Microelectronic Devices and Circuits- EECS105
Final Exam

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Your Name: Official Solutions
(last) *(first)*

Your Signature: ______________________

1. *Print and sign your name on this page before you start.*
2. *You are allowed three, 8.5"x11" handwritten sheets. No books or notes!*
3. *Do everything on this exam, and make your methods as clear as possible.*

Problem 1 ________ */ 24*
Problem 2 ________ */ 26*
Problem 3 ________ */ 26*
Problem 4 ________ */ 24*
TOTAL ________ */ 100*

MOS Device Data (you may not have to use all of these...)
$\mu_n C_{ox} = 50\mu A/V^2$, $\mu_p C_{ox} = 25\mu A/V^2$, $V_{Tn} = -V_{Tp} = 1V$, $L_{min} = 2\mu m$. $V_{BS} = 0$.
$\lambda_n = \lambda_p = 0.1V^{-1}$ when $L = 1\mu m$, and it is otherwise proportional to $1/L$
$C_{ox} = 2.3fF/\mu m^2$, $C_{jn} = 0.1fF/\mu m^2$, $C_{jp} = 0.3fF/\mu m^2$, $C_{jswn} = 0.5fF/\mu m$,
$C_{jswp} = 0.35fF/\mu m$, $C_{ovn} = 0.5fF/\mu m$, $C_{ovp} = 0.5fF/\mu m$

Problem 1 of 4: Answer each question briefly and clearly. (4 points each, total 24)

Why are bipolar transistors capable of providing more drive current compared to MOS transistors that occupy similar area? (give a qualitative answer)

Bipolars are primarily based on diffusion currents which are exponentially related to applied voltages, while MOS devices are primarily based on drift currents, which increase linearly with applied voltage.

Comparing a Common Collector to a Common Drain voltage buffer amplifier, one sees some advantages and disadvantages. Place a mark below to indicate your choice, trying to get the largest DC voltage gain.

Aspect	CC	CD
Rin		X
Rout	X	
Av	X	

In the IC industry "layout designers" can manipulate lateral device dimensions (L, W, area of base-emitter junction, etc.) while "process designers" manipulate vertical dimensions (Tox, base-width) and doping levels. List a parameter that each designer can change to affect the respective parameter, or write "none" if the designer cannot affect the value of the respective parameter:

Parameter	Layout Designer	Process Designer
V_{Tn}	none	doping, Cox, tox
r_o (NMOS)	L or I_D	λ_n
g_m (NMOS)	$\frac{W}{L}$ or I_D	μ_n,Cox, doping or tox
r_o (npn)	I_c, A_E	V_A
g_m (npn)	I_c, A_E	none
Cgs	W or L	Cov, Cox or tox

What advantage(s) does a cascode configuration has over a cascade configuration?

A cascode uses less power since you don't need a seperate "leg" for each amp.

A cascode uses less area since seperate current source transistors are not needed for each amp.

Which conditions must be satisfied so that the open circuit time constant method leads to an exact solution?

The poles are widely spaced.

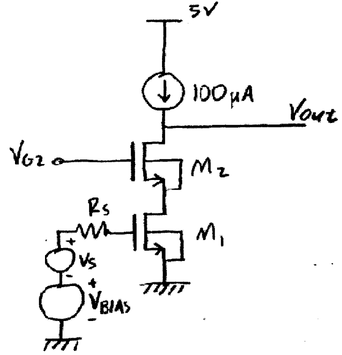
Any zeros are at much higher frequencies than the first pole.

In your own words, how does the dreaded "Miller effect" limit frequency response of a high voltage gain amplifier?

The Miller effect makes a cap between the input and output nodes appear much bigger to the input node because of the amplification of voltage across the cap. A larger cap means a larger RC and hence a lower ω_{-3dB} frequency.

Problem 2 of 4 (26 points)

Consider the following cascode amplifier, driven by a perfect current source ($r_{oc}=\infty$)



For each of the following questions, make sure that you show the expressions before you plug in the specific values. A correct expression is worth 70% of the credit, even if the numerical calculation is incorrect!

a) Find $(W/L)_1$ *ratio* so that the *overall* Gm of this amp is 1mS. (Do not specify values for W and for L here. That comes later). (5 points)

$$G_m = g_{m1} = 1mS = \sqrt{2\frac{W}{L}\mu_n C_{ox} I_{DSAT}}$$

$$1mS = \sqrt{2\frac{W}{L}\, 50\times10^{-6}\cdot 100\times10^{-6}}$$

$$1mS = 100\times10^{-6}\sqrt{\frac{W}{L}}$$

$$10 = \sqrt{\frac{W}{L}}$$

$$\frac{W}{L} = 100$$

Expression for $(W/L)_1$	Value
$(W/L)_1$= $\frac{G_M^2}{2\mu_n C_{ox} I_{DSAT}}$	100

b) Assume that $g_{m2}=g_{m1}$, and $r_{o2} = r_{o1}$. Find the value of L_1 so that r_{o1} = 200kΩ, and calculate the respective value of the overall Rout of this amplifier. (5 points)

$r_{o1} = \frac{1}{\lambda I_D}$ $\lambda = \frac{.1}{L}$

$I_D = 100\mu A$

$200k\Omega = \frac{L}{.1(100\mu A)}$

$L = 2$

Expression for L_1	Value
$L_1 = r_{o1} \cdot (.1) \cdot I_D$	$2\ \mu m$

$R_{out} = g_{m2} r_{o2} r_{o1} \| r_{oc}$

$= 1mS(200k\Omega)(200k\Omega)$

$= 40M\Omega$

Expression for Rout	Value
Rout = $g_{m2} r_{o2} r_{o1}$	$40M\Omega$

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c) Find the open circuit voltage gain of this two stage amplifier ($r_{oc}=\infty$). (5 points)

$G_m R_{out} = 1mS \cdot 40M\Omega = 40,000$

Expression for Voltage Gain	Value	in db
vout/~~vin~~ = Vs $G_m R_{out}$	40000	92

d) Calculate V_{BIAS} (ignoring channel-length modulation). Assume that $(W/L)_1 = (W/L)_2 = 16$ (note that this is <u>not</u> the correct answer to question 2.a) (5 points)

$I_D = \frac{W}{2L} \mu_n C_{ox} (V_{Bias} - V_{Tn})^2$

$100\mu A = \frac{16}{2} \cdot 50 \times 10^{-6} (V_{Bias} - V_{Tn})^2$

$.25 = (V_{Bias} - V_{Tn})^2$

$.5 = V_{Bias} - V_{Tn}$

$V_{Bias} = 1.5$

Expression for V_{BIAS}	Value
$V_{BIAS} = \sqrt{\frac{2I_D}{\frac{W}{L}\mu_n C_{ox}}} + V_{Tn}$	1.5V

e) Assuming that $(W/L)_2 = 16$, find the value for V_{G2} that will give you the maximum voltage swing for this amp. Explain your thinking in one sentence (ignore channel length modulation). (6 points)

V_{DS_1} must be greater than $1.5 - 1V$

$V_{DS_1} \geq .5V$

$V_{g2} - V_{DS_1} = V_{gs_1} = 1.5V$

$V_{g2} > 2V$

$V_{g2\,min} = 2V$

What limits Vout min?

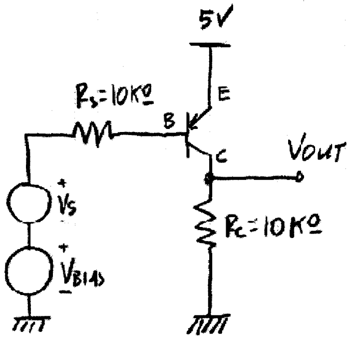
M_1 and M_2 must be in saturation

$V_{DS} > V_{gs} - V_T$

Expression for V_{G2}	Value
$V_{G2} =$ $V_{g1} + V_{DS_1}$ - OR - $V_{g2} = V_{DS_1} + V_{DS_2} + V_T$ $V_{g2} = V_{out\,min} + V_T$	2V

Problem 3/4 (26 points)

Consider the following pnp CE amplifier. Note that $\beta o = 50$, $I_S = 10^{-17}A$ and V_A = infinity. (Be very careful with signs in this problem!).



For each of the following questions, make sure that you show the expressions ***before*** *you plug in the specific values. A correct expression is worth 70% of the credit, even if the numerical calculation is incorrect!*

a) Calculate V_{BIAS} so that Vout = 2.5V. Ignore I_B and Rs for this question. (Do NOT assume that V_{BE} is exactly -0.7V). (5 points)

$$I_C = -\frac{V_{OUT} - 0}{R_C} = -\frac{2.5V}{10k\Omega} = -250\mu A$$

$$I_C = -I_S e^{-V_{BE}/V_{th}} \Rightarrow V_{BE} = -V_{th} \ln \frac{I_c}{I_S} = -26mV \ln \frac{250\mu A}{10^{-17}A} = -26mV \cdot \ln 250 \cdot 10^{11}$$

$V_{BE} = -800mV$

$V_{BIAS} = 5V + V_{BE} = 4.2\ V$

Expression for V_{BIAS} (3)	Value(2)
$V_{BIAS} =$ $5V - V_{th} \ln \frac{\lvert I_c \rvert}{I_S}$	4.2 V

b) Find Rout and the voltage gain, if R_L = infinity. (8 points)

$$r_o = \frac{V_A}{I_C} \to \infty$$

Expression for Rout (3)	Value(1)

Rout = $R_C // r_o = R_C$
(3)
	10kΩ
	(1)

$$g_m = \frac{I_C}{V_{th}} = \frac{250\mu A}{26mV} = 9.6\cdot10^{-3}\ A/V$$

$$r_\pi = \frac{\beta}{g_m} = \frac{50}{9.6\cdot10^{-3}} = 5.2k\Omega$$

Expression for Voltage Gain (3)	Value(1)
vout/~~vin~~ V_s = $\underbrace{\left(\frac{r_\pi}{r_\pi+R_S}\right)}_{(1)\ 0.34}\underbrace{(-g_m)(R_C)}_{(2)\ -96}$	-33 (1)

c) Calculate the value of R_L that will cut the gain by a factor of two. (Assume that R_L is connected through a small coupling capacitor, so that it does not disrupt the biasing of the transistor.)
(5 points)

$$\frac{V_o}{V_{in}} = \left(\frac{r_\pi}{r_\pi+R_S}\right)(-g_m)(R_C // R_L)$$

$$R_C // R_L = 5k\Omega$$

Expression for R_L that cuts the gain by a factor of 2. (3)	Value (2)
R_L = R_C (3)	10kΩ (2)

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d) If you could increase βo, how much would you have to increase it in order to increase the gain by 10%. (Hint: assume that the new, improved βo' = Xβo, and write an expression that you can use to calculate the value of the factor X). (8 points)

$$\frac{V_o}{V_S} = \left(\frac{\beta_o'/g_m}{\beta_o'/g_m + R_S}\right)(-g_m)(R_C // R_L)$$

$$\frac{X\beta_o/g_m}{X\beta_o/g_m + R_S} = 1.1\left(\frac{\beta_o/g_m}{\beta_o/g_m + R_S}\right)$$

$$R_S\left(\frac{g_m}{\beta_o}\right) = 10k\Omega\left(\frac{9.6\cdot10^{-3}}{50}\right) = 1.9$$

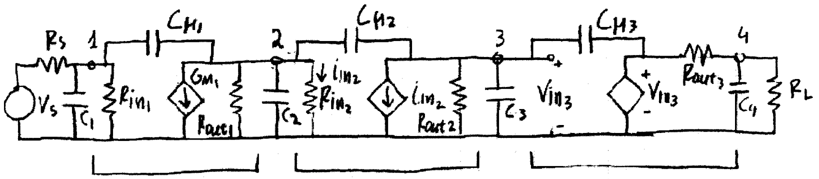
$$\frac{X}{X + R_S\left(\frac{g_m}{\beta_o}\right)} = 1.1\left(\frac{1}{1 + R_S\left(\frac{g_m}{\beta_o}\right)}\right)$$

$$X = \frac{1.1\left(\frac{1}{1+R_S\left(\frac{g_m}{\beta_o}\right)}\right)R_S\left(\frac{g_m}{\beta_o}\right)}{1 - 1.1\left(\frac{1}{1+R_S\left(\frac{g_m}{\beta_o}\right)}\right)}$$

Expression for X (multiplier for increasing βo.)	Value
X = $\frac{1.1\left(\frac{1}{1+R_S\left(\frac{g_m}{\beta_o}\right)}\right)R_S\left(\frac{g_m}{\beta_o}\right)}{1 - 1.1\left(\frac{1}{1+R_S\left(\frac{g_m}{\beta_o}\right)}\right)} = \frac{1.1 R_S}{R_S - \frac{0.1\beta_o}{g_m}}$	1.16

Problem 4/4 (24 points)

The following is a cascade of three 2-ports: a transconductance amplifier, a current buffer and a voltage buffer. The aim of this circuit is to produce lots of voltage gain over a wide bandwidth.



$R_{in_1} = 1K\Omega$ $R_{out_1} = 100K$ $R_{in_3} = \infty$ $R_{out_3} = 1K\Omega$

$G_{M_1} = 1mS$ $R_{in_2} = 1K\Omega$ $R_{out_2} = 10M\Omega$

$C_1 = C_2 = C_3 = 1pF$ $C_4 = 1pF$ $R_S = 1K\Omega$ $R_L = 10K\Omega$

$C_{\mu_1} = C_{\mu_2} = C_{\mu_3} = 0.1pF$

a) Find the low frequency voltage gain vout/v~~in~~s (this means that you can ignore all the capacitors). Do this in stages as shown in the table below: (6 points)

+4 +2

Expression	Value
$v_2/v_s = -\frac{R_{in1}}{R_{in1}+R_S} G_{m1}(R_{out_1} // R_{in2})$	-0.495
$v_3/v_2 = -\frac{R_{out2}//R_{in3}}{R_{in2}} = -\frac{R_{out2}}{R_{in2}}$	-10000
$v_{out}/v_3 = \frac{R_L}{R_{out3}+R_L}$	0.91
$v_{out}/v_s = \frac{V_2}{V_S} \cdot \frac{V_3}{V_2} \cdot \frac{V_{out}}{V_3} = \frac{R_{in1}}{R_{in1}+R_S} G_{m1}(R_{out1}//R_{in1})\left(\frac{R_{out2}}{R_{in2}}\right)\left(\frac{R_L}{R_{out3}+R_L}\right)$	4500

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b) Replace all "cross-over" caps $C_{\mu1}$, $C_{\mu2}$, $C_{\mu3}$, with their Miller equivalent C_{M1}, C_{M2}, C_{M3}. (6 points)

$$\frac{V_2}{V_1} = -G_{m1}(R_{out1}//R_{in2}) = -0.001S(100K\Omega // 1K\Omega) = -0.99 \cong -1$$

$$C_{M1} = C_{\mu1}\left(1-\frac{V_2}{V_1}\right) = 0.1pF(1-(-1)) = 0.2pF$$

$$C_{M2} = C_{\mu2}\left(1-\frac{V_3}{V_2}\right) = 0.1pF(1-(-10000)) = 1nF$$

$$C_{M3} = C_{\mu3}\left(1-\frac{V_{out}}{V_3}\right) = 0.1pF(1-1) = 0$$

+4 +2

Expression	Value
$C_{M1} = C_{\mu1}\left(1-\frac{V_2}{V_1}\right)$	0.2pF
$C_{M2} = C_{\mu2}\left(1-\frac{V_3}{V_2}\right)$	1nF
$C_{M3} = C_{\mu3}\left(1-\frac{V_{out}}{V_3}\right)$	0

c) Calculate the Open Circuit Time Constant for the nodes 1, 2, 3 and 4. (6 points)

+2 +2 +2

Expression	RC	Value
$R_{T1} = R_S // R_{in1}$	$RC_1 = R_{T1}(C_{M1}+C_1)$	0.6ns
$R_{T2} = R_{out1} // R_{in2}$	$RC_2 = R_{T2}(C_{M2}+C_2)$	1μs
$R_{T3} = R_{out2}$	$RC_3 = R_{T3}C_3$	10μs
$R_{T4} = R_{out3} // R_L$	$RC_4 = R_{T4}C_4$	0.9ns
Total		11.015μs

d) Calculate the ω_{3db} of this amp (6 points)

$$\omega_{3dB} \cong \frac{1}{\sum \tau} = \frac{1}{11.015\mu s} = 9.079 \times 10^{4}\ \mathrm{rad}/s$$

Expression for ω_{3db}.	Value
$\omega_{3db} = \dfrac{1}{\sum \tau}$	$9.1 \times 10^{4}\ \mathrm{rad}/s$

~ That's All Folks! ~