

Session #14: Homework Solutions

Problem #1

- (a) Determine the amount (in grams) of boron (B) that, substitutionally incorporated into 1 kg of germanium (Ge), will establish a charge carrier density of $3.091 \times 10^{17}/\text{cm}^3$.
- (b) Draw a schematic energy band diagram for this material, and label all critical features.

Solution

- (a) The periodic table gives the molar volume of Ge as 13.57 cm^3 and 1 mole of Ge weighs 72.61 g, so set up the ratio $\frac{72.61}{13.6} = \frac{1000 \text{ g}}{x}$ and solve for x to get 187.30 cm^3 for the total volume. The addition of boron gives 1 charge carrier/B atom.

→ B concentration in Si must be $3.091 \times 10^{17} \text{ B}/\text{cm}^3$

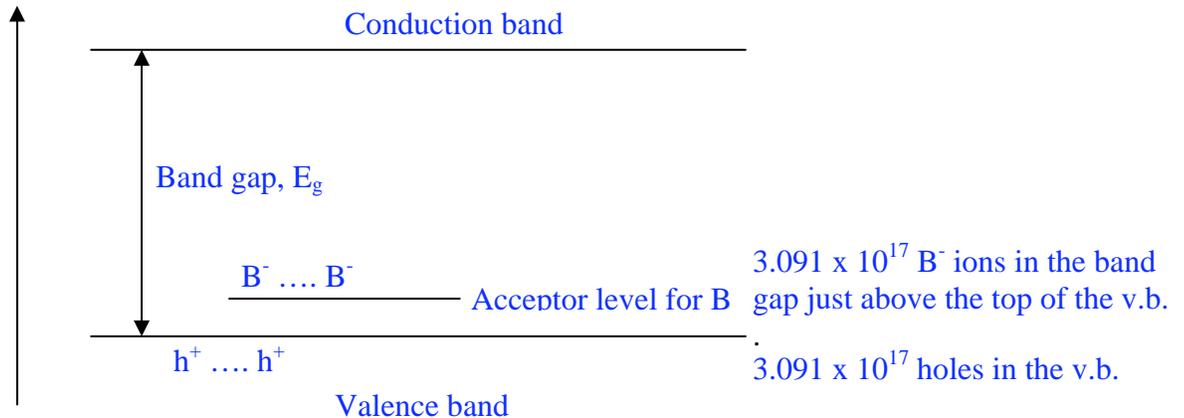
N_A of B atoms weighs 10.81 g

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

∴ for every 1 cm^3 of Ge, add $5.55 \times 10^{-6} \text{ g B}$

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

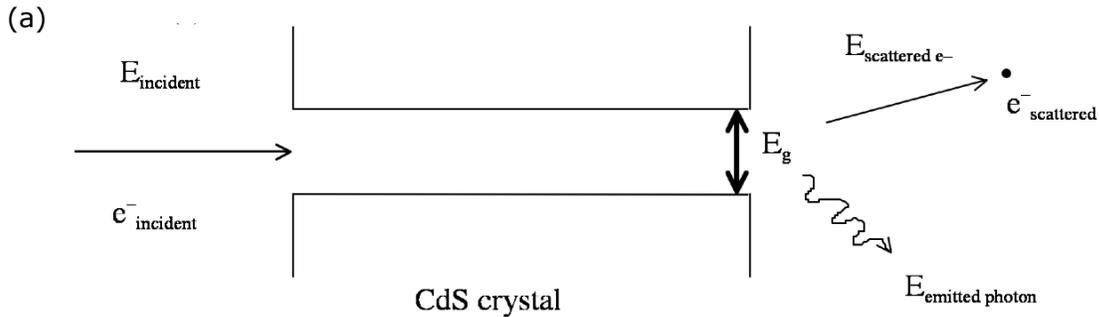
(b)



Problem #2

- (a) An electron beam strikes a crystal of cadmium sulfide (CdS). Electrons scattered by the crystal move at a velocity of $4.4 \times 10^5 \text{ m/s}$. Calculate the 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.

Solution



$$\begin{aligned}
 E_{\text{incident } e^-} &= E_{\text{emitted } \gamma} + E_{\text{scattered } e^-} = E_g + \frac{mv^2}{2} \\
 &= 2.45 \text{ eV} + \frac{1}{2} \times \frac{9.11 \times 10^{-31} \text{ kg} \times (4.4 \times 10^5 \text{ m/s})^2}{1.6 \times 10^{-19} \text{ eV/J}} \\
 &= 2.45 \text{ eV} + 0.55 \text{ eV} = 3.00 \text{ eV}
 \end{aligned}$$

(b) $E_g(\text{CdTe}) < E_g(\text{CdS})$

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.

Problem #3

AlN and GaSb are compounds, solid at room temperature. On the basis of bonding considerations and data provided in the periodic table, attempt to predict differences in the properties of these solids.

Solution

Both compounds are of the III-V family, which hybridize and form "adamantine" (diamond-like) structures which places them into the category of semiconductor.

AlN $\Delta EN = 1.43$. The covalent radii of the constituents are small and, combined with the large EN, the bonds (polar covalencies) are very strong – the semiconductor is expected to **exhibit a large band gap** (likely transparent).

GaSb $\Delta EN = 0.24$. The covalent radii of both constituents are significantly larger (than those of AlN), the ionic contribution to bonding is small – the semiconductor is expected to **exhibit a much smaller band gap than AlN**.

AlN: $E_g = 3.8 \text{ eV}$

GaSb: $E_g = 0.8 \text{ eV}$

Problem #4

Explain the difference between extrinsic and intrinsic semiconductors.

Solution

An extrinsic semiconductor is a semiconductor which contains foreign elements capable of contributing mobile charge carriers, electrons, to the conduction band (n-type) or holes to the valence band (p-type). An intrinsic semiconductor contains no foreign elements.

Problem #5

The number of electron-hole pairs in intrinsic germanium (Ge) is given by:

$$n_i = 9.7 \times 10^{15} T^{3/2} e^{-E_g/2KT} [\text{cm}^3] \quad (E_g = 0.72 \text{ eV})$$

- (a) What is the density of pairs at $T = 20^\circ\text{C}$?
(b) Will undoped Ge be a good conductor at 200°C ? If so, why?

Solution

- (a) Recall: T in thermally activated processes is the absolute temperature: $T^\circ\text{K} = (273.16 + t^\circ\text{C})$; Boltzmann's constant = $k = 1.38 \times 10^{-23} \text{ J}/^\circ\text{K}$

$T = 293.16\text{K}$:

$$n_i = 9.7 \times 10^{15} \times 293.16^{\frac{3}{2}} \times e^{-\frac{0.72 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 293.16}}$$

$$= 9.7 \times 10^{15} \times 5019 \times 6.6 \times 10^{-7}$$

$$n_i = 3.21 \times 10^{13} / \text{cm}^3$$

- (b) $200^\circ\text{C} = 473.16\text{K}$

$$n_i = 9.7 \times 10^{15} \times 473.16^{\frac{3}{2}} \times e^{-\frac{0.72 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 473.16}}$$

$$n_i(200\text{K}) = 9.7 \times 10^{15} \times 1.03 \times 10^4 \times 1.47 \times 10^{-4}$$

$$n_i = 1.47 \times 10^{16} / \text{cm}^3$$

The number of conducting electrons (in the conduction band) at 200°C is by about five orders of magnitude less than that of a good conductor. The material will not be a good conductor. (There are additional factors which contribute to the relatively poor conductivity of Ge at this temperature.)

Problem #6

If no electron-hole pairs were produced in germanium (Ge) until the temperature reached the value corresponding to the energy gap, at what temperature would Ge become conductive? ($E_{th} = 3/2 kT$)

Solution

$$E_{th} = \frac{3kT}{2}; E_g = 0.72 \times 1.6 \times 10^{-19} \text{ J}$$

$$T = \frac{0.72 \times 1.6 \times 10^{-19} \times 2}{3 \times 1.38 \times 10^{-23}} = 5565\text{K} = 5.3 \times 10^3 \text{ }^\circ\text{C}$$

The temperature would have to be $5.3 \times 10^3 \text{ }^\circ\text{C}$, about 4400°C above the melting point of Ge.

Problem #7

- (a) How do you expect the conductivity to vary in an intrinsic semiconductor with increasing temperature? Explain your answer.
- (b) How do you expect the conductivity to vary in a metallic conductor with increasing temperature?

Solution

- (a) From our limited knowledge of the conduction behavior, we must assume that in semiconductors the conductivity will increase with T since the number of electrons in the conduction band increases.
- (b) As a first approximation, we can say that the number of free electrons is independent of T ; that, however, the atoms in the lattice will, with increasing temperature, be subject to increased oscillations about their (relatively) fixed position. These oscillations provide greater opportunity for "scattering" of conducting electrons and thus will "reduce" the mobility of the electrons. We can expect the electrical conductivity of metals to decrease with increasing temperature.

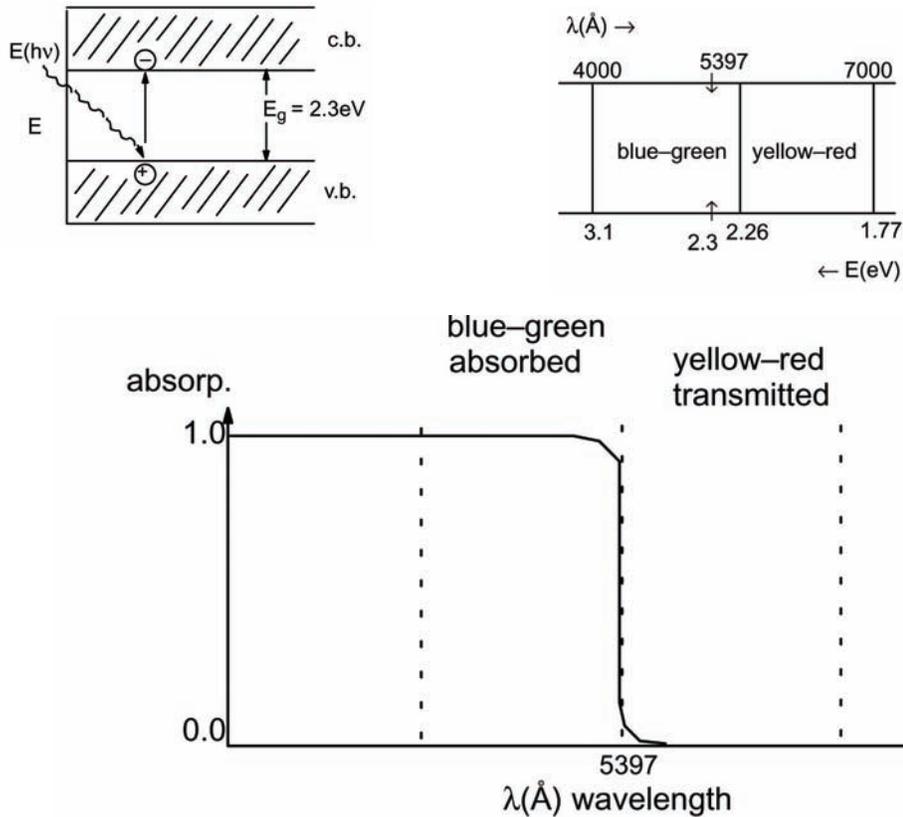
Problem #8

The energy gap (E_g) of ZnSe is 2.3 eV.

- (a) Is this material transparent to visible radiation? Substantiate your answer.
- (b) How could you increase the electrical conductivity of this material? Give the reasons for the effectiveness of your suggested approach.

Solution

- (a) The optical properties of ZnSe can be explained when comparing the energy band of the visible spectrum with the energy band diagram of ZnSe. Absorption takes place via photoexcitation for all radiation with $E \geq 2.3 \text{ eV}$.



From the energy distribution of the visible spectrum we recognize that the blue-green portion has photon energies in excess of the band gap ($E_g = 2.3\text{eV}$) and thus will be absorbed. The yellow-red portion, on the other hand, has photon energies less than the band gap - it will be transmitted. ZnSe, therefore, is expected to exhibit a yellowish-red color.

(b) In principle there are two ways to increase the electrical conductivity of ZnSe:

- a. A temperature rise. Any rise in temperature will increase the number of "thermally activated" charge carriers in the conduction band (electrons) and in the valence band (holes) and, thus, the electronic conductivity.

Aside: The electrical conductivity of solids, demonstrated by the flow of electronic charge carriers under an applied electric field (E), can be formulated through Ohm's law, $J = \sigma E$, which states that the current density ($J =$ number of charges transported through a unit area in a unit time) is proportional ($\sigma =$ conductivity) to the applied electric field. Accordingly:

$$J = N e \bar{v}_d$$

where $N =$ number of charge carriers/unit volume, $e =$ electronic charge and $\bar{v}_d =$ average drift velocity of charge carriers in an applied electric field. We thus obtain:

$$\sigma = (N e \bar{v}_d) / E$$

and if we define $(\bar{v}_d / E) = \mu$, the charge carrier mobility, we have:

$$\sigma = N e \mu$$

In intrinsic semiconductors we have both electrons and holes contributing to conduction:

$$\sigma = N_e e \mu_e + N_h e \mu_h = N e (\mu_e + \mu_h)$$

since $N_e = N_h$. Taking the number of thermally generated charge carriers, given by the relationship

$$N = A T^{3/2} e^{-E_g/2KT}$$

we obtain the temperature dependence of the conductivity as:

$$\sigma = A T^{3/2} e^{-E_g/2KT} \times e(\mu_e + \mu_h)$$

To assess the temperature dependence of electrical conductivity we must take into consideration that, because of increased vibration of the atoms about their lattice positions, the charge carrier mobility will decrease (increased scattering of charge carriers) with increasing temperature. This effect explains why the electronic conductivity in metals, where N is constant, will decrease with increasing temperature. In semiconductors, where N increases with temperature, the accompanying mobility effect is not apparent at low temperatures (conductivity increases), but becomes pronounced at high temperatures (conductivity decreases).

- b. Introduction of shallow impurity (or defect) states close to the conduction or valence band. This is accomplished by the incorporation of appropriate dopant elements into the crystal matrix. If these impurities are shallow (~ 0.01 eV from the conduction or valence band), they will be totally ionized at room temperature and each will contribute an electron (donor dopant: K, Na) or holes (acceptor dopant: G, Br), thus increasing the electrical conductivity without the necessity of a temperature rise. (Be aware that certain defects in the crystal lattice may also increase the electronic conductivity.)

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