NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

ACADEMIC YEAR 2023
Term 1

H3 Semiconductor Physics & Devices

TUTORIAL 2

Energy Bands

Question 1

State the electronic configuration of silicon atom in the ground state. Based on Fig. 3.4 (Chapter 3) explain how the energy bands and forbidden band of silicon are formed. If the equilibrium lattice spacing were to change by a small amount, discuss how you would expect the electrical properties of silicon to change. Explain why the energy bandgap decreases as temperature increases.

Question 2

Gallium arsenide (GaAs) has an energy bandgap of 1.42 eV at room temperature. For light incident on the semiconductor, what is the maximum wavelength to create electron-hole pairs?

[875 nm]

Question 3

Draw the energy band diagram of a semiconductor with and without the application of an electric field ξ. Show that the electric field ξ is related to the electron energy E by

$$\xi = \frac{1}{q}\frac{dE}{dx}$$

Question 4

Considering the *E*-*k* diagram in Fig 3.14 (Chapter 3) explain the direct and indirect bandgap semiconductors. Explain also, why indirect bandgap semiconductor is not suitable for light emitting devices.

Question 5

A voltage is applied across an intrinsic semiconductor sample at 300 K. There is negligible current when the sample is in the dark or illuminated by light of wavelength $\lambda \geq 874$ nm. When the sample is exposed to light of wavelength $\lambda = 650$ nm, a large current is measured. Determine the bandgap of the semiconductor.

NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

ACADEMIC YEAR 2023
Term 1

H3 Semiconductor Physics & Devices

TUTORIAL 3

Thermal equilibrium, Donor & acceptor impurities, Fermi-Dirac Distribution

Question 1

a) Describe how boron atoms act as impurities in a Si crystal.
b) Describe how phosphorus atoms act as impurities in a Si crystal.

Question 2

A silicon sample is doped with donor impurities to a concentration of 1×10^{15} /cm^3. Describe how the electron concentration in the conduction band changes with temperature.

Question 3

Assuming that the electrons in a particular material follow the Fermi-Dirac distribution function,

a) show that the probability of finding a hole with energy E is given by

$$\frac{1}{1+\exp[(E_F-E)/k_BT]}$$

b) calculate the temperature at which there is a 1% probability that a state 0.30 eV below the Fermi energy level will contain a hole,
c) show that the Fermi-Dirac function is symmetrical about the Fermi energy.

[757 K]

Question 4

Consider the two energy levels E_1 and E_2 with $E_1 > E_2$ and an energy separation of 1.12 eV. Assume that the Fermi level E_F is in between the two levels and that T = 300 K. If $E_1 - E_F$ = 0.30 eV, determine the probability that an energy state at $E = E_1$ is occupied by an electron and the probability that an energy state at $E = E_2$ is empty.

[9.2×10^{-6}, 1.73×10^{-14}]

Question 5

The probability that an energy state E_y is empty is 97%. What is the probability that an energy state 0.1 eV below E_y is occupied by an electron? Assume that T = 300 K.

[0.597]

NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

ACADEMIC YEAR 2023
Term 1

H3 Semiconductor Physics & Devices

TUTORIAL 4

Thermal equilibrium, Doping, Carrier Concentration

Question 1

Write down the expression for thermal equilibrium electron and hole concentrations in terms of the effective density of states, the band edges and the Fermi level. Hence,

a) obtain the expression of the intrinsic Fermi level E_i to the center of the band gap E_{mid} and calculate the displacement of E_i from E_{mid} at 300 K, assuming the electron and hole effective masses are 1.1 m_0 and 0.56 m_0 respectively.

b) justify the position of the Fermi energy level in the energy band diagram for an intrinsic, *n*-type and *p*-type doped semiconductor.

[–0.013 eV]

Question 2

Consider a silicon crystal doped with boron atoms to a concentration of 5×10^{17} cm^{-3} at 300 K,

a) determine the majority and minority carrier concentrations,

b) determine the position of the Fermi energy level inside the bandgap.

Take n_i to be 1.5×10^{10} cm^{-3} .

[5×10^{17} cm^{-3}, 450 cm^{-3}, 0.448 eV below E_i]

Question 3

Consider a germanium sample at 350 K which has been doped with donor impurities to a concentration of 6.0×10^{13} cm^{-3}. Taking the intrinsic carrier concentration as 2×10^{13} cm^{-3},

a) calculate the thermal equilibrium electron and hole concentrations.

b) determine the position of the Fermi energy level inside the bandgap.

[6.6×10^{13} cm^{-3}, 6.05×10^{12} cm^{-3}, 0.031 eV above E_i]

Question 4

Show that the intrinsic carrier concentration is related to the energy bandgap as

$$n_i = \sqrt{N_c N_v}\exp\left[-\frac{E_g}{2k_B T}\right]$$

Based on the material parameters given in the following table, calculate the intrinsic carrier concentrations of silicon and germanium at 300K.

Table 1:

	silicon	germanium
N_c [cm^{-3}]	2.8×10^{19}	1.04×10^{19}
N_v [cm^{-3}]	1.04×10^{19}	6.0×10^{18}
Bandgap [eV]	1.12	0.66

[6.8×10^{9} cm^{-3}, 2.3×10^{13} cm^{-3}]

Question 5

A semiconductor sample is doped with donor atoms to a concentration of 2.0×10^{14} cm^{-3}. The bandgap energy and intrinsic carrier concentration of the semiconductor at 310 K are 0.9 eV and 6.0×10^{13} cm^{-3}, respectively.

(a) Determine the minority and majority carrier concentrations in the sample.

(b) Calculate the position of the Fermi level E_F with respect to the intrinsic Fermi level E_i. Sketch the band diagram of the sample and indicate clearly the positions of E_C, E_V, E_i and E_F.

(c) The sample is subsequently doped with acceptor impurity atoms such that the Fermi level is shifted to a position 0.05 eV below E_i. Determine the acceptor impurity concentration used.

[1.66×10^{13} cm^{-3}, 2.17×10^{14} cm^{-3}, 0.034 eV above E_i, 5.9×10^{14} cm^{-3}]

NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

ACADEMIC YEAR 2023
Term 1

H3 Semiconductor Physics & Devices

TUTORIAL 5

Carrier Transport

Question 1

A pure silicon sample maintained at room temperature has an intrinsic carrier concentration of 1.5×10^{10} cm^{-3}. It is first doped with donors of concentration 2×10^{14} cm^{-3}, followed by acceptors of concentration 4×10^{14} cm^{-3}. Assuming that the carrier mobilities are μ_n = 1350 cm^2/Vs and μ_p = 480 cm^2/Vs,

a) calculate the majority and minority carrier concentrations,

b) what is the resistivity of the pure sample, prior to the two types of dopings?

c) how will the resistivity change after the dopings?

[2×10^{14} cm^{-3}, 1.125×10^{6} cm^{-3}, $2.\times10^{5}$ Ω-cm, 65 Ω-cm]

Question 2

The electron concentration in silicon at 300K is given by

$$n(x) = 10^{16}\exp\left(-\frac{x}{a}\right)\ \text{cm}^{-3}$$

where a = 18 μm and x is valid for $0 \le x \le 25$ μm. The electron diffusion coefficient is 25 cm^2/s and the electron mobility is 960 cm^2/Vs. The total electron current density through the semiconductor is constant and equal to –40 A/cm^2. The electron current has both diffusion and drift current components. Determine the electric field as a function of x which must exist in the semiconductor.

[$14.5 - 26.0\exp(x/18)$ V/cm]

Question 3

A constant electric field, ξ = 12 V/cm, exists in the $+x$ direction of an n-type GaAs semiconductor for $0 \le x \le 50$ μm. The total electron current density is a constant and is J = 100 A/cm^2. At x = 0, the drift and diffusion currents are equal. Assuming the sample is at 300 K and the electron mobility μ_n is 8000 cm^2/V-s,

a) determine the expression for the electron concentration $n(x)$.

b) calculate the electron concentration at x = 0 and x = 50 μm.

c) calculate the drift and diffusion current densities at x = 50 μm.

[$6.5\times10^{15} - 3.24\times10^{15}\exp(-x/2.16\times10^{-3})$ /cm^3, 3.26×10^{15} /cm^3, 6.18×10^{15} /cm^3, 94.9 A/cm^2, 5.1 A/cm^2]

Question 4

A semiconductor material has electron and hole mobilities μ_n and μ_p, respectively. Show that the minimum value of conductivity $\sigma_{\min}$ is given by

$$\sigma_{\min} = 2qn_i\left(\mu_n\mu_p\right)^{1/2}$$

Question 5

The electric field ξ in a p-type semiconductor sample at 300 K is given by

$$\xi = -10^4 x \ \ \text{V/cm}$$

where the distance x is valid for $0 \le x \le 20\ \mu\text{m}$. The total hole current density is zero throughout the sample and the hole concentration at x = 0 is 10^{15} cm^{-3}. Assume that the hole mobility is μ_p = 650 cm^2/V-s.

(a) Determine the hole concentration as a function of x.

(b) Calculate the hole drift and diffusion current densities at x = 5 μm.

[$p = 10^{15} \exp\left(-1.93\times10^{5} x^{2}\right)\ \ \text{cm}^{-3}, J_{drift} = -0.496\ \ \text{A/cm}^{2}$]

NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

ACADEMIC YEAR 2023
Term 1

H3 Semiconductor Physics & Devices

TUTORIAL 6

Non-Equilibrium

Question 1

A p-type silicon sample has an acceptor doping concentration of 10^{16} cm^{-3}. At $t < 0$, it is uniformly irradiated with light of an appropriate wavelength resulting in the generation of electron-hole pairs at a rate of $G_L = 10^{17}$ cm^{-3}s^{-1}. For a temperature of 300 K,

(a) assuming a minority carrier lifetime of $\tau_{n0} = 10$ µs, calculate the steady state excess carrier concentrations,

(b) determine the quasi-Fermi energy levels and indicate their positions in an energy band diagram.

Take $n_i = 1.5\times10^{10}$ cm^{-3}.

[10^{12} cm^{-3}, 0.347 eV, 0.109 eV]

Question 2

A piece of p-type doped silicon at 300 K has an acceptor concentration of 5×10^{14} /cm^3. Assume excess carriers are present and that $E_F - E_{Fpq} = 0.01\ k_BT$ and intrinsic concentration of 1.5×10^{10} /cm^3.

(a) Does this condition correspond to low injection?

(b) Determine $E_{Fnq} - E_i$.

[Yes, 0.150 eV]

Question 3

A silicon sample at 300 K is n-type with $N_d = 5\times10^{16}$ cm^{-3} and $N_a = 0$. The sample has a length of 0.1 cm and a cross-sectional area of 10^{-4} cm^2. A voltage of 5 V is applied between the ends of the sample. For $t < 0$, the sample has been illuminated with light, producing an excess-carrier generation rate of 5×10^{21} cm^{-3}s^{-1} uniformly throughout the entire silicon. The minority carrier lifetime is 0.3 µs. At $t = 0$, the light is turned off. Derive the expression for the current in the sample as a function of time $t \geq 0$.

Take $\mu_n = 1350$ cm^2/Vs, $\mu_p = 480$ cm^2/Vs and $n_i = 1.5\times10^{10}$ /cm^3.

[$54 + 2.2 \exp(-t/\tau_{p0})$ mA]

Question 4

a) Consider a semi-infinite p-type silicon bar doped homogeneously to a value of 1.39×10^{16} /cm^3 at 300 K. The intrinsic carrier concentration is 1.5×10^{10} /cm^3. The applied electric field is zero. A minority carrier concentration is electrically injected at one end of the sample ($x = 0$) such that the excess minority carrier concentration at $x = 0$ is 2.49×10^{13} /cm^3. The electron mobility and the electron lifetime are 1450 cm^2/V-s and 10^{-6} s respectively.

i) Calculate the steady state excess electron concentration as function of x.

ii) Calculate the electron diffusion current density at $x = 0$ and $x = 10$ μm.

[$2.49\times10^{13}\exp(-x/61.4\times10^{-4})$ /cm^3, 24.5 mA/cm^2, 20.8 mA/cm^2]

b) Consider a semi-infinite n-type silicon bar doped homogeneously to a value of 2.16×10^{16} /cm^3 at 300 K. The intrinsic carrier concentration is 1.5×10^{10} /cm^3. The applied electric field is zero. A minority carrier concentration is electrically injected at one end of the sample ($x = 0$) such that the excess minority carrier concentration at $x = 0$ is 1.6×10^{13} /cm^3. The hole mobility and the hole lifetime are 450 cm^2/V-s and 10^{-8} s respectively.

i) Calculate the steady state excess hole concentration as function of x.

ii) Calculate the hole diffusion current density at $x = 0$.

[$1.6\times10^{13}\exp(-x/3.42\times10^{-4})$ /cm^3, 87.6 mA/cm^2]

Question 5

A bias voltage of V_s is applied across an n-type Si sample with a length of 0.6 cm and a cross-sectional area of 2×10^{-4} cm^2. The acceptor and donor impurity concentrations in the sample are $N_a = 3\times10^{16}$ cm^{-3} and $N_d = 6\times10^{16}$ cm^{-3}, respectively. The sample is uniformly illuminated with light at time $t < 0$ to produce a steady-state excess carrier concentration of $\Delta p = 3\times10^{14}$ cm^{-3}. The excitation light is removed at time $t = 0$. The current in the sample at time $t = 0.1$ μs is 1 mA. Assume that $T = 300$ K, $L_p = 80$ μm, $\mu_n = 200$ cm^2/V-s, $\mu_p = 2110$ cm^2/V-s and $n_i = 5\times10^{10}$ cm^{-3}.

(a) Calculate the majority carrier concentration in the compensated semiconductor.

(b) Determine the lifetime of the minority carrier and the optical generation rate at time $t < 0$.

(c) Derive an expression for the conductivity of the Si sample as a function of time t after the excitation light is removed. Hence find the value of V_s.

[3×10^{16} cm^{-3}, 1.174 μs, 2.56×10^{20} cm^{-3}/s, $\sigma(t) = 0.111\exp(-t/1.174\ \mu s) + 0.9612$, 2.822 V]