IMPORTANT: Besides your **calculator** and the sheets you use for calculations you are only allowed to have an A4 sized **"copy sheet"** during this exam. Notes, problems and alike are not permitted. **Please submit your "copy sheet" along with your solutions.** You may get your "copy sheet" back after your solutions have been graded. ***Do not forget to write down units and convert units carefully! Cell phones are not allowed and should be placed on the front desk before the exam.***

EHB222E INTRODUCTION TO ELECTRONICS (11394)
Midterm Exam #1 ✐ 3 November 2015 ⌛ 13.30-15.30
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EEF 4104

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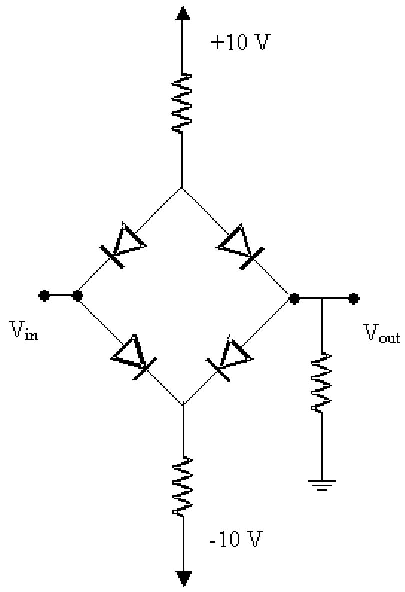
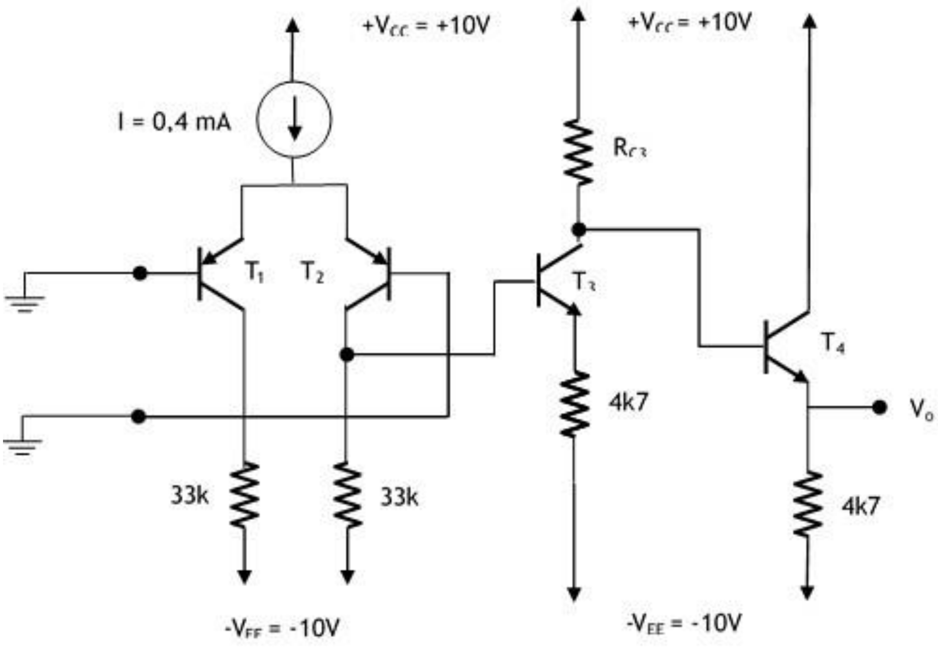
1. Assume you have a diode made of n- and p-typed doped silicon with the following parameters: $\mu_n = 1600\ cm^2/Vs$, $\mu_p = 600\ cm^2/Vs$. $n_i = 1,5\ 10^{10}\ 1/cm^3$, $q = 1,602\ 10^{-19}$ C, $\varepsilon_r = 12$, $\varepsilon_o = 8,85\ 10^{-12}$ F/m, $V_T = 25$ mV.
   a. Find the specific resistances of n- and p-type silicon if dopant densities are $4\ 10^{15}/cm^3$ and $2\ 10^{16}/cm^3$, respectively. (8 points)
   b. Calculate minority and majority carrier densities for both doped regions. (5 points)
   c. Find the barrier voltage and saturation current for a junction area of **0,2 mm²**. (8 points) $\tau_n = \tau_p = 1\ \mu sec$.
   d. Determine the depletion zone width in **unbiased** state, when the junction is reverse biased at **2,75 V** and when it is forward biased at **0,25 V**. (9 points)



2. For the circuit shown on the right sketch V_{out} as a function of V_{in} for V_{in}: -10 V to +10 V assuming all three resistors are 10k and the voltage drop across conducting diodes are constant at 0,6 V. (30 points)
   HINT: Analyze the circuit first at V_{in} = 0V; then at +10 V and –10 V, and finally at values in between.

3. Study DC characteristics of the 3-stage BJT amplifier circuit with $|V_{BE}|$ = **0,6 V**, h_{FE} **= 200** for all four transistors. **Do not neglect base currents.**
   a. Design a current source that will provide **0,4 mA biasing current** to the differential stage. (10 points)
   b. Choose R_{C3} such that, T_3 is in active mode (30 points)



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SOLUTIONS:

1. Using Einstein Equation , i.e., $D_{p/n} = V_T\mu_{p/n} \Rightarrow D_p = 15\,\frac{cm^2}{s};\ D_n = 40\,\frac{cm^2}{s}$

a. $$\sigma_p = q\cdot\left(\frac{n_i^2}{N_A}\mu_n + N_A\mu_p\right) \cong qN_A\mu_p = 1.92/\Omega cm \Rightarrow \rho_p = \underline{\underline{0{,}52\Omega cm}}$$

$$\sigma_n = q\cdot\left(N_D\mu_n + \frac{n_i^2}{N_D}\mu_p\right) \cong qN_D\mu_n = 1{,}03/\Omega cm \Rightarrow \rho_n = \underline{\underline{0.98\Omega cm}}$$

b. $$n_n = N_D = \underline{\underline{4\cdot 10^{15}/cm^3}};\ p_n = \frac{n_i^2}{N_D} = \underline{\underline{5{,}6\cdot 10^4/cm^3}}$$

$$p_p = N_A = \underline{\underline{2\cdot 10^{16}/cm^3}};\ n_p = \frac{n_i^2}{N_A} = \underline{\underline{1{,}13\cdot 10^4/cm^3}}$$

c. $V_B = V_T\cdot\ln\left(\frac{N_A\cdot N_D}{n_i^2}\right) = \underline{\underline{665mV}}$ and $I_o = A\cdot q\cdot n_i^2\cdot\left[\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right] = \underline{\underline{926\,fA}}$

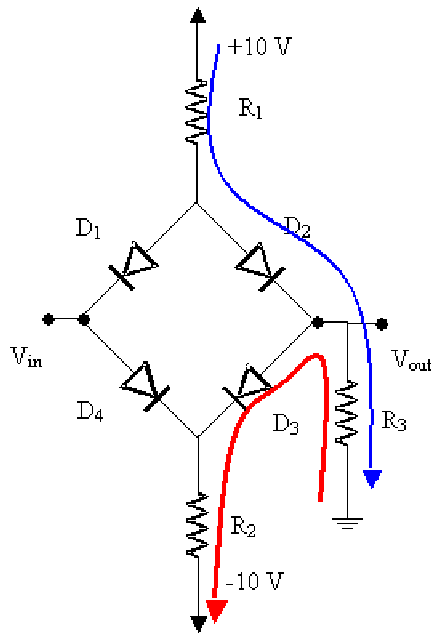
Where $L_{n/p} = \sqrt{D_{n/p}\tau_{n/p}} \Rightarrow L_n = 632nm; L_p = 387nm;$

d. unbiased $w_{dep} = \sqrt{\frac{2\cdot\varepsilon_o\cdot\varepsilon_r\cdot V_B}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)} = \underline{\underline{0{,}51\mu m}}$

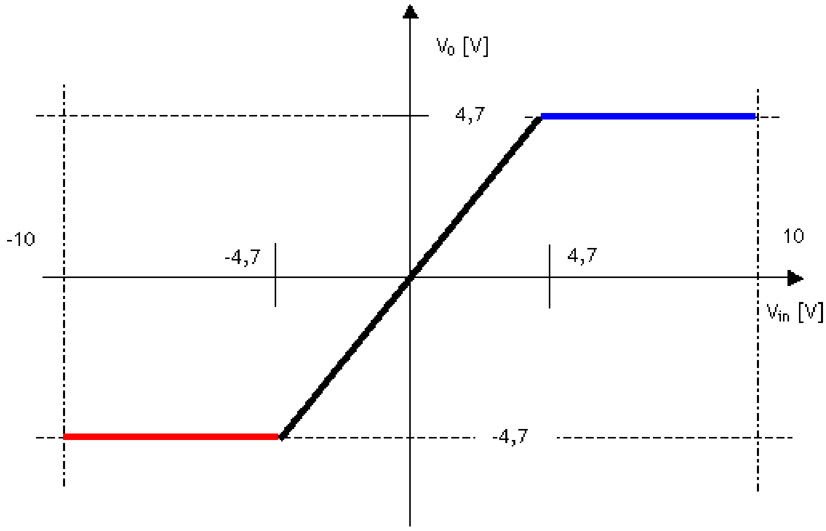
with reverse bias at 2,5 V, $w_{dep} = \sqrt{\frac{2\cdot\varepsilon_o\cdot\varepsilon_r\cdot(V_B+V_{bias})}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)} = \underline{\underline{1{,}17\mu m}}$

with forward bias at 0,25 V, $w_{dep} = \sqrt{\frac{2\cdot\varepsilon_o\cdot\varepsilon_r\cdot(V_B-V_{bias})}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)} = \underline{\underline{0{,}41\mu m}}$

2. Assume there is no V_{in}. V_{out} = 0V because of the symmetry of the circuit, and because all diodes are conducting. This is the same as V_{in} = 0V. Now assume V_{in} = 10V. We can easily see that D_1 and D_3 are reverse biased because most of the voltage drop from +10 V to –10 V is over the resistors R_1 and R_2. In other words, the anode of D_1 is much less than +10V whereas the cathode is at +10V (reverse bias). Also, D_4 is conducting, thus, the cathode of D_3 is at 9,4V wheras the anode of D_3 is much less than +9,4V. That means current flows (a) from +10V over R_1, D_2 , and R_3 to ground (**follow blue line**), and (b) from V_{in} over D_4 and R_4 to –10V. Since only 0,6V drops on the conducting diodes 9,4V drops over the two resistors R_1 and R_3. Since R_1 and R_3 have equal values, we divide the voltage drop by 2 and this is V_{out} = 4.7V.



Now assume V_{in} = -10V. Similar to the observations above, D_4 and D_2 are reverse biased because most of the voltage drop from +10 V to –10 V is again over the resistors R_1 and R_2. In other words, the cathode of D_4 is much higher than -10V whereas the anode is at -10V (reverse bias again). Also, D_1 is conducting, thus, the anode of D_2 is at -9,4V whereas the cathode of D_2 is much higher than -9,4V. That means current flows (a) from the ground over R_3, D_3 , and R_2 to –10V (**follow red line**), and (b) from +10V over R_1 and D_1 to V_{in}. Since only 0,6V drops on the conducting diodes 9,4V drops over the two resistors R_2 and R_3. Since R_2 and R_3 have equal values, we divide the voltage drop by 2 and this is V_{out} = 4.7V. Finally, we need to consider the output for 0V ≥ V_{in} ≥ -10V and 0V ≤ V_{in} ≤ +10V. One sees easily that when all the 4 diodes are conducting, the output V_{out} follows the input V_{in} because the circuit is symmetrical. When do all the 4 diodes conduct? See the sketch below….Capito???? DO NOT JUST MEMORIZE GUYS, TRY TO ANALYZE…



3. DC characteristics are to be studied.
   a. You do your own design!
   b. Without neglecting the base currents of the differential (the very first) stage, for V_i = 0 V

$$I_{C1} = I_{C2} = \frac{h_{FE}}{h_{FE}+1}\cdot\frac{I_{ref}}{2} = \frac{200}{200+1}\cdot\frac{0{,}4mA}{2} \Rightarrow I_{C1} = I_{C2} = \underline{\underline{0{,}199mA}}$$

$$-(I_{C2}-I_{B3})33k + V_{BE3} + (h_{FE}+1)I_{B3}4k7 = 0$$

$$I_{C3} = h_{FE}\frac{33k * I_{C2} - V_{BE3}}{(h_{FE}+1)4k7+33k} = 200\frac{33k*0{,}199mA - 0{,}6V}{(200+1)4k7+33k} = \underline{\underline{1{,}2mA}}$$

Now we need to find the base voltage of T_3. $V_{B3} = -10V + (I_{C2} - I_{B3})33k = \underline{\underline{-3{,}63V}}$

For T_3 to be in active mode $V_{B3} \le V_{C3}$. I take $V_{C3} = -3{,}5V > -3{,}63V$. Thus

$$V_{C3} = V_{B4} = -10V + 4k7\cdot I_{E4} + V_{BE4} = -10V + 4k7\cdot I_{B4}(h_{FE}+1) + 0{,}6V = -3{,}5V$$

$$\Rightarrow I_{C4} = h_{FE}\cdot I_{B4} = h_{FE}\frac{10V - 3{,}5V - 0{,}6V}{4k7\cdot(h_{FE}+1)} = \underline{\underline{1{,}2mA}}$$

For T_3 to be in active mode

$$V_{C3} = -3{,}5V = 10V - R_{C3}(I_{C3}+I_{B4}) \Rightarrow R_{C3} \le \frac{10V+3{,}5V}{(I_{C3}+I_{B4})} = \underline{\underline{11k1}}$$