ECE 3040B Microelectronic Circuits

Exam 2

July 3, 2001

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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 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 **<u>ONE</u>** of the two following cases:

I DID NOT observe any ethical violations during this exam: ________________

I observed an ethical violation during this exam: ________________

***First 25%* Multiple Choice (Select the most correct answer)**

1.) (5-points) When analyzing a circuit using the ideal diode model, which of the following is true:

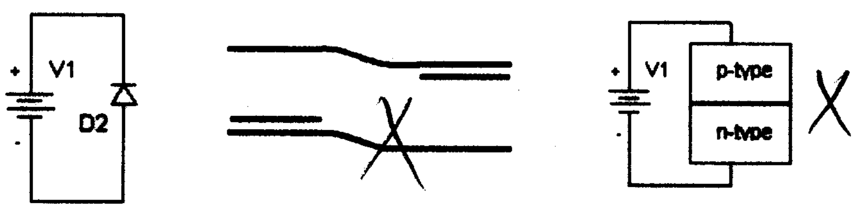
a.) The diode is replaced with either an open or a short circuit
b.) The diode is replaced with a battery plus an open or short circuit
c.) The diode has a small non-zero leakage current flowing in reverse bias
d.) The diode has an offset voltage equal to the built in voltage of the diode
e.) None of the above.

2.) (5-points) The emitter injection efficiency, γ...

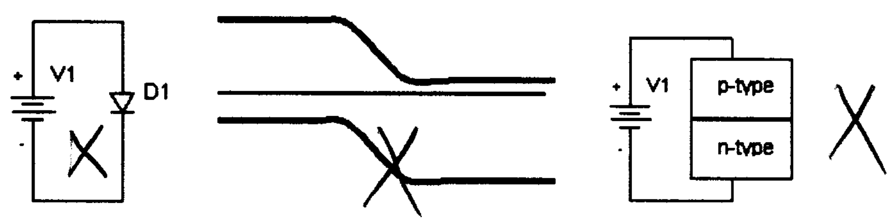
a.) ...characterizes the ability of a diode to handle large currents.
b.) ...characterizes the ability of a transistor to handle large currents.
c.) ... characterizes the percentage of minority carriers in the base that make it to the collector.
d.) ... characterizes how effectively the emitter can inject carriers into the base
e.) ... characterizes how effectively the collector can inject carriers into the base

3.) (5-points) Which of the following bias diagrams is consistent with reverse bias (all three diagrams must be correct, i.e. the schematic symbols, energy band diagrams and the material drawing must have the correct polarity)?

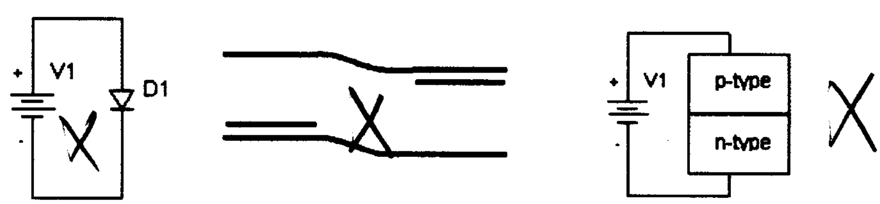
a.)



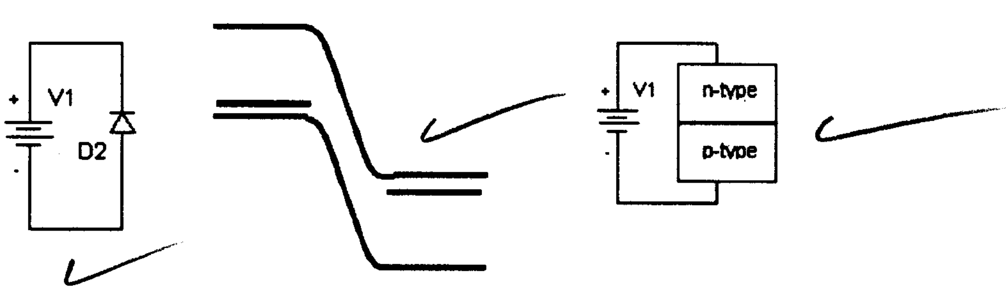
b.)



c.)

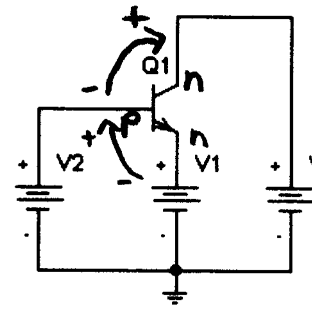


d.)



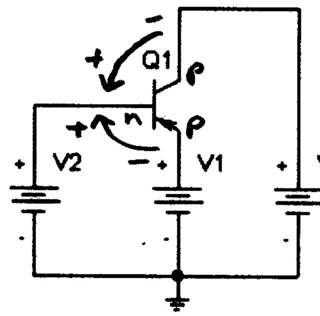
4.) (5-points) If we want to bias this transistor into forward active mode, which of the following is true?

a.) V3>V2>V1
b.) V1>V2>V3
c.) V2>V1>V3
d.) V1>V3>V2
e.) You cannot bias a transistor without resistors.



5.) (5-points) If we want to bias this transistor into cutoff, which of the following is true?

a. V3>V1 and V1>V3
b. V1>V2 and V3>V2
c. V2>V3 and V1>V3
d. V2>V1 and V2>V3
e. You cannot bias a transistor without resistors.



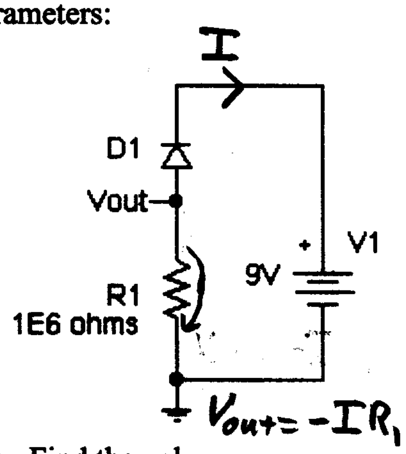
Second 15% Short Answer and Fill in the blank:

6.) (3-points each, 15 points total) The (a.) emitter of a BJT biased into forward active mode is (b. circle one) Lightly / Heavily doped and is responsible for injecting it's majority carriers into the (c.) base where they diffuse to the (d.) collector and are "collected" by a large (e.) electric field.

Third 20%

7.) (20-points total in two parts) A GaAs p+ n diode has the following parameters:

Intrinsic concentration n_i= 2e6 cm^{-3}
Relative dielectric constant, K_s (or ε_r)=13.1
Area= 256 um^2 (16 um x 16 um)
Minority carrier diffusion coefficient, D_p, in the p side of 5 cm^2/Sec
Minority carrier diffusion length, L_p, in the p-side of 0.1 um
p-type doping of 1e19 cm^{-3}
Minority carrier diffusion coefficient, D_n, in the n side of 10 cm^2/Sec
Minority carrier diffusion length, L_n, in the n-side of 0.5 um
n-type doping of 1e15 cm^{-3}.



The diode is to be used as a photodetector biased with the circuit shown. Find the value of the output voltage, Vout, for (a. 10-points) dark conditions where there is no light and (b. 10-points) for lighted conditions when a generation rate of 1e19 electron-hole pairs/cm^3-Second illuminates the diode.

a.) Dark: $I = I_o\left(e^{V/0.0259} - 1\right)$

But clearly D1 can only be reverse biased so, $I \simeq -I_o$

$$I_o = qA\left(\frac{D_n}{L_n}\frac{n_i^2}{N_A} + \frac{D_p}{L_p}\frac{n_i^2}{N_D}\right)$$

$$= 1.6e{-19}\,(0.0016\,cm \times 0.0016\,cm)\left(\frac{10\,cm^2/s}{5e{-5}\,cm}\frac{(2e6)^2\,cm^{-6}}{1e19\,cm^{-3}} + \frac{5\,cm^2/s}{1e{-5}\,cm}\frac{(2e6)^2\,cm^{-6}}{1e15}\right)$$

$$= 8.2e{-22}\ A$$

$$V_{out} = -IR_1 = +I_oR_1$$

$$\boxed{V_{out} = 8.2\,e{-16}\ \text{volts}}$$

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

b.) Light: $I = I_{dark} + I_{Light}$

$= -I_o - qA(L_n + W + L_p)G_L$

we need W,

$$W = \sqrt{\frac{2k_s\epsilon_o}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)(V_{bi} - V_A)}$$

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$V_{bi} = 1.28$ volts

$$\Rightarrow W = \sqrt{\frac{2(13.1)(8.854e\text{-}14\ F/cm)}{(1.6e\text{-}19)}\left(\frac{1e19+1e15}{(1e19)(1e15)}\right)(1.28+9)}$$

$W = 0.000386\,cm \quad (3.86\,\mu m)$

so $I = -I_o - 1.6e\text{-}19\,(.0016)^2(1e\text{-}5cm + 3.86e\text{-}4cm$

$+ 5e\text{-}5\,cm)\,1e19\,cm^{-3}/s$

$= -1.83e\text{-}9$

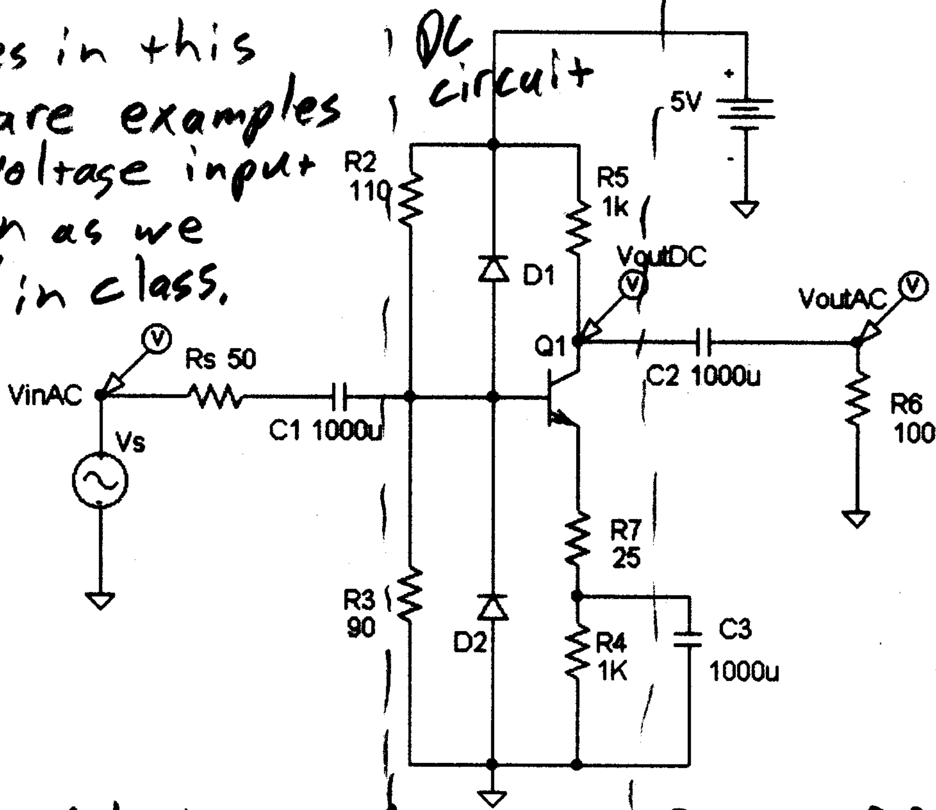
$V_{out} = -IR_1$

$V_{out} = 1.83\,mV$

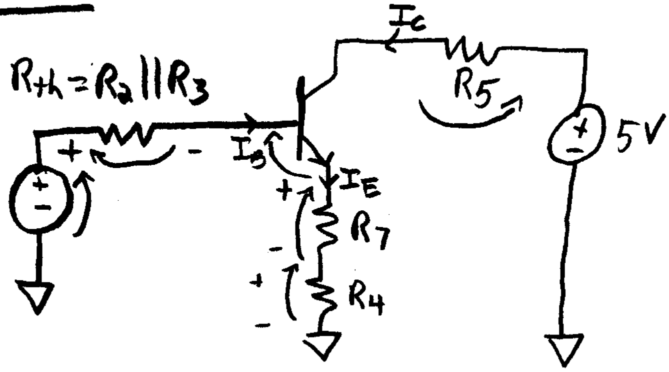
(4th Section - 40%) Pulling all the concepts together for a useful purpose:

8.) (40-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 0.6 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.

The diodes in this circuit are examples of over-voltage input protection as we discussed in class.



D.C. Solution: Assume D1 + D2 are off



$$V_{Th} = 5V \frac{R_3}{R_2 + R_3}$$

$$0 = V_{th} - I_B R_{th} - V_{BE} - I_E R_7 - I_E R_4$$

$$5\left(\frac{90}{90+110}\right) = I_B(49.5) + 0.6 - (100+1) I_B (25+1000)$$

$$I_B = \frac{1.65V}{49.5 + 101(1025)} = 15.9\ \mu A$$

$I_c = 1.59\ mA$ $\quad I_E = \left(\frac{100+1}{100}\right) I_c = 1.61\ mA$

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

$$V_c = 5 - I_c R_5$$
$$= 5 - (1.59e-3)(1e3)$$
$$V_c = 3.41\ V$$

$$V_B = V_{th} - I_B R_{th}$$
$$= 5\left(\frac{90}{90+110}\right) - (15.9e-6)\,49.5$$
$$V_B = 2.25\ V$$

$$V_E = I_E(R_4 + R_7)$$
$$= (1.61e-3)(1025)$$
$$= 1.65\ V$$

Forward Active is correct assumption.

D_1 is off since $V_B < 5V$

D_2 is off since $V_B > 0V$

Small Signal Parameters:

$$g_m = \frac{I_c}{V_T} = \frac{1.59e-3}{0.0259} = 0.0614\ S \qquad (0)$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{0.0614} = 1.629\ k\Omega \qquad (1)$$

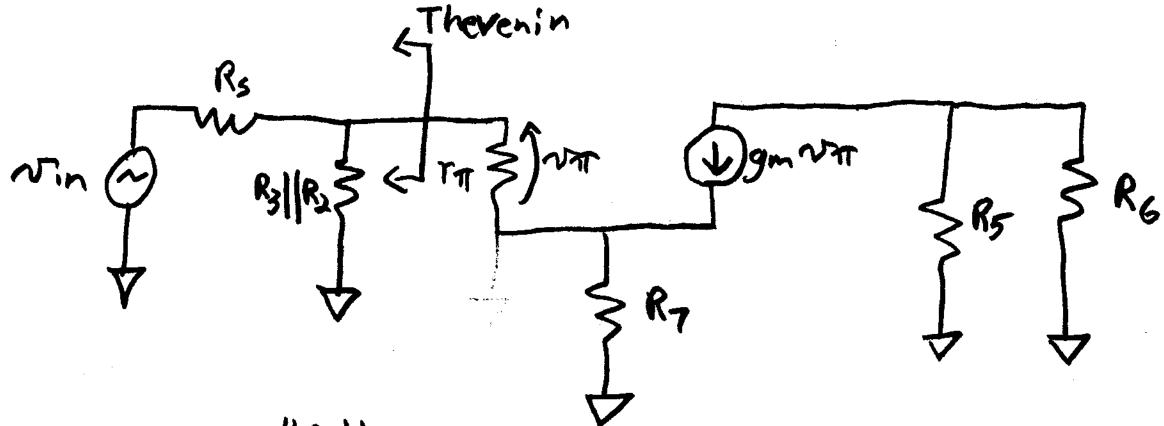
$$r_o = \frac{V_A + V_{CE}}{I_c} = \frac{\infty}{I_c} = \infty$$

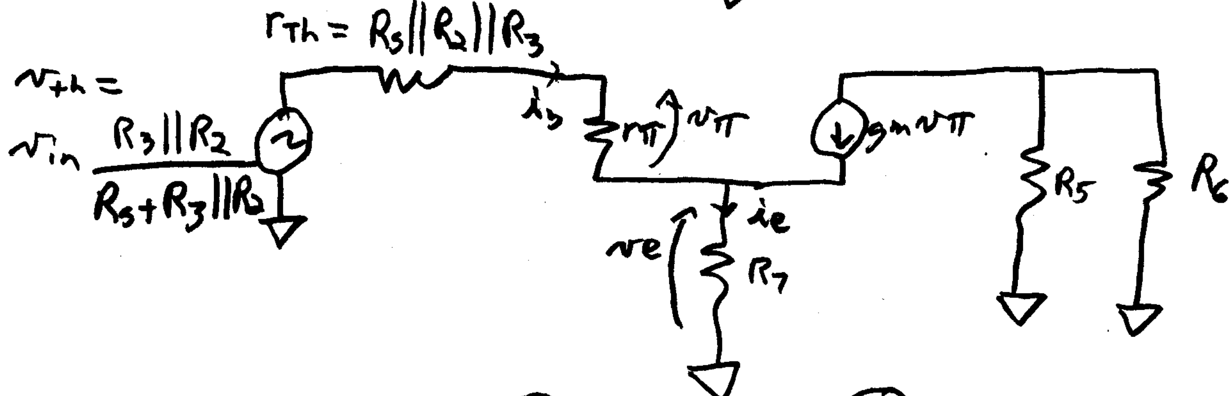
Diode: $$g_d = \frac{I_D + I_s}{V_T} = \frac{-I_s + I_s}{V_T} = 0$$

$$r_d = \frac{1}{g_d} = \infty$$

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

A.C. Solution:





$$A_v = \underset{1.}{\left(\frac{v_{out}}{v_\pi}\right)} \underset{2.}{\left(\frac{v_\pi}{v_{th}}\right)} \underset{3.}{\left(\frac{v_{th}}{v_{in}}\right)}$$

Term 1.) $v_{out} = -g_m v_\pi (R_5 || R_6)$

$$\frac{v_{out}}{v_\pi} = -g_m (R_5 || R_6) \quad \text{check: unitless} \checkmark$$

$$= -60.8 \text{ V/V}$$

Term 3.) $v_{th} = v_{in} \frac{R_3||R_2}{R_3||R_2 + R_S}$

$$\frac{v_{th}}{v_{in}} = \frac{R_3||R_2}{R_3||R_2 + R_S} \quad \text{check: unitless} \checkmark$$

$$= 0.497 \text{ V/V}$$

(6)

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

Term 2.) $v_{th} = i_b (R_S || R_2 || R_3) + v_\pi + v_e$

($i_b \to \frac{v_\pi}{r_\pi}$; $i_e \to \frac{v_\pi}{r_\pi} + g_m v_\pi$; $v_e \to i_e R_7$)

$$v_{th} = \frac{v_\pi}{r_\pi}(R_S || R_2 || R_3) + v_\pi + \left(\frac{v_\pi}{r_\pi} + g_m v_\pi\right) R_7$$

$$\frac{v_\pi}{v_{th}} = \frac{1}{\frac{R_S || R_2 || R_3}{r_\pi} + 1 + R_7\left(\frac{1}{r_\pi} + g_m\right)}$$

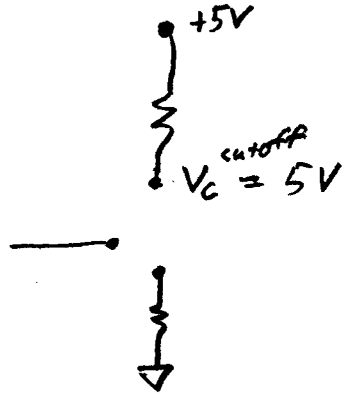
$$= 0.3898 \text{ V/V} \qquad (9)$$

$$A_v = (-60.8)(0.3898)(0.497)$$

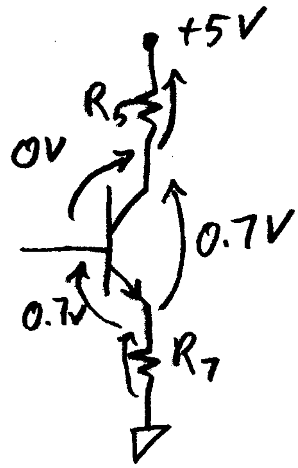
$$\boxed{A_v = -11.8 \text{ V/V}}$$

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.

1st extreme: Onset of cutoff:



2nd extreme: Onset of saturation:



$$5V = I_E R_7 + 0.7 + I_C R_5$$

$$4.3V = \left(\left(\frac{100+1}{100}\right) R_7 + R_5\right) I_C$$

$$I_C = 4.19 \text{ mA}$$

$$V_C = 5V - I_C R_5$$

$$V_C = 0.805 \text{ V}$$