ANSWER QUESTIONS ON THESE SHEETS USING BACKS IF NECESSARY

1. Equation sheet is on last page of test.
2. Unless otherwise stated, use transistor parameters on equation sheet.
3. Non-programmable calculator allowed; No other aids allowed
4. Grading indicated by [ ]. Attempt all questions since a blank answer will certainly get 0.

<table>
<thead>
<tr>
<th>Question</th>
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Last Name: _________________________
First Name: _______________________
Student #: _______________________
(max grade = 36)
[6] **Question 1:** Consider the circuit below where all transistors are in the active region. The numbers beside the transistors indicate the transistor width (in $\mu$m).

\[ V_{DD} = 3V \]

20$\mu$A

\[ \frac{v_o}{v_s} = \]

\[ f_{3dB} = \]

a) Find the small-signal gain $\frac{v_o}{v_s}$

b) Estimate the 3db frequency cutoff, $f_{3dB}$. For $C_{db}$ values assume $V_{db} = 0$. 

\[ f_{3dB} = \]
[6] **Question 2:** Consider the 3 current mirrors shown below. For all transistors, \( L = 0.18 \, \mu m \), \( W = 3 \, \mu m \). Also, \( I = 100 \, \mu A \).

\[ I \quad I_o \quad V_o \]
\[ 0.7V \quad 0.7V \quad 0.3V \]
\[ A = 20 \]

a) For the current mirror in (I), estimate the change in the output current for an output voltage change of 0.5\( V \). Also, what is the minimum output voltage, \( V_{o(min)} \), while keeping transistors in the active region.

\[ \Delta I = \]
\[ V_{o(min)} = \]

b) Repeat question a) for the mirror in (II)

\[ \Delta I = \]
\[ V_{o(min)} = \]
c) Repeat question a) for the mirror in (III)

\[ \Delta I = \]  
\[ V_{\text{opt} \text{min}} = \]

\[ V_{DD} \]

\[ R_D \quad 1k\Omega \quad M_1 \quad V_B \quad R_1 \quad M_2 \quad R_{out} \]

\[ R_S \quad 1k\Omega \quad 10k\Omega \]

\[ R_2 \quad 10k\Omega \quad I \quad (\text{ideal}) \]

\[ g_{m1} = g_{m2} = 2mA/V \]
\[ r_{o1} = r_{o2} \rightarrow \infty \]

a) Find \( L \), \( A_{\infty} \) and \( d \).

\[

\begin{align*}
L = \\
A_{\infty} = \\
d =
\end{align*}
\]

b) Find \( v_o/v_s \), \( R_{in} \) and \( R_{out} \).

\[

\begin{align*}
v_o/v_s = \\
R_{in} = \\
R_{out} =
\end{align*}
\]
[6] **Question 4**: The circuit below is called a “super source follower”. Assume the current sources are realized using single transistors with $L = 0.18\,\mu\text{m}$ (include their output resistances $r_{o3}$ and $r_{o4}$).

The circuit diagram is shown with transistors $M_1$ and $M_2$. The current sources $I_3 = 200\,\mu\text{A}$ and $I_4 = 100\,\mu\text{A}$ are indicated.

All $L = 0.18\,\mu\text{m}$

All $|V_{ov}| = 200\text{mV}$

Find the value for the output resistance, $R_{out}$, assuming $g_m r_o \gg 1$.

$$R_{out} =$$
[6] Question 5: Consider the circuit shown below. For the opamp, \( A_o = 40 \), \( R_{id} = 10k\Omega \), \( R_o = 1k\Omega \). For \( M_1 \), \( V_{ov} = 200\text{mV} \) and \( L = 0.18\mu m \) (include \( r_o \)).

Assume \( I_{D1} = 200\mu A \)

\[
\begin{align*}
V_D &= 5V \\
R_S &= 1k\Omega \\
R_{id} &= 10k\Omega \\
R_o &= 1k\Omega \\
M_1 &= V_{ov} = 200\text{mV} \\
L &= 0.18\mu m \\
R_{in} &= R_{out} \\
R_1 &= 5k\Omega \\
R_2 &= 5k\Omega \\
R_L &= 1k\Omega \\
V_S &= 3V \\
(I_{ideal}) \\
I &= \frac{V_D - V_S}{R_1} \\
V_o &= \frac{I}{R_2} \\
R_o &= \frac{V_{ov} - V_o}{I} \\
\end{align*}
\]

a) Find \( L \), \( A_{\infty} \) (assume \( d \) is about 0).

\[
\begin{array}{|c|}
\hline
L = \\
A_{\infty} = \\
\hline
\end{array}
\]
b) Find $v_o/v_s$, $R_{in}$ and $R_{out}$.

\[ v_o/v_s = \]
\[ R_{in} = \]
\[ R_{out} = \]
[6] **Question 6:** Assume an opamp is ideal but has the following open-loop gain and will be used in a non-inverting configuration with 2 resistors.

\[ A(s) = \frac{10^4}{(1 + s/\omega_{p1})(1 + s/\omega_{p2})(1 + s/\omega_{p3})} \]

where \( \omega_{p1} = 10^5 \), \( \omega_{p2} = 10^7 \), \( \omega_{p3} = 10^8 \).

a) Draw the Bode plot for the above open-loop gain (both mag and phase)
b) Estimate the minimum closed-loop gain, $A_{\text{min}}$, that can be realized while having a phase margin about 45°.

$$A_{\text{min}} = \boxed{}$$

c) If it is desired to have a closed-loop gain of 10 estimate the new value of $\omega_{p1}$ if it is moved to a lower freq and a phase margin of about 45° is desired.

$$\omega_{p1} = \boxed{}$$
ECE331

Analog Electronics

Equation Sheet

Constants: \( k = 1.38 \times 10^{-23} \) JK\(^{-1}\); \( q = 1.602 \times 10^{-19} \) C; \( V_T/k = 26 \) mV at 300 \(^\circ\)K ;
\( \varepsilon_0 = 8.854 \times 10^{-12} \) F/m; \( C_{ox} = 3.9 \); \( C_{ox} = (\varepsilon_0/2)\varepsilon_{ox} \)

NMOS: \( k_n = \mu_n C_{ox}(W/L) ; V_{DS} = 0 \); \( V_{DS} = v_{GS} - V_{th} \)
(triode) \( V_{DS} \geq v_{th} \); \( i_D = k_n(v_{GS} - V_{th}) \); \( i_D = k_n(v_{GS} - V_{th}^2) \)
(Active) \( V_{DS} \geq v_{th} \); \( i_D = 0.5k_n v_{th}^2 (1 + \lambda v_{DS}) \); \( g_m = k_n v_{GS} = 2I_D/V_{th} = \sqrt{2pD_D} \); \( r_s = 1/g_m \); \( r_o = L/(2|v_D|) \)

PMOS: \( k_p = \mu_p C_{ox}(W/L) ; V_{DS} < 0 \); \( V_{DS} = v_{GS} - V_{th} \)
(triode) \( V_{DS} \leq v_{th} \); \( i_D = k_p(v_{GS} - V_{th}) \); \( i_D = k_p(v_{GS} - V_{th}^2) \)
(Active) \( V_{DS} \leq v_{th} \); \( i_D = 0.5k_p v_{th}^2 (1 + \lambda v_{DS}) \); \( g_m = k_p v_{GS} = 2I_D/V_{th} = \sqrt{2pD_D} \); \( r_s = 1/g_m \); \( r_o = L/(2|v_D|) \)

BJT: (Active) \( I_C = I_{B}^2 (1 + (V_{CE}/V_{th})) ; g_m = \alpha r_s = I_C/\beta V_T ; r_s = \beta/g_m ; r_o = |V_A|/I_C \)
\( i_C = \beta I_B ; i_C = (\beta + 1) i_B ; \alpha = \beta/(\beta + 1) ; i_C = \alpha i_E ; R_B = (\beta + 1)(r_s + R_E) ; R_s = (R_B + r_s)/(\beta + 1) \)

Cascode: \( \frac{1}{R_{out}} = R_s + r_s + \frac{g_m r_s R_s}{(1 + g_m R_s)} \)

Diff Pair: \( A_D = g_m R_D ; A_{CM} = -(R_D/(2R_{SO}))(\Delta R_D/R_D) ; A_{CM} = -(R_D/(2R_{SO}))(\Delta g_m/g_m) \)
\( V_{ox} = \Delta V_T ; V_{ox} = (V_{th} + 2)/(\Delta W/L)/(W/L) \)

1st order: \( f_1 = 1/(2\pi \tau) \) unity gain freq
Freq: \( f_1 = (1 + s/z_1)(1 + s/z_2) \) \( (1 + s/z_m) \)

Miller: \( f_H = 1/(2\pi \tau) \) \( \max \) dominant pole estimate

MOS: \( C_{gs} = (2/3)W L C_{ox} + W L C_{ox} ; C_{gd} = W L C_{ox} ; C_{db} = C_{db0}/(1 + V_{th}/V_T) \)
\( f_t = g_m/(2\pi (C_{gs} + C_{gd})) \) \( f_t = (\lambda V_m)/(4\pi L^2) \)

Feedback: \( A_f = A/(1 + A\beta) ; x_f = (1/(1 + A\beta)) x_t \); \( dA_f/dA_f = (1/(1 + A\beta)) dA/dA ; dA_f/dA_f = dA/dA ; \)
\( \omega_f = \omega_f/(1 + A\beta) \); \( \omega_f = \omega_f/(1 + A\beta) \)

Loop Gain \( \Delta L = \lambda \); \( A_f = A/(1 + A\beta) ; d/(1 + A\beta) ; Z_{pout} = Z_{pout}(1/L_2)/(1 + L_2) \)
PM: \( x_L = \omega_L \); \( \omega_L = 180 \) \( \text{GM} = |L/(\omega_{180})| \)

Pole Splitting \( 1/(\omega_{180} C) \); \( 1/(g_m R_c C_{1/2}) \)

Pole Pair \( s^2 + \omega_n^2 = 0 \); \( Q \leq 0.5 \) real poles; \( Q > 1/2 \) freq resp peaking

MOS Transistor: CMOS basic parameters. Channel length = 0.18\( \mu \)m

<table>
<thead>
<tr>
<th></th>
<th>( V_t ) (V)</th>
<th>( \mu C_{ox} ) (( \mu A/V^2 ))</th>
<th>( \lambda ) (( \mu m/V ))</th>
<th>( C_{ox} ) (F/m(^2 ))</th>
<th>( t_{ox} ) (nm)</th>
<th>( L_{ov} ) (( \mu m ))</th>
<th>( C_{db0}/W ) (( \mu F/\mu m ))</th>
</tr>
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<tbody>
<tr>
<td>NMOS</td>
<td>0.24</td>
<td>240</td>
<td>0.05</td>
<td>8.5</td>
<td>4</td>
<td>0.04</td>
<td>0.3</td>
</tr>
<tr>
<td>PMOS</td>
<td>-0.4</td>
<td>60</td>
<td>-0.05</td>
<td>8.5</td>
<td>4</td>
<td>0.04</td>
<td>0.3</td>
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