VE320 Intro to Semiconductor Devices
Summer 2024 — Problem Set 3
Due: 11:59pm 12th June

10' 1) Explain the physical meaning of the Fermi energy level.

15' 2) A silicon piece at $\mathrm{T} = 300\mathrm{K}$ has $N_a = 7 \times 10^{14} cm^{-3}$ and $p_0 = 2 \times 10^5 cm^{-3}$

5' a) Is the material n type or p type?

5' b) What are the majority and minority carrier concentrations?

5' c) What must be the concentration of donor impurities?

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

10' a) Plot the concentration of electrons versus temperature over the range $200\mathrm{K} \leq \mathrm{T} \leq 600\mathrm{K}$. (qualitatively)

10' b) For the device to operate properly, the intrinsic carriers must contribute no more than 5 percent to the total electron concentration. Calculate the maximum temperature it can work out.

20' 4) The magnitude of the product $g_c(E) f_F(E)$ in the conduction band is a function of energy. Assume the Boltzmann approximation is valid.

10' a) Determine the energy with respect to E_c at which the maximum occurs.

10' b) Repeat part a) for the magnitude of the product $g_v(E)[1 - f_F(E)]$ in the valence band.

15' 5) For a particular semiconductor, $E_g = 1.50eV$, $m_p^* = 10m_n^*$, $\mathrm{T} = 300\mathrm{K}$, and $n_i = 1 \times 10^5 cm^{-3}$.

5' a) Determine the position of the intrinsic Fermi energy level with respect to the center of the bandgap.

10' b) Impurity atoms are added so that the Fermi energy level is 0.45eV below the center of the bandgap. Assume complete ionization.

5' i) Are acceptor or donor atoms added?

5' ii) What is the concentration of impurity atoms added?

10' 6) A particular semiconductor material is doped at $N_d = 2 \times 10^{14} cm^{-3}$, and $N_a = 1.2 \times 10^{14} cm^{-3}$. The thermal equilibrium electron concentration is found to be $n_0 = 1.1 \times 10^{14} cm^{-3}$. Assuming complete ionization, determine:

5' a) the intrinsic carrier concentration

5' b) the thermal equilibrium hole concentration

10' 7)

5' a) What is meant by complete ionization?

5' b) What is meant by freeze-out?

1) Chapter 3, slide 66: At equilibrium, when an electron is added to the system, the change of the the system energy 5'

energy level that probability that a quantum state at energy E_F is occupied by an electron is $1/2$. } also okay

also, it's the highest occupied energy level of electrons at 0K.

2) a) $n_0 = \frac{n_i^2}{p_0} = \frac{(1.5\times10^{10})^2}{2\times10^5} = 1.125\times10^{15}\ cm^{-3}$

$n_0 \gg p_0 \Rightarrow$ n type 5'

b) majority: electron, $n_0 = 1.125\times10^{15}\ cm^{-3}$ 5'

minority: hole, $p_0 = 2\times10^5\ cm^{-3}$

c) $N_d = N_a + n_0 = 7\times10^{14} + 1.125\times10^{15} = 1.825\times10^{15}\ cm^{-3}$ 5'

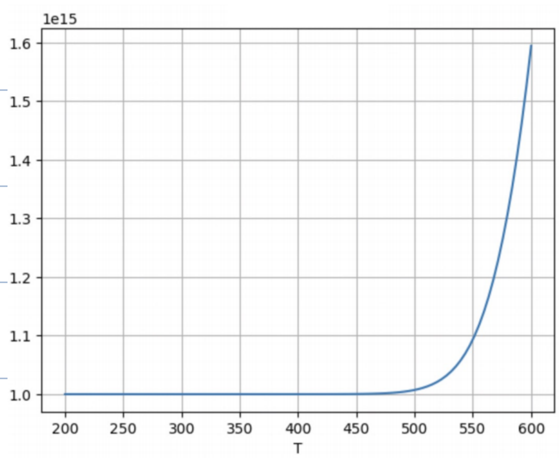
3) a) $n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d-N_a}{2}\right)^2 + n_i^2}$

$= \frac{10^{15}}{2} + \sqrt{\left(\frac{10^{15}}{2}\right)^2 + 4\cdot\frac{(2\pi m_n^* kT)^{3/2}}{h^3}\cdot\frac{(2\pi m_p^* kT)^{3/2}}{h^3}\cdot \exp\left(-\frac{E_g}{2kT}\right)}$

$= 5\times10^{14} + \sqrt{2.5\times10^{29} + 1.0785\times10^{31}\,T^3 \exp(-12973/T)}$

$T = 200K,\ n_0 = 1\times10^{15}\ cm^{-3}$

$T = 600K,\ n_0 = 1.595\times10^{15}\ cm^{-3}$



10'

b) $n_0 = 1.05 N_d$ 5'

$1.05\times10^{15} - 5\times10^{14} = \sqrt{2.5\times10^{29} + n_i^2} \Rightarrow n_i^2 = 5.25\times10^{28}$

$5.25\times10^{28} = (2.8\times10^{19})\times(1.04\times10^{19})\times\left(\frac{T}{300}\right)^3\times\exp\left(-\frac{1.12}{0.0259\times T\div300}\right)$ trial and error

$T = 536.5K$ 5' (10% error is acceptable)

4) a) $g_c(E) f_F(E) \propto \sqrt{E-E_c}\, \exp\left(-\frac{(E-E_F)}{kT}\right) = \sqrt{E-E_c} \cdot \exp\left(-\frac{(E-E_c)}{kT}\right) \cdot \exp\left(-\frac{(E_c-E_F)}{kT}\right)$

let $E-E_c = x$

$g_c f_F \propto \sqrt{x}\, \exp\left(\frac{-x}{kT}\right)$

$\frac{d(g_c f_F)}{dx} = 0$, $\frac{d(g_c f_F)}{dx} \propto \frac{1}{2} x^{-\frac{1}{2}} \exp\left(\frac{-x}{kT}\right) - \frac{1}{kT} x^{\frac{1}{2}} \exp\left(-\frac{x}{kT}\right)$ 5'

$x = \frac{kT}{2} \Rightarrow E = E_c + \frac{kT}{2}$ 5'

b) $g_v(E)(1-f_F(E)) \propto \sqrt{E_v-E}\, \exp\left(-\frac{(E_F-E)}{kT}\right) = \sqrt{E_v-E} \cdot \exp\left(-\frac{(E_v-E)}{kT}\right) \cdot \exp\left(-\frac{(E_F-E_v)}{kT}\right)$

let $E_v - E = x$

$g_v(1-f_F) \propto \sqrt{x}\, \exp\left(\frac{-x}{kT}\right)$

$\frac{d(g_v(1-f_F))}{dx} = 0$, $\frac{d(g_v(1-f_F))}{dx} \propto \frac{1}{2} x^{-\frac{1}{2}} \exp\left(\frac{-x}{kT}\right) - \frac{1}{kT} x^{\frac{1}{2}} \exp\left(-\frac{x}{kT}\right)$ 5'

$x = \frac{kT}{2} \Rightarrow E = E_v - \frac{kT}{2}$ 5'

5) a) $E_{Fi} - E_{midgap} = \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right)$

$= \frac{3}{4} \times 0.0259 \times \ln 10$

$= 0.0447\ eV$ 5'

b) i) acceptor 5'

ii) $E_{Fi} - E_F = 0.0447 + 0.45 = 0.4947\ eV$

$p_0 = n_i \exp\left(\frac{E_{Fi}-E_F}{kT}\right)$

$= 10^5 \times \exp\left(\frac{0.4947}{0.0259}\right)$

$p_0 = N_a = 1.97 \times 10^{13}\ cm^{-3}$ 5'

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

$1.1\times10^{14} = \frac{2\times10^{14} - 1.2\times10^{14}}{2} + \sqrt{\left(\frac{2\times10^{14} - 1.2\times10^{14}}{2}\right)^2 + n_i^2}$

$n_i = 5.74\times10^{13}\ cm^{-3}$ 5'

b) $p_o = \frac{n_i^2}{n_o} = \frac{3.3\times10^{27}}{1.1\times10^{14}} = 3\times10^{13}\ cm^{-3}$ 5'

7) complete ionization: impurity atoms all ionized $\Rightarrow N_d^+ = N_d,\ N_a^- = N_a$ 5'

freeze out: no ionized impurity atoms $\Rightarrow N_d^+ = 0,\ N_a^- = 0$ 5'