ECE 3040B Microelectronic Circuits

Exam 2, Makeup Version

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Print your name clearly and largely: Solution

Instructions: NOTE: MAKEUP EXAMS ARE DESIGNED TO BE SLIGHTLY HARDER THAN THE ORIGINAL EXAM IN ORDER TO ENCOURAGE EXAM ATTENDANCE!
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 can not 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:
Diode and BJT Semiconductor Physics

1.) (50-points total) As an employee of Texas Instruments Corporation, your boss asks you to design a npn BJT transistor with a DC Common Emitter Current gain, $\beta_{DC}$, greater than 1000 and a high frequency response requiring a very low base-emitter capacitance of 10 pF under the conditions specified below. The transistor will only be used in an amplifier biased into forward active mode with a collector current of 1 mA and a base-emitter voltage of 0.7 V.

a.) (7 points) What are the two contributing sources of capacitance in the emitter-base junction? Diffusion Capacitance and Depletion Capacitance.

b.) (8 points) Explain the origin of each of these two sources of capacitance.

Depletion Cap.: From majority carriers separated by the depletion width, $W_d$.

Diffusion Cap.: From minority carriers injected across the junction. These minority carriers are separated by the depletion width, $W_d$.

c.) (35 points) Design a transistor by specifying doping in the base, emitter, the base quasi-neutral region width which will meet the above design criteria given these parameters:

- Intrinsic concentration $n_i = 1 \times 10^{16}$ cm$^{-3}$
- Relative dielectric constant, $K_s$ (or $\varepsilon_r$) = 11.0
- Area = 25,600 um$^2$ (160 um x 160 um)
- Minority carrier diffusion coefficient in the base, $D_B$, in the p side of 15 cm$^2$/Sec
- Minority carrier diffusion length in the base, $L_B$, in the p side of 50 um
- Minority carrier diffusion coefficient in the emitter, $D_E$, in the n side of 10 cm$^2$/Sec
- Minority carrier diffusion length in the emitter, $L_E$, in the n side of 1 um

Answers:

Emitter Doping __________________ cm$^{-3}$  Base Doping __________________ cm$^{-3}$

Base Width __________________ um
Design Criteria

\[ C_{EB} = C_B + C_j < 10 \mu F \text{ and } \beta_c > 1000 \]

\[ \beta_c : \text{ Assume } W \ll L_B \]

\[ \beta_c > 1000 \]

\[ \frac{D_B L_E N_E}{D_E W N_B} > 1000 \Rightarrow \text{ since } n^+ \text{ emitter } \gg p \text{ base} \]

arbitrarily chose \( N_E = 1 \times 10^9 \) and \( N_B = 1 \times 10^{15} \)

These are arbitrary choices.

\( W < 15 \mu m \)

\[ C_{EB} = 1^{st} \]

\[ C_j = A \sqrt{q \times 1 \times 60 \frac{N_A N_D}{(N_A + N_D)^2} \frac{1}{V_B} \rightarrow \frac{kT}{q} \ln \left( \frac{N_B N_B}{n_i^2} \right)} \]

\( V_B = 0.835 > 0.7 V \)

\[ \Rightarrow \text{ If } V_B < 0.7 V \text{ (our turn on voltage)} \]

we would have needed to increase the doping

\[ C_j = (0.016 \text{ cm})^2 \frac{1}{\sqrt{1.6e-19} \times (8.854e-14)(1e15) \frac{1}{0.835}} \]

\[ = 2.47 \mu F \]

\[ C = 10 \mu F - 2.47 \mu F = 7.53 \mu F \]
Extra work can be done here, but clearly indicate with problem you are solving.

\[ C_j = \frac{C_{j0}}{\sqrt{1 - \frac{V_A}{V_{Bi}}}} = \frac{2.47}{\sqrt{1 - \frac{0.7}{0.835}}} \]

\[ C_j = 6.14 \text{ pF} \]

\[ C_B = 10 \text{ pF} - 6.14 \text{ pF} \]

\[ = 3.86 \text{ pF} = C_F \cdot 9 \text{ m} \]

\[ = C_F \frac{I_C}{V_T} \]

\[ = C_F \frac{1 \times 10^{-3}}{0.0259} \]

\[ C_F = 3.1 \times 10^{-10} \text{ s} \quad (100 \text{ pS}) \]

\[ C_F = \frac{W^3}{2 \cdot D_B} = \frac{W^3}{2(15)} \]

\[ W = 0.55 \text{ mm} \]

Check: \( W \ll L_B \)
Second 50%

2. (50 points) Given the following “video amplifier circuit” and BJT Parameters, what is
the AC voltage gain, VoutAC/VinAC? Assume: $\beta_{dc}=100$, Early voltage is infinite, 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. 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.

Hint: neglect the DC circuit.

Use the CVD model for the then in
reduction in the base circuit.

Since $0 < V_B < 5 V$ we
will assume D1 is off
and D2 is on:

$$5V = I R_2 + 0.7 + I R_{10}$$

$$I = 578 \mu A$$

$$V_{th} = 0.7 + I R_{10} = 1.37 V$$

$$R_{th} = R_2 || R_{10} = 1096 \Omega$$
\[ O = 1.37 - I_B (1096) - 0.7 - (\beta+1)I_B (R_7+R_4) \]
\[ \uparrow \quad \uparrow \quad \uparrow \]
\[ V_{th} \quad R_{th} \quad V_{BE} \quad I_E \]

\[ I_B = 8.66 \mu A \quad V_B = V_{th} - I_B R_{th} = 1.36 V \]
\[ I_C = 866 \mu A \quad V_C = 5V - I_C R_5 = 3.27 V \]
\[ I_E = 875 \mu A \quad V_E = I_E (R_7+R_4) = 0.66 V \]

\[ \Rightarrow \quad \text{Forward Active mode is verified.} \]
\[ \text{Voltages confirm Diode assumptions.} \]

**Small signal model parameters**:

\[ g_d = \frac{I_0 + I_S}{V_T} = \frac{0.000518}{0.0259} = 0.02 \]

\[ r_d = \frac{1}{g_d} = 50 \Omega \quad \text{Note: } r_d \parallel R_2 \approx 50 \Omega \]

\[ g_m = \frac{I_C}{V_T} = \frac{866e-6}{0.0259} = 0.0334 S \]

\[ r_T = \frac{\beta}{g_m} = 2990 \Omega \]

\[ r_0 = \frac{V_A + V_{CE}}{I_C} \rightarrow 0 \]

**Small signal model**

\[ \text{Diagram of circuit configuration.} \]
Extra work can be done here, but clearly indicate with problem you are solving.

1) \[ V_{th} = V_{in} \frac{r_d || R_2}{R_5 + R_d || R_2} = 0.5 \frac{V_{in}}{V_{th}} = 2.5 \frac{V}{2} \]

\[ \frac{V_{th}}{V_{in}} = 0.5 \frac{v}{v} \]

2) \[ V_{out} = -g_m V_{th} \frac{R_5 || R_6}{V_{th}} = -65.5 \frac{v}{v} \]

\[ \frac{V_{out}}{V_{th}} = -65.5 \frac{v}{v} \]

3) We now need: \( \frac{V_{th}}{V_{out}} \)

\[ V_{th} = i_e R_7 + V_{th} + i_b R_{th} = (g_m V_{th} + \frac{V_{th}}{r_{th}}) R_7 + V_{th} + \frac{(V_{out})}{r_{th}} R_{th} \]

\[ \frac{V_{th}}{V_{out}} = \frac{1}{(g_m + \frac{1}{r_{th}}) R_7 + 1 + \frac{r_{th}}{r_{th}}} \]

\[ = 0.54 \]

So \[ A_V = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_{th}} \frac{V_{th}}{V_{in}} = -12.7 \frac{v}{v} \]
Bonus of 15 points total:
In the last problem, what is the minimum and maximum “Large signal” output swing possible before distortion begins? Note: I am asking for the “actual” voltage swing, not the simpler “worst case” voltage swing.

Examine the circuit at the onset of cutoff and the onset of saturation.

**Cutoff:**

\[ V_c = 5 \text{V} \]

\[ I_c = \frac{5 - 0.7}{R5 + \left(\frac{101}{100}\right) R7} \]

\[ I_c = 2.12 \text{mA} \]

\[ V_c = 5 - I_c R5 \]

\[ = 0.75 \text{V} \]

So the output voltage swing looks like:

**Sagging:**

\[ 5 \text{V} \text{ onset of cutoff} \]

\[ V_c = 3.27 \text{V} \]

\[ 1.73 \text{V} \]

\[ 0.75 \text{V} \text{ onset of Saturation} \]

\[ 2.52 \text{V} \]