Semiconductors & Defects: Exercise 6 (14 Dec. '21)

General remark: Always try to come up with a short answer that catches the essence.

17. Discussion and formula: Describe the effective mass! How is it defined, and why do we use effective masses rather than the original mass? What is special about the effective mass of the valence band, and how is that specialty treated when holes are introduced? Sometimes we have two values of the effective masses for electrons or holes – where does that come from, and what does that imply?

18. Discussion and formula: What does the effective mass (may) depend on in arbitrary real-world 3D crystals? (Hint: Just look at its definition!) What may happen to the effective mass in 2D or 1D structures, compared to the 3D case? What is the practical consequence of the effective masses with respect to high frequency device applications: If there are different effective masses, which is the more beneficial one for high frequency applications, and why? Try to explain how "strained silicon" is helpful in that respect. (Consult the World Wide Web for basic information about "strained silicon".)

20. Discussion and formulae: What is meant by the net recombination rate? What does the SRH model finally give (under certain conditions) as an explicit result for the minority carrier lifetime in a direct semiconductor? What are those "certain conditions" for which this result for the lifetime is obtained? What is the main technologically adjustable factor that limits the minority carrier lifetime in a direct semiconductor?

21. Calculation: Derive the result presented in the lecture, that in Boltzmann approximation, $[1 - f(E_{DL})] / f(E_{DL})$ gives $\exp[-(E_F - E_{DL})/(kT)]$.

22. Discussion only, no formulae, no details: To calculate the recombination rate for an indirect semiconductor, what is most important in the SRH model regarding the underlying microscopic notions? What applies in general, and what specifically when considering majority and minority charge carriers?
(The idea behind this task is to catch the essence of the SRH model: What do you need to have understood well enough so that you are, at least in principle, able to derive the formulae yourself?)

23. Discussion and formulae: What does the SRH model finally give (under certain conditions) as an explicit result for the minority carrier lifetime in an indirect semiconductor? What are those "certain conditions" for which this result for the lifetime is obtained? What are the main technologically adjustable factors that limit the minority carrier lifetime in an indirect semiconductor? How does the energetic position of a defect state ("deep level") influence the lifetime in an indirect semiconductor, and what is the deeper reason that there is a particularly relevant energy range for its influence?

25. Calculation and discussion: Have a look at the Advanced module "Solving the Poisson Equation for pn-Junctions" (https://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_2/advanced/t2_3_3.html). Find (some of) the errors in the calculation, and try to correct them (yes, just try; it is sufficient to make suggestions how it could be "repaired"). Point out what is unclear to you. Find the main error in the illustration showing the whole situation in one drawing. (Hint: The latter is possible by just looking at the drawing itself; one doesn't need to go through all the equations to find the relevant error.)

(See next page for continuation)

26. Discussion and drawing: What is meant by the terms “inversion”, “depletion”, “flat-band”, and “accumulation” (describing cases possibly found at the surface of a semi-conductor)? Draw (i) schematic band diagrams and (ii) corresponding charge carrier densities (both of majorities and minorities) vs. the lateral coordinate *x* illustrating these cases for a p-type semiconductor! What polarity do the fixed charges at the outer surface have in each case?

27. Discussion and drawing: Explain the basic idea of how the so-called “back surface field” (and similar means) reduce(s) minority carrier recombination in solar cells. (Information about the back surface field [or BSF, for short] can be found, *e.g.*, here: https://www.pveducation.org/pvcdrom/design-of-silicon-cells/surface-recombination)

28. Discussion and formula: What is meant by the term “Debye length”, and for which kind of charge carriers is it relevant – for majorities or for minorities? Write down the explicit formula for it, and name the relevant approximation for which this explicit result was obtained. Describe (i) the generally relevant physics leading to the Debye length and (ii) the “physical effect” expressed by the above explicit result for the Debye length. What does that imply for the Debye length of metals?

29. Discussion and formula: What is meant by the term “dielectric relaxation time”? How is the dielectric relaxation time related to the Debye length? Describe (i) the generally relevant physics leading to the dielectric relaxation time and (ii) the “physical effect” expressed by the dielectric relaxation time. Why does that imply that lateral charge equilibration for minorities (*i.e.*, the reduction of a lateral variation of the minority carrier density) is always driven just by diffusion?

30. Calculation: Consider a p–n junction in thermal equilibrium. The minority carrier densities can be obtained (i) from the mass action law, $n_{\mathrm{min}}\, n_{\mathrm{maj}} = n_i^2$, valid at each side of the junction separately, and (ii) via a Boltzmann factor from the corresponding majority carrier density at the other side of the junction, as follows: $n_{\mathrm{min}}^{\alpha} = n_{\mathrm{maj}}^{\beta} \exp[-\mathrm{e}V^{\mathrm{n}}/(\mathrm{k}T)]$. Here, α and β denote the p- and the n-side (or vice versa), and $\mathrm{e}V^{\mathrm{n}}$ is the energy difference in any of the bands between p and n side ($V^{\mathrm{n}} = \Delta E_F/\mathrm{e}$ is also known as the built-in potential, with ΔE_F being the difference in the Fermi energies of the two bulk sides “before junction formation”). Show that these two approaches lead to the same result for the minority carrier densities.