ECE 3040 Microelectronic Circuits

Exam 2
July 2, 2002

Dr. W. Alan Doolittle

Note: The length of this exam was adjusted for the summer semester (1 hr 10 min)

Print your name clearly and largely: Solutions

Instructions:
Read all the problems carefully and thoroughly before you begin working. You are allowed to use 1 new sheet of notes (1 page front and back), your note sheet from the previous exam as well as a calculator. There are 100 total points in this exam. Observe the point value of each problem and allocate your time accordingly. SHOW ALL WORK AND CIRCLE YOUR FINAL ANSWER WITH THE PROPER UNITS INDICATED. Write legibly. If I cannot read it, it will be considered to be a wrong answer. Do all work on the paper provided. Turn in all scratch paper, even if it did not lead to an answer. Report any and all ethics violations to the instructor. Good luck!

Sign your name on ONE of the two following cases:

I DID NOT observe any ethical violations during this exam:

I observed an ethical violation during this exam:
Average=51.1
Std. Dev.=19.7
Maximum=97
Minimum=21
First ~1/3% Multiple Choice (Select the most correct answer)

1.) (5-points) When a diode is reverse biased, the net current that flows is a result of:
   a.) Minority carriers that are collected by the large electric field, better known as diffusion current
   b.) Minority carriers that are collected by the large electric field, better known as drift current
   c.) Majority carriers that surmount the energy barriers, better known as diffusion current
   d.) Majority carriers that surmount the energy barriers, better known as drift current
   e.) None of the above because no current flows in reverse bias.

2.) (5-points) The Early Voltage...
   a.) ...results from the 8:00 AM start time of our class
   b.) ...results from the base-collector depletion region overlapping the base-emitter depletion region
   c.) ...results from the base-collector depletion region "consuming" part of the base quasi-neutral region width making W a function of $V_{bc}$
   d.) ... is $kT/q$
   e.) both c and d

3.) (5-points) When a BJT is to be used as a switch that is conducting (on) which bias mode is required?
   a.) Forward bias
   b.) Reverse bias
   c.) Forward Active
   d.) Inverse Active
   e.) Saturation
   f.) Cutoff

4.) (5-points) When a BJT is to be used as a switch that is not conducting (off) which bias mode is required?
   a.) Forward bias
   b.) Reverse bias
   c.) Forward Active
   d.) Inverse Active
   e.) Saturation
   f.) Cutoff

5.) (5-points) When a BJT is to be used as an amplifier which bias mode is required?
   a.) Forward bias
   b.) Reverse bias
   c.) Forward Active
   d.) Inverse Active
   e.) Saturation
   f.) Cutoff

6.) (5-points) For a given power supply voltage (one single supply) which mode of operation has the smallest magnitude of collector to emitter voltage?
   a.) Forward bias
   b.) Reverse bias
   c.) Forward Active
   d.) Inverse Active
   e.) Saturation
   f.) Cutoff

7.) (5-points) When using the small signal analysis, ...
   a.) Diodes are replaced by resistors
   b.) BJT's are replaced by the hybrid Pi model
   c.) Only small inputs are valid
   d.) You must first solve the DC solution
   e.) All of the above

8.) (5-points) When using the small signal analysis, ...
   a.) is only useful for voltages greater than $kT/q$ (~26 mV at room temperature).
   b.) The model can often still be used for large signals but results in the introduction of distortion
   c.) Must be replaced by the large signal model if distortion is to be analyzed
   d.) Is a simpler "linearized" version of the large signal model valid for only small perturbations around the DC operating point.
   e.) Both a and b
   f.) Both c and d
9.) (20-points total in three parts) Given the following BJT structure,
(a- 3 points) Label the emitter, base and collector
(b- 12 points) Find the DC common emitter ($\beta_{DC}$) and common base current gains ($\alpha_{DC}$).
(c- 5 points) Determine three parameters that you can change that increase BOTH the DC common emitter current gain ($\beta_{DC}$) and the operational speed of the BJT.

\[
\begin{align*}
\mu &= 1000 \, \text{cm}^2/\text{V} \cdot \text{Sec} \\
\tau &= 100 \, \mu\text{Sec} \\
N_0 &= 1 \times 10^{18} \, \text{cm}^{-3}
\end{align*}
\]

\[20 \, \mu\text{m}\]

\[\text{Depletion Region}\]

\[
\begin{align*}
\mu &= 250 \, \text{cm}^2/\text{V} \cdot \text{Sec} \\
\tau &= 25 \, \mu\text{Sec} \\
N_A &= 1 \times 10^{17} \, \text{cm}^{-3}
\end{align*}
\]

\[5 \, \mu\text{m}\]

\[\text{Depletion Region}\]

\[
\begin{align*}
N_D &= 1 \times 10^{15} \, \text{cm}^{-3} \\
\text{No other} \\
\text{Parameters Known}
\end{align*}
\]

\[500 \, \mu\text{m}\]
Based on Doping ↓ Emitter

\[ \mu = 1000 \text{ cm}^2/\text{vsec} \]
\[ C = 100 \mu \text{s} \]
\[ N_0 = 1 \times 10^{18} \text{ cm}^{-3} \]

Depletion Region

\[ \mu = 250 \text{ cm}^2/\text{vsec} \]
\[ C = 25 \mu \text{s} \]
\[ N_A = 1 \times 10^{17} \text{ cm}^{-3} \]

Depletion Region

\[ N_D = 1 \times 10^{15} \text{ cm}^{-3} \]
No parameters given

500 μm

5 μm

20 μm

\[ D_E = \frac{hT}{q} \mu_{\text{Emitter}} = 0.0259 \times (1000) = 25.9 \text{ cm}^2/\text{sec} \]

\[ D_B = \frac{hT}{q} \mu_{\text{Base}} = 0.0259 \times (250) = 6.48 \text{ cm}^2/\text{sec} \]

\[ L_E = \sqrt{D_E D_E} = \sqrt{25.9 \times (1000)} = 0.05089 \text{ cm} \text{ (or 508.9 μm)} \]

\[ \beta_{DC} = \frac{D_B L_E N_E}{D_E W N_B} = \frac{6.48 \times (0.05089) \times 10^{18}}{25.9 \times (5 \times 10^{-4} \text{ cm}) \times 10^{17}} = 254.6 \]

\[ \alpha_{DC} = \frac{\beta_{DC}}{\beta_{DC} + 1} = \frac{254.6}{255.6} = 0.996 \]
Since \( \text{Boc} = \frac{D_E}{W_N_B} \times \frac{W_E}{W_N_E} \)

\( \Rightarrow \) can increase mobility or \( v \) in base.

\( \Rightarrow \) can raise Emitter Doping

\( \Rightarrow \) can lower base doping.

\( \Rightarrow \) can shrink base width.

\( \Rightarrow \) can kill mobility or \( v \) in emitter.

\[ b + t_F = \frac{W^2}{2 \times D_B} \]

is the base transport time.

Thus, our only 3 choices are to increase \( U_{\text{base}} \) or \( t_{\text{base}} \)

to increase \( D_B \) or decrease \( W \)

(Base quasi neutral width).

Note: since lowering \( N_B \) lowers \( U_{\text{base}} \) due to decreased ionized impurity scattering, lowering \( N_B \) was accepted as well.
(4th Section - 40%) Pulling all the concepts together for a useful purpose:

10.) (40-points) Given the following amplifier circuit and BJT Parameters, what is the AC voltage gain, $V_{out}/V_{ac}$? Assume: $\beta_{DC}=100$, Early voltage is infinite, and the turn on voltages for all forward biased junctions are 0.7 V. You may assume all capacitors are very large values and are thus, AC shorts and any inductors are very large values, and thus AC opens. Additionally consider the circuit to be operated at low frequencies where you can neglect all small signal capacitances. Also, neglect all resistances that result from quasi-neutral regions. For full Credit, be sure to check your assumptions on the mode of operation of the transistor.

Hint: Use the CVD/Beta analysis for the DC solution. Then apply your results to convert to the small signal model for both the BJT and diode (i.e. do not ignore the small signal model of the diode).
DC Solution: Thevenize base circuit

\[ V_{th} = V_{oc} - I_{oc} R_1 \]

\[ = 15 - (5.18 \times 10^{-4}) 15 \Omega \]

\[ = 7.23 \text{ V} \]

\[ R_{th} = R_1 = 15 \Omega \]
Extra work space. Show your work clearly and label which problem this page contains.

\[ V_{TH} - I_B R_{TH} - V_{BE} - I_E (R_e + R_2) = 0 \]

\[ V_{TH} - V_{BE} = I_B \left[ R_{TH} + (\beta+1)(R_e + R_2) \right] \]

\[ I_B = \frac{7.23 - 0.7}{15k + (101)(50+250)} = 144 \mu A \]

\[ I_C = \beta I_B = 14.4 \mu A \]

\[ I_E = (\beta+1)I_B = 14.56 mA \]

Check Assumption of Forward Active:

\[ V_B = V_{TH} - I_B R_{TH} = 5.07 V \]

\[ V_C = V_{OC} - I_C R_C = 7.8 V \]

\[ V_E = I_E (R_e + R_2) = 4.37 V \]

\[ V_B > V_E \checkmark \]

\[ V_C > V_B \checkmark \text{ Assumption verified} \]
AC Solution:

\[
\begin{align*}
\text{Diode} & : \\
R_d &= \frac{V_T}{I_\text{ac}} = \frac{0.0259}{518uA} = 50\Omega \\
\text{Current through diode is the source current } V_{ac} \\
\text{Thevenin base circuit} & : \\
R_{load} & = R_s \parallel r_{rl}
\end{align*}
\]

\[
\begin{align*}
V_{th} &= V_{ac} \\
\frac{V_{th}}{V_{ac}} &= \frac{R_s}{R_s + R_s}
\end{align*}
\]

\[
\begin{align*}
1. & \quad V_{out+} = i_c \left( R_{c1} \parallel R_{load} \right) = -gm \frac{V_{th}}{V_{ac}} \left( R_{c1} \parallel R_{load} \right) \\
2. & \quad i_c = \beta \frac{i_b}{R_s} \\
3. & \quad V_{th} = i_c R_e + i_b \frac{V_{th}}{V_{ac}} + R_s \frac{R_s}{R_{RL}} \\
& \quad = \left[ (\beta+1) R_e + \frac{V_{th}}{V_{ac}} + R_s \parallel R_{RL} \right] i_b
\end{align*}
\]

\[
\begin{align*}
\frac{V_{out+}}{V_{ac}} &= \left( \frac{V_{out+}}{i_c} \right) \left( \frac{i_c}{i_b} \right) \left( \frac{i_b}{V_{th}} \right) \left( \frac{V_{th}}{V_{ac}} \right)
\end{align*}
\]

\[\Rightarrow \text{cont'd, on next page}\]
Extra work space. Show your work clearly and label which problem this page contains.

\[
\frac{V_{\text{out}}^+}{V_{\text{ac}}} = -\left(\frac{R_c}{|R_{\text{load}}|}\right)^3 \left[ \frac{1}{\frac{1}{r \pi} + (\beta + 1) R_c + \frac{R_s}{|R_{\text{load}}|}} \right] \left[ \frac{R_{\text{load}}}{R_d + R_s} \right]
\]

\[
= \left(\frac{500}{11\pi}\right) 100 \left[ \frac{1}{179.9 + 101(50) + (50)(50)} \right] \left[ \frac{50}{50 + 50} \right]
\]

\[
\frac{V_{\text{out}}^+}{V_{\text{ac}}} = -3.17 \ V / V
\]