Exercise Series 7

Exercise 1: Generalities on recombination mechanisms

a) Name the three main bulk recombination mechanism ocurring in a semiconductor and give a brief description. Illustrate each of these mechanisms with a band diagram.

1. Radiative (or band to band) recombination
2. Auger recombination
3. Shockley-Read-Hall recombination (SRH), also called trap-assisted recombination

b) Explain how carrier concentration affects the recombinations rates.

Reminder:

- carrier concentration $n = n_0 + \Delta n$ (same with p) is the sum of carrier concenration in the equilibrium state n_0 (generally the doping concentration at 25°C) and carrier injection Δn (out of equilibrium concentration, coming from generation, carrier diffusion, etc.). When we study recombinations, we study the **minority** carrier concentration, n or p.
- for "low injection" condition, we have: $n_0 \gg \Delta n$, thus $n \approx n_0$. For "high injection conditions, we have $n_0 \ll \Delta n$, thus $n \approx \Delta n$.

c) What is the predominant recombination mechanism occuring in low doped (or low injection) Si? What happens if the carrier concentration increases?

d) Why there is recombination at the surface of a semicondctor? How do we call this type of recombination? Does it have the same dependance on carrier concentration as a bulk recombination?

Exercise 2: Shockley-Read-Hall recombination

As has been discussed in the lecture, the Shockley-Read-Hall recombination model describes recombination in the bulk as a two-step process through a defect level situated within the bandgap at energy E_T. The recombination rate U_{SRH} is given by the formula below:

$$U_{\mathrm{SRH}} = \frac{v_{\mathrm{th}} N_{\mathrm{t}} (n \cdot p - n_{\mathrm{i}}^2)}{\frac{1}{\sigma_{\mathrm{p}}}(n + n_1) + \frac{1}{\sigma_{\mathrm{n}}}(p + p_1)} \quad (1)$$

with v_{th} [$\mathrm{cm\,s^{-1}}$] being the thermal velocity, N_{t} [$\mathrm{cm^{-3}}$] the trap or defect level density, σ_{n} and σ_{p} [$\mathrm{cm^{-2}}$] being the electron and hole capture cross-section respectively and n_1 and p_1 are the carrier concentration when $E_F = E_T$.

a) Show that at low minority carrier injection the Shockley-Read-Hall recombination rate U_{SRH} in an n-type silicon wafer is given by:

$$U_{\mathrm{SRH}} \quad = \quad \frac{\Delta p\, v_{\mathrm{th}}\, N_{\mathrm{t}}\, \sigma}{1 + \frac{2n_{\mathrm{i}}}{N_{\mathrm{D}}} \cosh(\frac{E_{\mathrm{T}} - E_{\mathrm{F}}^{\mathrm{i}}}{kT})} \tag{2}$$

Use the following hints:

(i) Assume equal capture cross-sections for electrons and holes: $\sigma_{\mathrm{n}} = \sigma_{\mathrm{p}} = \sigma$

(ii) For low injection the following relation holds: $p_0 \ll \Delta n = \Delta p \ll n_0$

(iii) And $n \approx N_{\mathrm{D}}$

b) Determine the expression for Shockley-Read-Hall lifetime τ_{SRH} in a n-type silicon wafer using the result from a). The result is shown in Fig. 1.

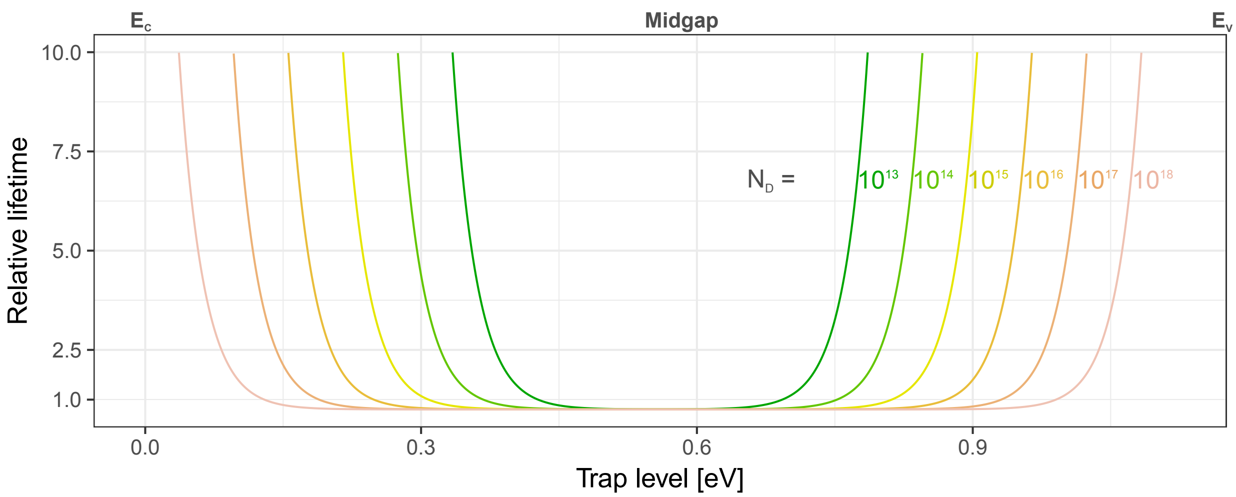

Figure 1: Carrier lifetime as a function of the position of the trap level in the bandgap of crystalline silicon, given for various doping levels. ["Crystalline Silicon Solar Cells", 1994, A. Goetzberger, J. Knobloch, and B. Voss].

Exercise 3: Surface recombination

The Fig. 2 represents a silicon rod which is homogeneously illuminated with infrared light (i.e. homogeneous photogeneration). Surface recombination occurs only at the surface for $x = 0$ with a surface recombination velocity S_p.

(a) Sketch the density of holes $p(x)$ (i.e. $p(x) = p_0 + \Delta p$) that you expect for $S_p \to 0$ and $S_p \to \infty$.

(b) Find the differential equation and the boundary condition at $x = 0$ to find $p(x)$
Hint : The boundary condition for $x = 0$ *is found by equalizing the diffusion current at* $x = 0$ *with the current induced by the surface recombinations in steady-state condition.*

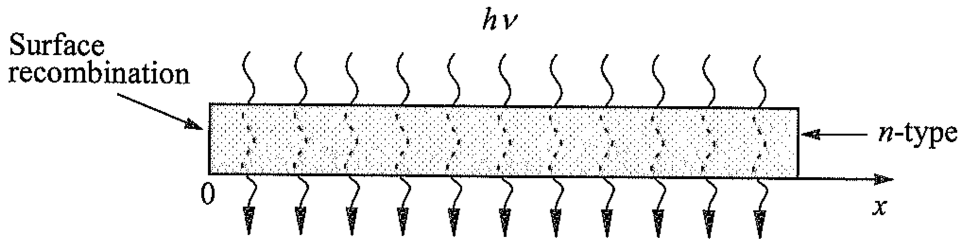

Figure 2: Silicon rod with a recombinant surface at $x = 0$. From S.M. Sze, Semiconductor Devices, Physics and Technology.

(c) The solution of the differential equation found in b) is the following:

$$p(x) = p_0 + \tau_p G \left(1 - \frac{\tau_p S_p}{L_p + S_p \tau_p} e^{\frac{-x}{L_p}}\right)$$

What is happening if $S_p \to \infty$ and $S_p \to 0$? Does it fit with your findings at point a)?

(d) Calculate the injection level difference between a "perfect surfaces" case and $S_p = 100\,\mathrm{cm\,s^{-1}}$, in the middle of a 200 µm thick wafer. What is the loss in V_{oc} resulting from the bad surface passivation?
Input values: Doping level = $10^{16}\,\mathrm{cm^{-3}}$, intrinsic carrier concentration at 300 K = $10^{10}\,\mathrm{cm^{-3}}$, minority carrier lifetime = 10 ms, diffusion length = 0.35 cm, homogeneous generation rate = $10^{18}\,\mathrm{cm^{-3}\,s^{-1}}$.
Hint: the voltage can be deduced by the injection level[1]:

$$V_{oc} = \frac{K_B T}{q} \ln \left[\frac{(N_D + \Delta p)\Delta p}{n_i^2}\right]$$

Exercise 4: Surface recombination vs Bulk recombination

Consider a 150 µm thick n-type wafer with well passivated surfaces (S on both side is equal to $100\,\mathrm{cm\,s^{-1}}$) at room temperature. This wafer contains $10^{13}\,\mathrm{cm^{-3}}$ nickel impurities that are situated at 0.23 eV above the valence band with a cross section $\sigma = 10^{-15}\,\mathrm{cm^{-2}}$.

(a) Express τ_{eff} as a function of the different recombination processes. Mention which recombination processes vary with the carrier density (i.e. doping or injection level).

[1] This phenomenon will de described in the next lectures and referred as the quasi Fermi level splitting.

(b) For an injection level of $10^{16}\,\text{cm}^{-3}$, and two different doping levels, respectively of 10^{17} and $10^{14}\,\text{cm}^{-3}$, calculate τ_{eff}.