Material Properties and Characterization

Exercise 1: Electrical Properties I

September 23, 2008

1 Material Classification

The enormous variation in electrical conductivity of insulators, semiconductors and metals as shown in Figure 1 may be explained qualitatively in terms of their energy bands: The electron occupation of the highest band or the highest two bands determines the conductivity of a solid. Figure 2 shows the energy band diagrams of the classes of solids.

Tasks

- Explain the meaning of conduction band and valence band in your own words.
- Figure 2 shows typical energy band diagrams for semiconductors, insulators and metals. Which picture (a, b, c) belongs to which material class?
- Give an explanation why the band gap energy is an important quantity to qualify electrical conductivity.
Figure 2: Schematic energy band representation of different material classes (semiconductor, insulator, metal).

Figure 3: Intrinsic carrier densities in Si and GaAs as a function of the reciprocal of temperature.

2 Intrinsic Carrier Density

The intrinsic carrier density $n_i$ of a semiconductor is defined as

$$n_i^2 = np = N_C N_V \exp\left(-\frac{E_g}{kT}\right)$$  \hspace{1cm} (1)
where $N_C$ and $N_V$ denote the effective density of states in the conduction and valence band, respectively. $E_g$ denotes the band gap energy, $T$ the temperature and $k = 1.38066 \times 10^{-23} \text{ J/K} = 8.617385 \times 10^{-5} \text{ eV/K}$ is the Boltzmann constant.

The effective density of states for the typical semiconductors Silicon and GaAs are

\begin{align*}
N_C^{Si} &= 2.86e19 \text{ cm}^{-3}, \quad N_V^{Si} = 2.66e19 \text{ cm}^{-3} \\
N_C^{GaAs} &= 4.70e17 \text{ cm}^{-3}, \quad N_V^{GaAs} = 7.00e18 \text{ cm}^{-3}
\end{align*}

and the band gap energies at $T = 300 \text{ K}$ are

\begin{align*}
E_g^{Si} &= 1.12 \text{ eV} \\
E_g^{GaAs} &= 1.42 \text{ eV}
\end{align*}

Tasks

- Calculate the intrinsic densities for Si and GaAs at $T = 300 \text{ K}$ and compare the results to Figure 3. Are you close to the result?
- Calculate the intrinsic densities for Si and GaAs at $T = 373 \text{ K}$ and compare the results to Figure 3. The differences should be bigger. Can you explain the differences?

3 Extrinsic Semiconductors

When a semiconductor is doped with impurities, the semiconductor becomes extrinsic and impurity energy levels are introduced. For shallow donors, there is usually enough thermal energy to ionize all donor impurities at room temperature and thus provide the same numbers of electrons in the conduction band:

\[ n = N_D \]  \hspace{1cm} (6)

Similarly, for shallow acceptors, the concentration of holes in the valence band is given by

\[ p = N_A \]  \hspace{1cm} (7)

The electron and hole densities can further be related to the intrinsic carrier density $n_i$ and the intrinsic Fermi $E_i$ level (which is in the middle of the band gap):

\begin{align*}
    n &= n_i \exp \left[ (E_F - E_i)/kT \right] \\
p &= n_i \exp \left[ (E_i - E_F)/kT \right]
\end{align*}

Note that the product of $n$ and $p$ equals $n_i^2$.

Tasks
Figure 4: Schematic energy band diagram of an n-doped semiconductor. $E_D$ denotes the impurity-induced energy level.

- A silicon ingot is doped with $1\text{e}^{16}$ arsenic atoms/cm$^3$ (n-doped). Find the carrier concentrations $n, p$ and the Fermi level $E_F$ at $T = 300$ K. Then evaluate the Fermi distribution at the energy $E = E_D$. Explain the meaning of your result.

- Assume that the silicon is doped with $1\text{e}^{17}$ boron atoms/cm$^3$ (p-doped). Find the carrier concentrations $n, p$ and the Fermi level $E_F$ at $T = 300$ K.

4 Effective Mass

In figure 5 the conduction band valley of material A and B is shown.

Figure 5: Conduction band valley of material A and B.

Tasks

- Calculate the effective electron mass of material A and B.