Name Solutions

Exam #1 — EE 482

Winter 2009

Mean = 57.07

Std. Dev. = 29.07

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 5 problems on 4 pages.

1. Sketch energy band diagrams (E versus k) for two semiconductor (A and B). Assume that the two materials have the same scattering lifetime and the properties of the two materials are such that:

   a) • Semiconductor A has a significantly smaller electron mobility than B.

   b) • Semiconductor A has a larger density of states in its valence band than B. (They each have a single valence band).

   c) • Semiconductor A has a much smaller intrinsic carrier concentration than B.

   d) • Most recombination in semiconductor A gives off photons, while only a small fraction of recombination events emit photons in B.

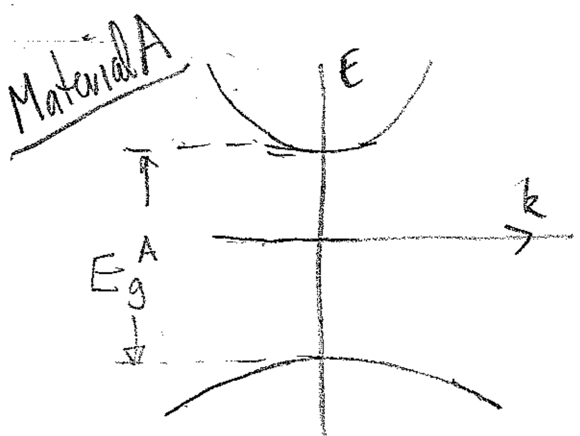
   To get partial credit, note what you can conclude about the bandstructure from each of these properties. (25)

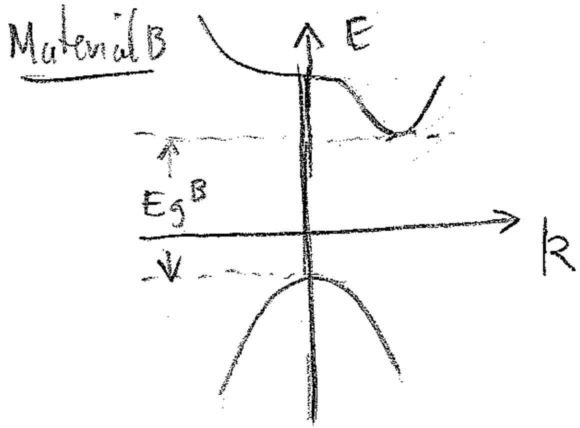
a) $\mu_n = \frac{q\tau}{m_e^*}$; $\mu_n^A < \mu_n^B \Rightarrow \frac{1}{m_{eA}^*} < \frac{1}{m_{eB}^*} \Rightarrow \left(\frac{\partial^2 E}{\partial k^2}\right)_A^{cb} < \left(\frac{\partial^2 E}{\partial k^2}\right)_B^{cb}$

b) $N_v = 2\left(\frac{2\pi m_{h,dos}^* kT}{h^2}\right)^{3/2}$; $N_v^A > N_v^B \Rightarrow m_{h,dos A}^* > m_{h,dos B}^* \Rightarrow \left(\frac{\partial^2 E}{\partial k^2}\right)_A^{vb} < \left(\frac{\partial^2 E}{\partial k^2}\right)_B^{vb}$

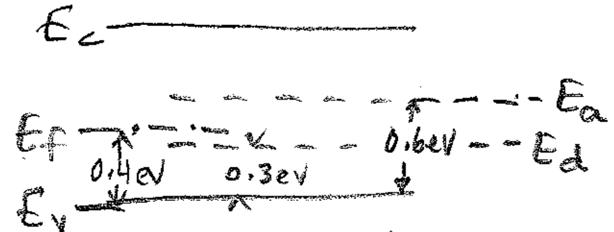
c) $n_i^2 = N_c N_v \exp(-E_g/kT)$; Given effective masses, $E_g^A > E_g^B$

d) Radiative recombination implies direct bandgap





2. Heavily damaged silicon ($E_g = 1.12$eV) is doped with $N_a = 5 \times 10^{16}\text{cm}^{-3}$ of boron. It is found that at 300K the Fermi level is located 0.4eV above the valence band maximum. The lattice defects resulting from damage have a donor level 0.3eV above the valence band and an acceptor level 0.6eV above the E_V.



(a) What is the density of lattice defects? (15)

$E_f > E_d + 3kT$, so donor states nearly full $\Rightarrow$ not ionized

$E < E_a - 3kT$, so acceptor states nearly empty $\Rightarrow$ not ionized

Use Boltzmann approximation:

$N_{ld}^- \cong N_{ld}^{total} \exp\left(-\frac{E_a - E_f}{kT}\right) = 0.0004\, N_{ld}^{total}$ negligible

$N_{ld}^+ \cong N_{ld}^{total} \exp\left(-\frac{E_f - E_d}{kT}\right) = 0.021\, N_{ld}^{total}$

Boron shallow, so full ionized.

$p = N_V \exp\left(-\frac{E_f - E_v}{kT}\right) = 2.5 \times 10^{19}\,\text{cm}^{-3} \exp\left(-\frac{0.4}{kT}\right) = 4.9 \times 10^{12}\,\text{cm}^{-3}$

Charge neutrality: $p + N_{ld}^+ - \cancel{N_{ld}^-} - N_B = 0$ $\quad N_{ld}(0.021) = N_B \Rightarrow \underline{N_{ld} = 2.4 \times 10^{18}\,\text{cm}^{-3}}$

(b) What is the resistivity of this sample (assume that only ionized impurities contribute significantly to scattering)? (15)

Total ionized impurities $= 5 \times 10^{16} + 5 \times 10^{16} = 10^{17}\,\text{cm}^{-3}$

$p = 4.9 \times 10^{12}\,\text{cm}^{-3} >> n$ $\qquad \mu_p = 340\,\text{cm}^2/\text{V}\cdot\text{s}$

$\rho = \frac{1}{q \mu_p p} = \frac{1}{(1.6 \times 10^{-19}\,\text{C})(340\,\frac{\text{cm}^2}{\text{s}})(4.9 \times 10^{12}\,\text{cm}^{-3})} = \underline{3.75 \times 10^3\,\Omega\text{-cm}}$

$(3750\,\Omega\text{-cm})$

3. Light is incident on a silicon wafer doped with 10^{14}cm^{-3} of boron. The recombination lifetimes are $\tau_n = 1\mu\text{s}$ and $\tau_p = 2\mu\text{s}$. 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)

$$p_o = 10^{14}\,\text{cm}^{-3}, \quad n_o = \frac{n_i^2}{p_o} = \frac{10^{20}\,\text{cm}^{-6}}{10^{14}\,\text{cm}^{-3}} = 10^{6}\,\text{cm}^{-3}$$

using $n_i = 10^{10}\,\text{cm}^{-3}$

$$n = 10^{10} n_o = 10^{10} \times 10^{6}\,\text{cm}^{-3} = 10^{16}\,\text{cm}^{-3} \cong \Delta n \gg p_o$$

$$p_1 = n_i \exp\left(\frac{0.2\,\text{eV}}{kT}\right) = 2.26 \times 10^{13}\,\text{cm}^{-3}$$

$$n_1 = 4.43 \times 10^{6}\,\text{cm}^{-3}$$

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

$$= \frac{(p_o+\Delta p)(\cancel{n_o}+\Delta n) - \cancel{n_i^2}}{\tau_p(\cancel{n_o}+\Delta n+\cancel{n_1}) + \tau_n(p_o+\Delta p+\cancel{p_1})}$$

$$= \frac{(1.01\times10^{16}\,\text{cm}^{-3})(\cancel{10^{16}}\,\text{cm}^{-3})}{2\times10^{-6}\,\text{s}\,(\cancel{10^{16}}\,\text{cm}^{-3}) + 10^{-6}\,\text{s}\,(1.01\times\cancel{10^{16}}\,\text{cm}^{-3})} = \frac{1.01\times10^{16}\,\text{cm}^{-3}}{3.01\times10^{-6}\,\text{s}}$$

$$= \underline{\underline{3.36\times10^{21}\,\text{cm}^{-3}\text{s}^{-1}}}$$

4. In a silicon sample in equilibrium, the net doping is $N_d(x) = 10^{17}\exp(x/100\text{nm})\text{cm}^{-3}$ (no variation in y and z). Assuming charge neutrality, what is the electric field at $x = 0$. (15)

$J_n = qD_n \frac{dn}{dx} + q\mu_n n \mathcal{E} = 0$ in equilibrium

Charge neutrality gives $n = N_d^+$, so

Use Einstein relation

$$\mathcal{E} = -\frac{\cancel{q} D_n \, dn/dx}{\cancel{q}\mu_n n}$$

$$= -\frac{kT}{q}\frac{1}{n}\frac{dn}{dx}$$

$$= -\frac{0.0259\text{V} \; \dfrac{\cancel{10^{17}\text{cm}^{-3}}}{100\text{nm}} \cancel{\exp\left(\frac{x}{100\text{nm}}\right)}}{\cancel{10^{17}\text{cm}^{-3}} \cancel{\exp(x/100\text{nm})}}$$

$$\mathcal{E} = -\frac{0.0259\text{V}}{10^{-5}\text{cm}} = \underline{-2.6\times10^{3}\frac{\text{V}}{\text{cm}}}$$

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5. For an ideal interface between silicon ($E_g = 1.12$eV, $\chi_s = 4.05$V) doped such that $E_F - E_V = 0.1eV$ and copper ($\phi_M = 4.4$V), what would be the voltage dropped between metal and semiconductor with zero applied bias? (10)

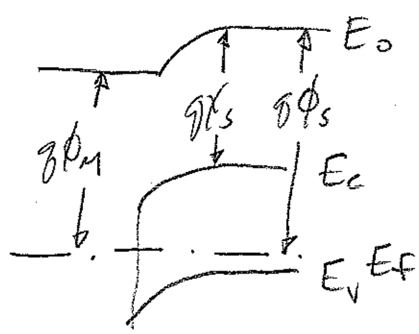
$|\phi_i| = |\phi_{MS}| = |\phi_M - \phi_s|$

$= |4.4\text{V} - 5.07\text{V}|$

$= 0.67\text{ V}$

$\phi_s = \chi_s + \frac{E_g}{q} - (E_f - E_v) = 4.05 + 1.12 - 0.1$

$= 5.07\text{ V}$



Metal is at higher electrical potential than Si (lower potential for electrons) so answer is $\underline{+0.67\text{V}}$

End Of Exam