Organic Electronic Devices

Week 3: Charge Transport
Tutorial 3.1: Homework Solutions

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**Solutions to Problem 1**

- **Problem Statement**

A time-of-flight (TOF) device outputs the following transient photocurrent curve. Note that the thickness of the device is 5000 nm and the applied bias to the device was 80 V. Calculate the mobility of the semiconductor.

- **Solution**

\[
\mu = \frac{d^2}{Vt}
\]

\[
\mu = \frac{d^2}{Vt} = \frac{(5000 \times 10^{-7})^2}{(80 \, V) \times (3 \times 10^{-5} \, s)}
\]

\[
\mu = 1.05 \times 10^{-4} \, cm^2 \, V^{-1} \, s^{-1}
\]
Solutions to Problem 2

• Problem Statement

The room temperature electrical conductivity of a silicon specimen is 1000 ohm\(^{-1}\) m\(^{-1}\). The hole concentration is known to be 1.0 \times 10^{23} m\(^{-3}\). Assuming the electron and hole mobility values to be 0.14 m\(^2\) V\(^{-1}\) s\(^{-1}\) and 0.05 m\(^2\) V\(^{-1}\) s\(^{-1}\), respectively, compute the electron concentration. On the basis of this calculation, state whether the specimen is intrinsic, n-type, or p-type.

• Solution

\[ \sigma = e (p \mu_h + n \mu_e) \]

\[ \frac{\sigma}{p \mu_h} = \frac{e \mu_e}{n} \]

\[ \therefore n = \frac{e \mu_e}{\mu_h} \]

\[ n = \frac{1000 \text{ ohm}^{-1} \text{ m}^{-1}}{1.602 \times 10^{-19} \text{ C}} \times \left( 1.0 \times 10^{23} \text{ m}^{-3} \right) \left( 0.05 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1} \right) \]

\[ n = \frac{0.14 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}}{1.0 \times 10^{21} \text{ m}^{-3}} = 8.87 \times 10^{21} \text{ m}^{-3} \]

The specimen is p-type because \( p > n \)
Solutions to Problem 3

• Problem Statement

Calculate the room temperature electrical conductivity of silicon that has been doped with $N_D = 5 \times 10^{17}$ m$^{-3}$ of P atoms. Supposed the number of majority carriers is $n = N_D \exp(-E_D/kT)$ where $E_D = 0.05$ eV is the energy difference between the impurity level and the closest band. Estimate the position of the Fermi level and the concentration of minority carriers. $N_c$ and $N_v$ for Si are $2.98 \times 10^{25}$ m$^{-3}$ and $1.04 \times 10^{25}$ m$^{-3}$, respectively. The electron and hole mobility values are 0.14 m$^2$ V$^{-1}$ s$^{-1}$ and 0.05 m$^2$ V$^{-1}$ s$^{-1}$, respectively. Assume room temperature conditions.

• Solution

$$n = N_D \times \exp\left[\frac{-E_D}{kT}\right] = \left(5 \times 10^{17} \text{ m}^{-3}\right) \times \exp\left[\frac{-0.05 \text{ eV}}{0.026 \text{ eV}}\right] = 7.31 \times 10^{16} \text{ m}^{-3}$$

$$np = n_i^2 = N_c \, N_v \times \exp\left[\frac{(-E_g)}{kT}\right]$$

$$p = \frac{N_c \, N_v \times \exp\left[\frac{(-E_g)}{kT}\right]}{n}$$
Solutions to Problem 3 (Continued)

\[ np = n_i^2 = N_c N_v \times \exp \left[ \frac{(-E_g)}{kT} \right] \]

\[ N_c N_v \times \exp \left[ \frac{(-E_g)}{kT} \right] \]

\[ p = \frac{n}{n} \]

\[ p = \frac{\left(2.98 \times 10^{25} \text{ m}^{-3}\right) \left(1.04 \times 10^{25} \text{ m}^{-3}\right) \times \exp \left[ \frac{-1.17 \text{ eV}}{0.026 \text{ eV}} \right]}{7.31 \times 10^{16} \text{ m}^{-3}} \]

\[ p = 1.17 \times 10^{14} \text{ m}^{-3} \]

\[ \sigma = e (p \mu_h + n \mu_e) \]

\[ \sigma = 1.602 \times 10^{-19} \text{ C} \times \left( \left(1.17 \times 10^{14} \text{ m}^{-3}\right) \left(0.05 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}\right) + \left(7.31 \times 10^{16} \text{ m}^{-3}\right) \left(0.14 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}\right) \right) \]

\[ \sigma = 1.6 \times 10^{-3} \text{ ohm}^{-1} \text{ m}^{-1} \]
Solutions to Problem 3 (Continued)

\[ n_i^2 = np = \left(7.31 \times 10^{16} \ m^{-3}\right) \times \left(1.17 \times 10^{14} \ m^{-3}\right) \]

\[ n_i^2 = 8.55 \times 10^{30} \ m^{-6} \]

\[ n_i = 2.92 \times 10^{15} \ m^{-3} \]

\[ E_F = E_i + kT \ln \left( \frac{n}{n_i} \right) = \frac{E_g}{2} + kT \ln \left( \frac{n}{n_i} \right) \]

\[ E_F = \frac{1.17 \ eV}{2} + (0.026 \ eV) \ln \left( \frac{7.31 \times 10^{16} \ m^{-3}}{2.92 \times 10^{15} \ m^{-3}} \right) \]

\[ E_F = 0.669 \ eV \]
• **Problem Statement**

An initially intrinsic sample of Ge at \( T = 300 \) K is doped with \( 2 \times 10^{22} \) m\(^{-3} \) As atoms. Calculate the intrinsic carrier concentration in Ge. Assuming all As dopants are ionized, identify the majority and minority carriers and calculate their concentrations. Also, calculate the resistivity (the inverse of the conductivity) of the doped Ge sample. Finally, calculate the temperature at which this semiconductor becomes degenerate (i.e., when \( E_C - E_F = 3 \) kT). For Ge: \( E_g = 0.66 \) eV, \( N_c = 1.05 \times 10^{25} \) m\(^{-3} \), \( N_v = 3.92 \times 10^{24} \) m\(^{-3} \), \( \mu_e = 0.39 \) m\(^2\) V\(^{-1}\) s\(^{-1} \), \( \mu_h = 0.19 \) m\(^2\) V\(^{-1}\) s\(^{-1} \).

• **Solution**

Because As has 1 more valence electron than Ge, the majority carrier will be electrons in this system.

\[
n \approx N_D = 2 \times 10^{22} \text{ m}^{-3}
\]

\[
n_i^2 = N_c \ N_v \times \exp \left( \frac{-E_g}{kT} \right) = \left( 1.05 \times 10^{25} \text{ m}^{-3} \right) \left( 3.92 \times 10^{24} \text{ m}^{-3} \right) \exp \left[ \frac{(-0.66 \text{ eV})}{0.026 \text{ eV}} \right]
\]

\[
n_i^2 = 3.89 \times 10^{38} \text{ m}^{-6}
\]
\[ n_i^2 = 3.89 \times 10^{38} \, m^{-6} \]

\[ p = \frac{n_i^2}{n} = \frac{3.89 \times 10^{38} \, m^{-6}}{2 \times 10^{22} \, m^{-3}} = 1.95 \times 10^{16} \, m^{-3} \]

\[ \sigma = e \left( p \mu_h + n \mu_e \right) \]

\[ \sigma = 1.602 \times 10^{-19} \, C \left[ \left( 1.95 \times 10^{16} \, m^{-3} \right) \left( 0.19 \, m^2 V^{-1} s^{-1} \right) + \left( 2 \times 10^{22} \, m^{-3} \right) \left( 0.39 \, m^2 V^{-1} s^{-1} \right) \right] \]

\[ \sigma = 1249 \, ohm^{-1} \, m^{-1} \]

\[ \rho = \frac{1}{\sigma} = \frac{1}{1249 \, ohm^{-1} \, m^{-1}} = 8 \times 10^{-4} \, ohm - m \]

\[ E_F = E_i + kT \ln \left( \frac{n}{n_i} \right) = E_c - \frac{E_g}{2} + kT \ln \left( \frac{n}{n_i} \right) \]

\[ E_c - E_F = 3kT = \frac{E_g}{2} - kT \ln \left( \frac{n}{n_i} \right) \]

\[ kT \left( 3 + \ln \left( \frac{n}{n_i} \right) \right) = \frac{E_g}{2} \]
Solutions to Problem 4 (Continued)

\[ kT \left( 3 + \ln \left( \frac{n}{n_i} \right) \right) = \frac{E_g}{2} \]

\[ T = \frac{E_g}{2k \left( 3 + \ln \left( \frac{n}{n_i} \right) \right) / \left( 8.62 \times 10^{-5} \text{ eV K}^{-1} \right)} \]

\[ T = 386 \text{ K} \]

\[ T = \frac{0.66 \text{ eV}}{2} \]

\[ T = \frac{0.66 \text{ eV}}{2 \left( \frac{2 \times 10^{22} \text{ m}^{-3}}{1.97 \times 10^{19} \text{ m}^{-3}} \right)} \]

\[ T = \frac{0.66 \text{ eV}}{2 \left( \frac{2 \times 10^{22} \text{ m}^{-3}}{1.97 \times 10^{19} \text{ m}^{-3}} \right)} \]

\[ T = 386 \text{ K} \]