VE320 Homework 5

Due Nov. 11, 23:59pm

In the following problems, if not stated, T = 300K, and:
For silicon pn junctions: Dn=25cm^2/s,Dp=10 cm^2/s,$\tau n0$=5×$10^{-7}s$,$\tau p0$=$10^{-7}s$.
For GaAs pn junctions: Dn=205 cm^2/s,Dp=9.8 cm^2/s,$\tau n0$=5×$10^{-8}s$,$\tau p0$=$10^{-8}s$.

1. Consider a silicon n^+p junction diode. The critical electric field for breakdown in silicon is approximately $E_{crit} = 4 \times 10^5$ V/cm. Determine the maximum p-type doping concentration such that the breakdown voltage is (*a*) 40 V and (*b*) 20 V.

2. A silicon p^+n junction has doping concentrations of $N_a = 2 \times 10^{17}$ cm^{-3} and $N_d = 2 \times 10^{15}$ cm^{-3}. The cross-sectional area is 10^{-5} cm^2. Calculate (a) V_{bi} and (b) the junction capacitance at reverse bias V_R (i) V_R = 1V, (ii) V_R = 3V, and (iii) V_R =5 V. (c) plot $1/C^2$ versus V_R and identify how the slope and intercept at the voltage axis are related to N_d and V_{bi}, repectively.

3. 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?

4. 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.

5. 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 $\mu_n = 5500 cm^2/V - s$ and $\mu_p = 220 cm^2/V - s$, 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 $V_a = 1V$

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

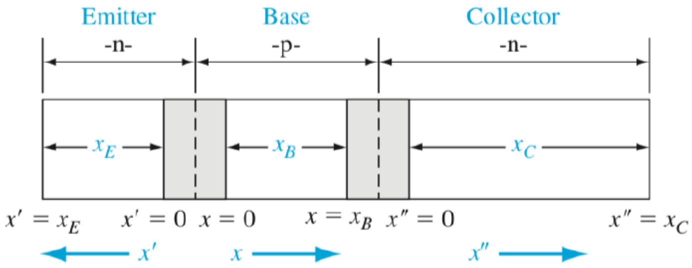


Figure 12.13 | Geometry of the npn bipolar transistor used to calculate the minority carrier distribution.

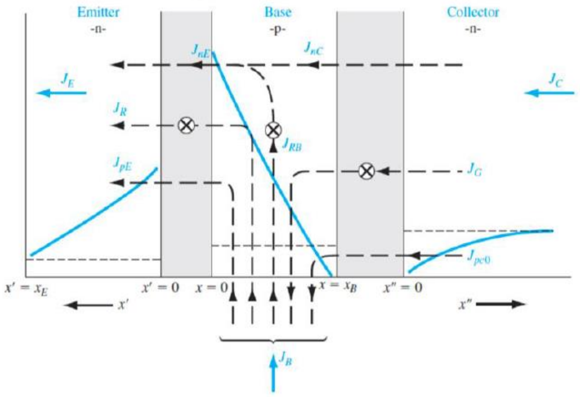
6. For a uniformly doped $n^{++}p^{+}n$ bipolar transistor in the thermal equilibrium,
   (a) Sketch the energy-band diagram.
   (b) Sketch the electric field through the device.
   (c) Repeat parts (a) and (b) for the transistor biased in the forward-active region.

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. An npn bipolar transistor is biased in the forward-active mode. (*a*) The collector current is $I_C = 1.2$ mA when biased at $V_{CE} = 2$ V. The Early voltage is $V_A = 120$ V. Determine (*i*) the output resistance r_o, (*ii*) the output conductance g_o, and (*iii*) the collector current when biased at $V_{CE} = 4$ V. (*b*) Repeat part (*a*) if the collector current is $I_C = 0.25$ mA when biased at $V_{CE} = 2$ V and the Early voltage is $V_A = 160$ V.

10. A uniformly doped pnp silicon bipolar transistor has a base doping of $N_B = 10^{16}$ cm^{-3}, a collector doping of $N_C = 10^{15}$ cm^{-3}, a metallurgical base width of $x_{B0} = 0.70$ μm, a base minority carrier diffusion coefficient of $D_B = 10$ cm^2/s, and a B–E cross-sectional area of $A_{BE} = 10^{-4}$ cm^2. The transistor is biased in the forward-active mode with $V_{EB} = 0.625$ V. Neglecting the B–E space charge width and assuming $x_B \ll L_B$, (*a*) determine the change in neutral base width as V_{BC} changes from 1 to 5 V, (*b*) find the corresponding change in collector current, (*c*) estimate the Early voltage, and (*d*) find the output resistance.



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.

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

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

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

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

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

Emitter injection efficiency

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

Base transport factor

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

Recombination factor

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

Common-base current gain

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

Common-emitter current gain

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

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

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

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

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

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