VE320 Intro to Semiconductor Devices
Summer 2022 — Problem Set 3

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Exercise 3.1

The thermal equilibrium hole concentration in silicon at $T = 300$ K is $p_0 = 2\times10^5$ cm^{-3}. Determine the thermal-equilibrium electron concentration. Is the material n type or p type?

Answer:

$$n_o = \frac{n_i^2}{p_o} = \frac{\left(1.5\times10^{10}\right)^2}{2\times10^5} = 1.125\times10^{15}\ \mathrm{cm}^{-3}$$
$$n_o > p_o \Rightarrow \text{ n-type}$$

Exercise 3.2

In silicon at $T = 300$ K, it is found that $N_a = 7\times10^{15}$ cm^{-3} and $p_0 = 2\times10^4$ cm^{-3}.
(a) Is the material n type or p type?
(b) What are the majority and minority carrier concentrations?
(c) What must be the concentration of donor impurities?

Answer:
(a) $p_o << n_i \Rightarrow$ n-type
(b) $p_o = \frac{n_i^2}{n_o} \Rightarrow n_o = \frac{n_i^2}{p_o}\ n_o = \frac{\left(1.5\times10^{10}\right)^2}{2\times10^4} = 1.125\times10^{16}$ cm^{-3}
$\Rightarrow$ electrons are majority carriers
$p_o = 2\times10^4$ cm^{-3}
$\Rightarrow$ holes are minority carriers
(c) $n_o = N_d - N_a$ $1.125\times10^{16} = N_d - 7\times10^{15}$ so $N_d = 1.825\times10^{16}$ cm^{-3}

Exercise 3.3

A silicon device is doped with donor impurity atoms at a concentration of 10^{15} 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 $T = 300$ 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?

Answer:

(a)

$$n_o = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}$$

$$n_o = 1.05 N_d = 1.05 \times 10^{15} \text{ cm}^{-3}$$

$$\left(1.05 \times 10^{15} - 0.5 \times 10^{15}\right)^2 = \left(0.5 \times 10^{15}\right)^2 + n_i^2$$

so $n_i^2 = 5.25 \times 10^{28}$ Now

$$n_i^2 = \left(2.8 \times 10^{19}\right)\left(1.04 \times 10^{19}\right)\left(\frac{T}{300}\right)^3 \times \exp\left[\frac{-1.12}{(0.0259)(T/300)}\right]$$

$$5.25 \times 10^{28} = \left(2.912 \times 10^{38}\right)\left(\frac{T}{300}\right)^3 \times \exp\left[\frac{-12972.973}{T}\right]$$

By trial and error, $T = 536.5$ K

(b) At $T = 300$ K,

$$E_c - E_F = kT \ln\left(\frac{N_c}{n_o}\right)$$

$$E_c - E_F = (0.0259) \ln\left(\frac{2.8 \times 10^{19}}{10^{15}}\right) = 0.2652 \text{eV}$$

At $T = 536.5$ K,

$$kT = (0.0259)\left(\frac{536.5}{300}\right) = 0.046318 \text{eV}$$

$$N_c = \left(2.8 \times 10^{19}\right)\left(\frac{536.5}{300}\right)^{3/2} = 6.696 \times 10^{19} \text{ cm}^{-3}$$

$$E_c - E_F = kT \ln\left(\frac{N_c}{n_o}\right)$$

$$E_c - E_F = (0.046318)\ln\left(\frac{6.696\times10^{19}}{1.05\times10^{15}}\right)$$

$$= 0.5124\text{eV}$$

then $\Delta\left(E_c - E_F\right) = 0.2472\text{eV}$

(c) Closer to the intrinsic energy level.

Exercise 3.4

Silicon is doped at $N_d = 10^{15}$ cm^{-3} and $N_a = 0$.

(a) Plot the concentration of electrons versus temperature over the range $300 \le T \le 600$ K.

(b) Calculate the temperature at which the electron concentration is equal to 1.1×10^{15} cm^{-3}.

Answer:

(a) WIP

(b) $n = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}$ Then

$$1.1\times10^{15} = 5\times10^{14} + \sqrt{\left(5\times10^{14}\right)^2 + n_i^2}$$

which yields

$$n_i^2 = 1.1\times10^{29}$$

Now

$$n_i^2 = N_c N_v \exp\left(\frac{-E_g}{kT}\right)$$

$1.1\times10^{29} = \left(2.8\times10^{19}\right)\left(1.04\times10^{19}\right)\left(\frac{T}{300}\right)^3$

$$\times\exp\left[\frac{-1.12}{(0.0259)(T/300)}\right]$$

By trial and error,

$$T \cong 552\text{ K}$$

Exercise 3.5

GaAs at $T = 300$ K is doped with donor impurity atoms at a concentration of 7×10^{15} cm^{-3}. Additional impurity atoms are to be added such that the Fermi level is 0.55eV above the intrinsic Fermi level. Determine the type (donor or acceptor) and concentration of impurity atoms to be added.

Answer:

$$
\begin{aligned}
n_o &= n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right] \\
&= \left(1.8 \times 10^6\right) \exp\left[\frac{0.55}{0.0259}\right] \\
&= 3.0 \times 10^{15} \text{ cm}^{-3}
\end{aligned}
$$

Add additional acceptor impurities

$$
\begin{aligned}
n_o &= N_d - N_a \\
3 \times 10^{15} &= 7 \times 10^{15} - N_a \\
\Rightarrow N_a &= 4 \times 10^{15} \text{ cm}^{-3}
\end{aligned}
$$

Exercise 3.6

A compensated p-type silicon material at $T = 300$ K has impurity doping concentrations of $N_a = 2.8 \times 10^{17}$ cm^{-3} and $N_d = 8 \times 10^{16}$ cm^{-3}. Determine the

(a) hole mobility
(b) conductivity
(c) resistivity

Answer:

(a) For $N_I = N_a + N_d = 2.8 \times 10^{17} + 8 \times 10^{16} = 3.6 \times 10^{17}$ cm^{-3}, $\Rightarrow \mu_p = 200$ cm^2/V $\cdot$ s
(b) $\sigma = e\mu_p \left(N_a - N_d\right)$

$$
= \left(1.6 \times 10^{-19}\right)(200)\left(2 \times 10^{17}\right)
$$

$$
\sigma = 6.4(\Omega \cdot \text{cm})^{-1}
$$

(c) $\rho = \frac{1}{\sigma} = \frac{1}{6.4} = 0.156\Omega \cdot \text{cm}$

Exercise 3.7

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

$$
\begin{aligned}
N_c &= 2 \times 10^{19}(T/300)^{3/2} \text{ cm}^{-3} \\
N_v &= 1 \times 10^{19}(T/300)^{3/2} \text{ cm}^{-3} \\
E_g &= 1.10\text{eV}
\end{aligned}
$$

(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.)

Answer:

(a) $n_i^2 = N_c N_v \exp\left(\frac{-E_g}{kT}\right)$

$$
= \left(2 \times 10^{19}\right)\left(1 \times 10^{19}\right) \exp\left(\frac{-1.10}{0.0259}\right)
$$

$$= 7.18 \times 10^{19}$$

or

$$n_i = 8.47 \times 10^9 \text{ cm}^{-3}$$

For $N_d = 10^{14}$ cm^{-3} $>> n_i \Rightarrow n_o = 10^{14}$ cm^{-3} Then

$$\begin{aligned} J &= \sigma \text{E} = e\mu_n n_o \text{E} \\ &= \left(1.6 \times 10^{-19}\right)(1000)\left(10^{14}\right)(100) \end{aligned}$$

or

$$J = 1.60 \text{ A/cm}^2$$

(b) A 5% increase is due to a 5% increase in electron concentration, so

$$n_o = 1.05 \times 10^{14} = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}$$

which becomes

$$\left(1.05 \times 10^{14} - 5 \times 10^{13}\right)^2 = \left(5 \times 10^{13}\right)^2 + n_i^2$$

and yields

$$\begin{aligned} n_i^2 &= 5.25 \times 10^{26} \\ &= \left(2 \times 10^{19}\right)\left(1 \times 10^{19}\right)\left(\frac{T}{300}\right)^3 \exp\left(\frac{-E_g}{kT}\right) \end{aligned}$$

or

$$2.625 \times 10^{-12} = \left(\frac{T}{300}\right)^3 \exp\left[\frac{-1.10}{(0.0259)(T/300)}\right]$$

By trial and error, we find

$$T = 456 \text{ K}$$

Reference

1. Neamen, Donald A. Semiconductor physics and devices: basic principles. McGraw-hill, 2003.