

May 5, 2011. Total of 3 pages.

You need to show important steps leading to the answer, unless instructed otherwise. For all numerical answers, using two significant figures is acceptable.

Good luck!

1. (10 points) What is the value of $k_B T$ in unit of meV for the RT (room temperature: $T = 300$ K)? Here, k_B is the Boltzmann constant. For this problem, you don't need to show any derivation. Just write down the answer, if you know it already. However, *if* necessary, you can use these numbers: $k_B = 1.381 \times 10^{-23}$ J/K and $e = 1.6 \times 10^{-19}$ C.
2. (10 points) What is the wave number, in unit of \AA^{-1} , of a photon with energy 1 eV? Recall that $\omega = ck$ for the photon. $\hbar c = 1973$ eV \AA . If you want to start by using the SI unit, please ask. You can leave the answer as a fraction, if you like.
3. (10 points) What is the wave number, in unit of \AA^{-1} , of a free electron with 1 eV kinetic energy? You can use $m_e c^2 = 0.5110$ MeV (MeV = mega eV, i.e. 1×10^6 eV) and $\hbar c = 1973$ eV \AA . If you want to start by using the SI unit, please ask.
4. (10 points) Define a metal and an insulator, as sharply and concisely as possible within the band theory. Define a semi-metal and a semi-conductor, as well, also within the band theory.
5. (10 points) Define a degenerate semiconductor and a non-degenerate semiconductor, as sharply and concisely as possible. Explain briefly the rationale behind the definitions.
6. (10 points) At 300 K, the intrinsic carrier density of the electron for Si is given (approximately) as $n_i = 1.0 \times 10^{10}$ cm^{-3} . For a B-doped Si semiconductor, it is found that the hole density $p = 3.0 \times 10^{14}$ cm^{-3} . Find the value of the electron density n . You can use the law of mass action without derivation.
7. (50 points) Consider a Si crystal.
 - (a) Draw a diagram of a cubic unit cell (with side length a) of an fcc lattice.
 - (b) Explain the structure of a Si crystal, starting from the fcc lattice.
 - (c) Find the expression for the number density of Si atoms as a function of a .
 - (d) Mark a (111) lattice plane of the crystal in your diagram of (a).
 - (e) Draw a separate two dimensional diagram of a (111) lattice plane, clearly indicating its own two dimensional crystal structure consisting of Si atoms.

- (f) (extra credit, 10 points; (e) and (f) are somewhat difficult.) Find the expression for the areal density of Si atoms in the (111) plane as a function of a .
8. (60 points) InSb has the dielectric constant $\varepsilon = 17$, and the effective masses $m_n^* = 0.014m_e$ and $m_p^* = 0.015m_e$, where m_e is the mass of the bare electron, i.e. the electron in vacuum. InSb is a direct semiconductor with 0.17 eV energy gap. The following portion of the periodic table may be helpful for this problem.

3	4	5	6
B	C	N	O
Al	Si	P	S
Ga	Ge	As	Se
In	Sn	Sb	Te
Tl	Pb	Bi	Po

- (a) A Se atom is doped into this material, and replaces an In atom or an Sb atom. Assume that we do not necessarily know whether it replaces In or Sb. Does Se act as a donor or an acceptor? Is the answer dependent on which atom it replaces? Briefly explain.
- (b) Assume, for the rest of this problem, that a Se atom replaces an Sb atom. Find the impurity energy level for the Se impurity. You need to explain the ε and m^* dependences of the impurity energy level, based on the Bohr theory of atoms. However, the Rydberg constant, 13.6 eV, can be used without derivation.
- (c) Draw a band energy diagram. Your energy diagram should include all of the following: the energy level of the Se impurity, the position of the valence band, the position of the conduction band, the position of the Fermi level at $T = 0$, the *rough* position of the Fermi level at room temperature, and finally the position of E_i (the Fermi level for the intrinsic crystal).
- (d) What is the radius of the orbital of the impurity level? You need to explain the ε and m^* dependences of the radius, based on the Bohr theory of atoms. However, the Bohr radius, 0.529 Å, can be used without derivation.
- (e) Based on the information given in this problem alone, would you expect a high mobility or a low mobility for carriers in InSb? Why?
- (f) (extra credit, 10 points) Find the impurity concentration at which the orbits around adjacent impurities begin to overlap. What new effect would you expect to occur, and why?

Only three out of the following six problems are required. However, you need to do at least one out of 9-11 and at least one out of 12-14. If you do more than three out of six, you probably will earn some extra credit.

9. (10 points) Consider a one dimensional tight binding band for the $1s$ orbital of hydrogen. Explain briefly why the band dispersion has a minimum at $k = 0$ and a maximum at $k = \pi/a$ (k is the crystal momentum).
10. (10 points) Explain why when two semiconductors (or any two materials, actually) are in contact and in mutual equilibrium, the Fermi levels of the two materials must become equalized.
11. (10 points) Give brief definitions and units for the following quantities: resistance, conductance, resistivity, conductivity.

In these problems, assume that your curious, intelligent, but uninformed, little sister/brother (or your friend of similar quality) asks the question. Your job is to provide the best descriptive answer and make her/him say “Yup, that makes sense.” Assume that the person who asks the question has some general knowledge of classical mechanics (e.g. motion in a potential well) and waves (e.g. diffraction), but not so much quantum mechanics. Use descriptive language, analogy, and diagram. Use math equation, only if you find it absolutely necessary to do so.

12. (10 points) “I heard that an “electron” in a semiconductor crystal can have a very funky mass. It can be ten times or hundred times lighter! What does it mean? I don’t suppose that electrons go on a diet in a crystal! Tell me what really happens!”
13. (10 points) “I heard that there are these things called “holes” as well as electrons in a semiconductor, while the raw ingredients of a semiconductor are electrons only (apart from protons and neutrons that make up nuclei). Me thinks that the hole is spooky – the concept sounds so superfluous to me. What is exactly this “hole”? Please define it! Give me some example experiments where I absolutely need to use the concept of the hole, and explain why!”
14. (10 points) “I heard that the quantum mechanical tunneling is an essential ingredient for understanding how the conduction occurs in metals or semiconductors. What is this thing called tunneling? How does it occur in a solid? How does that cause conduction?” In answering this question, you can assume that the questioner already knows about the discrete atomic levels ($1s$, $2s$ and so on).