VE320 Homework 7

Due: July 3, 2019, 10:00am

In the following problems 1-5, **if not stated**,
For silicon pn junctions: $D_n = 25cm^2/s, D_p = 10cm^2/s, \tau_{n0} = 5 \times 10^{-7}s, \tau_{p0} = 10^{-7}s.$
For GaAs pn junctions: $D_n = 205cm^2/s, D_p = 9.8cm^2/s, \tau_{n0} = 5 \times 10^{-8}s, \tau_{p0} = 10^{-8}s.$

1. Consider an ideal silicon pn junction diode.
   (a) What must be the ratio of N_d/N_a so that 90% of the current in the depletion region is due to the flow of electrons?
   (b) Repeat part (a) if 80% of the current in the depletion region is due to the flow of holes?

2. An ideal silicon pn junction at $T = 300K$ is under zero bias. The minority carrier lifetimes are $\tau_{n0} = 10^{-6}s$, and $\tau_{p0} = 10^{-7}s$. The doping concentration in the n region is $N_d = 10^{16}cm^{-3}$.
   Plot the ratio of hole current to the total current crossing the space charge region as the p region doping concentration varies over the range $10^{15} \leq N_a \leq 10^{18}cm^{-3}$. (Use a log scale for the doping concentrations.)

3. Consider a silicon pn junction diode with an applied reverse-biased voltage of $V_R = 5V$. The doping concentrations are $N_d = N_a = 4 \times 10^{16}cm^{-3}$ and the cross-sectional area is $A = 10^{-4}cm^2$. Assume minority carrier lifetimes of $\tau_0 = \tau_{n0} = \tau_{p0} = 10^{-7}s$. Calculate
   (a) the ideal reverse-saturation current,
   (b) the reverse-biased generation current,
   (c) the ratio of the generation current to ideal saturation current.

4. Consider a GaAs pn junction diode with a cross-sectional area of $A = 2 \times 10^{-4}cm^2$ and doping concentrations of $N_d = N_a = 7 \times 10^{16}cm^{-3}$. The electron and hole mobility values are $\mu_n = 5500cm^2/V-s$ and $\mu_p = 220cm^2/V-s$, respectively, and the lifetime values are $\tau_0 = \tau_{n0} = \tau_{p0} = 2 \times 10^{-8}s$.
   Calculate the ideal diode current at a
   (a) reverse-biased voltage of $V_R = 3V$
   (b) forward-bias voltage of $V_a = 0.6V$
   (c) forward-bias voltage of $V_a = 0.8V$
   (d) forward-bias voltage of $V_a = 1V$

5. Consider a GaAs pn diode at $T = 300K$ with $N_d = N_a = 10^{17}cm^{-3}$ and with a cross-sectional area of $A = 5 \times 10^{-3}cm^2$. The minority carrier mobilities are $\mu_n = 3500cm^2/V-s$ and $\mu_p = 220cm^2/V-s$. The electron-hole lifetimes are $\tau_0 = \tau_{n0} = \tau_{p0} = 10^{-8}s$.
   Plot the diode forward-bias current include including recombination current between diode voltages of $0.1 \leq V_D \leq 1V$. Compare this plot to that for an ideal diode.

The following questions are about BJT, you can use the transistor geometry shown below. You may also find the last page useful.

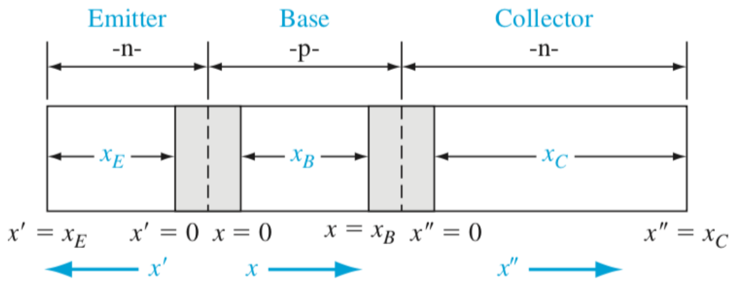


Figure 12.13 | Geometry of the npn bipolar transistor used to calculate the minority carrier distribution.

6. For a uniformly doped $n^{++}p^{+}n$ bipolar transistor in the thermal equilibrium,
   (a) Sketch the energy-band diagram.
   (b) Sketch the electric field through the device.
   (c) Repeat parts (a) and (b) for the transistor biased in the forward-active region.

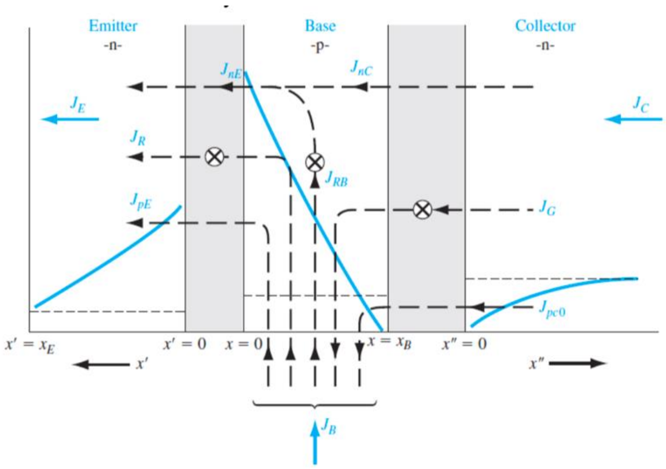
7. A uniformly doped silicon npn bipolar transistor at $T = 300K$ is biased in the forward-active mode. The doping concentrations are $N_E = 8 \times 10^{17} cm^{-3}, N_B = 10^{16} cm^{-3}$, and $N_C = 10^{15} cm^{-3}$.
   (a) Find the thermal-equilibrium values p_{E0}, n_{B0}, and p_{C0}.
   (b) Calculate the values of n_B at $x = 0$ and p_E at $x' = 0$ for $V_{BE} = 0.64V$.
   (c) Sketch the minority carrier concentrations through the device and label each curve.

8. (a) The following currents are measured in a uniformly doped npn bipolar transistor.
   $I_{nE} = 0.50mA, I_{nC} = 0.495mA, I_{pE} = 3.5\mu A, I_R = 5\mu A, I_G = 0.5\mu A, I_{pc0} = 0.5\mu A$
   Determine the following current gain parameters: $\gamma, \alpha_T, \delta, \alpha, \beta$ (see next page).
   (b) If the required value of common-emitter current gain is $\beta = 120$, determine new values of I_{nC}, I_{pE} and I_R to meet this specification assuming $\gamma = \alpha_T = \delta$.

9. The emitter in a BJT is often made very thin to achieve high operating speed. In this problem, we investigate the effect of emitter width on current gain. Consider the emitter injection efficiency given by

$$\gamma = \frac{1}{1 + \frac{p_{E0} D_E L_B}{n_{B0} D_B L_E} \cdot \frac{\tanh(x_B/L_B)}{\tanh(x_E/L_E)}}$$

   Assume that $N_E = 100 N_B, D_E = D_B, L_E = L_B$. Also let $x_B = 0.1 L_B$.
   Plot the emitter injection efficiency for $0.01 L_E \le x_E \le 10 L_E$.
   From these results, discuss the effect of emitter width on the current gain.



Diffusion of electrons into the base from emitter

$$J_{nE} = \frac{eD_B n_{B0}}{L_B}\left\{\frac{1}{\sinh(x_B/L_B)} + \frac{[\exp(eV_{BE}/kT) - 1]}{\tanh(x_B/L_B)}\right\}$$

Diffusion of electrons leaving the base

$$J_{nC} = \frac{eD_B n_{B0}}{L_B}\left\{\frac{[\exp(eV_{BE}/kT) - 1]}{\sinh(x_B/L_B)} + \frac{1}{\tanh(x_B/L_B)}\right\}$$

Diffusion of holes into the emitter from base

$$J_{pE} = \frac{eD_E p_{E0}}{L_E}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right] \cdot \frac{1}{\tanh(x_E/L_E)}$$

$$J_R = \frac{e x_{BE} n_i}{2\tau_0}\exp\left(\frac{eV_{BE}}{2kT}\right) = J_{r0}\exp\left(\frac{eV_{BE}}{2kT}\right)$$

$$p_{E0} = \frac{n_i^2}{N_E} \quad \text{and} \quad n_{B0} = \frac{n_i^2}{N_B}$$

$$J_{s0} = \frac{eD_B n_{B0}}{L_B \tanh(x_B/L_B)}$$

J_{nE}: Due to the diffusion of minority carrier electrons in the base at $x = 0$.

J_{nC}: Due to the diffusion of minority carrier electrons in the base at $x = x_B$.

J_{RB}: The difference between J_{nE} and J_{nC}, which is due to the recombination of excess minority carrier electrons with majority carrier holes in the base. The J_{RB} current is the flow of holes into the base to replace the holes lost by recombination.

J_{pE}: Due to the diffusion of minority carrier holes in the emitter at $x' = 0$.

J_R: Due to the recombination of carriers in the forward-biased B–E junction.

J_{pc0}: Due to the diffusion of minority carrier holes in the collector at $x'' = 0$.

J_G: Due to the generation of carriers in the reverse-biased B–C junction.

Emitter injection efficiency

$$\gamma \approx \frac{1}{1 + \frac{N_B}{N_E} \cdot \frac{D_E}{D_B} \cdot \frac{x_B}{x_E}} \qquad (x_B \ll L_B),\ (x_E \ll L_E)$$

Base transport factor

$$\alpha_T \approx \frac{1}{1 + \frac{1}{2}\left(\frac{x_B}{L_B}\right)^2} \qquad (x_B \ll L_B)$$

Recombination factor

$$\delta = \frac{1}{1 + \frac{J_{r0}}{J_{s0}}\exp\left(\frac{-eV_{BE}}{2kT}\right)}$$

Common-base current gain

$$\alpha = \gamma\alpha_T\delta \approx \frac{1}{1 + \frac{N_B}{N_E} \cdot \frac{D_E}{D_B} \cdot \frac{x_B}{x_E} + \frac{1}{2}\left(\frac{x_B}{L_B}\right)^2 + \frac{J_{r0}}{J_{s0}}\exp\left(\frac{-eV_{BE}}{2kT}\right)}$$

Common-emitter current gain

$$\beta = \frac{\alpha}{1 - \alpha} \approx \frac{1}{\frac{N_B}{N_E} \cdot \frac{D_E}{D_B} \cdot \frac{x_B}{x_E} + \frac{1}{2}\left(\frac{x_B}{L_B}\right)^2 + \frac{J_{r0}}{J_{s0}}\exp\left(\frac{-eV_{BE}}{2kT}\right)}$$

$$\gamma = \left(\frac{J_{nE}}{J_{nE} + J_{pE}}\right) = \frac{1}{\left(1 + \frac{J_{pE}}{J_{nE}}\right)} = \frac{1}{1 + \frac{p_{E0} D_E L_B}{n_{B0} D_B L_E} \cdot \frac{\tanh(x_B/L_B)}{\tanh(x_E/L_E)}}$$

$$\alpha_T = \frac{J_{nC}}{J_{nE}} \approx \frac{\exp(eV_{BE}/kT) + \cosh(x_B/L_B)}{1 + \exp(eV_{BE}/kT)\cosh(x_B/L_B)}$$

$$\approx \frac{1}{\cosh(x_B/L_B)} \approx \frac{1}{1 + \frac{1}{2}(x_B/L_B)^2} \approx 1 - \frac{1}{2}(x_B/L_B)^2$$

$$\delta = \frac{J_{nE} + J_{pE}}{J_{nE} + J_R + J_{pE}}$$

$$\alpha = \left(\frac{J_{nE}}{J_{nE} + J_{pE}}\right)\left(\frac{J_{nC}}{J_{nE}}\right)\left(\frac{J_{nE} + J_{pE}}{J_{nE} + J_R + J_{pE}}\right)$$