

Semiconductors & Defects: Exercise 8 (11 Jan. '22)

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

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, $n_{\min} n_{\max} = n_i^2$, 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: $n_{\min}^\alpha = n_{\max}^\beta \exp[-eV^n/(kT)]$. Here, α and β denote the p- and the n-side (or vice versa), and eV^n is the energy difference in any of the bands between p and n side ($V^n = \Delta E_F/e$ 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.
31. Discussion (and maybe formulae): Starting from a p–n junction in thermal equilibrium, by which basic considerations can its theoretical treatment be extended to stationary non-equilibrium, brought about by an external voltage applied in forward direction?
33. Discussion: Why and how does a p–n junction work as a diode (*i.e.*, as a rectifier)? What are the relevant charge carrier transport mechanisms? What is the physical reason for the current–voltage characteristic of a p–n junction being an exponential function?
34. Drawing and discussion: Draw the quasi-Fermi energies at a p–n junction under forward and reverse bias; describe the relevant physics.
35. Discussion: Have a look at the Wikipedia entry explaining holes in semiconductors (https://en.wikipedia.org/wiki/Electron_hole) and comment on its scientific quality: What errors and problematic aspects do you notice in the very first two paragraphs? *Important:* Do **not** try to fix it, just point out the problems. To do so, also think about possible consequences: What fundamental law of physics would be violated if the present version (as of 29 June 2021) of the explanation were correct? (You might also have a look at the entries given in other languages about this topic – are they as bad, too?)
36. Drawing and discussion: What is the meaning of “Auger recombination”? Illustrate the Auger process in a schematic band structure. Why is this recombination mechanism so important in optoelectronic devices? What other recombination channels are there in a doped semiconductor?
37. Discussion: What are excitons in semiconductors? Give a remarkable example where excitons are relevant for the functioning of an optoelectronic device; discuss in some detail why it is so remarkable.

(See next page for continuation)

38. Discussion: What possibilities are there for the doping of compound semiconductors, especially of III-V materials? What is similar to the doping of group-IV materials, what is fundamentally different?
39. Discussion: What is “wavelength engineering”? How can it be achieved? What kind of technical questions and physical aspects must be kept in mind when realizing it? What is the special technical advantage of $\text{Al}_x\text{Ga}_{1-x}\text{As}$? What limits usability of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ as an optoelectronic material?
40. Discussion and drawing (maybe generated electronically): When we discussed about task #32 last week, the idea behind the solution became clear, but in my eyes the final result wasn't fully convincing. We were able to find some errors here and there, but the “true” curves for the carrier densities at an asymmetrically doped p–n junction in thermal equilibrium remained unclear. Also, in the literature (WWW, books) I only found qualitative drawings that weren't fully satisfying. However, the more trustworthy ones at least hinted at a fact that we should reconsider:
Why is it reasonable that, for an asymmetrically doped p–n junction, the crossing point between the electron and the hole density (*i.e.*, the position for which it holds that $n_e = n_h = n_i$) is **not** identical to the point where the underlying doping abruptly changes from n-type to p-type; where should this crossing point be found instead? Make a new drawing of the carrier densities for this situation.
(If you want to be on the safe side, let the computer plot the carrier densities. For this, use the analytic solution obtained from the zeroth-order approximation for the charge densities in the space-charge region; *i.e.*, just consider the constant densities of charged dopant atoms, giving a linearly increasing and decreasing electric field, and a quadratic function for the electrostatic potential. Use the latter to give an analytic expression for the band bending, from which analytic expressions for the carrier densities can be obtained. Then, use the computer just to plot these analytic solutions.)