

## VE320 Homework 3

Due Oct. 9, 23:59pm

1. (a) For silicon, find the ratio of the density of states in the conduction band at  $E=E_c+kT$  to the density of states in the valence band at  $E=E_v-kT$ . (b) Repeat part (a) for GaAs.
2. (a) The Fermi energy in silicon is  $0.30\text{eV}$  below the conduction band energy  $E_c$  at  $T=300\text{K}$ . Plot the probability of a state being occupied by an electron in the conduction band over the range  $E_c \leq E \leq E_c+2kT$ . (b) The Fermi energy in silicon is  $0.25\text{eV}$  above the valence band energy  $E_v$ . Plot the probability of a state being empty by an electron in the valence band over the range  $E_v-2kT \leq E \leq E_v$ .
3. (a) Calculate the temperature at which there is a  $10^{-8}$  probability that an energy state  $0.60\text{eV}$  above the Fermi energy level is occupied by an electron. (b) Repeat part (a) for a probability of  $10^{-6}$ .
4. (a) The carrier effective masses in a semiconductor are  $m_n^* = 1.21 m_0$  and  $m_p^* = 0.70 m_0$ . Determine the position of the intrinsic Fermi level with respect to the center of the bandgap at  $T = 300 \text{ K}$ . (b) Repeat part (a) if  $m_n^* = 0.080 m_0$  and  $m_p^* = 0.75 m_0$ .
5. Silicon at  $T = 300 \text{ K}$  is doped with boron atoms such that the concentration of holes is  $p_0 = 5 \times 10^{15} \text{ cm}^{-3}$ . (a) Find  $E_F - E_v$ . (b) Determine  $E_c - E_F$ . (c) Determine  $n_0$ . (d) Which carrier is the majority carrier? (e) Determine  $E_{Fi} - E_F$ .
6. (a) Consider a germanium semiconductor at  $T = 300 \text{ K}$ . Calculate the thermal equilibrium electron and hole concentrations for (i)  $N_d = 2 \times 10^{15} \text{ cm}^{-3}$ ,  $N_a = 0$ , and (ii)  $N_a = 10^{16} \text{ cm}^{-3}$ ,  $N_d = 7 \times 10^{15} \text{ cm}^{-3}$ . (b) Repeat part (a) for GaAs. (c) For the case of GaAs in part (b), the minority carrier concentrations are on the order of  $10^{-3} \text{ cm}^{-3}$ . What does this result mean physically?
7. (a) Silicon at  $T = 300 \text{ K}$  is uniformly doped with boron atoms to a concentration of  $3 \times 10^{16} \text{ cm}^{-3}$  and with arsenic atoms to a concentration of  $1.5 \times 10^{16} \text{ cm}^{-3}$ . Is the material n type or p type? Calculate the thermal equilibrium concentrations of majority and minority carriers. (b) Additional impurity atoms are added such that holes are the majority carrier and the thermal equilibrium concentration is  $p_0 = 5 \times 10^{16} \text{ cm}^{-3}$ . What type and concentration of impurity atoms must be added? What is the new value of  $n_0$ ?
8. A silicon device is doped with donor impurity atoms at a concentration of  $10^{15} \text{ cm}^{-3}$ . For the device to operate properly, the intrinsic carriers must contribute no more than 5 percent to the total electron concentration. (a) What is the maximum temperature that the device may operate? (b) What is the change in  $E_c - E_F$  from the  $T = 300 \text{ K}$  value to the maximum temperature value determined in part (a). (c) Is the Fermi level closer or further from the intrinsic value at the higher temperature?
- 9.

For a particular semiconductor,  $E_g = 1.50$  eV,  $m_p^* = 10 m_n^*$ ,  $T = 300$  K, and  $n_i = 1 \times 10^5 \text{ cm}^{-3}$ . (a) Determine the position of the intrinsic Fermi energy level with respect to the center of the bandgap. (b) Impurity atoms are added so that the Fermi energy level is 0.45 eV below the center of the bandgap. (i) Are acceptor or donor atoms added? (ii) What is the concentration of impurity atoms added?

10.

Silicon atoms, at a concentration of  $7 \times 10^{15} \text{ cm}^{-3}$ , are added to gallium arsenide. Assume that the silicon atoms act as fully ionized dopant atoms and that 5 percent of the concentration added replace gallium atoms and 95 percent replace arsenic atoms. Let  $T = 300$  K. (a) Determine the donor and acceptor concentrations. (b) Is the material n type or p type? (c) Calculate the electron and hole concentrations. (d) Determine the position of the Fermi level with respect to  $E_{Fi}$ .

11.

Consider a semiconductor that is uniformly doped with  $N_d = 10^{14} \text{ cm}^{-3}$  and  $N_a = 0$ , with an applied electric field of  $E = 100 \text{ V/cm}$ . Assume that  $\mu_n = 1000 \text{ cm}^2/\text{V-s}$  and  $\mu_p = 0$ . Also assume the following parameters:

$$N_c = 2 \times 10^{19} (T/300)^{3/2} \text{ cm}^{-3}$$

$$N_v = 1 \times 10^{19} (T/300)^{3/2} \text{ cm}^{-3}$$

$$E_g = 1.10 \text{ eV}$$

(a) Calculate the electric-current density at  $T = 300$  K. (b) At what temperature will this current increase by 5 percent? (Assume the mobilities are independent of temperature.)

12.

The effective density of states functions in silicon can be written in the form

$$N_c = 2.8 \times 10^{19} \left( \frac{T}{300} \right)^{3/2} \quad N_v = 1.04 \times 10^{19} \left( \frac{T}{300} \right)^{3/2}$$

Assume the mobilities are given by

$$\mu_n = 1350 \left( \frac{T}{300} \right)^{-3/2} \quad \mu_p = 480 \left( \frac{T}{300} \right)^{-3/2}$$

Assume the bandgap energy is  $E_g = 1.12$  eV and independent of temperature. Plot the intrinsic conductivity as a function of  $T$  over the range  $200 \leq T \leq 600$  K.

13.

Consider an n-type semiconductor at  $T = 300$  K in thermal equilibrium (no current). Assume that the donor concentration varies as  $N_d(x) = N_{d0} e^{-x/L}$  over the range  $0 \leq x \leq L$  where  $N_{d0} = 10^{16} \text{ cm}^{-3}$  and  $L = 10 \mu\text{m}$ . (a) Determine the electric field as a function of  $x$  for  $0 \leq x \leq L$ . (b) Calculate the potential difference between  $x = 0$  and  $x = L$  (with the potential at  $x = 0$  being positive with respect to that at  $x = L$ ).

14.

Consider a semiconductor at  $T = 300$  K. (a) (i) Determine the electron diffusion coefficient if the electron mobility is  $\mu_n = 1150$  cm<sup>2</sup>/V-s. (ii) Repeat (i) of part (a) if the electron mobility is  $\mu_n = 6200$  cm<sup>2</sup>/V-s. (b) (i) Determine the hole mobility if the hole diffusion coefficient is  $D_p = 8$  cm<sup>2</sup>/s. (ii) Repeat (i) of part (b) if the hole diffusion coefficient is  $D_p = 35$  cm<sup>2</sup>/s.

15.

The steady-state electron distribution in silicon can be approximated by a linear function of  $x$ . The maximum electron concentration occurs at  $x = 0$  and is  $n(0) = 2 \times 10^{16}$  cm<sup>-3</sup>. At  $x = 0.012$  cm, the electron concentration is  $5 \times 10^{15}$  cm<sup>-3</sup>. If the electron diffusion coefficient is  $D_n = 27$  cm<sup>2</sup>/s, determine the electron diffusion current density.