Semiconductors & Defects: Exercise 3 (16 Nov. '21)

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

3. Discussion and drawing: What is the special significance of the Brillouin zones? Assuming a regular 1D chain of atoms, explain why an electron (treated in the nearly free particle approximation) exhibits two energy values at $\boldsymbol{k} = \boldsymbol{k}_{\mathrm{BZ}}$ ($\boldsymbol{k}$: wave vector). Draw the $E(\boldsymbol{k})$ diagram for (i) the free electron gas and (ii) the free electron gas with diffraction at the first Brillouin zone edge. What is the advantage of the reduced zone scheme?

4. Formula and discussion: What is the Bloch theorem and its special significance for electrons in a crystal? For a Bloch wave, discuss the meaning of the "quasi wave vector" and the "crystal momentum."

8. Discussion, drawing, and formula: What is meant by an "intrinsic semiconductor"? Is it possible to have a perfect intrinsic SC in practical life? Why? Draw the schematic band diagram for conduction band, valence band, and Fermi energy for a perfect intrinsic SC. What is the "intrinsic carrier density" n_i? Using the Fermi–Dirac distribution function, express the density of electrons and holes in different bands, assuming identical densities of state in valence and conduction band. How will this distribution change if one increases the temperature? Hence, how does n_i depend on the temperature, and on the bandgap?

9. Discussion, drawing, and formula: What is meant by an "extrinsic semiconductor"? Draw the schematic band diagram of an extrinsic SC having conduction band, valence band, donor level, and acceptor level. Specify the charge neutrality condition in an extrinsic SC, and explain why the various charges are counted this way. Which important quantity can be obtained from this condition (for a given temperature)?

10. Discussion and numbers: What are "minority charge carriers" in general, and by which physical principle? What are the majority and minority charge carriers in a p-type and an n-type SC? How can one make Si n-type or p-type? By how many orders of magnitude may differ the density of the majorities from that of the minorities (roughly)? How to find the minority charge carrier density in a doped SC if the doping level and n_i are known?

12. Discussion: What are semiconductors (SCs) in general, and by which "condition" are only some of them (in principle; there are a few exceptions) of technological relevance? Explain the main differences between metals, semiconductors and insulators. Give examples for different kinds of SCs that can be formed by elements of the periodic table.

13. Formulae and discussion: Explain the quantity "mobility": How is it defined, and how can it be written in the simple scattering time approximation – and why so? What are the main factors affecting the mobility of charge carriers, and in which way? How can these effects be understood on the basis of the model of nearly free electrons? How do these effects depend on temperature – and why so?

14. Discussion, drawing, and formula: Demonstrate the band-bending and the formation of a space charge region at the surface of a **p-type** semiconductor. Why is it called space charge region? Why is the surface charged at all? (Could there be a situation where it is

not charged?) Show the directions of electric field lines. Specify the expression giving the width of the space charge region, and provide a microscopic interpretation of the involved quantities (*i.e.*, explain why those quantities influence the width of the space charge region the way they do it according to the formula).

15. Discussion and formulae: Consider an ideal p–n junction without the contribution of the space charge region.
a) The forward current is a diffusion current of majority carriers. However, when *increasing* the doping levels of the bulk materials (and, therefore, also the majority carrier density), this current is *reduced*. Why? For giving the reason, do **not** simply use the diode equation given in the script but come up with a different explanation.
b) How do forward and reverse current depend on temperature?
c) Now, consider an asymmetrically doped p–n junction, made from a direct SC, under forward bias (*i.e.*, acting as an LED): Which side provides the larger contribution to the light output, the higher or the lower doped one? Why? (For this question now use the diode equation given in the script.)