Semiconductors & Defects: Exercise 11 (24 Jan. '23)

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

29. 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?

30. Drawing, formulae, and discussion: Consider a p–n junction in thermal equilibrium and draw the relevant distribution of the electrons and holes across the space charge region (SCR). Given that there is a constant acceptor (donor) density N_A (N_D) in the p-type (n-type) region, how is the hole (electron) density related to the local value of the electrostatic potential $V(x)$, and how can, in principle, the band bending (*i.e.*, the spatial variation of the band edge) in the SCR be calculated? Write down the relevant equations (only those to be solved, not their solution)! Compare the example shown graphically in the solution of "Exercise 2.3.5-1" (https://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_2/exercise/s2_3_1.html) to the charge carrier distribution just drawn by you: What fundamental simplification has been made in the graphics shown in the solution of "Exercise 2.3.5-1"? (Indirect hint: It is correctly shown in this graphics that there is no band bending in the bulk regions outside the SCR – but why is this so?)

32. Drawing and discussion: Draw the quasi-Fermi energies at a p–n junction under forward and reverse bias; describe the relevant physics.

33. Discussion: Have a look at the English 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 paragraph?
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 26 November 2022) 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?)

34. 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?

35. 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.

36. Calculation: Perform Exercise 5.1.2-1 from the hyperscript (https://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_5/exercise/e5_1_1.html), *i.e.* calculate the injected carrier densities from the forward current of junctions. Proceed as follows: Consider the formula giving the current density for a symmetrically doped p–n junction under forward bias and neglect the generation term from the space charge region as well as the –1 term. Then, for silicon and gallium arsenide, (i) calculate the current density for some relevant values of N_{dop}, L and τ (follow the above link to the exercise to find a link to data from which these values can be obtained) in dependence on the diode forward voltage, and

considering the carriers of this current to not recombine in the space-charge region (but just passing through), (ii) calculate the carrier density (per volume) by using the width of the space-charge region matching the given forward voltage.

37. Discussion and drawing (maybe generated electronically): As in task #30, consider a p–n junction in thermal equilibrium and draw the relevant distribution of the electrons and holes across the space charge region (SCR), but now for a strongly asymmetrically doped junction: Why is it reasonable that 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; it was done like this in the Advanced module "Solving the Poisson Equation for p–n Junctions", cf. https://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_2/advanced/t2_3_3.html. Use the electrostatic potential 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.)

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 $Al_xGa_{1-x}As$? What limits usability of $Al_xGa_{1-x}As$ as an optoelectronic material?

40. Discussion: Download the paper "Si and Zn Co-Doped InGaN–GaN White Light-Emitting Diodes" using this link. Briefly review the different ways to come to a white-light-emitting device described in the introduction of this paper. Try to give an interpretation of the electroluminescence spectrum shown in Fig. 1: How can it be explained that the band edge emission peak depends so strongly on the current strength? What might be an explanation for the blue shift of the broad emission peak attributed to the donor–acceptor transition? (Remark: No relevant explanations are given in the paper itself!)