**Photonics, Spring 2025**

**Submit your answers as a PDF file via Google Classroom before deadline (07.04.2025 at 10.00).** If problems, contact the course assistant joonas.mustonen@helsinki.fi.

If you utilize LLM models as assistance in solving the task, please specify their usage at the end of your submission.

**Exercise 9, 31.3.2025**

This week’s exercises are a continuation of last week (**Optoelectronics and Photonics: Chapter 3**). A few fundamental concepts from last week relating to semiconductors are summarized here.

As a material is cooled, it’s electrons evidently lose energy. 0 K then serves as a useful reference to determine an important energy level. The Fermi energy is defined as the difference between the lowest occupied and the highest empty energy states at 0 K. An electron will become conductive i.e., free, once its energy is raised above the Fermi energy. In semiconductors an energy gap (bandgap ) exists between free conduction electrons (conduction band CB) and bound electrons (valence band VB). Semiconductors with a relatively large bandgap are referred to as nondegenerate; the number of electrons in the CB is far less than those in the VB. In contrast, degenerate semiconductors are so heavily doped that they behave more like a metal than a semiconductor.

Two important statistical concepts describe free electrons within an energy band. The first is density of states (DOS) , which basically represents the number of possible (allowed) electron energy states at a particular energy level. The Fermi-Dirac function is then the probability of finding an electron in a quantum state corresponding to the energy . Evidently at , . The product of the two functions then essentially represents the energy distribution of electrons i.e., how many electrons are found per unit energy per unit volume at a given energy . The integral of this product then gives the electron concentration in the energy range dictated by the integration limits. For nondegenerate semiconductors the Fermi-Dirac statistics can be reduced to Boltzmann statistics. For instance, the corresponding integral for electrons in the CB of a nondegenerate semiconductor gives the conduction electron concentration:

1. **Extrinsic n-Si** (2 points)

Extrinsic semiconductors are semiconductors that have been doped such that the concentrations of carriers of one polarity greatly outweigh that of the opposite polarity. Consider a Si crystal that has been doped n-type with phosphorous donors. The electron drift mobility depends on the total concentration of ionized dopants , as described in Table 1.

**Hint**: Check “*mass action law*” and Table 3.1. in the course textbook. When , the conduction electron concentration will be nearly equal to . You can assume that doped Si is nondegenerate.

1. What is the conductivity of the crystal?
2. Where is the Fermi level with respect to the intrinsic crystal ()?

**Hint**: Find expressions for the intrinsic/dopant concentrations separately as functions of their respective Fermi levels, then take their ratio.

1. **Compensation doping in n-type Si** (5 points)

Compensation doping refers to the doping of a semiconductor with both donors and acceptors, which can lead to the reversal of the doping type. Consider an n-type Si sample that has been doped with phosphorous atoms per .

1. What are the electron and hole concentrations?
2. Calculate the room temperature conductivity of the sample.
3. Where is the Fermi level with respect to ?
4. If we now dope the crystal with an additional boron acceptors per , what will be the conduction electron and hole concentrations?
5. Where is the Fermi level corresponding to (d), with respect to ?

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Dopant concentration () |  |  |  |  |  |  |
| GaAs, () | 8500 | - | 8000 | 7000 | 5000 | 2400 |
| GaAs, () | 400 | - | 380 | 310 | 250 | 160 |
| Si, () | 1450 | 1420 | 1370 | 1200 | 730 | 280 |
| Si, () | 490 | 485 | 478 | 444 | 328 | 157 |

Table 1: Drift mobilities of conductivity electrons and holes (, ) at various dopant concentrations.