Name Solutions

Average = 63
Std. Dev = 21

Exam #1 — EE 482
Fall 2002

The test is open book/open notes. Show all work. Be sure to state all assumptions made and **check** them when possible. The number of points per problem are indicated in parentheses. Total of 100 points in 4 problems on 4 pages.

1. Sketch energy band diagrams (E versus k in primary symmetry directions) for two hypothetical materials A and B which have the following properties. Assume the materials have the same scattering lifetimes. Indicate your reasoning. (25)

   (a) The effective mass of holes is larger in material A than in material B.

   (b) The intrinsic carrier concentration is *much* larger in material A than in B.

   (c) The electron mobility is larger in material A than in material B.

   (d) Recombination in material B is dominated by processes involving deep levels.

   (e) Most recombination in Material A results in photon emission.

$m_h^A > m_h^B$: Material B has larger curvature at maximum of valence band

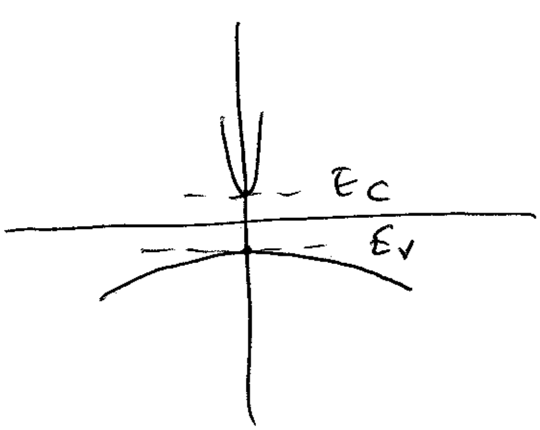
$n_i^A >> n_i^B$: $n_i^2 = N_c N_v \exp\left(-\frac{E_g}{kT}\right)$, so $E_g^A < E_g^B$

$\mu_n^A > \mu_n^B$: $\mu = \frac{q\tau}{m^*}$, τ are same, so $m_e^A < m_e^B$, Material A has larger C-band curvature

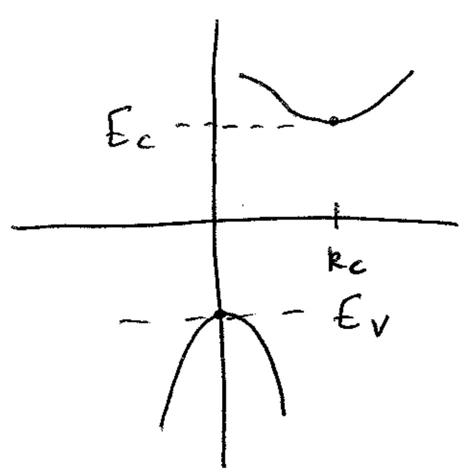
indirect recombination in B (SRH), so indirect bandgap ($k_c \neq k_v$)

radiative recombination is direct, so A has direct bandgap ($k_c = k_v$)

A



B



2. A silicon wafer ($E_g = 1.12$eV) is doped with 10^{18}cm^{-3} of cobalt which has an acceptor level 0.39eV above the valence band. The material also contains another shallow dopant. If the Fermi level is 0.25eV above the valence band at 300K,

(a) What is the type and concentration of the shallow dopant? (20)

$$E_f = E_v + 0.25eV \qquad p = N_v \exp\left(-\frac{0.25eV}{kT}\right) = 1.04\times10^{19}\,cm^{-3} \exp\left(-\frac{0.25}{0.026}\right)$$

$$= 6.9\times10^{14}\,cm^{-3}$$

$E_f < E_a^{Co}$, so state is mostly empty $\Rightarrow$ not ionized

$$N_{Co}^- = N_{Co}^0 \exp\left(-\frac{E_a^{Co} - E_f}{kT}\right) \cong N_{Co} \exp\left(-\frac{0.39 - 0.25eV}{kT}\right) = 4.6\times10^{15}\,cm^{-3}$$

Charge neutrality: $p - \underbrace{\cancel{n}}_{\text{negligible } (p \gg n_i)} - N_{Co}^- + (N_d^+ - N_a^-)_{shallow} = 0$

$$(N_d^+ - N_a^-)_{shallow} = 4.6\times10^{15}\,cm^{-3} - 6.9\times10^{14}\,cm^{-3}$$

$$= \underline{\underline{3.9\times10^{15}\,cm^{-3}}} \text{ donors } (>0)$$

(b) What is the resistivity of this sample (assume that only ionized impurities contribute significantly to scattering)? (10)

$$\rho = \frac{1}{q(\mu_n n + \mu_p p)} \cong \frac{1}{q \mu_p p}$$

$$p = 6.9\times10^{14}\,cm^{-3}$$

$$\mu_p(N_{total}) = \mu_p(8.5\times10^{15}\,cm^{-3}) = 410\,\frac{cm^2}{V\cdot s}$$

$$\rho = \left[(1.6\times10^{-19}C)\left(410\frac{cm^2}{V\cdot s}\right)(6.9\times10^{14}\,cm^{-3})\right]^{-1}$$

$$= \underline{\underline{22.1\ \Omega\text{-}cm}}$$

$$N_{total} = N_{Co}^- + N_{d\,shallow}^+ = 4.6\times10^{15} + 3.9\times10^{15}\,cm^{-3} = 8.5\times10^{15}\,cm^{-3}$$

3. Light is incident on a silicon wafer doped with 10^{14}cm^{-3} of boron. The recombination lifetimes are $\tau_n = 1\mu s$ and $\tau_p = 2\mu s$. The traps are located at 0.2eV below the intrinsic Fermi level. If the electron concentration is increased by a factor of 10^{10} due to the light, determine the generation rate of hole-electron pairs. Justify any assumptions made (20)

$$p_o \cong C_B = 10^{14}\text{ cm}^{-3}$$

$$n_o = n_i^2/p = \frac{2.2\times10^{20}\text{ cm}^{-6}}{10^{14}\text{ cm}^{-3}} = 2.2\times10^{6}\text{ cm}^{-3}$$

$$\Delta n = (10^{10}-1)\,n_o = 2.2\times10^{16}\text{ cm}^{-3} \gg p_o$$ very high level injection

$$G_L = U = \frac{pn - n_i^2}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

$E_t < E_i$, so $n_1 < n_i$, $p_1 = n_i \exp\left(\frac{0.2\text{eV}}{kT}\right) = 3.3\times10^{13}$

$p, n \cong \Delta n = 2.2\times10^{16}$, $n_1, p_1 \ll p, n$

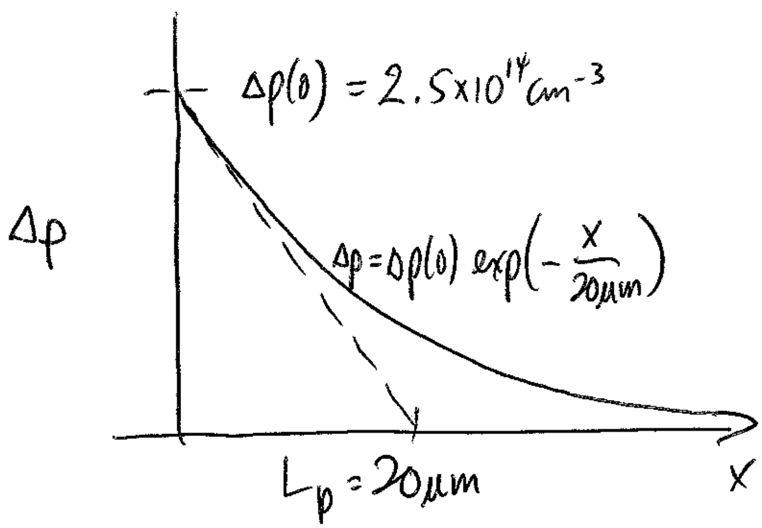
$$G_L = \frac{\Delta n^2}{(\tau_p + \tau_n)\Delta n} = \frac{\Delta n}{\tau_n + \tau_p} = \frac{2.2\times10^{16}\text{ cm}^{-3}}{3\times10^{-6}\text{ s}}$$

$$= 7.3\times10^{21}\text{ cm}^{-3}\text{ s}^{-1}$$

4. A very thick silicon wafer is doped with 10^{17}cm^{-3} of phosphorus. Light incident on the wafer surface ($x = 0$) is so strongly absorbed by silicon that it can be assumed to result in *surface* generation of 10^{18} carriers $\text{cm}^{-2}\text{sec}^{-1}$ (note generation is per unit *area*, not volume).

Assume $D_n = 20\text{cm}^2\text{sec}^{-1}$, and $D_p = 8\text{cm}^2\text{sec}^{-1}$. The bulk minority carrier recombination lifetimes are $\tau_n = 0.8\mu\text{s}$ and $\tau_p = 0.5\mu\text{s}$ and the surface recombination velocity is low enough to be neglected.

What is the steady-state minority carrier concentration at the wafer surface? Sketch the minority carrier density versus depth. (25)



n-type material (P)

minority carriers are holes

$D_p = 8\,\frac{cm^2}{s}$

$L_p = \sqrt{D_p \tau_p} = 2\times10^{3}\,cm$

$= 20\,\mu m$

$p_0 = \frac{n_i^2}{n} = \frac{2.2\times10^{20}\,cm^{-6}}{10^{17}\,cm^{-3}} = 2.2\times10^{3}\,cm^{-3}$

For minority carriers, can use diffusion approximation

$$\cancel{\frac{d\Delta p}{dt}}^{\,0 \text{ in s.s.}} = D_p \frac{d^2\Delta p}{dx} + \cancel{G_L}^{\,0 \text{ in bulk}} - \frac{\Delta p}{\tau_p}$$ assuming low level injection

No bulk generation, so $\Delta p = Ae^{-x/L_p} + \cancel{B}^{\,0}e^{x/L_p}$ since must not diverge as $x \Rightarrow \infty$

At surface, $G_s = J_p = -D_p\frac{d\Delta p}{dx}$

$10^{18}\,cm^{-2}s^{-1} = D_p\frac{A}{L_p} = \frac{8\,cm^2/s}{2\times10^{-3}\,cm}A$

$A = \frac{(2\times10^{-3}\,cm)(10^{18}\,cm^{-2}s^{-1})}{8\,cm^2/s} = 2.5\times10^{14}\,cm^{-3}$

$\underline{p \cong \Delta p = 2.5\times10^{14}\,cm^{-3}\exp\left(-\frac{x}{20\mu m}\right)}$

$\Delta p(0) = A = 2.5\times10^{14}\,cm^{-3}$

$\Delta p \ll n_0$, so l.l.i. assumption checks

End Of Exam