ECE 3040B Microelectronic Circuits

Exam 2, Makeup Version

July 7, 2001

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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:

First 50% **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, β_{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? Difussion Capacitance
and
Depletion Capacitance

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

Depletion Cap.: From majority carriers seperated by the depletion width, W.
Diffusion Cap.: From minority carriers injected across the junction. These minority carriers are seperated by the depletion width, W.

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

Intrinsic concentration n_i= 1e10 cm^{-3}
Relative dielectric constant, K_s (or ε_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

Extra work can be done here, but clearly indicate with problem you are solving.

Design Criteria: $C_{EB} = C_B + C_j < 10pF$ and $\beta_{DC} > 1000$

C_B: diffusion Cap. C_j: depletion Cap.

β_{DC}: Assume $W << L_B$

$\beta_{DC} > 1000$

$$\frac{D_B L_E N_E}{D_E W N_B} > 1000$$

$\Rightarrow$ since n^+ emitter >> p base arbitrarily chose

$$\frac{15(1e{-4})1e19}{10(W)1e15} > 1000$$

$N_E = 1e19$ + $N_B = 1e15\ cm^{-3}$ These are arbitrary choices.

$W < 15\ \mu m$

C_{EB}: 1st) $C_{jo} = A\sqrt{\frac{qK_s\epsilon_0}{2}\underbrace{\frac{N_A N_D}{(N_A+N_D)}}_{N_A}\frac{1}{V_{Bi}}}$

$V_{Bi} \rightarrow \frac{kT}{q}\ln\left(\frac{N_E N_B}{n_i^2}\right)$

N_A for our choices of $N_D >> N_A$

$V_{Bi} = 0.835 > 0.7V$

If $V_{bi} < 0.7V$ (our turn on voltage) we would have needed to increase the doping

$$C_{jo} = (0.016\ cm)^2\sqrt{\frac{(1.6e{-19})\,11\,(8.854e{-14})}{2}(1e15)\frac{1}{0.835}}$$

$= 2.47\ pF$

~~2nd) $C_B = 10pF - 2.47pF = 7.53pF$~~

Extra work can be done here, but clearly indicate with problem you are solving.

$$C_j = \frac{C_{jo}}{\sqrt{1 - \frac{V_A}{V_{Bi}}}} = \frac{2.47}{\sqrt{1 - \frac{0.7}{0.835}}}$$

$$C_j = 6.14\ pF$$

$$C_B = 10pF - 6.14pF$$

$$= 3.86pF = \tau_F\, g_m$$

$$= \tau_F \frac{I_C}{V_T}$$

$$= \tau_F \frac{1e{-3}}{0.0259}$$

$$\tau_F = 1e{-10}\ s \quad (100ps)$$

$$\tau_F = \frac{W^2}{2D_B} = \frac{W^2}{2(15)}$$

$$\boxed{W = 0.55\,\mu m}$$

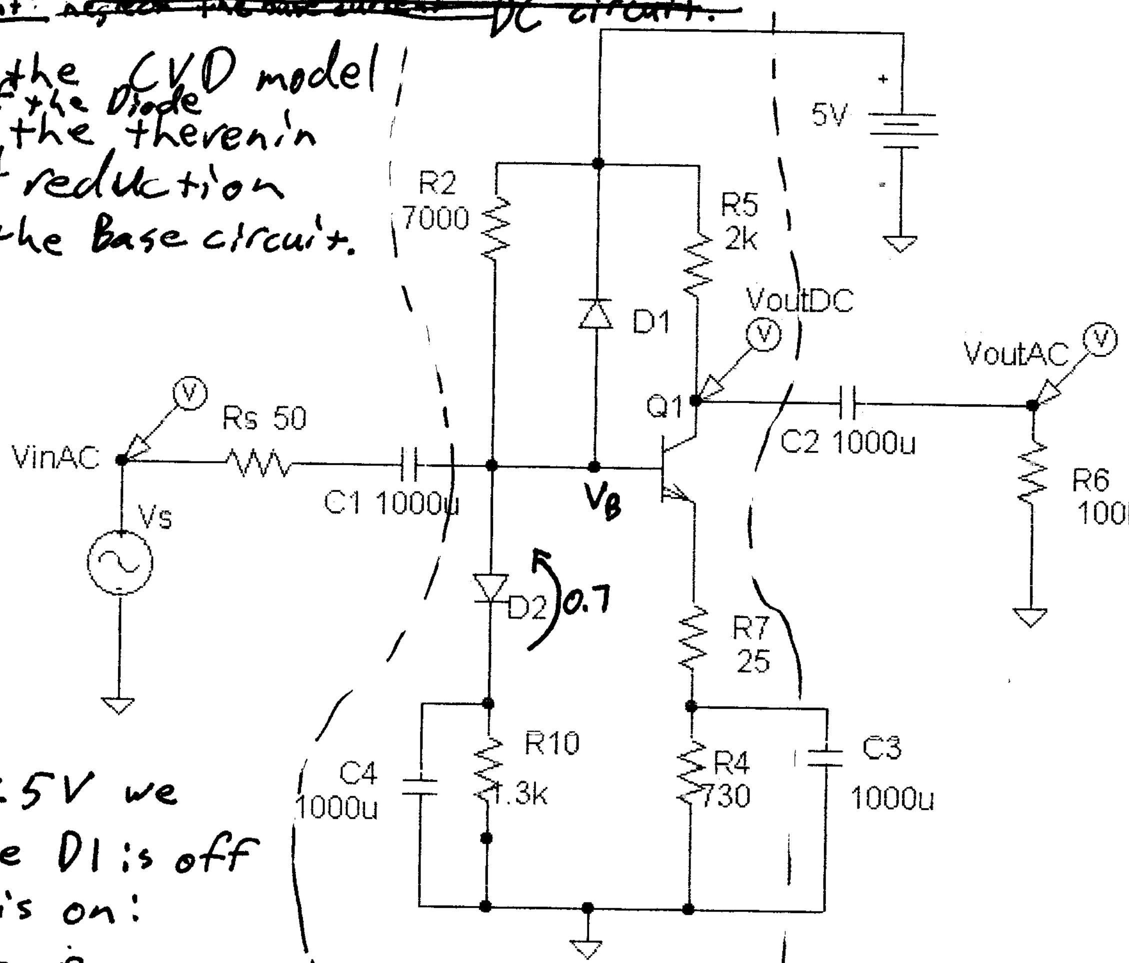
Check: $W \ll L_B$ ✓✓

Second 50%

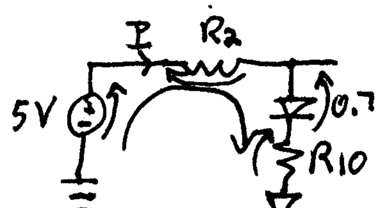
2.) (50-points) Given the following "video amplifier circuit" and BJT Parameters, what is the AC voltage gain, VoutAC/VinAC? Assume: β_{DC}=100, Early voltage is infinite, turn on voltages for all forward biased junctions are 0.7 V. You may assume all capacitors are very large values and are thus, AC 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 base current~~ DC circuit.

Use the CVD model of the Diode for the thevenin ~~and~~ reduction in the Base circuit.



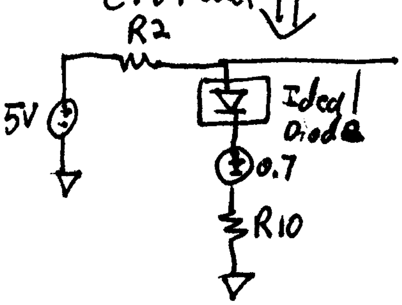
Since ~~ok~~ $V_B < 5V$ we will assume D1 is off and D2 is on:



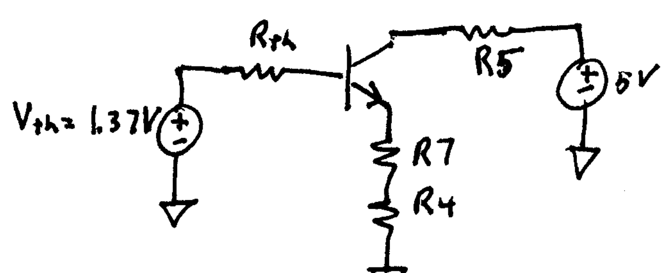
$$5V = \underset{7K}{I R_2} + 0.7 + \underset{1.3K}{I R10}$$

$$I = 518 \mu A$$

CVD Model



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



$R_{th} = R_2 || R_{10}$

$= 1096 \ \Omega$

... here, but clearly indicate with problem you are solving.

$$0 = \underset{V_{th}}{\underset{\uparrow}{1.37}} - I_B(\underset{R_{th}}{\underset{\uparrow}{1096}}) \underset{V_{BE}}{\underset{\uparrow}{-0.7}} - \underbrace{(\beta+1)I_B}_{I_E}(R_7 + R_4)$$

$I_B = 8.66\,\mu A$ $\qquad V_B = V_{th} - I_B R_{th} = 1.36\,V$

$I_C = 866\,\mu A$ $\qquad V_C = 5V - I_C R_5 = 3.27\,V$

$I_E = 875\,\mu A$ $\qquad V_E = I_E(R_7 + R_4) = 0.66\,V$

$\Longrightarrow$ Forward Active mode is verified. Voltages confirm Diode assumptions.

Small signal model Parameters:

$$g_d = \frac{I_D + I_S}{V_T} = \frac{0.000518}{0.0259} = 0.02$$

$$r_d = \frac{1}{g_d} = 50\,\Omega$$

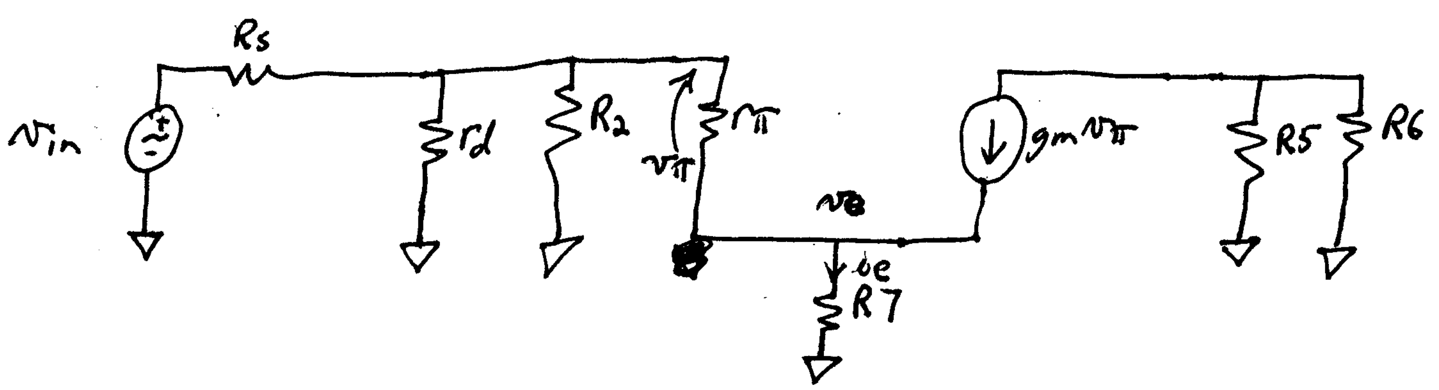
Note: $r_d \| R_2 \approx 50\,\Omega$ so we have impedance matched the $50\,\Omega$ (R_S) transmission Line.

$$g_m = \frac{I_C}{V_T} = \frac{866e{-}6}{0.0259} = 0.0334\,S$$

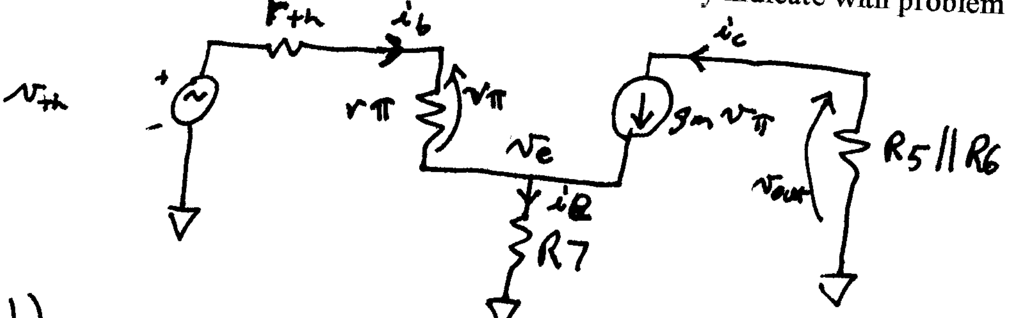
$$r_\pi = \frac{\beta}{g_m} = 2990\,\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \infty$$

Small signal Model



Extra work can be done here, but clearly indicate with problem you are solving.



1.) $v_{th} = v_{in} \dfrac{r_d || R_2}{R_s + r_d || R_2} = 0.5\, v_{in}$

$r_{th} = R_s || R_2 || r_d$
$= 25\Omega$

$\dfrac{v_{th}}{v_{in}} = 0.5 \; v/v$

2.) $v_{out} = -g_m v_\pi \; R_5 || R_6$
$= -65.5\, v_\pi$

$\dfrac{v_{out}}{v_\pi} = -65.5 \; v/v$

3.) We now need: $\dfrac{v_\pi}{v_{th}}$

$v_{th} = i_e R_7 + v_\pi + i_b r_{th}$

$= \Big(\underbrace{g_m v_\pi}_{i_c} + \underbrace{\dfrac{v_\pi}{r_\pi}}_{i_b}\Big) R_7 + v_\pi + \underbrace{\left(\dfrac{v_\pi}{r_\pi}\right)}_{i_b} r_{th}$

$\dfrac{v_\pi}{v_{th}} = \dfrac{1}{\left(g_m + \frac{1}{r_\pi}\right) R_7 + 1 + \frac{r_{th}}{r_\pi}}$

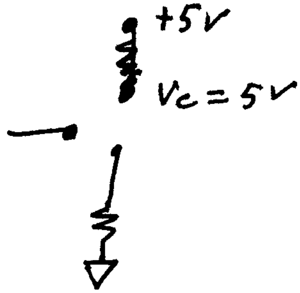
$= 0.54$

so $\boxed{A_v = \dfrac{v_{out}}{v_{in}} = \dfrac{v_{out}}{v_\pi} \dfrac{v_\pi}{v_{th}} \dfrac{v_{th}}{v_{in}} = -17.7 \; v/v}$

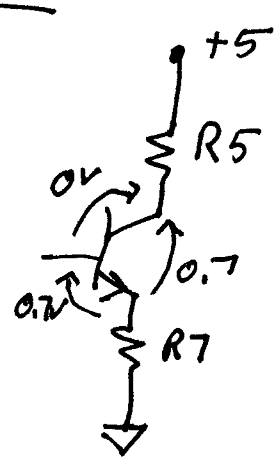
Bonus of 15 points total:
In the last problem, what is the minimum and maximum "Large signal" output swing possible before distortion begins? Note: I am asking for the "actual" voltage swing, not the simpler "worst case" voltage swing.

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

Cutoff:



Saturation:



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

$$I_c = 2.12\ mA$$

$$V_c = 5 - I_c R_5$$

$$= 0.75\ V$$

So the output voltage swing looks like: