu_nC_{ox}=50 \mu A/V^2 \), \( V_T=0.6V/2 \), \( \lambda=0.1/V \cdot \mu m \).\(^{-1} \) (in \( \mu m \)), \( \delta=0.42 V \), \( \mu_n=700 \text{ cm}^2/\text{V} \cdot \text{sec} \). Also, the saturation velocity of electrons, \( v_{sat}=10 \text{ cm/sec} \).

3.1 Place the appropriate check marks on the table below (5pts)

<table>
<thead>
<tr>
<th>( V_{GS} )</th>
<th>( V_{DS} )</th>
<th>( V_{RS} )</th>
<th>Cutoff?</th>
<th>Triode?</th>
<th>Saturation</th>
<th>( v_{sat} ) limited?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>✓</td>
<td>❑</td>
<td>❑</td>
<td>❑</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>✓</td>
<td>❑</td>
<td>❑</td>
<td>❑</td>
</tr>
<tr>
<td>1.5</td>
<td>0.5</td>
<td>0.5</td>
<td>✓</td>
<td>❑</td>
<td>❑</td>
<td>❑</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>✓</td>
<td>❑</td>
<td>❑</td>
<td>❑</td>
</tr>
</tbody>
</table>

3.2 Draw the small signal model of the transistor in saturation. Do not include any of the parasitic capacitances of the transistor, but do connect a capacitor \( C_{out} \) between the drain and the source (5pts).

3.3 Find the transfer function expression for \( V_d/V_{gs} \) as a function of \( g_m, r_0 \) and \( C_{out} \) (5pts)

\[
V_d = Z_{in} I_d = g_m V_{gs} \]
\[
Z_{in} = r_0 / Z_C = \frac{r_0}{(1/j \omega) C_{out}} \]
\[
\frac{V_d}{V_{gs}} = \frac{g_m r_0}{(1/j \omega) r_0 C_{out}} \]

3.4 Find the 3db break frequency \( \omega_{3dB} \) expression as a function of \( I_d \) and \( C_{out} \) (6pts)

\[
\omega_{3dB} = \frac{1}{r_0 C_{out}} \]
\[
I_d = \frac{1}{\lambda} \frac{1}{C_{out}} \]
\[
\omega_{3dB} = \frac{\lambda I_d}{C_{out}} \]

3.5 Find the 3db break frequency \( \omega_{3dB} \) expression as a function of \( V_{GS} \), assuming \( V_{DS}=1.5V \), \( V_{BS}=0V \) (5pts)

\[
I_d = \frac{1}{2} \mu_n (\omega L) (V_{GS} - V_T)^2 (1 + \lambda V_{DS}) \]
\[
\omega_{3dB} = \frac{\lambda}{2 \mu_n C_{ox} (1 + \lambda V_{DS})} \left( V_{GS} - V_T \right)^2 (1 + \lambda V_{DS}) \]
\[
\omega_{3dB} = \frac{\lambda}{2 \mu_n C_{ox} (1 + \lambda V_{DS})} \left( V_{GS} - V_T \right)^2 (1 + \lambda V_{DS}) \]