Semiconductors & Defects: Exercise 10 (25 Jan. '22)

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

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 and drawing (maybe generated electronically): When we discussed about task #32, 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.
    Why is it sufficient to consider the zeroth-order approximation for the charge densities in the space-charge region (*i.e.*, to just consider the constant densities of charged dopant atoms) for gaining a **generally** valid qualitative understanding?
    (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, 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.)

41. Formula and discussion: Give the formula for the total efficiency of light generation and describe all factors involved.

43. Discussion and drawing: Why is a standard p–n junction diode usually a rather bad light emitter? What device structure is a better choice for an efficient light emitter, and why? Give an explanation based on a schematic drawing of the band structure (it suffices to consider it in equilibrium): What kind of junctions have to be involved, and why?

44. Discussion and drawing: When making heterojunctions, what are the important band structure parameters one must keep in mind? Consider the straddling case (type I) and discuss the formation of a p–n junction; describe the role of the band discontinuities at the junction. Why are two different types of p–n junctions possible in this case? What is their main difference with respect to current flow under forward bias?

45. Discussion and drawing: How to make a single quantum well (SQW) using two semiconductors with different bandgaps? Draw the lateral conduction and valence band (CB

and VB) diagram for a real SQW structure using AlAs and GaAs layers. Schematically, draw the resulting CB and VB energy levels inside the SQW (as they are to be expected from the particle-in-a-box model; for the latter, remember the solution to task #1).

46. Discussion: Download the paper "Electronic band gap of Si/SiO_2 quantum wells: Comparison of *ab initio* calculations and photoluminescence measurements" using this link. Figure 2 shows a series of normalized photoluminescence (PL) spectra of various Si/SiO_2 multi quantum well (MQW) structures, recorded at low temperatures. Explain the observed dependency of the PL peak position on the well width of the MQW structure.

47. Discussion: Describe the concept of "modulation doping" and explain how it leads to a two-dimensional electron gas (or 2DEG, for short). What is the main reason that this 2DEG can have a high mobility? What other way(s) to obtain a 2DEG do you know of? What fundamental physical effect was observed in a 2DEG, resulting in a Nobel prize? (Hint: This effect occurs when the 2DEG is placed in a perpendicular magnetic field.)

48. 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!)

49. Discussion and drawing: How can a certain heterojunction be used to increase the current efficiency of an LED? As an example for an actual device structure, have a look at Fig. 10 shown in the Nobel lecture of Shuji Nakamura. The compositions of the various layers are as follows: n-type $Al_{0.15}Ga_{0.85}N$, Zn-doped (i.e., p-type) $In_{0.06}Ga_{0.94}N$, and p-type $Al_{0.15}Ga_{0.85}N$; draw the relevant band diagram. For the band offsets, use the information given on https://www.nature.com/articles/nature01665/figures/2 about the binary materials AlN, GaN, and InN, and linearly interpolate them according to the given compositions.

50. Discussion: Describe the processes of fundamental absorption, spontaneous emission, and stimulated emission; explain their role in lasers.