3.091 Fall Term 2002

Homework #5 with Solutions

(for weekly quiz)

1. Chemical analysis of a germanium crystal reveals indium at a level of 0.0003 atomic percent.

(a) Assuming that the concentration of thermally excited charge carriers from the Ge matrix is negligible, calculate the density of free charge carriers (carriers/cm^3) in this Ge crystal?

(b) Draw a schematic energy band diagram for this material and label all critical features.

2. Show that green light ($\lambda = 5 \times 10^{-7}$ m) can excite electrons across the band gap of silicon.

3. Determine the amount (in grams) of arsenic required to be substitutionally incorporated into a mole of silicon in order to achieve in it a free-electron density of $5 \times 10^{17}/cm^3$.

4. (a) Electromagnetic radiation of frequency 3.091×10^{14} Hz illuminates a crystal of germanium. Calculate the wavelengths of all photons generated by this interaction. Germanium is an elemental semiconductor with a band gap, E_g, of 0.7 eV.

(b) Sketch the absorption spectrum of germanium, i.e., plot % absorption *vs* wavelength, λ.

5. (a) Chemical analysis of a silicon crystal reveals arsenic at a level of 0.0002 atomic percent. Assuming that the concentration of thermally excited charge carriers from the Si matrix is negligible, calculate the density of free charge carriers (carriers/cm^3) in this Si crystal?

(b) Draw a schematic energy band diagram for this material and label all critical features.

6. (a) Determine the amount (in grams) of boron required to be substitutionally incorporated into 1 kg of germanium in order to establish a charge carrier density of $3.091 \times 10^{17}/cm^3$.

(b) Draw a schematic energy band diagram for this material and label all critical features.

7. (a) An electron beam strikes a crystal of cadmium sulfide (CdS). Electrons scattered by the crystal move at a velocity of 4.4×10^5 m/s. Calculate the electron energy of the incident beam. Express your result in eV. CdS is a semiconductor with a band gap, E_g, of 2.45 eV.

(b) Cadmium telluride (CdTe) is also a semiconductor. Do you expect the band gap of this material to be greater or less than the band gap of CdS? Explain.

8. (a) Aluminum phosphide (AlP) is a semiconductor with a band gap, E_g, of 3.0 eV. Sketch the absorption spectrum of this material, *i.e.*, plot % **absorption** *versus* **wavelength**, λ.

(b) Aluminum antimonide (AlSb) is also a semiconductor. Do you expect the band gap of this material to be greater than or less than the band gap of AlP? Explain.

9. You wish to make n-type germanium.

(i) Name a suitable dopant.

(ii) Name the majority charge carrier in the doped material.

(iii) Draw a schematic energy band diagram of the doped material. Label the valence band, conduction band, and any energy levels associated with the presence of the dopant.

1. Each In atom will attract an electron and thus create a "mobile hole"; we only have to determine the number of In atoms/cm^3. The atomic volume of the host crystal (Ge) is given on your PT as 13.57 cm^3/mole.

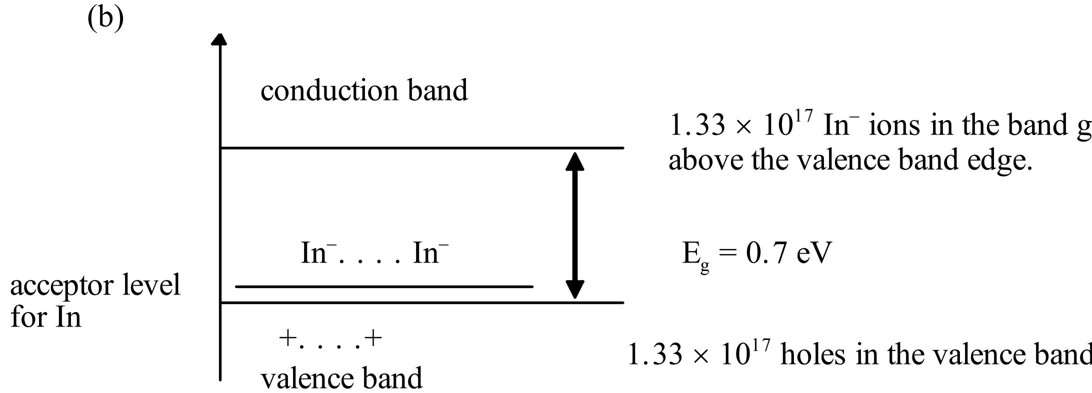
(a) # Ge atoms/cm^3 = $\frac{6.02\times10^{23}\ \text{atoms}}{1\ \text{mole}}\times\frac{1\ \text{mole}}{13.57\ \text{cm}^3}$

$= 4.44 \times 10^{22}$ atoms/cm^3

In atoms/cm^3 = $4.44 \times 10^{22} \times 0.0003 \times 10^{-2} = 1.33 \times 10^{17}$ In/cm^3

The number of free charge carriers ("holes") is 1.33×10^{17}/cm^3; they are created through the acquisition of one electron by each In atom from the valence band of the host crystal.

(b)



2. $\lambda_{crit} = \frac{hc}{E_g} = \frac{6.62\times10^{-34}\times3\times10^{8}}{1.1\times1.6\times10^{-19}} = 1.13\times10^{-6}$ m

The critical λ for silicon is 1.1×10^{-6} m; thus radiation of $\lambda = 5 \times 10^{-7}$ m $= 0.5 \times 10^{-6}$ m has even more energy than that required to promote electrons across the band gap.

3. We determine the atomic (molar) volume of Si (PT); thus we know the total number of As atoms required, and convert that number into number of grams of As:

Si (Atomic Volume): At.Wt./ρ = 12.1×10^{-6} m^3/mole

# of As atoms required = $12.1 \times 5 \times 10^{17} = 6.1 \times 10^{18}$ As/mole of Si

g of As required: 6.1×10^{18} As atoms × {74.92 g/(6.02×10^{23})}

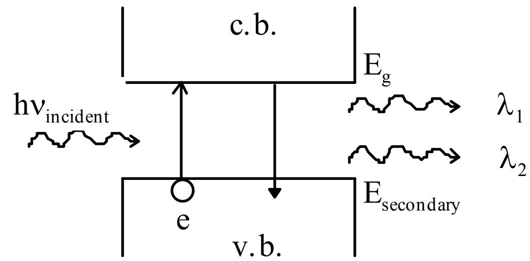
= 7.59 × 10^{-4} g As

4. (a) First compare E of the incident photon with E_g:

$E_{\text{incident photon}} = h\nu = 6.6 \times 10^{-34} \times 3.091 \times 10^{14} = 2.04 \times 10^{-19}$ J

$E_g = 0.7\ \text{eV} = 1.12 \times 10^{-19}\ \text{J} < E_{\text{incident photon}}$

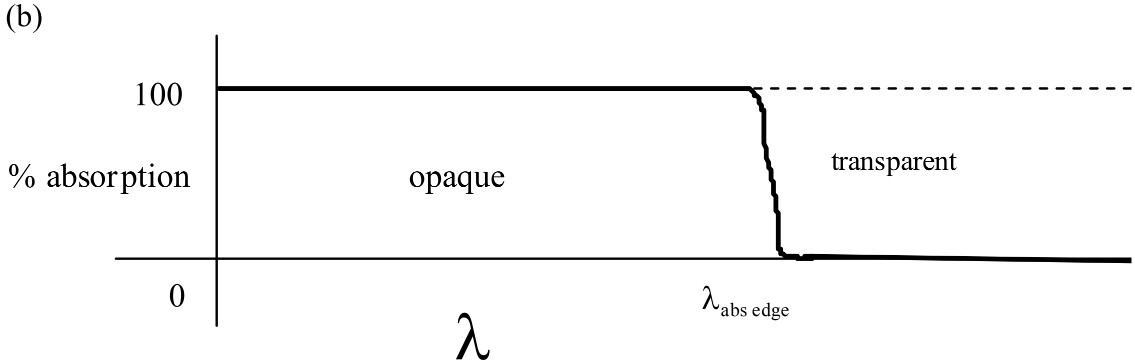
∴ electron promotion followed by emission of a new photon of energy equal to E_g occurs, and transmission of a secondary photon of energy, $E_{secondary} = E_{incident} - E_g$, and thus of longer λ than that of the incident photon



$$\lambda_1 = \frac{hc}{E_g} = \frac{6.6\times10^{-34}\times3\times10^{8}}{0.7\times1.6\times10^{-19}} = 1.77\times10^{-6}\,\text{m}$$

$$\lambda_2 = \frac{hc}{E_{incident} - E_g} = \frac{6.6\times10^{-34}\times3\times10^{8}}{2.04\times10^{-19} - 1.12\times10^{-19}} = 2.15\times10^{-6}\,\text{m}$$

(b)



$\lambda_{abs\ edge}$ = λ_1 as calculated in part (a) = 1.77 μm

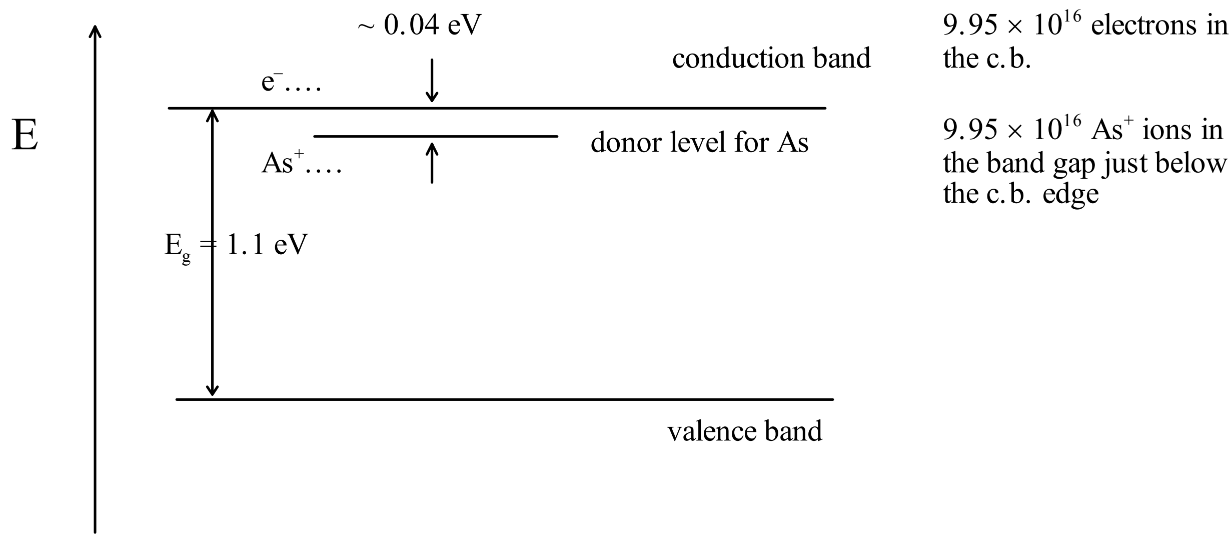
5. Each As atom will donate a free electron to the conduction band; we only have to determine the number of As atoms/cm^3. The molar volume of Si is given on your PT as $V_{molar} = 12.1\ cm^3/mole$.

(a) $\#\ \text{Si atoms/cm}^3 = \frac{6.02\times10^{23}\ \text{atoms}}{1\ \text{mole}} \times \frac{1\ \text{mole}}{12.1\ \text{cm}^3} = 4.98\times10^{22}\ \text{atoms/cm}^3$

$\#\ \text{As atoms/cm}^3 = 4.98\times10^{22}\times0.0002\times10^{-2} = 9.95\times10^{16}\ \text{As/cm}^3$

free charge carriers is $9.95\times10^{16}/cm^3$.

(b)



6. PT gives molar volume of Ge as 13.57 cm^3 and 1 mole of Ge weighs 72.61 g

set up ratio: $\dfrac{72.61}{13.6} = \dfrac{1000 \text{ g}}{x}$ and solve for x to get 187.30 cm^3

addition of boron gives 1 charge carrier/B atom

☞ B concentration in Si must be 3.091×10^{17} B/cm^3

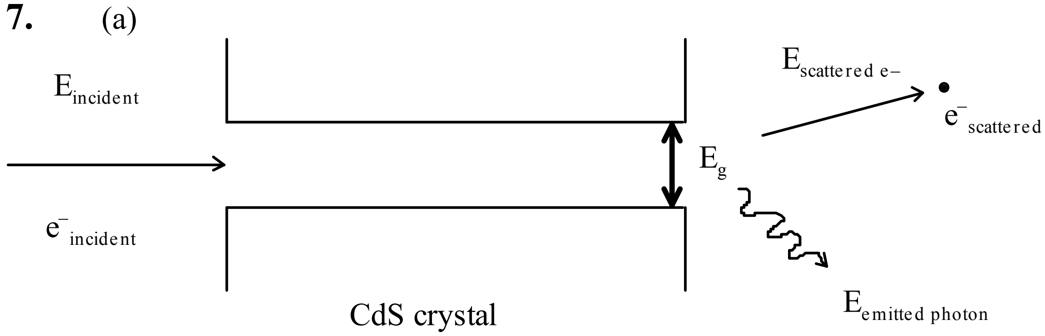
N_{av} B atoms weigh 10.81 g

$\therefore$ 3.091×10^{17} B atoms weigh $\dfrac{3.091 \times 10^{17}}{6.02 \times 10^{23}} \times 10.81 = 5.55 \times 10^{-6}$ g

$\therefore$ to 1 cm^3 of Ge, add 5.55×10^{-6} g B

☞ to 187.30 cm^3 of Ge, add $187.30 \times 5.55 \times 10^{-6} = 1.04 \times 10^{-3}$ g B

7. (a)



$E_{incident\ e-} = E_{emitted\ photon} (=E_g) + E_{scattered\ e-} = E_g + \frac{1}{2} mv^2$

$$= 2.45 \text{ eV} + \frac{1}{2} \times \frac{9.11 \times 10^{-31} \text{ kg} \times \left(4.4 \times 10^{5} \text{ m/s}\right)^2}{1.6 \times 10^{-19} \text{ eV/J}}$$

$= 2.45 \text{ eV} + 0.55 \text{ eV} = 3.00 \text{ eV}$

(b) $E_g(CdTe) < E_g(CdS)$

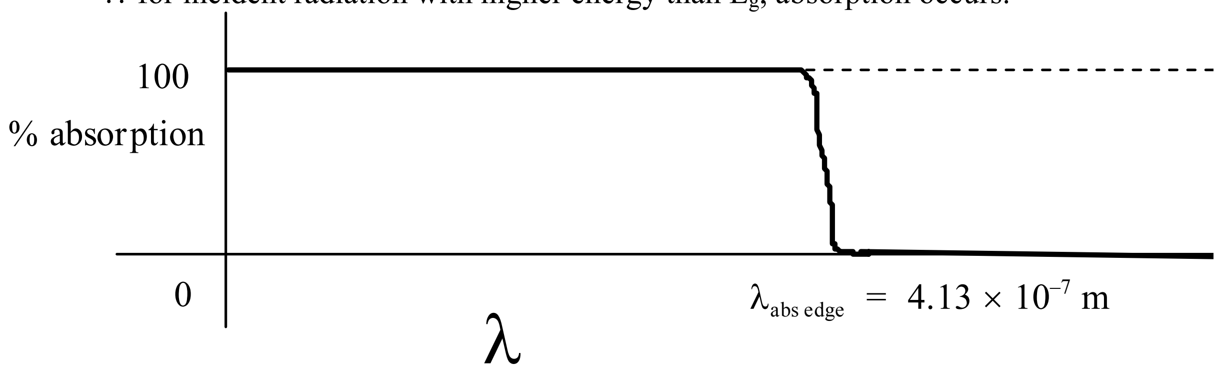
the Cd–S bond is stronger than Cd–Te bond because although both S and Te are group 16, Te is much larger than S

8. (a) first calculate the absorption edge:

$$E_g = \frac{hc}{\lambda_{abs\ edge}} \quad ☞ \quad \lambda_{abs\ edge} = \frac{hc}{E_g} = \frac{6.6 \times 10^{-34} \times 3 \times 10^{8}}{3.0 \times 1.6 \times 10^{-19}}$$

$$= 4.13 \times 10^{-7} \text{ m}$$

∴ for incident radiation with higher energy than E_g, absorption occurs.



(b) $E_g(AlSb) < E_g(AlP)$

the Al–P bond is stronger than Al–Sb bond because although both P and Sb are group 15, Sb is much larger than P.

9. (i) You need to dope with an electron donor, which means an element from Group 15. So this gives you P, As, Sb as candidates.

(ii) The majority charge carrier is the electron, which moves in the conduction band.

(iii) See answer to 5 (b).