Homework 4

Wednesday, October 6, 2021 10:19 AM

"I pledge my honor I have abided by the Stevens Honor system."

- Alex Dawkins

6.1 Consider silicon at $T = 300$ K that is doped with donor impurity atoms to a concentration of $N_d = 5 \times 10^{15}$ cm^{-3}. The excess carrier lifetime is 2×10^{-7}s. (*a*) Determine the thermal equilibrium recombination rate of holes. (*b*) Excess carriers are generated such that $\delta n = \delta p = 10^{14}$ cm^{-3}. What is the recombination rate of holes for this condition?

$n_i = 1.5 \times 10^{10}/\text{cm}^3 \qquad N_d = 5 \times 10^{15}/\text{cm}^3$

a.) $n = \dfrac{(1.5\times10^{10})^2}{5\times10^{15}} = 45000$

$R_{po} = \dfrac{p_o}{\tau} = \dfrac{45000}{2\times10^{-7}}$

$\boxed{R_{po} = 2.25\times10^{11}/\text{cm}^3\cdot\text{s}}$

b.) $R = \dfrac{(N_d + p_o)}{\tau_{po} N_d}\Delta p = \dfrac{(5\times10^{15} + 45000)}{(2\times10^{-7})(5\times10^{15})}(10^{14})$

$\boxed{R = 5\times10^{20}/\text{cm}^3\cdot\text{s}}$

6.10 Germanium at $T = 300$ K is uniformly doped with donor impurity atoms to a concentration of 4×10^{13} cm^{-3}. The excess carrier lifetime is found to be $\tau_{p0} = 2 \times 10^{-6}$ s. (*a*) Determine the ambipolar (*i*) diffusion coefficient and (*ii*) mobility. (*b*) Find the electron and hole lifetimes.

$n = \dfrac{N_d}{2} + \sqrt{\left(\dfrac{N_d}{2}\right)^2 + n_i^2} = \dfrac{4\times10^{13}}{2} + \sqrt{\left(\dfrac{4\times10^{13}}{2}\right)^2 + (2.4\times10^{13})^2} = 5.124\times10^{13}/\text{cm}^3$

$p = \dfrac{n_i^2}{n} = \dfrac{(2.4\times10^{13})^2}{5.124\times10^{13}}$

$p = 1.124\times10^{13}/\text{cm}^3$

a.) [i] $\dfrac{\mu_n}{D_n} = \dfrac{e}{kT} \qquad D_n = (0.0259)(3900) = 101.01\,\text{cm}^2/\text{s} \qquad \dfrac{\mu_p}{D_p} = \dfrac{e}{kT} \qquad D_p = (0.0259)(1900) = 49.21\,\text{cm}^2/\text{s}$

$D' = \dfrac{D_n D_p (n+p)}{D_n n + D_p p} = \dfrac{(101.01)(49.21)(5.124\times10^{13} + 1.124\times10^{13})}{(101.01)(5.124\times10^{13}) + (49.21)(1.124\times10^{13})} = \boxed{54.21\,\text{cm}^2/\text{s}}$

[ii] $\mu' = \dfrac{\mu_n\mu_p(p-n)}{\mu_n n + \mu_p p} = \dfrac{(3900)(1900)(1.124\times10^{13} - 5.124\times10^{13})}{(3900)(5.124\times10^{13}) + (1900)(1.124\times10^{13})} = \boxed{-1340.01\,\text{cm}^2/\text{V}\cdot\text{s}}$

b.) Excess carrier lifetime = hole lifetime = $\tau_{po} = \boxed{2\times10^{-6}\,\text{s}}$

$\dfrac{n}{\tau_{no}} = \dfrac{p}{\tau_{po}}$

$\dfrac{5.124\times10^{13}}{\tau_{no}} = \dfrac{1.124\times10^{13}}{2\times10^{-6}}$

$\tau_{no} = \boxed{9.12\times10^{-6}\,\text{s}}$

electron lifetime

6.13 An n-type GaAs semiconductor at $T = 300$ K is uniformly doped at $N_d = 5 \times 10^{15}$ cm^{-3}. The minority carrier lifetime is $\tau_{p0} = 5 \times 10^{-8}$ s. Assume mobility values of $\mu_n = 7500$ cm^2/V-s and $\mu_p = 310$ cm^2/V-s. A light source is turned on at $t = 0$ generating excess carriers uniformly at a rate of $g' = 4 \times 10^{21}$ cm^{-3} s^{-1} and turns off at $t = 10^{-6}$ s.
(*a*) Determine the excess carrier concentrations versus time over the range $0 \le t \le \infty$.
(*b*) Calculate the conductivity of the semiconductor versus time over the same time period as part (*a*).

a.) For t: $0 \le t \le 10^{-6}$

$$\Delta p = g' \tau_{p0}\left[1 - \exp\left(\frac{-t}{\tau_{p0}}\right)\right] = (4 \times 10^{21})(5 \times 10^{-8})\left(1 - e^{-\left(\frac{t}{5\times10^{-8}}\right)}\right)$$

$$\Delta p = (2 \times 10^{14})\left(1 - e^{-\left(\frac{t}{5\times10^{-8}}\right)}\right)$$

For $t > 10^{-6}$:

$$\Delta p = g' \tau_{p0}\left[\exp\left(-\frac{t}{\tau_{p0}}\right)\right] = (4 \times 10^{21})(5 \times 10^{-8})\left(e^{-\left(\frac{t}{5\times10^{-8}}\right)}\right)$$

$$\Delta p = (2 \times 10^{14})\left(e^{-\left(\frac{t}{5\times10^{-8}}\right)}\right)$$

$$\boxed{\Delta p = \begin{cases} (2\times10^{14})\left(1 - e^{-\left(\frac{t}{5\times10^{-8}}\right)}\right), & 0 \le t \le 10^{-6} \\ (2\times10^{14})\left(e^{-\left(\frac{t}{5\times10^{-8}}\right)}\right), & t > 10^{-6} \end{cases}}$$

b.) $\sigma_1 = e\mu_n N_d \quad \sigma_2 = e(\Delta n \mu_n + \Delta p \mu_p) \quad \sigma = \sigma_1 + \sigma_2$

$$\sigma = 1.6 \times 10^{-19}\left(7500(5 \times 10^{15}) + (7500 + 310)(2 \times 10^{14})\left(1 - e^{-\left(\frac{t}{5\times10^{-8}}\right)}\right)\right)$$

$$\boxed{\sigma = 6 + 0.25\left(1 - e^{-\left(\frac{t}{5\times10^{-8}}\right)}\right) / \Omega \cdot \text{cm}}$$

6.16 In a GaAs material at $T = 300$ K, the doping concentrations are $N_d = 8 \times 10^{15}$ cm^{-3} and $N_a = 2 \times 10^{15}$ cm^{-3}. The thermal equilibrium recombination rate is $R_o = 4 \times 10^4$ cm^{-3} s^{-1}. (*a*) What is the minority carrier lifetime? (*b*) A uniform generation rate for excess carriers results in an excess carrier recombination rate of $R' = 2 \times 10^{21}$ cm^{-3} s^{-1}. What is the steady-state excess carrier concentration? (*c*) What is the excess carrier lifetime?

$$n_o = N_d - N_a = 8 \times 10^{15} - 2 \times 10^{15} = 6 \times 10^{15} / \text{cm}^3$$

$$p_o = \frac{n_i^2}{n_o} = \frac{(1.8 \times 10^6)^2}{6 \times 10^{15}} = 5.4 \times 10^{-4} / \text{cm}^3$$

a.) $R_o = \frac{p_o}{\tau_{po}}$ $\quad \tau_{po} = \frac{p_o}{R_o} = \frac{5.4 \times 10^{-4}}{4 \times 10^4} = \boxed{1.35 \times 10^{-8}\ \text{s}}$

b.) $\Delta p = g' \tau_{po} = (2 \times 10^{21})(1.35 \times 10^{-8})$

$$\boxed{\Delta p = 2.7 \times 10^{13} / \text{cm}^3}$$

c.) Minority carrier lifetime = Excess carrier lifetime

$$\boxed{1.35 \times 10^{-8}\ \text{s}}$$

6.18 A semiconductor is uniformly doped with 10^{17} cm^{-3} acceptor atoms and has the following properties: $D_n = 27$ cm^2/s, $D_p = 12$ cm^2/s, $\tau_{n0} = 5 \times 10^{-7}$ s, and $\tau_{p0} = 10^{-7}$ s. An external source has been turned on for $t < 0$ producing a uniform concentration of excess carriers at a generation rate of $g' = 10^{21}$ cm^{-3} s^{-1}. The source turns off at time $t = 0$ and back on at time $t = 2 \times 10^{-6}$ s. (*a*) Derive the expressions for the excess carrier concentration as a function of time for $0 \le t \le \infty$. (*b*) Determine the value of excess carrier concentration at (*i*) $t = 0$, (*ii*) $t = 2 \times 10^{-6}$ s, and (*iii*) $t = \infty$. (*c*) Plot the excess carrier concentration as a function of time.

a.) $\Delta n = g' \tau_{no} \exp\left(\frac{-t}{\tau_{no}}\right) = (10^{4})(5\times10^{-7})e^{-t/\tau_{no}}$

$= (5\times10^{14})e^{\frac{-t}{\tau_{no}}}$

@ $t = 2\times10^{-6}$ s

$\Delta n_1 = (5\times10^{14})e^{\frac{-2\times10^{-6}}{5\times10^{-7}}} = 9.16\times10^{12}/cm^3$

$\Delta n = (5\times10^{14} - 9.16\times10^{12})\left[1-\exp\left(\frac{-t}{\tau_{no}}\right)\right] + 9.16\times10^{12}$

$$\boxed{\Delta n = (4.908\times10^{14})\left[1-\exp\left(\frac{-t}{\tau_{no}}\right)\right] + 9.16\times10^{12}\ /cm^3}$$

b.)

[i] $t = 0$ s

$\Delta n = (5\times10^{14})e^{\frac{-t}{\tau_{no}}} = (5\times10^{14})e^{\frac{0}{\tau_{no}}} = (5\times10^{14})/cm^3$

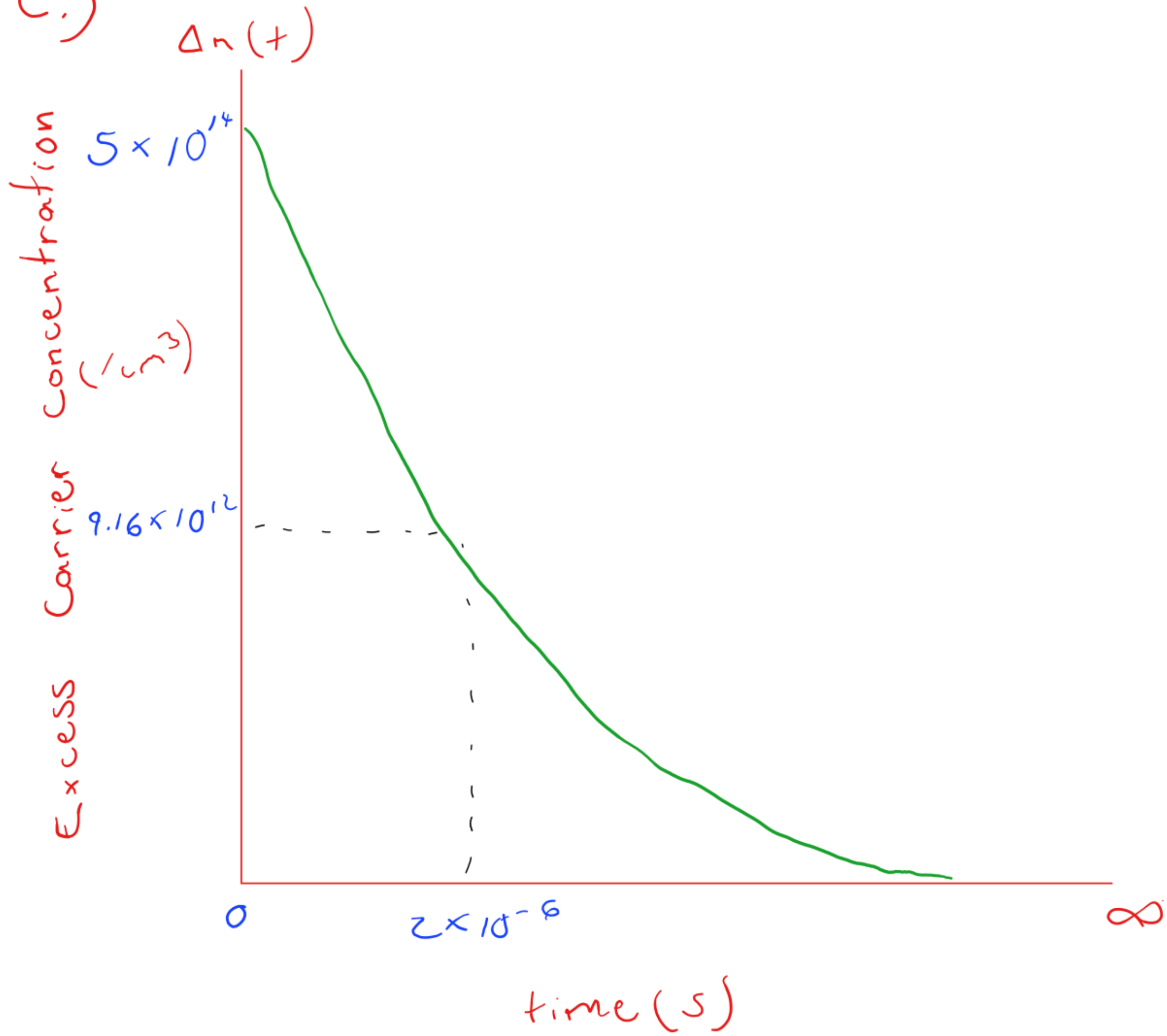
[ii] $t = 2\times10^{-6}$ s

$\Delta n = (5\times10^{14})e^{\frac{-2\times10^{-6}}{5\times10^{-7}}} = 9.16\times10^{12}/cm^3$

[iii] $t = \infty$

$\Delta n = (5\times10^{14})e^{\frac{\infty}{5\times10^{-7}}} = (5\times10^{14})/cm^3$

c.)



Δn(t)
5×10^14
9.16×10^12
Excess Carrier concentration (/cm3)
0
2×10^-6
∞
time(s)

6.30 An n-type silicon semiconductor, doped at $N_d = 4 \times 10^{16}$ cm^{-3}, is steadily illuminated such that $g' = 2 \times 10^{21}$ cm^{-3} s^{-1}. Assume $\tau_{n0} = 10^{-6}$ s and $\tau_{p0} = 5 \times 10^{-7}$ s.
(*a*) Determine the thermal-equilibrium value of $E_F - E_{Fi}$. (*b*) Calculate the quasi-Fermi levels for electrons and holes with respect to E_{Fi}. (*c*) What is the difference (in eV) between E_{Fn} and E_F ?

a.) $n_i = 1.5 \times 10^{10}$

$$E_F - E_{F_i} = kT\left[\ln\left(\frac{n_0}{n_i}\right)\right] = 0.259 \ln\left(\frac{4 \times 10^{16}}{1.5 \times 10^{10}}\right)$$

$$= \boxed{0.383225 \text{ eV}}$$

b.) $$\Delta n = g' \tau_{p0} = (2 \times 10^{21})(5 \times 10^{-7}) = 10^{15}/\text{cm}^3 \cdot \text{s}$$

Holes:

$$E_{F_i} - E_{F_p} = kT\left[\ln\left(\frac{p_0}{p_i}\right)\right] = 0.259 \ln\left(\frac{5.625 \times 10^{3} + 10^{15}}{1.5 \times 10^{10}}\right)$$

$$= \boxed{0.287680 \text{ eV}}$$

Electrons:

$$E_{F_n} - E_{F_i} = kT\left[\ln\left(\frac{n_0}{n_i}\right)\right] = 0.259 \ln\left(\frac{4 \times 10^{16} + 10^{15}}{1.5 \times 10^{10}}\right)$$

$$= \boxed{0.383865 \text{ eV}}$$

c.) $$E_{F_n} - E_F = (E_{F_n} - E_{F_i}) - (E_F - E_{F_i})$$

$$= 0.3838 - 0.3832 = \boxed{0.000640 \text{ eV}}$$