Tutorial 2 Solar Energy 23.11.20

1) $D_n = 36 \frac{cm^2}{s}$ $\quad n = 2{,}7 \cdot 10^{16} cm^{3}$

$$J_{n\,diff} = q D_n \nabla_n n$$

$$\nabla n \, \nabla_n = \frac{dn}{dx} = \frac{2{,}7 \cdot 10^{16} cm^{-3} - 1 \cdot 10^{15} cm^{-3}}{2 \cdot 10^{-4} cm^{-1}} = 1{,}3 \cdot 10^{20} cm^{-4}$$

$$J_{n,diff} = q D_n \nabla n = 1{,}6 \cdot 10^{-19} \cdot 36 \cdot 1{,}3 \cdot 10^{20} = 749 A/cm^2$$

2) $\mu_n = 1350 \, cm^2 \, 1/V \, 1/s$

Elektric field

$$J_{n\,diff} = J_{n\,Drift} = q \cdot n \cdot \mu_n \, \xi$$

$$\xi = \frac{J_{n\,diff}}{q n \cdot \mu_n} = \frac{749}{1 \cdot 10^{15} \cdot 1{,}6 \cdot 10^{-19} \cdot 1350} = 3468 \, V/cm$$

3)

a) $N_D = \frac{1{,}5 \cdot 10^{13}}{10^3 cm^3} = 1{,}5 \cdot 10^{16} cm^{-3}$

Volleum

Number of phosphorous atoms per 1 million silicon atoms:

$$\frac{1{,}5 \cdot 10^{16} \, 1/cm^{3}}{5 \cdot 10^{22} \, 1/cm^{3}} \cdot 10^6 = 0{,}3 ppm$$

b) 1,1eV ← bandgap

intrinsic concentration

$$n_i^2 = np = N_c N_v \exp\left(-\frac{E_g q}{k_B T}\right)$$

$$n_i = \left[6{,}2 \cdot 10^{15} \cdot \sqrt[2]{300^3} \cdot 3{,}5 \cdot 10^{15} \cdot \sqrt[2]{300^3} \cdot \exp\left(-\frac{1{,}1 eV \cdot 1{,}602 \cdot 10^{-19}}{1{,}38 \cdot 10^{-23} \cdot 300 K}\right)\right]^{1/2} = 1{,}4 \cdot 10^{10} \, 1/cm^3$$

Because $N_D >> n_i$

$$n \approx N_D = 1{,}5 \cdot 10^{16} \, 1/cm^3$$

p

$$p = \frac{(n_i)^2}{n} = \frac{(1{,}4 \cdot 10^{10} \, 1/cm^3)^2}{1{,}5 \cdot 10^{16} \, 1/cm^3} = 1{,}3 \cdot 10^4 \, 1/cm^3$$

3)

c) $$E_F - E_c = -\frac{k_B T}{q}\ln\left(\frac{N_c}{N_D}\right) = -\frac{1{,}38\cdot 10^{-23}\cdot 300}{1{,}602\cdot 10^{-19}}\ln\left(\frac{6{,}2\cdot 10^{15}\cdot\sqrt[2]{300^3}}{1{,}5\cdot 10^{16}}\right) = -0{,}2\,eV$$

d)

Since n_i is much ~~to~~ smaller than N_D, the c-Si is n-type and the majority carriers are electrons. Because Doping with Phosphorous.

e(b)

$$E_g[q]$$

$$n_i^2 = np = N_c N_v \exp\left(-\frac{\cancel{E_g[q]}}{k_B T}\right)$$

$$n_i = \left[6{,}2\cdot 10^{15}\cdot\sqrt[2]{1000^3}\cdot 3{,}5\cdot 10^{15}\sqrt[2]{1000^3}\cdot\exp\left(-\frac{1{,}1eV\cdot 1{,}602\cdot 10^{-19}}{1{,}38\cdot\underset{10^{-23}}{\cancel{10^{-23}}}\cdot 1000K}\right)\right]^{1/2}$$

$$= 2{,}48\cdot 10^{17}\cdot 1/cm^3$$

Because $n_i \cancel{\gg} > N_D$:

$$n = n_i = 2{,}48\cdot 10^{17}\,1/cm^3$$

p calculate:

$$p = \frac{(n_i)^2}{n} \approx \frac{(2{,}8\cdot 10^{17}\,1/cm^3)^2}{2{,}48\cdot 10^{17}\,1/cm^3} = 2{,}48\cdot 10^{17}\,1/cm^3$$

e(c) Fermi level i respect to the conduction band edge

$$E_F - E_C = \frac{-k_B T}{q}\ln\left(\frac{n}{N_c}\right) = -\frac{1{,}38\cdot 10^{-23}\cdot 1000}{1{,}602\cdot 10^{-19}}\ln\left(\frac{2{,}48\cdot 10^{17}}{6{,}2\cdot 10^{15}\cdot(1000)^{3/2}}\right) = -0{,}57\,eV$$

e(d) Since $n = p$, there are no majority carriers and the silicon slap is an i-type semiconductor.

f) At room temperature (300 K) doping can be used to manipulate the concentration of charge carriers. The crystalline silicon slab is n-type. At high temperatures the intrinsic charge carrier concentration ~~becau~~ becomes dominant and doping becomes seeppressed. The cristalline silicon slab behaves as i-type. Due to increased thermal energy more Si bonds are brokes and electron-hole pairs are created. Doping becomes less significant. In practice this means that by higher temperatures both p- and n- regions become intrinsic-like. The p-n junction will disapear. Since both regions will become intrinsic-like, there will be no ~~effect~~ net diffusion from one region to another and therefore also no depletion region with ~~intrinsic~~ internal ~~election~~ electric field. The p-n junction loses its rectifying properties.

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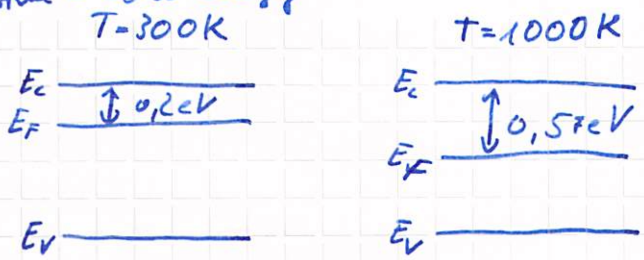
g)



The position of the Fermi level at room temperature is close to the conduction band, since the c-Si slab became an n-type semiconductor by phosphorous doping. At high temperatures, the effect of doping becomes less important and the Fermi level will shift towards the intrinsic level by thermal generation of charge carriers.

h) The hole drift current density can be calculated as:

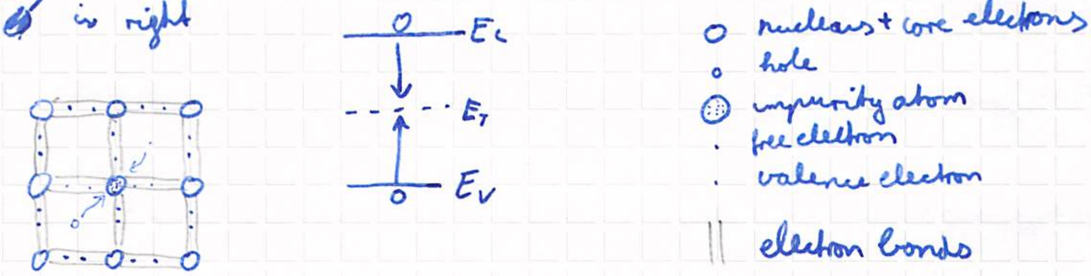
$$J_{p,\,drift} = q\, p\, \mu_p E$$

where p is the number of holes, equal to the acceptor doping concentration since the dopant atoms are ionized

$$N_A = p = \frac{J_{p\,drift}}{q\, \mu_p E} = \frac{110\,\mathrm{A\,cm^{-2}}}{1{,}602\cdot 10^{-19}\,\mathrm{C}\cdot 470\,\mathrm{cm^2\,V^{-1}\,s^{-1}}\cdot 25\,\mathrm{V\,cm^{-1}}} = 5{,}85\cdot 10^{16}\ \frac{1}{\mathrm{cm^3}}$$

4) c)

is right



5)

~~Diffusion~~ Diffusion length:

$$L = \sqrt{D\tau} = \sqrt{\cancel{2}\ 25{,}6\,\frac{\mathrm{cm^2}}{\mathrm{s^{-1}}}\cdot 10\,\mu\mathrm{s}} = 160\,\mu\mathrm{m}$$

6)

carrier lifetime: $\tau = \frac{L^2}{D} = \frac{(200\,\mu\mathrm{m})^2}{27\cdot 10^{+8}\,\mu\mathrm{m}^2\,\frac{1}{\mathrm{s}}} = 1{,}48\cdot 10^{-5}\,\mathrm{s} = 14{,}8\,\mu\mathrm{s}$

7)

a)

$$\alpha = \frac{4\pi k}{\lambda} = \frac{4\pi \cdot 0{,}015}{650\,nm} = 2{,}9 \cdot 10^{5} \frac{1}{m}$$

b) The reflectance at interface air/Si is calculated as:

komplex

$$R = \left[\frac{n_{air} - n_{Si}}{n_{air} + n_{Si}}\right]^2 = [0{,}59 + i\ 0{,}001]^2 = 0{,}34$$

c)

$$P = hc\,\phi_{ph} \cdot \frac{1}{\lambda}$$

The incident photon flux at wavelength of 650 nm (at $x=0$) is expressed as:

$$\phi^{0}_{ph} = P\frac{\lambda}{hc} = 3{,}3 \cdot 10^{21} \frac{1}{cm^2 s^1}$$ – no reflektion

The photon flux entering the wafer is calculated taking the reflection into account.

Therefore, $\Phi(x=0)$ is expressed as:

$$\Phi(0) = \bar{\phi}^{0}_{ph}(1-R) = 3{,}3 \cdot 10^{21} \cdot (1-0{,}34) = 2{,}15 \cdot 10^{21} \frac{1}{cm^2 s^1}$$

The photon flux at $x = 50\,\mu m$ after reflection can be calculated by using Lambert-Beer equation:

$$\Phi(x) = \Phi(0)e^{-\alpha x} = 2{,}15 \cdot 10^{21} \cdot 5{,}3 \cdot 10^{-7} = 1{,}14 \cdot 10^{15} \frac{1}{cm^2 s}$$

d)

The generation rate at $x = 50\,\mu m$ is written as the product between the photon flux calculated at $50\,\mu m$ and the absorbtion coefficient at 650 nm:

$$g_L(x = 50\,\mu m) = \alpha\,\Phi(x = 50\,\mu m) = 3{,}9 \cdot 10^{5} \cdot 1{,}14 \cdot 10^{15} = 3{,}3 \cdot 10^{20} \frac{1}{m^3 s}$$

e) $L_n = 60\,\mu m \quad D_n = 29 \frac{cm^2}{s}$

Drift diffusion and recombination-generation processes give rise to a change in the carrier concentration in time. The combined. The combined effects of all the types of carrier actions are described by the continuity equation. In particular, such equation for the electrons in a p-type wafer (assuming dominat R-G process) is written as:

$$\frac{dn}{dt} = \frac{dn}{dt}\Big|_{diff} + \frac{dn}{dt}\Big|_{drift} + \frac{dn}{dt}\Big|_{thermal\ R-G} + \frac{dn}{dt}\Big|_{photogeneration}$$

7)

c)

If there is no current flowing to the wafer the first two terms are equal to zero. Moreover, in steady state conditions there is no change in the carrier concentration with the time. Therefore, the generation rate equals the R-G thermal recombination rate and the continuity equation becomes:

$$\frac{dn}{dt} = \frac{dn}{dt}\Big|_{\text{thermal R-G}} + \frac{dn}{dt}\Big|_{\text{photogeneration}} = 0$$

In conditions of low injection levels and dominant R-G process the time rate of change in the carrier concentration is expressed as:

$$\frac{dn}{dt}\Big|_{\text{thermal R-G}} = -\frac{\Delta n}{\tau_n}$$

Therefore, the continuity equation assumes the final expression:

$$\frac{dn}{dt} = -\frac{\Delta n(x=50\mu m)}{\tau_n} + g_L(x=50\mu m) = 0$$

The excess of the minority concentration can be calculated as:

$$\Delta n = \tau_n\, g_L = 1{,}24 \cdot 10^{-6}\, s \cdot 3{,}3 \cdot 10^{20} \frac{1}{m^3 s} = 4{,}1 \cdot 10^{14}\, 1/m^3$$

Where τ_n is the minority carrier lifetime calculated as:

$$\tau_n = \frac{L_n^2}{D_n} = \frac{(60\mu m)^2}{29\, cm^2 1/s} = 1{,}24 \cdot 10^{-6}\, s$$

KÜHNE+NAGEL