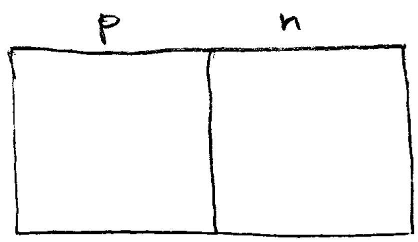
Physics 116A Fall 2004: Exam 2

11/23/2004

Closed book and notes except for two 8.5 in x 11 in sheets of paper. Show reasoning for full credit. There are 3 problems and 100 points.



1. *(≈ 30 points)* The figure above shows an unbiased silicon pn junction at $T = 300$ K. For Si at 300 K, the density of atoms is 5×10^{28} m^{-3} and the intrinsic concentration is 1.5×10^{16} m^{-3}. The free electron and hole mobilities are 0.13 m^{2}V^{-1}s^{-1} and 0.05 m^{2}V^{-1}s^{-1}, respectively. The magnitude of the electron charge, q, is 1.6×10^{-19} C. At $T = 300$ K, $kT/q = 26$ mV.

   (a) The n-type material is doped with one part per 10^8 of a donor impurity.

      i. Find n_n, the electron concentration, **and** p_n, the hole concentration in the n-type bulk material (i.e., far from the junction).

      ii. Find the conductivity, σ, of the n-type bulk material.

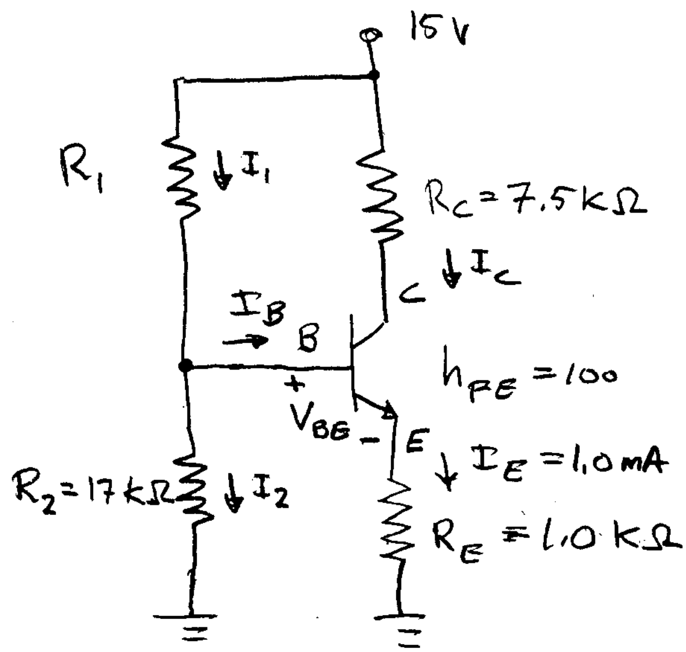
   (b) Imagine that you could bring p-type and n-type materials together and join them to make the pn junction shown above. Consider the semiconductor region near the junction.

      i. What physical process is responsible for an initial current of electrons from the n-type into the p-type material?

      ii. After thermal equilibrium has been reached, there is no longer a net current across the junction. What has happened to oppose the initial current?

      iii. Explain why a region depleted of mobile charge carriers is formed near the junction.

      iv. Is the energy of the bottom edge of the conduction band the same in the p-type bulk material as it is in the n-type bulk material? Explain why or why not.



2. *(≈ 30 points)* In the circuit above, assume R_1 has the correct value for the BJT to be in the active region with $I_E = 1.0\,\text{mA}$ (at least, as far as the base circuit is concerned). $h_{FE} = 100$.

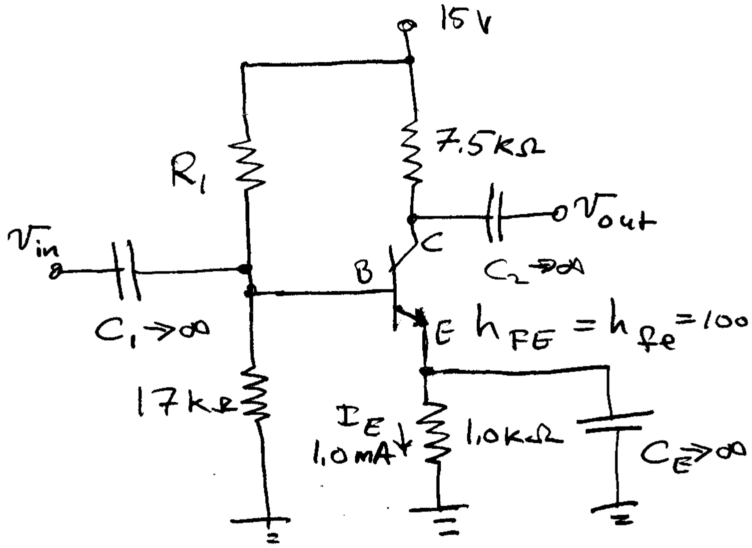
   (a) Find V_B. (Hint: first find V_E and use your estimate of V_{BE} in the active region.)

   (b) Find I_B.

   (c) Find I_1, the current in R_1.

   (d) Now find the value of R_1.

   (e) Find V_C and verify that the BJT is in the active region.



3. *(≈ 40 points)* The Q point for this amplifier with $I_E = 1.0$ mA was found in Problem 2. Capacitors have been added to make a common emitter amplifier. *Use your calculated value for* R_1. The emitter resistor has been bypassed with a large capacitor so that the BJT emitter voltage remains constant for small AC input signals. For the BJT, $h_{fe} = 100$ and $T = 300$ K.

   (a) Draw the small signal AC equivalent circuit. Use the simple small-signal AC BJT model containing r_e and a current source. Assume all C's are infinite so they are short circuits for AC (not for DC, of course). **Use your small signal AC equivalent circuit to solve the following sub-problems.**

   (b) Evaluate r_e for this circuit.

   (c) Find an expression for $v_{in}(= v_b)$ as a function of i_b. **Use this** to find $R_b \equiv v_b/i_b$, the effective resistance looking into the BJT base.

   (d) Find the input impedance of the circuit. Evaluate numerically.

   (e) Find an expression for v_{out} in terms of i_c.

   (f) Find the voltage gain, $A_v \equiv v_{out}/v_{in}$. Evaluate numerically.

   (g) One could have designed this amplifier to work with the same $I_{E_Q} = 1.0$ mA with $R_E = 0$ by choosing different values of R_1 and R_2. Then C_E would not have been needed. What is the advantage of using the circuit given above with nonzero R_E? Hint: what would happen if the BJT temperature were to increase significantly?

1. (a) i. $n_n = N_D = 5\times10^{28} \times 10^{-8} = \underline{5\times10^{20}}\ m^{-3}$.

$$p_n = \frac{n_i^2}{n_n} = \frac{(1.5\times10^{16})^2}{5\times10^{20}}\ m^{-3} = 4.5\times10^{11}\ m^{-3}$$

ii. $\sigma = (n\mu_n + p\mu_p)q \simeq n\mu_n q = 5\times10^{20}\ m^{-3} \times 0.13\ m^2/Vs \times 1.6\times10^{-19}\ c$

$= 10.4\ \mho/m$

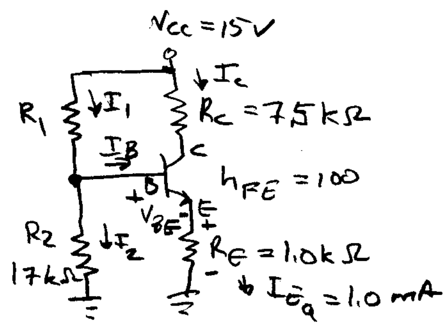
(b) i) diffusion

ii) Uncovered ions sets up $\vec{\mathcal{E}}$ field which sets up an opposing drift current.

iii) Electrons and holes occupying the region near the junction recombine, producing depletion region.

iv) No. $\vec{\mathcal{E}}$ field results in a "barrier" (or built-in) potential difference between the n and p material.

2.



(a) $V_B = V_{BE} + V_E$

$= 0.7\,V + I_{E_Q} R_E$

$= 0.7\,V + 1mA\times1k\Omega = \underline{1.7\,V}$

(b) $I_B + I_c = I_E = 1.0\,mA$

$I_B + h_{FE} I_B = 1.0\,mA$

$I_B = 1.0\,mA/(h_{FE}+1) = \frac{1.0\,mA}{101} = \underline{9.9\,\mu A}$

(c) $I_1 = I_2 + I_B$, $I_2 = V_B/17k\Omega = \frac{1.7V}{17k\Omega} = \underline{100\,\mu A}$

$I_1 = 100 + 9.9 = \underline{110\ \mu A}$

(d) $R_1 = (V_{cc} - V_B)/I_1 = (15V - 1.7V)/110\,\mu A = \underline{121\,k\Omega}$

(e) $V_c = V_{cc} - I_c R_c = 15V - h_{FE} I_B R_c = 15V - 100\times 9.9\,\mu A \times 7.5\,k\Omega$

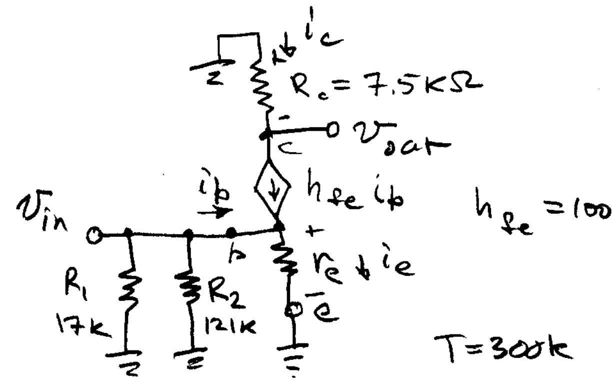
$= 15V - 7.4\,V = \underline{7.6\,V}$

For active region, $V_{CE} > 0.2V$

$V_{CE} = V_{C_Q} - I_{E_Q} R_E = 7.6V - 1k\Omega\times1mA$

$= 7.6 - 1.0 = 6.6\,V > 0.2V$ <u>Ok</u>

3, (a)



(b) $r_e = \frac{kT/q}{I_{EQ}} = \frac{26\,mV}{I_{EQ}} = \frac{26\,mA\cdot\Omega}{1.0\,mA} = \underline{26\,\Omega}$

(c) $v_b = i_e r_e = (h_{fe} i_b + i_b) r_e = (h_{fe}+1) i_b r_e$

$R_b \equiv \frac{v_b}{i_b} = (h_{fe}+1) r_e = 101 \times 26\,\Omega = 2626\,\Omega.$

(d) $R_{in} = R_b \| R_1 \| R_2 = \left[\frac{1}{2626} + \frac{1}{17k} + \frac{1}{121k}\right]^{-1}\Omega$

$= \underline{2.2\,k\Omega}$

(e) $v_{out} = -i_c R_c$

(f) $A_v = \frac{v_{out}}{v_{in}} = \frac{-i_c R_c}{v_b} = \frac{-h_{fe} i_b R_c}{(h_{fe}+1) i_b r_e}$

$= -\frac{h_{fe}}{h_{fe}+1}\frac{R_c}{r_e} \approx -\frac{R_c}{r_e} = -\frac{7.5k\Omega}{26\Omega} = \underline{-288}$

(g) R_E provides bias stability.

If T increases, I_E increases for a given V_{BE}. But this increases the voltage drop across R_E, reducing V_{BE} (for fixed V_B), decreasing I_E toward the desired I_{EQ}.

Without R_E, I_E could increase enough so the voltage drop across R_C ($=\alpha I_E R_E$) could take the BJT into saturation ($V_{CE} \approx 0.2V$).