Problem 1 of 4: Answer each question briefly and clearly. (5 pts each, 40 total)

1.1 Assume a diffused resistor with a fixed thickness. What happens to the Sheet Resistance (Rs) if the doping level doubles (assuming that there is only a single dopant and that mobility does not change)?

- stays the same
- doubles
- is reduced by 50%
- none of the above.

$\sigma = \frac{Q}{V} \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ n = N_0$  

1.2 Find the "built-in potential" $\Phi_B$ of a junction that has $N_d = 10^{16}/cm^3$ and $N_A = 10^{17}/cm^3$.

$$\Phi_B = \phi_n - \phi_p = 1780 \text{mV}$$

1.3 Place check marks where appropriate to indicate the correct region of operation, assuming that $V_{th} = V_{tp} = 1 \text{V}$.

<table>
<thead>
<tr>
<th>Transistor</th>
<th>$V_{GS}$</th>
<th>$V_{DS}$</th>
<th>$I_{OFF}$</th>
<th>Triode</th>
<th>Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOS</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>NMOS</td>
<td>2</td>
<td>0.5</td>
<td>0</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>PMOS</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>PMOS</td>
<td>-2</td>
<td>-0.5</td>
<td>0</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
</tbody>
</table>

1.4 Choose the most appropriate answer.

A negatively charged "depletion" region in doped Si is characterized by...

- an abundance of electrons and negative ions
- too many electrons, too few holes
- a severe imbalance between negative ions and holes
- the complete depletion of charge density

(In fact, we only have fixed, negative ions.)

1.5 We have a 2-terminal device that accumulates charge as a function of voltage according to the equation: $Q = 5V^2 + 3V + 2$, where $Q$ is in pico Cb and $V$ is in volts. Find the small signal capacitance of this device in pF at 2V.

$$C = \frac{\partial Q}{\partial V} = \left(2 \cdot 5 \cdot V + 3\right) \frac{\text{pico Cb}}{\text{V}}$$

$$\text{for } V = 2 \text{V} \quad \frac{\partial Q}{\partial V} = 23 \frac{\text{pico Cb}}{\text{V}} = 23 \text{pF}$$

1.6 Write the expression of a transfer function that corresponds to the Bode plot drawn.

$$\text{Bode plot}$$

$$10 \log_{10} (1000) = 50 \text{dB}$$

1.7 The value of a voltage source is $5 + 0.02\cos(10^4t + 45^\circ)$ Volts. Please complete the list below:

$V_a = 5$ large signal

$V_a = 0.02 \cos (10^4t + 45^\circ)$ small signal

$V_a = 5 + 0.02 \cos (10^4t + 45^\circ)$ total signal

1.8 For the n-channel MOS transistor shown below, please consider the two ends of the channel (near the source and near the drain) and indicate whether or not each must be inverted so that this device is in saturation.

$\text{This end is NOT inverted}$

$\text{This end is inverted}$
Problem 2 of 4: Answer each question briefly and clearly. (20 points)

The C/V plot below was taken by “scanning” the gate-to-bulk voltage of an MOS structure. We know (from other measurements) that $V_{fn} = 0.55\text{V}$ and $C_{ox} = 2.3\text{nF/\mu m}^2$. Also, $\varepsilon_0 = 8.85\times10^{-14}\text{F/cm}$, $\varepsilon_r = 3.9$ and $\varepsilon_o = 11.7\varepsilon_0$. Use the graph to calculate:

2.1 The oxide thickness $t_{ox}$.

2.2 The maximum depth of the depletion region (What is the $V_{cb}$ voltage that yields the maximum depth of the depletion region?).

2.4 The charge density of the inversion layer (in CH/cm²) when $V_{cb}$ is 2V.

Above $V_{th}$, structure acts as a linear capacitor with

\[ C_{ox} = \frac{\Delta Q}{\Delta V} = -C_{ox} \cdot \Delta V = -C_{ox} (2V - V_{th}) \]

expression | value and units
---|---
$V_{cb}$ when maximum depletion depth is achieved = 0.6V as shown in figure

expression | value and units
---|---
$N_a = N_i \cdot 10 \left( \frac{V_{gs} - V_{th}}{60\text{mV}} \right)$ | $10^{19}$/cm$^3$

expression | value and units
---|---
$N_a = N_i \cdot 10 \left( \frac{V_{fb} + V_{th}}{60\text{mV}} \right)$ | $10^{19}$/cm$^3$
Problem 3 of 4: Answer each question briefly and clearly. (20 points)
Consider the circuit below. Assume \( R_1 = 1 \text{M} \Omega, R_2 = 100 \Omega, \) and \( C = 1 \text{pF}. \)

3.1. Write the transfer function \( V_{\text{out}}/V_{\text{in}}. \)

Classic voltage divider:

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{R_L}{R_L + \left( \frac{1}{f_R} \right) w C} = \frac{R_L}{R_L + \left( \frac{1}{f_R} \right) w (R || R_C)}
\]

3.2. Calculate the gain at DC, the gain at extremely high frequencies (\( w = \text{infinity} \)), and the numerical values of any poles and/or zeros that this function has.

<table>
<thead>
<tr>
<th>Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Gain at DC} = 20 \log \left( \frac{R_2}{R_1 + R_2} \right) )</td>
<td>( \approx -80 \text{dB} )</td>
</tr>
<tr>
<td>( \text{Gain at } w = \text{infinity} = 20 \log \left( \frac{1}{f_R} \right) \text{ cap } )</td>
<td>0 dB</td>
</tr>
<tr>
<td>( \text{Pole 1} = \sqrt{C (R</td>
<td></td>
</tr>
<tr>
<td>( \text{Pole 2} = \text{function has only one pole} \ldots )</td>
<td>10620 rad/s</td>
</tr>
<tr>
<td>( \text{Zero 1} = \frac{1}{R_C} )</td>
<td>10670 rad/s</td>
</tr>
<tr>
<td>( \text{Zero 2} = \text{function has only one zero} \ldots )</td>
<td>10670 rad/s</td>
</tr>
</tbody>
</table>

Problem 4 of 4: Answer each question briefly and clearly. (20 points)
You are given an nmos transistor, connected as shown.

4.1 Find an expression for \( W \) so that the output voltage \( V_{\text{out}} \) is 2.5V. Assume \( \lambda_n = 0.1 \text{V}^{-1} \) when \( L = 1 \mu\text{m} \), and it is otherwise proportional to \( 1/L \).

Transistor in saturation since \( V_{GS} > V_{GS} - V_{TH}. \)

\[
I_D = \frac{K_P}{2L} \left( V_{GS} - V_{TH} \right)^2 \left( 1 + \frac{1}{2} \lambda_n V_{DS} \right)
\]

\[
\lambda_n' = \lambda_n \frac{V_{DS}}{L}
\]

\[
I_D = \frac{5V - V_{\text{out}}}{R}
\]

expression

\[
W = \frac{(5V - V_{\text{out}})/R}{\frac{K_P}{2L} \left( V_{GS} - V_{TH} \right)^2 \left( 1 + \frac{1}{2} \lambda_n V_{DS} \right)}
\]

4.2 Assume \( R = 10 \text{k} \Omega, \mu_n C_{ox} = 50 \mu \text{A}/\text{V}^2, V_T = 1 \text{V}, \lambda_n = 0.1 \text{V}^{-1} \) when \( L = 1 \mu\text{m} \), and it is otherwise proportional to \( 1/L \). Find \( W/L \) when \( L = 2 \mu\text{m} \), and when \( L = 4 \mu\text{m} \).

\[
W = \frac{(5V - V_{\text{out}})/R}{\frac{K_P}{2L} \left( V_{GS} - V_{TH} \right)^2 \left( 1 + \frac{1}{2} \lambda_n V_{DS} \right)}
\]

\[
= \frac{2.25 \times 10^6 \text{A}}{50 \mu \text{A}/\text{V}^2 (1.5 \text{V})^2 \left( 1 + \frac{0.4 \times 5 \mu \text{m}}{L} \cdot 2.5 \right)}
\]

\[
= \frac{10}{1.5^2 (1 + \frac{0.1}{L})}
\]

value

\[
\frac{W}{L} \text{ when } L = 2 \mu\text{m} = \frac{4.44}{1.125} = 3.95
\]

\[
\frac{W}{L} \text{ when } L = 4 \mu\text{m} = \frac{4.44}{1.0625} = 4.18
\]