Serie 01 - Solution

Preamble

1.1 Dopant ionization

As seen during the course, the number of holes p_0 and electrons n_0 in a semiconductor are at equilibrium. Most of the interesting effects of the semiconductor arise from the carrier concentration gradient. To change the carrier concentration, we use dopants, which are atoms that are similar in size to the atoms in the semiconductor. Therefore, they can easily substitute them without significantly altering the lattice. Dopants have the ability to more easily give or capture electrons. We refer to this phenomenon of giving or taking electrons as dopant ionization. This phenomenon is temperature-dependent (more information on it in the next series). An approximation that is commonly made, and considered to be true in this course unless specifically denied, is that at room temperature all dopants are ionized.

For example, boron (B) is commonly used as an acceptor dopant in silicon (Si). At low temperatures, the acceptor atoms are not ionized and do not capture any electrons. As the temperature increases, the probability of the acceptor atom capturing an electron also increases. When this happens, the acceptor atom becomes negatively charged as it gets ionized, creating a hole in the valence band that carries a positive charge. This process maintains the overall neutrality of the semiconductor.

An analogous reasoning can be applied to donors. If the doping level or doping concentration of acceptors is denoted as N_a in $\left[cm^{-3}\right]$, the concentration of ionized acceptors is denoted as N_a^-, also in $\left[cm^{-3}\right]$. Similarly, the doping level for donors is denoted as N_d, and the concentration of ionized donors is denoted as N_d^+. Therefore, at room temperature, it is often stated:

$$N_a^- = N_a \qquad \& \qquad N_d^+ = N_d \tag{1}$$

As explained, the doping ionization phenomenon does not alter the overall neutrality of the semiconductor. Therefore, the charge neutrality equation can be written as:

$$\sum Q = p_o + N_d^+ - n_0 - N_a^- = 0 \tag{2}$$

Given constants

$k = 1.3806504 \cdot 10^{-23}\,[J/K]$
$q = 1.6021765 \cdot 10^{-19}\,[C]$

Exercise 01

Calculate the carrier concentration at thermal equilibrium in an n-type semiconductor at $T = 300\,[K]$ doped with $N_d = 10^{16}\,\left[cm^{-3}\right]$. The intrinsic carrier concentration in this semiconductor is $n_i = 1.5 \cdot 10^{10}\,\left[cm^{-3}\right]$.

Exercise 02

Calculate the carrier concentration at thermal equilibrium in a compensated p-type semiconductor at $T = 300\,[K]$ doped with $N_d = 3 \cdot 10^{15}\,\left[cm^{-3}\right]$ and $N_a = 10^{16}\,\left[cm^{-3}\right]$. The intrinsic carrier concentration in this semiconductor is $n_i = 1.5 \cdot 10^{10}\,\left[cm^{-3}\right]$.

Exercise 03

Consider a GaAs semiconductor sample with an intrinsic carrier concentration of $n_i = 2.14 \cdot 10^{6}\,\left[cm^{-3}\right]$ at a temperature of $T = 300\,[K]$. The sample is doped with a donor concentration of $N_d = 10^{16}\,\left[cm^{-3}\right]$ and no acceptors $N_a = 0\,\left[cm^{-3}\right]$. The electron mobility is $\mu_n = 8500\left[\frac{cm^2}{Vs}\right]$, and the hole mobility is $\mu_p = 400\left[\frac{cm^2}{Vs}\right]$. Calculate the drift current density for an applied electric field of $E = 10\left[\frac{V}{cm}\right]$.

Exercise 04

Consider a silicon-based semiconductor bar with a rectangular cross-section at $T = 300\,[K]$ and a doping concentration of $N_d = 5 \cdot 10^{15}\,\left[cm^{-3}\right]$. We aim to convert this semiconductor bar into a p-type semiconductor by introducing a doping concentration N_a. The resulting semiconductor bar exhibits a resistance of $R = 10\,[k\Omega]$ and a current density of $J = 50\left[\frac{A}{cm^2}\right]$ when a voltage of $V = 5\,[V]$ is applied across the bar, generating an electric field of $E = 100\left[\frac{V}{cm}\right]$ within it.

- Find the length L and the area A of the bar.
- Find the doping concentration N_a.

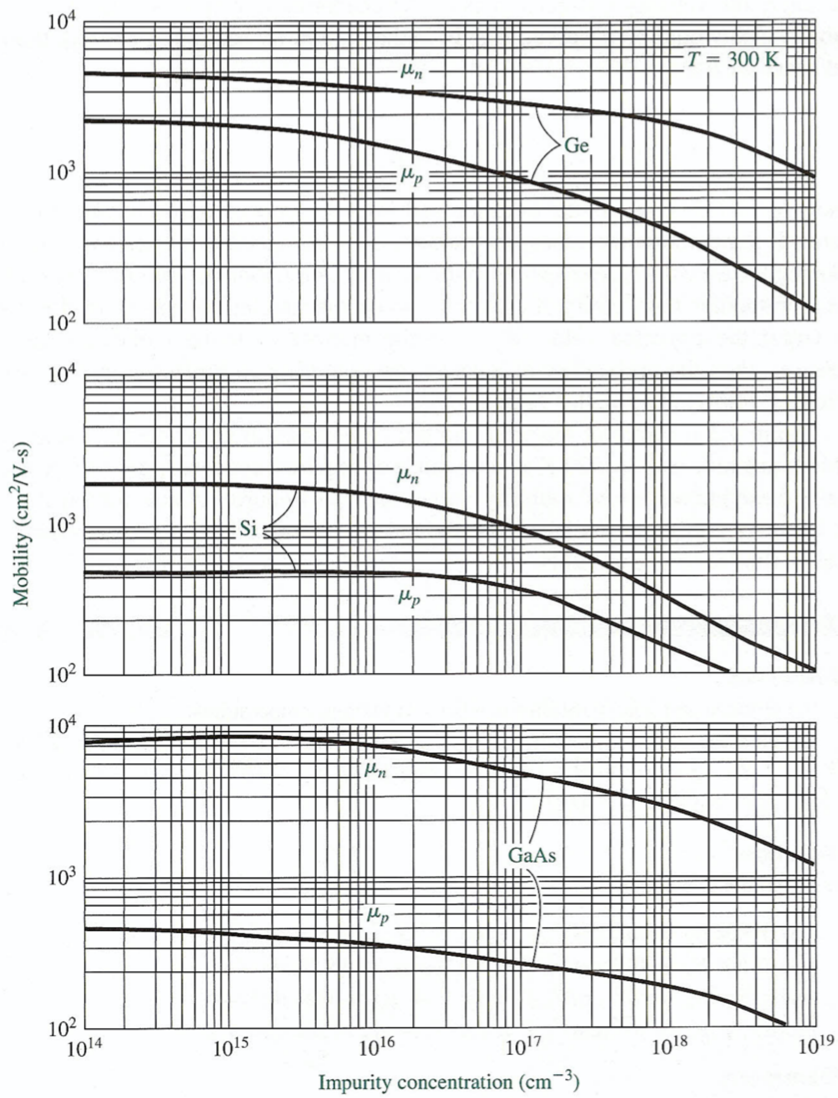

Figure 1: Electron and hole mobilities versus impurity concentrations for germanium, silicon, and gallium arsenide at $T = 300\,[K]$.