NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

ACADEMIC YEAR 2021/22
SEMESTER 2

EE2003 SEMICONDUCTOR FUNDAMENTALS

TUTORIAL 2

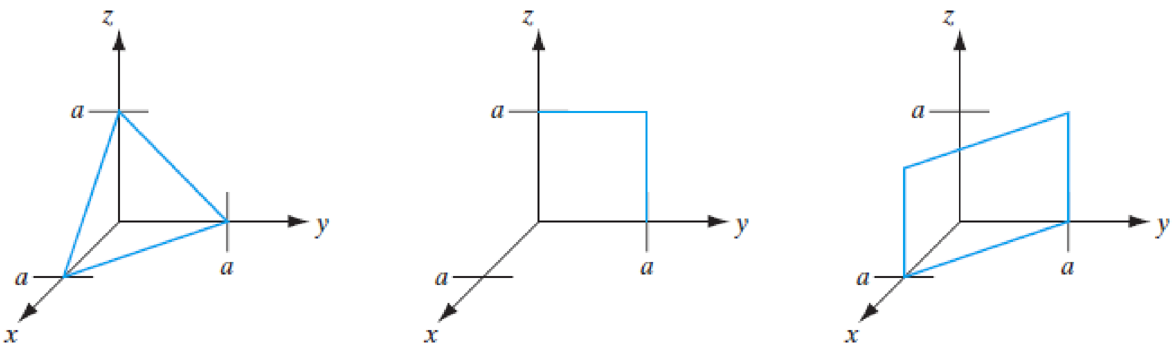
Electronics Configuration, Crystal Structure (Lectures 2, 3, 4 [slides #28-39])

Question 1

Schematically show the number of electrons in the various subshells of a Carbon (C) atom with the electronic configuration of $1s^2 2s^2 2p^2$ and a mass number of 12. Indicate how many protons and neutrons are in the nucleus. Is this atom chemically reactive? Explain your reason.

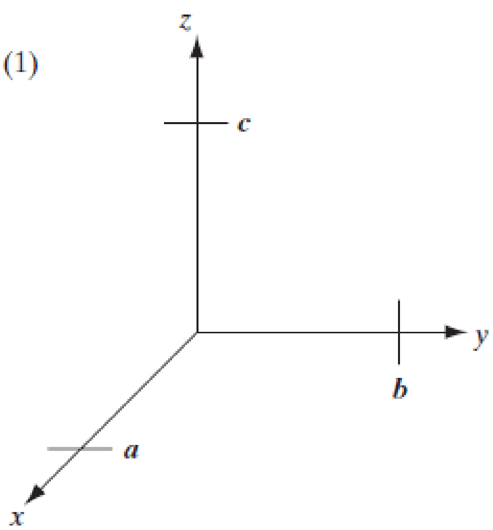
Question 2

(a) Label the following planes using the correct notation for a cubic lattice of unite cell edge length ***a*** (shown within the unit cell).

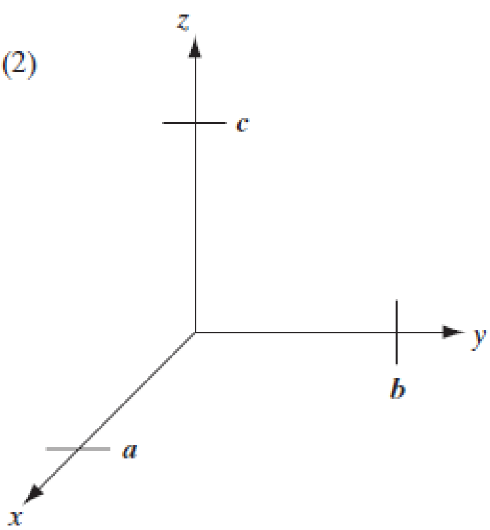


(b) On the following sets of axes, (i) sketch the [011] direction, and (ii) a (111) plane (for a cubic system with primitive vectors ***a***, ***b***, and ***c***).

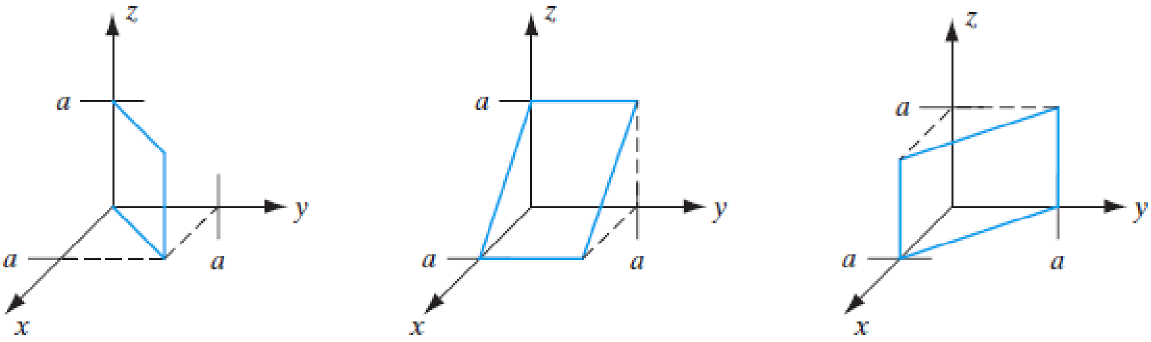
(1)



(2)



(c) The following planes (shown within the first quadrant for $0 < \boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z} < \boldsymbol{a}$ only, with the dotted lines for reference only) are all from the what one set of *equivalent* planes? Use the correct notation.



Question 3

Calculate the surface density of atoms on (111), (110) and (100) planes for the following crystal structure: (a) simple cubic, (b) body-centered cubic, and (c) face-centered cubic. Assume the lattice constant is ***a***. For each crystal structure, identify the plane with the highest surface density of atoms.

Question 4

Assume that each atom is a hard sphere with the surface of each atom in contact with the surface of its nearest neighbor. Determine the percentage of total unit cell volume that is occupied in a (a) simple cubic lattice, (b) face-centered cubic lattice, and (c) body-centered cubic lattice.

[52.4%, 74%, 68%]

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TUTORIAL 3

Si/GaAs Crystal Structure, Energy Bands (Lectures 4 [slides #40-53], 5, 6)

Question 1

For the unit cell of the silicon crystal with lattice constant of 5.43 Å,

a) determine the number of atoms in the unit cell,
b) calculate the shortest distance between any two atoms,
c) calculate the volume density of silicon atoms (number of atoms/cm^3) in the crystal

[8, 2.35 Å, 5.0×10^{22} atoms/cm^{-3}]

Question 2

Refer to Figure 2.7 (the diamond structure for Si) of your lecture notes.

(a) The surface of a Si wafer is a (100) plane. Sketch the placement of Si atoms on the surface of the wafer.
(b) Determine the number of atoms per cm^2 at the surface of the wafer. Take Si lattice constant as 5.43Å.
(c) Repeat parts (a) and (b), this time taking the surface of the Si wafer to be a (110) plane.

Question 3

Considering the *E*-*k* diagram in Fig. 2.1 for Si and GaAs:

(a) Which material appears to have the lowest electron effective mass in the conduction band?
(b) Which of these would you expect to produce photons (light) more efficiently through electron-hole recombination?
(c) Consistent with your answer to part (b), what would you expect the energy of the emitted photons to be? What would be their wavelength in µm? You can use E_g(Si) = 1.11 eV, and E_g (GaAs) = 1.43 eV.

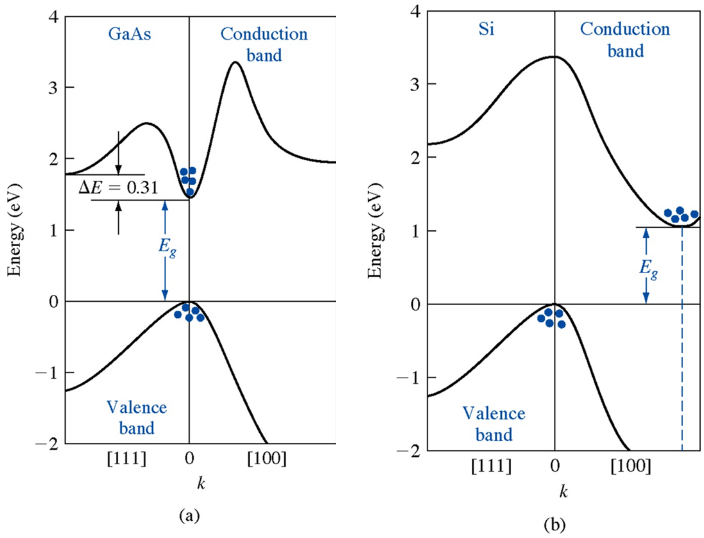

Fig. 2.1 Energy band structure of (a) GaAs and (b)

Question 4

Fig. 2.2 shows the parabolic E versus K curve in the valence band for a hole in two semiconductor materials A and B.

(i) Determine the relative effective mass (m^*/m_0) of the hole in valence band A.
(ii) Is the hole effective mass in the valence band B heavier or lighter? Justify your answer.

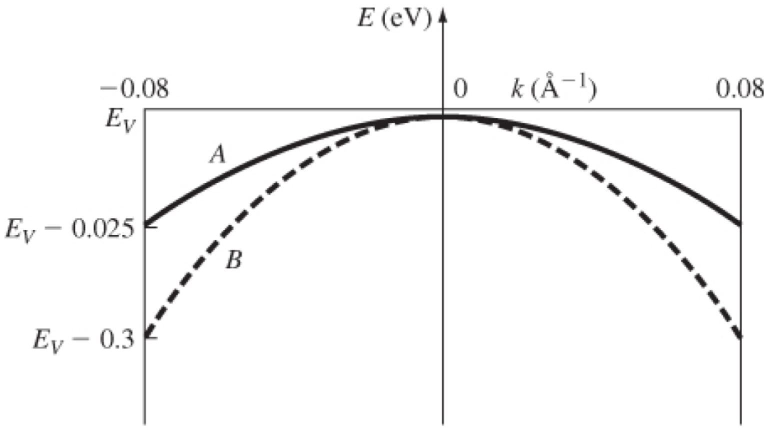

Fig. 2.2: E versus K curve in the valence band for a hole in two semiconductor materials A and B

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TUTORIAL 4

Donor & acceptor impurities, Thermal equilibrium (Lectures 7, 8, 9, 10, 11)

Question 1

Refer to the bonding model of GaAs in Fig. 3.1.

(a) Draw the bonding model for GaAs depicting the removal of the shaded Ga and As atoms. (*Hint: Ga and As take their bonding electrons with them when they are removed from the lattice*).

(b) Redraw the bonding model for GaAs showing the insertion of Si atoms into the missing Ga and As atom sites.

(c) Is the GaAs *p*- or *n*-type when Si atoms replace the Ga atoms? Explain.

(d) Is the GaAs *p*- or *n*-type when Si atoms replace the As atoms? Explain.

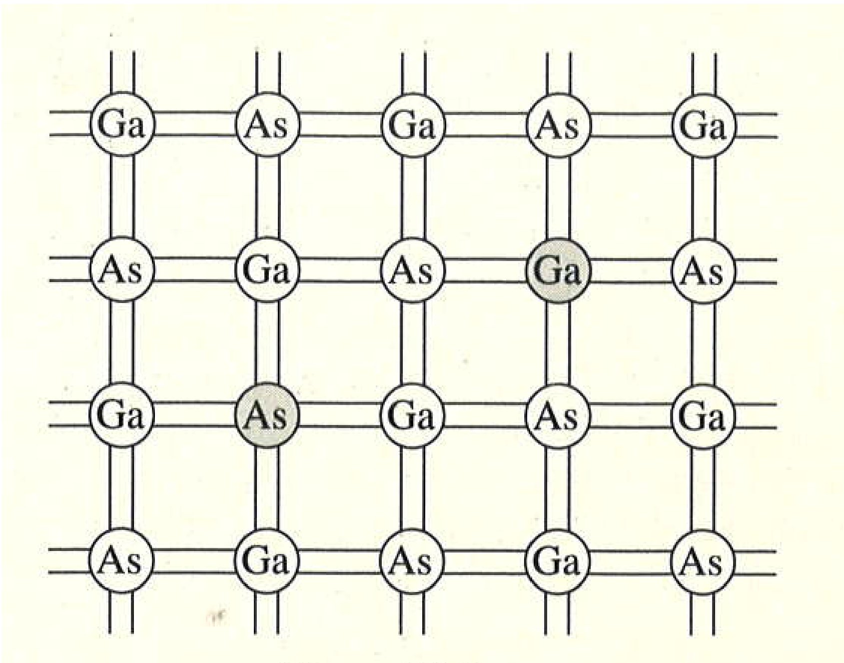

Fig. 3.1: The 2D bonding model for GaAs.

Question 2

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

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

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,

[757 K]

Question 3

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 4

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 5

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 6

A hypothetical semiconductor has an intrinsic carrier concentration of 1.0×10^{10} cm^{-3} at 300K, it has conduction and valence band effective densities of states N_c and N_v , both equal to 10^{19} cm^{-3}.

(a) What is the band gap E_g?

(b) If the semiconductor is doped with $N_d = 1.0 \times 10^{16}$ donors/cm^3, what are the equilibrium electron and hole concentrations at 300K?

(c) If the same piece of semiconductor, already having $N_d = 1.0 \times 10^{16}$ donors/cm^3, is now doped with $N_a = 2 \times 10^{16}$ acceptors/cm^3, what are the new equilibrium electron and hole concentrations at 300K?

(d) Consistent with your answer to part (c), what is the Fermi level position with respect to the intrinsic Fermi level, $E_F - E_i$?

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TUTORIAL 5

Carrier Transport (Lectures 12, 13)

Question 1

Under equilibrium conditions at room temperature, a certain region of a Si device of length L has non-uniform acceptor doping as follows:

$p(x) \approx N_A(x) = n_i \exp((a-x)/b)$ ……… $0 \le x \le L$

where a = 1.8 μm, b = 0.1 μm, and L = 0.8 μm.

(a) Draw the energy band diagram for the $0 \le x \le L$ region by showing E_c, E_f, E_i, and E_v on your diagram given the bandgap of silicon is 1.12eV. Explain your steps.

(b) Make a sketch of the electric field (ξ) inside the region as a function of position and compute the value of ξ at $x = L/2$.

Question 2

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 3

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 4

A silicon sample is doped such that electron concentration varies linearly across the sample, which is 0.5 μm thick. Donor concentration varies from 0 (at x = 0) to 10^{16} cm^{-3} (at x = 0.5 μm).

(a) Write equations for total electron and hole concentrations as a function of distance x.

(b) Determine electron and hole diffusion current densities if the diffusion coefficients are D_n = 30 cm^2/V.s and D_p = 12 cm^2/V.s, respectively.

(c) At x = 0.5 μm, determine the hole diffusion current density and the position of Fermi level E_F with respect to conduction band edge E_C. Assume temperature = 300K.