ECE 340: Semiconductor Electronics

Practice problems for chapter 1 to 4

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1. In an n-type silicon wafer ($N_d = 10^{17}$ cm^{-3}) illuminated uniformly with 10 mW/cm^2 of red light ($E_{ph} = 1.8$ eV). The absorption coefficient of red light in silicon is 10^{-3} cm^{-1}. The minority carrier lifetime is 10μs.

(a) Calculate the electron and hole densities
(b) Calculate the positions of the quasi-Fermi levels for the two carrier types and compare it to the Fermi energy in the absence of illumination.
(c) If the light was turned off at $t = 0$, find a formula for excess hole concentration $\delta p(t)$ for $t > 0$. Does low level injection condition satisfied in this case?

Solution:

1. (a) The generation rate of electrons and holes equals:

$$g_n = g_p = \alpha \frac{P_{opt}}{E_{ph} A} = 10^{-3} \frac{10^{-2}}{1.8 \times 1.6 \times 10^{-19}} = 3.5 \times 10^{13} cm^{-3} s^{-1}$$

where the photon energy was converted into Joules. The excess carrier densities are then obtained from:

$$\Delta n = \Delta p = g_p \tau_p = 3.5 \times 10^{13} \times 10 \times 10^{-6} = 3.5 \times 10^{8} cm^{-3}$$

So that the electron and hole densities equal:

$$n = n_0 + \Delta n = 10^{17} + 3.5 \times 10^{8} \approx 10^{17} cm^{-3}$$

$$p = p_0 + \Delta p = \frac{n_i^2}{n_0} + \Delta p = \frac{10^{20}}{10^{17}} + 3.5 \times 10^{8} \approx 3.5 \times 10^{8} cm^{-3}$$

(b) The quasi-Fermi energies are:

$$F_n - E_i = kTln\frac{n}{n_i} = 0.0259 \times ln\frac{10^{17}}{10^{10}} = 0.417eV$$

$$E_i - F_p = kTln\frac{p}{n_i} = 0.0259 \times ln\frac{3.5 \times 10^{8}}{10^{10}} = -0.086eV$$

In comparison, the Fermi energy in the absence of light equals

$$F_F - E_i = kTln\frac{n_0}{n_i} = 0.0259 \times ln\frac{10^{17}}{10^{10}} = 0.417eV$$

(c) Since Δn (or Δp) $\ll n_0 + p_0$, low-level injection condition is satisfied.

$$\delta p(t) = \Delta p e^{-t/\tau_p} = 3.5 \times 10^{8} e^{-t/10\mu s} cm^{-3}$$

2. Image at one end of a n-type silicon, all minority carriers are constantly swept out (i.e. p=0 at x=0), while the majority carrier remains the same. The doping concentration is 10^{15} cm^{-3}. The hole mobility is 1000 cm^2/V-s, $\tau_p = 1\mu s$, T=300K. For simplicity, assume KT/q=25mV at 300K.

(a) What is the excess hole concentration at x=0?
(b) Find the minority carrier concentration distribution p(x) and sketch p(x) vs x.
(c) At $x = 50\mu m$, calculate the hole diffusion current.

Solution:

(a) The excess hole concentration at x=0:

$$\Delta p = \mathrm{p} - p_0 = -p_0 = -\frac{n_i^2}{n_0} = -\frac{10^{20}}{10^{15}} = -10^5 cm^{-3}$$

(b) The diffusion coefficient $D_p = \frac{kT}{q}\mu_p = 0.025V * 1000cm^2V^{-1}s^{-1} = 25cm^2s^{-1}$

The diffusion length $L_p = \sqrt{D_p\tau_p} = \sqrt{25cm^2s^{-1} \times 1 \times 10^{-6}s} = 50\mu m$

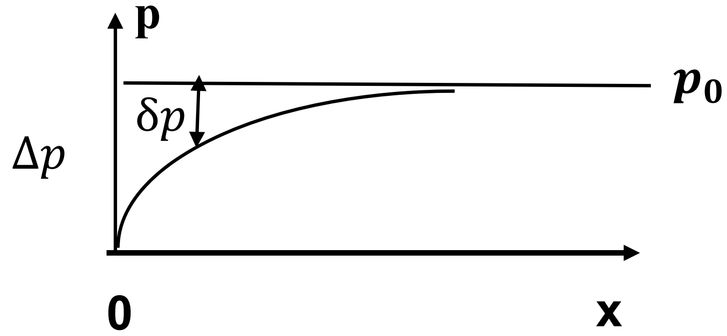
Excess hole concentration $\delta p = \Delta p e^{-x/L_p} = -10^5 cm^{-3} e^{-x/50\mu m}$

hole concentration $\mathrm{p} = p_0 + \delta p = 10^5 cm^{-3}(1\text{-}e^{-x/50\mu m})$

(c) At $\mathrm{x} = 50\mu m$ $\delta p = -10^5 cm^{-3} \times e^{-1} = 3.68 \times 10^4 cm^{-3}$

hole diffusion current

$$J_p = q\frac{D_p}{L_p}\delta p = -1.6 \times 10^{-19}C\,\frac{25cm^2s^{-1}}{5{\times}10^{-3}cm}\,3.68 \times 10^4 cm^{-3} = -2.9 \times 10^{-14}\mathrm{A}/cm^2$$



3. A silicon crystal is know to contain 10^{-4} atomic percent of arsenic (As) as an impurity. It then receives a uniform doping of $2\text{x}10^{16}$ phosphorus (P) atoms and a subsequent uniform doping of $1\text{x}10^{16}$ Gallium (Ga) atoms. A thermal annealing treatment then completely activates all impurities. (silicon has $5\text{x}10^{22}$ atoms cm^{-3}, intrinsic carrier concentration for silicon is $1.5\text{x}10^{10}$ cm^{-3})

(a) What is the conductivity type of this silicon sample?
(b) What is the electron and hole concentration?
(c) Find the location of the Fermi-level.

Solution:

(a) Because silicon has 5×10^{22} atoms cm^{-3} , 10^{-4} atomic percent implies that silicon is doped by As to a concentration of

$$N_{d1} = 5 \times 10^{22} \times 10^{-6} = 5 \times 10^{16}\ cm^{-3}$$

The added doping of P: $N_{d2} = 2 \times 10^{16}\ cm^{-3} \longrightarrow N_d = 7 \times 10^{16}\ cm^{-3}$

The added doping of Ga: $N_a = 1 \times 10^{16}\ cm^{-3}$

Hence the silicon is n type

(b) The electron concentration is $n = N_d - N_a = 6 \times 10^{16}\ cm^{-3}$

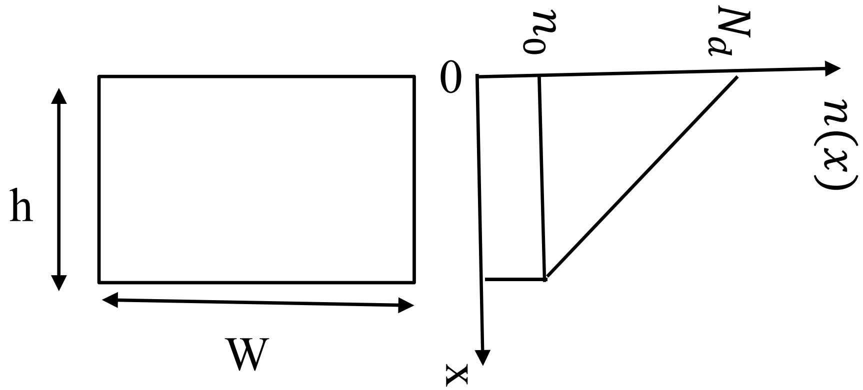
The hole concentration is

$$p = \frac{n_i^2}{n_0} = \frac{(1.5 \times 10^{10})^2}{6 \times 10^{16}} cm^{-3} = 3.5 \times 10^3 cm^{-3}$$

(c) The Fermi level position:

$$E_F - E_i = kTln\frac{n_0}{n_i} = 0.0259 \times ln\frac{6 \times 10^{16}}{1.5 \times 10^{10}} = 0.393eV$$

4. A n type silicon bar with height of h=100um, width W=1cm and length of L=10 cm, was doped by diffusion. The electron concentration profile is $n(x) = N_d\left(1 - \frac{x}{h}\right) + n_0$, where $N_d = 10^{15}$ cm^{-3}, $n_0 = 10^{13}$ cm^{-3}. Calculate the resistance of this bar along the length direction. Assume mobility is uniform μ_n=1000 cm^2/V-s.



$$\sigma = q\mu n = q\mu \frac{\int_0^h n(x)dx}{h} = q\mu(\frac{1}{2}N_d + n_0) \approx 0.08\ cm^{-1}\ \Omega^{-1}$$

$$\rho = \frac{1}{\sigma}$$

$$R = \rho \frac{L}{wh} = \frac{L}{wh\sigma} = 1.25 \times 10^4\ \Omega$$