# Solid State Electronics (EE113FZ)

## Tutorial 4

## X-Ray Diffraction, Doping & Conduction in Semiconductors

Answer the following questions.

1. What is Bragg's law? Write down the equation and explain all the terms in the equation.

2. For a wavelength of 26.5 nm with order of 1 and a separation distance of 25 nm, use Bragg's law to calculate the angle of diffraction.

3. Where the angle of diffraction is 42° and the distance between planes is 2 Å with an image order of 4, calculate the wavelength used. An Å is $10^{-10}$ m.

4. Niobium ($Z$ = 41) is in a body-centred cubic (BCC) structure with a lattice parameter of 2.88 Å. In a laboratory x-ray diffraction experiment carried out on niobium, the copper K-α radiation of a wavelength of 1.54 Å is used. Calculate at which angle the first-order diffraction peak from its (211) planes should occur. Show your calculation process.

5. Explain what is meant by an electron-hole pair (EHP) and how they occur.

6. Explain what happens when a group III element is added to a silicon (Si) matrix. How does this change the ability of the system to conduct current?

7. What is the symbol that is used for the concentration of donor atoms in an n-type semiconductor? What is the symbol that is used for the concentration of holes in an intrinsic semiconductor?

8. Given the following values, calculate the amount of n-type dopant in the system: $p_0 = 1 \times 10^{11}$ cm$^{-3}$ and $n_i = 1.5 \times 10^{10}$ cm$^{-3}$.

9. What are the TWO main ways that current flows in a semiconductor? Explain the difference between them.

10. Explain what is meant by the term 'conductivity' and what factors it is based on for a semiconductor (a relevant equation would be useful here).

11. Given that effective mass of an electron, $m_n^*$, is $9.11 \times 10^{-31}$ kg, $q$ is $1.6 \times 10^{-19}$ C, the mobility of said electron in silicon is 1400 cm$^2\cdot$(V$\cdot$s)$^{-1}$, calculate the mean time between

collisions at room temperature. Use the Einstein relationship to calculate the diffusion coefficient, $D_n$, for electrons in silicon.

12. (i) The bandgap of silicon is 1.14 eV. What is the probability of finding a free electron 0.6 eV above the Fermi level? 0.8 eV? 1 eV? Assume room temperature ($T$ = 300 K) and $k_B$ = $1.38 \times 10^{-23}$ J/K = $8.62 \times 10^{-5}$ eV/K.
    (ii) The silicon sample is now doped with $10^{17}$ arsenic (a donor) atoms/cm$^3$. Given the same energy levels, how do the probabilities above change? Assume that $n_i = 1.5 \times 10^{10}$ cm$^{-3}$.
    (iii) What is the equilibrium hole concentration, $p_0$, at 300 K in the doped sample and where is the Fermi level with respect to the intrinsic level?

13. (i) A silicon (Si) sample is doped with $10^{18}$ As atoms/cm$^3$. Arsenic is a donor atom dopant. What is the equilibrium hole concentration, $p_0$, at 300 K and where is the Fermi level with respect to the intrinsic level?
    (ii) If the substance were to be converted to *p*-type, what level of doping with boron would be required to move the Fermi level 0.2 eV BELOW the intrinsic level?

14. A sample of silicon is doped with $3.3 \times 10^{13}$ atoms/cm$^3$ of arsenic (As). Arsenic is a donor atom dopant. Find
    (i) the resulting electron concentration $n_0$;
    (ii) the hole concentration $p_0$;
    (iii) the Fermi level relative to the intrinsic level.
    How much further doping is necessary to increase the Fermi level so that it is 0.4 eV above the intrinsic level? Assume that $n_i$ (Si) = $1.5 \times 10^{10}$ cm$^{-3}$.