CHAPTER 18

ELECTRICAL PROPERTIES

PROBLEM SOLUTIONS

Ohm's Law
Electrical Conductivity

18.1 This problem calls for us to compute the electrical conductivity and resistance of a silicon specimen.

(a) We use Equations 18.3 and 18.4 for the conductivity, as

$$\sigma = \frac{1}{\rho} = \frac{Il}{VA} = \frac{Il}{V\pi\left(\frac{d}{2}\right)^2}$$

And, incorporating values for the several parameters provided in the problem statement, leads to

$$\sigma = \frac{(0.25\ \text{A})(45\ \text{x}\ 10^{-3}\ \text{m})}{(24\ \text{V})(\pi)\left(\frac{7.0\ \text{x}\ 10^{-3}\ \text{m}}{2}\right)^2} = 12.2\ (\Omega\text{ - m})^{-1}$$

(b) The resistance, R, may be computed using Equations 18.2 and 18.4, as

$$R = \frac{l}{\sigma A} = \frac{l}{\sigma\pi\left(\frac{d}{2}\right)^2}$$

$$= \frac{57\ \text{x}\ 10^{-3}\ \text{m}}{\left[12.2\ (\Omega - \text{m})^{-1}\right](\pi)\left(\frac{7.0\ \text{x}\ 10^{-3}\ \text{m}}{2}\right)^2} = 121.4\ \Omega$$

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18.2 For this problem, given that an aluminum wire 10 m long must experience a voltage drop of less than 1.0 V when a current of 5 A passes through it, we are to compute the minimum diameter of the wire. Combining Equations 18.3 and 18.4 and solving for the cross-sectional area A leads to

$$A = \frac{Il}{V\sigma}$$

From Table 18.1, for aluminum $\sigma = 3.8 \times 10^{7}\ (\Omega\text{-m})^{-1}$. Furthermore, inasmuch as $A = \pi\left(\frac{d}{2}\right)^2$ for a cylindrical wire, then

$$\pi\left(\frac{d}{2}\right)^2 = \frac{Il}{V\sigma}$$

or

$$d = \sqrt{\frac{4Il}{\pi V\sigma}}$$

When values for the several parameters given in the problem statement are incorporated into this expression, we get

$$d = \sqrt{\frac{(4)(5\ \text{A})(10\ \text{m})}{(\pi)(1.0\ \text{V})\left[3.8 \times 10^{7}\ (\Omega-\text{m})^{-1}\right]}}$$

$$= 1.3 \times 10^{-3}\ \text{m} = 1.3\ \text{mm}$$

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18.3 This problem asks that we compute, for a plain carbon steel wire 3 mm in diameter, the maximum length such that the resistance will not exceed 20 Ω. From Table 18.1 for a plain carbon steel $\sigma = 0.6 \times 10^7$ $(\Omega\text{-m})^{-1}$. If *d* is the diameter then, combining Equations 18.2 and 18.4 leads to

$$l = R\sigma A = R\sigma\pi\left(\frac{d}{2}\right)^2$$

$$= (20\ \Omega)\left[0.6 \times 10^7\ (\Omega-\text{m})^{-1}\right](\pi)\left(\frac{3 \times 10^{-3}\ \text{m}}{2}\right)^2 = 848\ \text{m}$$

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18.4 Let us demonstrate, by appropriate substitution and algebraic manipulation, that Equation 18.5 may be made to take the form of Equation 18.1. Now, Equation 18.5 is just

$$J = \sigma E$$

(In this equation we represent the electric field with an "E".) But, by definition, J is just the current density, the current per unit cross-sectional area, or $J = \frac{I}{A}$. Also, the electric field is defined by $E = \frac{V}{l}$. And, substituting these expressions into Equation 18.5 leads to

$$\frac{I}{A} = \sigma \frac{V}{l}$$

But, from Equations 18.2 and 18.4

$$\sigma = \frac{l}{RA}$$

and

$$\frac{I}{A} = \left(\frac{l}{RA}\right)\left(\frac{V}{l}\right)$$

Solving for V from this expression gives $V = IR$, which is just Equation 18.1.

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18.5 (a) In order to compute the resistance of this aluminum wire it is necessary to employ Equations 18.2 and 18.4. Solving for the resistance in terms of the conductivity,

$$R = \frac{\rho l}{A} = \frac{l}{\sigma A} = \frac{l}{\sigma \pi \left(\frac{d}{2}\right)^2}$$

From Table 18.1, the conductivity of aluminum is 3.8 x 10^7 $(\Omega\text{-m})^{-1}$, and

$$R = \frac{l}{\sigma \pi \left(\frac{d}{2}\right)^2} = \frac{5 \text{ m}}{\left[3.8 \text{ x } 10^7 \ (\Omega - \text{m})^{-1}\right](\pi)\left(\frac{5 \text{ x } 10^{-3} \text{ m}}{2}\right)^2}$$

$$= 6.7 \text{ x } 10^{-3} \ \Omega$$

(b) If V = 0.04 V then, from Equation 18.1

$$I = \frac{V}{R} = \frac{0.04 \text{ V}}{6.7 \text{ x } 10^{-3} \ \Omega} = 6.0 \text{ A}$$

(c) The current density is just

$$J = \frac{I}{A} = \frac{I}{\pi \left(\frac{d}{2}\right)^2} = \frac{6.0 \text{ A}}{\pi \left(\frac{5 \text{ x } 10^{-3} \text{ m}}{2}\right)^2} = 3.06 \text{ x } 10^5 \text{ A/m}^2$$

(d) The electric field is just

$$E = \frac{V}{l} = \frac{0.04 \text{ V}}{5 \text{ m}} = 8.0 \text{ x } 10^{-3} \text{ V/m}$$

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Electronic and Ionic Conduction

18.6 When a current arises from a flow of electrons, the conduction is termed *electronic*; for *ionic conduction*, the current results from the net motion of charged ions.

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Energy Band Structures in Solids

18.7 For an isolated atom, there exist discrete electron energy states (arranged into shells and subshells); each state may be occupied by, at most, two electrons, which must have opposite spins. On the other hand, an electron band structure is found for solid materials; within each band exist closely spaced yet discrete electron states, each of which may be occupied by, at most, two electrons, having opposite spins. The number of electron states in each band will equal the total number of corresponding states contributed by all of the atoms in the solid.

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Conduction in Terms of Band and Atomic Bonding Models

18.8 This question asks that we explain the difference in electrical conductivity of metals, semiconductors, and insulators in terms of their electron energy band structures.

For metallic materials, there are vacant electron energy states adjacent to the highest filled state; thus, very little energy is required to excite large numbers of electrons into conducting states. These electrons are those that participate in the conduction process, and, because there are so many of them, metals are good electrical conductors.

There are no empty electron states adjacent to and above filled states for semiconductors and insulators, but rather, an energy band gap across which electrons must be excited in order to participate in the conduction process. Thermal excitation of electrons will occur, and the number of electrons excited will be less than for metals, and will depend on the band gap energy. For semiconductors, the band gap is narrower than for insulators; consequently, at a specific temperature more electrons will be excited for semiconductors, giving rise to higher conductivities.

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Electron Mobility

18.9 The drift velocity of a free electron is the average electron velocity in the direction of the force imposed by an electric field.

The mobility is the proportionality constant between the drift velocity and the electric field. It is also a measure of the frequency of scattering events (and is inversely proportional to the frequency of scattering).

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18.10 (a) The drift velocity of electrons in Si may be determined using Equation 18.7. Since the room temperature mobility of electrons is 0.14 m^2/V-s (Table 18.3), and the electric field is 500 V/m (as stipulated in the problem statement),

$$v_d = \mu_e E$$

$$= (0.14 \text{ m}^2/\text{V-s})(500 \text{ V/m}) = 70 \text{ m/s}$$

(b) The time, t, required to traverse a given length, l (= 25 mm), is just

$$t = \frac{l}{v_d} = \frac{25 \text{ x } 10^{-3} \text{ m}}{70 \text{ m/s}} = 3.6 \text{ x } 10^{-4} \text{ s}$$

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18.11 (a) The number of free electrons per cubic meter for aluminum at room temperature may be computed using Equation 18.8 as

$$n = \frac{\sigma}{|e|\,\mu_e}$$

$$= \frac{3.8 \text{ x } 10^7\ (\Omega-\text{m})^{-1}}{(1.602 \text{ x } 10^{-19}\text{ C})(0.0012 \text{ m}^2/\text{V-s})}$$

$$= 1.98 \text{ x } 10^{29}\text{ m}^{-3}$$

(b) In order to calculate the number of free electrons per aluminum atom, we must first determine the number of copper atoms per cubic meter, N_{Al}. From Equation 4.2 (and using the atomic weight and density values for Al found inside the front cover—viz. 26.98 g/mol and 2.71 g/cm^3)

$$N_{\text{Al}} = \frac{N_{\text{A}}\rho'}{A_{\text{Al}}}$$

$$= \frac{(6.023 \text{ x } 10^{23}\text{ atoms/mol})(2.71\text{ g/cm}^3)(10^6\text{ cm}^3/\text{m}^3)}{26.98\text{ g/mol}}$$

$$= 6.03 \text{ x } 10^{28}\text{ m}^{-3}$$

(*Note*: in the above expression, density is represented by ρ' in order to avoid confusion with resistivity which is designated by ρ.) And, finally, the number of free electrons per aluminum atom is just n/N_{Al}

$$\frac{n}{N_{\text{Al}}} = \frac{1.98 \text{ x } 10^{29}\text{ m}^{-3}}{6.03 \text{ x } 10^{28}\text{ m}^{-3}} = 3.28$$

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18.12 (a) This portion of the problem asks that we calculate, for silver, the number of free electrons per cubic meter (n) given that there are 1.3 free electrons per silver atom, that the electrical conductivity is 6.8 x 10^7 (Ω-m)$^{-1}$, and that the density (ρ'_{Ag}) is 10.5 g/cm^3. (Note: in this discussion, the density of silver is represented by ρ'_{Ag} in order to avoid confusion with resistivity which is designated by ρ.) Since $n = 1.3N_{Ag}$, and N_{Ag} is defined in Equation 4.2 (and using the atomic weight of Ag found inside the front cover—viz 107.87 g/mol), then

$$n = 1.3N_{Ag} = 1.3\left[\frac{\rho'_{Ag}N_A}{A_{Ag}}\right]$$

$$= 1.3\left[\frac{(10.5\ \text{g/cm}^3)(6.023\ \text{x}\ 10^{23}\ \text{atoms/mol})}{107.87\ \text{g/mol}}\right]$$

$$= 7.62\ \text{x}\ 10^{22}\ \text{cm}^{-3} = 7.62\ \text{x}\ 10^{28}\ \text{m}^{-3}$$

(b) Now we are asked to compute the electron mobility, μ_e. Using Equation 18.8

$$\mu_e = \frac{\sigma}{n|e|}$$

$$= \frac{6.8\ \text{x}\ 10^7\ (\Omega-\text{m})^{-1}}{(7.62\ \text{x}\ 10^{28}\ \text{m}^{-3})(1.602\ \text{x}\ 10^{-19}\ \text{C})} = 5.57\ \text{x}\ 10^{-3}\ \text{m}^2/\text{V-s}$$

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Electrical Resistivity of Metals

18.13 We want to solve for the parameter *A* in Equation 18.11 using the data in Figure 18.37. From Equation 18.11

$$A = \frac{\rho_i}{c_i (1 - c_i)}$$

However, the data plotted in Figure 18.37 is the total resistivity, ρ_{total}, and includes both impurity (ρ_i) and thermal (ρ_t) contributions (Equation 18.9). The value of ρ_t is taken as the resistivity at $c_i = 0$ in Figure 18.37, which has a value of 1.7 x 10^{-8} (Ω-m); this must be subtracted out. Below are tabulated values of *A* determined at $c_i = 0.10$, 0.20, and 0.30, including other data that were used in the computations. (*Note:* the c_i values were taken from the upper horizontal axis of Figure 18.37, since it is graduated in atom percent zinc.)

c_i	$1 - c_i$	ρ_{total} (Ω-m)	ρ_i (Ω-m)	*A* (Ω-m)
0.10	0.90	4.0 x 10^{-8}	2.3 x 10^{-8}	2.56 x 10^{-7}
0.20	0.80	5.4 x 10^{-8}	3.7 x 10^{-8}	2.31 x 10^{-7}
0.30	0.70	6.15 x 10^{-8}	4.45 x 10^{-8}	2.12 x 10^{-7}

So, there is a slight decrease of *A* with increasing c_i.

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18.14 (a) Perhaps the easiest way to determine the values of ρ_0 and a in Equation 18.10 for pure copper in Figure 18.8, is to set up two simultaneous equations using two resistivity values (labeled ρ_{t1} and ρ_{t2}) taken at two corresponding temperatures (T_1 and T_2). Thus,

$$\rho_{t1} = \rho_0 + aT_1$$

$$\rho_{t2} = \rho_0 + aT_2$$

And solving these equations simultaneously lead to the following expressions for a and ρ_0:

$$a = \frac{\rho_{t1} - \rho_{t2}}{T_1 - T_2}$$

$$\rho_0 = \rho_{t1} - T_1\left[\frac{\rho_{t1} - \rho_{t2}}{T_1 - T_2}\right]$$

$$= \rho_{t2} - T_2\left[\frac{\rho_{t1} - \rho_{t2}}{T_1 - T_2}\right]$$

From Figure 18.8, let us take T_1 = –150°C, T_2 = –50°C, which gives ρ_{t1} = 0.6 x 10^{-8} (Ω-m), and ρ_{t2} = 1.25 x 10^{-8} (Ω-m). Therefore

$$a = \frac{\rho_{t1} - \rho_{t2}}{T_1 - T_2}$$

$$= \frac{\left[(0.6 \text{ x } 10^{-8}) - (1.25 \text{ x } 10^{-8})\right](\Omega\text{ - m})}{-150°\text{C} - (-50°\text{C})}$$

$$6.5 \text{ x } 10^{-11} \ (\Omega\text{-m})/°\text{C}$$

and

$$\rho_0 = \rho_{t1} - T_1\left[\frac{\rho_{t1} - \rho_{t2}}{T_1 - T_2}\right]$$

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$$= \left(0.6 \text{ x } 10^{-8}\right) - (-150) \frac{\left[\left(0.6 \text{ x } 10^{-8}\right) - \left(1.25 \text{ x } 10^{-8}\right)\right](\Omega\text{ - m})}{-150°\text{C} - (-50°\text{C})}$$

$$= 1.58 \text{ x } 10^{-8} \ (\Omega\text{-m})$$

(b) For this part of the problem, we want to calculate *A* from Equation 18.11

$$\rho_i = Ac_i (1 - c_i)$$

In Figure 18.8, curves are plotted for three c_i values (0.0112, 0.0216, and 0.0332). Let us find *A* for each of these c_i's by taking a ρ_{total} from each curve at some temperature (say 0°C) and then subtracting out ρ_i for pure copper at this same temperature (which is 1.7 x 10^{-8} Ω-m). Below is tabulated values of *A* determined from these three c_i values, and other data that were used in the computations.

c_i	$1 - c_i$	ρ_{total} (Ω-m)	ρ_i (Ω-m)	*A* (Ω-m)
0.0112	0.989	3.0 x 10^{-8}	1.3 x 10^{-8}	1.17 x 10^{-6}
0.0216	0.978	4.2 x 10^{-8}	2.5 x 10^{-8}	1.18 x 10^{-6}
0.0332	0.967	5.5 x 10^{-8}	3.8 x 10^{-8}	1.18 x 10^{-6}

The average of these three *A* values is 1.18 x 10^{-6} (Ω-m).

(c) We use the results of parts (a) and (b) to estimate the electrical resistivity of copper containing 2.50 at% Ni (c_i = 0.025) at120°C. The total resistivity is just

$$\rho_{total} = \rho_t + \rho_i$$

Or incorporating the expressions for ρ_t and ρ_i from Equations 18.10 and 18.11, and the values of ρ_0, *a*, and *A* determined above, leads to

$$\rho_{total} = (\rho_0 + aT) + Ac_i (1 - c_i)$$

$$= \left\{1.58 \text{ x } 10^{-8} \ (\Omega\text{ - m}) + \left[6.5 \text{ x } 10^{-11} \ (\Omega\text{ - m})/°\text{C}\right](120°\text{C})\right\}$$
$$+ \left\{\left[1.18 \text{ x } 10^{-6} \ (\Omega\text{ - m})\right](0.0250)(1 - 0.0250)\right\}$$

$$= 5.24 \text{ x } 10^{-8} \ (\Omega\text{-m})$$

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18.15 We are asked to determine the electrical conductivity of a Cu-Ni alloy that has a tensile strength of 275 MPa. From Figure 7.16(a), the composition of an alloy having this tensile strength is about 8 wt% Ni. For this composition, the resistivity is about 14 x 10^{-8} Ω-m (Figure 18.9). And since the conductivity is the reciprocal of the resistivity, Equation 18.4, we have

$$\sigma = \frac{1}{\rho} = \frac{1}{14 \text{ x } 10^{-8} \ \Omega - \text{m}} = 7.1 \text{ x } 10^{6} \ (\Omega \text{ - m})^{-1}$$

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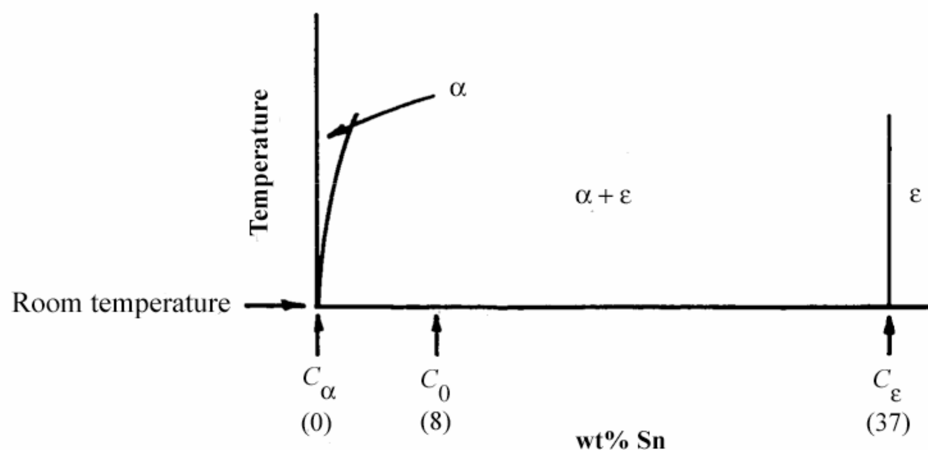
18.16 This problem asks for us to compute the room-temperature conductivity of a two-phase Cu-Sn alloy which composition is 89 wt% Cu-11 wt% Sn. It is first necessary for us to determine the volume fractions of the α and ε phases, after which the resistivity (and subsequently, the conductivity) may be calculated using Equation 18.12. Weight fractions of the two phases are first calculated using the phase diagram information provided in the problem.

We may represent a portion of the phase diagram near room temperature as follows:



Applying the lever rule to this situation

$$W_\alpha = \frac{C_\varepsilon - C_0}{C_\varepsilon - C_\alpha} = \frac{37 - 11}{37 - 0} = 0.703$$

$$W_\varepsilon = \frac{C_0 - C_\alpha}{C_\varepsilon - C_\alpha} = \frac{11 - 0}{37 - 0} = 0.297$$

We must now convert these mass fractions into volume fractions using the phase densities given in the problem statement. (*Note:* in the following expressions, density is represented by ρ' in order to avoid confusion with resistivity which is designated by ρ.) Utilization of Equations 9.6a and 9.6b leads to

$$V_\alpha = \frac{\dfrac{W_\alpha}{\rho'_\alpha}}{\dfrac{W_\alpha}{\rho'_\alpha} + \dfrac{W_\varepsilon}{\rho'_\varepsilon}}$$

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$$= \frac{\dfrac{0.703}{8.94\ \text{g/cm}^3}}{\dfrac{0.703}{8.94\ \text{g/cm}^3} + \dfrac{0.297}{8.25\ \text{g/cm}^3}}$$

$$= 0.686$$

$$V_\varepsilon = \frac{\dfrac{W_\varepsilon}{\rho'_\varepsilon}}{\dfrac{W_\alpha}{\rho'_\alpha} + \dfrac{W_\varepsilon}{\rho'_\varepsilon}}$$

$$= \frac{\dfrac{0.297}{8.25\ \text{g/cm}^3}}{\dfrac{0.703}{8.94\ \text{g/cm}^3} + \dfrac{0.297}{8.25\ \text{g/cm}^3}}$$

$$= 0.314$$

Now, using Equation 18.12

$$\rho = \rho_\alpha V_\alpha + \rho_\varepsilon V_\varepsilon$$

$$= \left(1.88 \text{ x } 10^{-8}\ \Omega\text{-m}\right)(0.686) + \left(5.32 \text{ x } 10^{-7}\ \Omega\text{-m}\right)(0.314)$$

$$= 1.80 \text{ x } 10^{-7}\ \Omega\text{-m}$$

Finally, for the conductivity (Equation 18.4)

$$\sigma = \frac{1}{\rho} = \frac{1}{1.80 \text{ x } 10^{-7}\ \Omega - \text{m}} = 5.56 \text{ x} 10^6\ (\Omega\text{-m})^{-1}$$

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18.17 We are asked to select which of several metals may be used for a 3 mm diameter wire to carry 12 A, and have a voltage drop less than 0.01 V per foot (300 mm). Using Equations 18.3 and 18.4, let us determine the minimum conductivity required, and then select from Table 18.1, those metals that have conductivities greater than this value. Combining Equations 18.3 and 18.4, the minimum conductivity is just

$$\sigma = \frac{Il}{VA} = \frac{Il}{V\pi \left(\frac{d}{2}\right)^2}$$

$$= \frac{(12\ \text{A})(300\ \text{x}\ 10^{-3}\ \text{m})}{(0.01\ \text{V})\ (\pi)\left(\frac{3\ \text{x}\ 10^{-3}\ \text{m}}{2}\right)^2} = 5.1\ \text{x}\ 10^7\ (\Omega\text{ - m})^{-1}$$

Thus, from Table 18.1, only copper, and silver are candidates.

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Intrinsic Semiconduction

18.18 (a) For this part of the problem, we first read, from Figure 18.16, the number of free electrons (i.e., the intrinsic carrier concentration) at room temperature (298 K). These values are n_i(Ge) = 5 x 10^{19} m^{-3} and n_i(Si) = 7 x 10^{16} m^{-3}.

Now, the number of atoms per cubic meter for Ge and Si (N_{Ge} and N_{Si}, respectively) may be determined using Equation 4.2 which involves the densities (ρ'_{Ge} and ρ'_{Si}) and atomic weights (A_{Ge} and A_{Si}). (*Note:* here we use ρ' to represent density in order to avoid confusion with resistivity, which is designated by ρ. Also, the atomic weights for Ge and Si, 72.59 and 28.09 g/mol, respectively, are found inside the front cover.) Therefore,

$$N_{Ge} = \frac{N_A \rho'_{Ge}}{A_{Ge}}$$

$$= \frac{(6.023 \text{ x } 10^{23} \text{ atoms/mol})(5.32 \text{ g/cm}^3)(10^6 \text{ cm}^3/\text{m}^3)}{72.59 \text{ g/mol}}$$

$$= 4.4 \text{ x } 10^{28} \text{ atoms/m}^3$$

Similarly, for Si

$$N_{Si} = \frac{N_A \rho'_{Si}}{A_{Si}}$$

$$= \frac{(6.023 \text{ x } 10^{23} \text{ atoms/mol})(2.33 \text{ g/cm}^3)(10^6 \text{ cm}^3/\text{m}^3)}{28.09 \text{ g/mol}}$$

$$= 5.00 \text{ x } 10^{28} \text{ atoms/m}^3$$

Finally, the ratio of the number of free electrons per atom is calculated by dividing n_i by N. For Ge

$$\frac{n_i(\text{Ge})}{N_{Ge}} = \frac{5 \text{ x } 10^{19} \text{ electrons/m}^3}{4.4 \text{ x } 10^{28} \text{ atoms/m}^3}$$

$$1.1 \text{ x } 10^{-9} \text{ electron/atom}$$

And, for Si

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$$\frac{n_i(\text{Si})}{N_{\text{Si}}} = \frac{7 \ \text{x} \ 10^{16} \ \text{electrons/m}^3}{5.00 \ \text{x} \ 10^{28} \ \text{atoms/m}^3}$$

$$= 1.4 \ \text{x} \ 10^{-12} \ \text{electron/atom}$$

(b) The difference is due to the magnitudes of the band gap energies (Table 18.3). The band gap energy at room temperature for Si (1.11 eV) is larger than for Ge (0.67 eV), and, consequently, the probability of excitation across the band gap for a valence electron is much smaller for Si.

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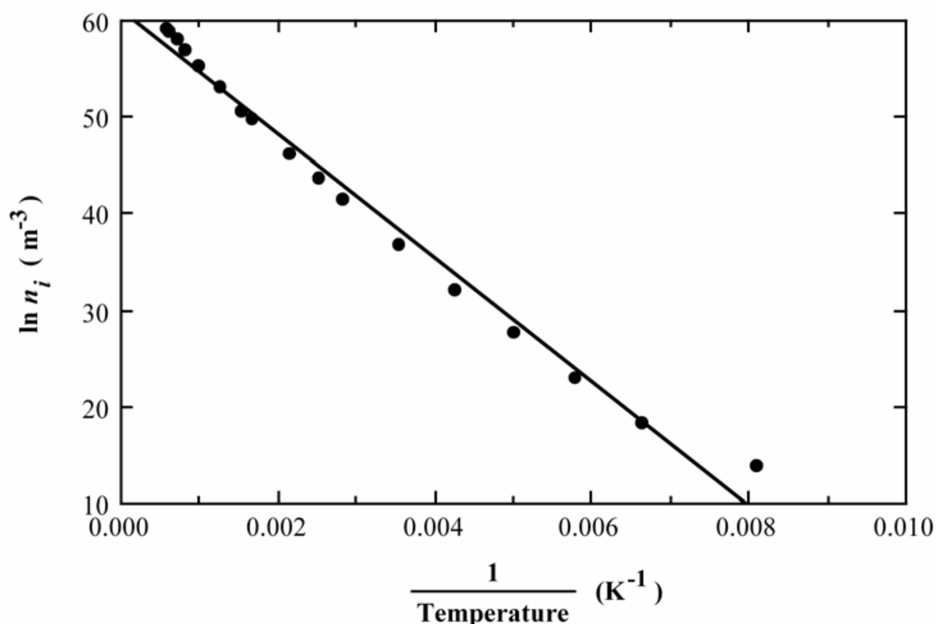
18.19 This problem asks that we make plots of ln n_i versus reciprocal temperature for both Si and Ge, using the data presented in Figure 18.16, and then determine the band gap energy for each material realizing that the slope of the resulting line is equal to $-E_g/2k$.

Below is shown such a plot for Si.



The slope of the line is equal to

$$\text{Slope} = \frac{\Delta \ln \eta_i}{\Delta\left(\frac{1}{T}\right)} = \frac{\ln \eta_1 - \ln \eta_2}{\frac{1}{T_1} - \frac{1}{T_2}}$$

Let us take $1/T_1 = 0.001$ and $1/T_2 = 0.007$; their corresponding ln η values are ln $\eta_1 = 54.80$ and ln $\eta_2 = 16.00$. Incorporating these values into the above expression leads to a slope of

$$\text{Slope} = \frac{\text{54.80ŹŹ 16.00}}{0.001 - 0.007} = -6470$$

This slope leads to an E_g value of

$$E_g = -2k\,(\text{Slope})$$

$$= -2\left(8.62 \times 10^{-5} \text{ eV/K}\right)(-6470) = 1.115 \text{ eV}$$

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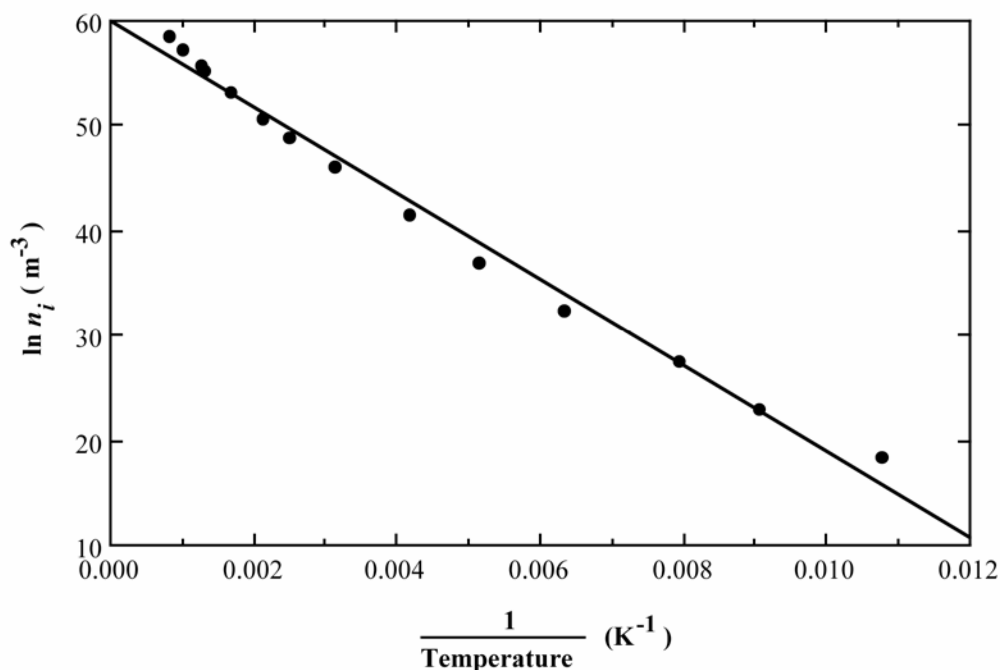
The value cited in Table 18.3 is 1.11 eV.

Now for Ge, an analogous plot is shown below.



We calculate the slope and band gap energy values in the manner outlined above. Let us take $1/T_1$ = 0.001 and $1/T_2$ = 0.011; their corresponding ln η values are ln η_1 = 55.56 and ln η_2 = 14.80. Incorporating these values into the above expression leads to a slope of

$$\text{Slope} = \frac{55.56 - 14.80}{0.001 - 0.011} = -4076$$

This slope leads to an E_g value of

$$E_g = -\,2k\ (\text{Slope})$$

$$= -2\left(8.62 \text{ x } 10^{-5} \text{ eV/K}\right)(-4076) = 0.70 \text{ eV}$$

This value is in good agreement with the 0.67 eV cited in Table 18.3.

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18.20 The factor 2 in Equation 18.35a takes into account the creation of two charge carriers (an electron and a hole) for each valence-band-to-conduction-band intrinsic excitation; both charge carriers may participate in the conduction process.

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18.21 In this problem we are asked to compute the intrinsic carrier concentration for PbS at room temperature. Since the conductivity and both electron and hole mobilities are provided in the problem statement, all we need do is solve for n and p (i.e., n_i) using Equation 18.15. Thus,

$$n_i = \frac{\sigma}{|e|(\mu_e + \mu_h)}$$

$$= \frac{25\ (\Omega\text{-m})^{-1}}{(1.602\ \text{x}\ 10^{-19}\ \text{C})(0.06\ +\ 0.02)\ \ \text{m}^2/\text{V-s}}$$

$$= 1.95\ \text{x}\ 10^{21}\ \text{m}^{-3}$$

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18.22 Yes, compound semiconductors can exhibit intrinsic behavior. They will be intrinsic even though they are composed of two different elements as long as the electrical behavior is not influenced by the presence of other elements.

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18.23 This problem calls for us to decide for each of several pairs of semiconductors, which will have the smaller band gap energy and then cite a reason for the choice.

(a) Germanium will have a smaller band gap energy than C (diamond) since Ge is lower in row IVA of the periodic table (Figure 2.6) than is C. In moving from top to bottom of the periodic table, E_g decreases.

(b) Indium antimonide will have a smaller band gap energy than aluminum phosphide. Both of these semiconductors are III-V compounds, and the positions of both In and Sb are lower vertically in the periodic table (Figure 2.6) than Al and P.

(c) Gallium arsenide will have a smaller band gap energy than zinc selenide. All four of these elements are in the same row of the periodic table, but Zn and Se are more widely separated horizontally than Ga and As; as the distance of separation increases, so does the band gap.

(d) Cadmium telluride will have a smaller band gap energy than zinc selenide. Both are II-VI compounds, and Cd and Te are both lower vertically in the periodic table than Zn and Se.

(e) Cadmium sulfide will have a smaller band gap energy than sodium chloride since Na and Cl are much more widely separated horizontally in the periodic table than are Cd and S.

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Extrinsic Semiconduction

18.24 These semiconductor terms are defined in the Glossary. Examples are as follows: intrinsic--high purity (undoped) Si, GaAs, CdS, etc.; extrinsic--P-doped Ge, B-doped Si, S-doped GaP, etc.; compound--GaAs, InP, CdS, etc.; elemental--Ge and Si.

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18.25 For this problem we are to determine the electrical conductivity of and *n*-type semiconductor, given that $n = 5 \times 10^{17}$ m^{-3} and the electron drift velocity is 350 m/s in an electric field of 1000 V/m. The conductivity of this material may be computed using Equation 18.16. But before this is possible, it is necessary to calculate the value of μ_e from Equation 18.7. Thus, the electron mobility is equal to

$$\mu_e = \frac{v_d}{E}$$

$$= \frac{350 \text{ m/s}}{1000 \text{ V/m}} = 0.35 \text{ m}^2/\text{V-s}$$

Thus, from Equation 18.16, the conductivity is

$$\sigma = n|e|\mu_e$$

$$= (5 \times 10^{17} \text{ m}^{-3})(1.602 \times 10^{-19} \text{ C})(0.35 \text{ m}^2/\text{V-s})$$

$$= 0.028 \ (\Omega\text{-m})^{-1}$$

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18.26 The explanations called for are found in Section 18.11.

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18.27 (a) No hole is generated by an electron excitation involving a donor impurity atom because the excitation comes from a level within the band gap, and thus, no missing electron is created within the normally filled valence band.

(b) No free electron is generated by an electron excitation involving an acceptor impurity atom because the electron is excited from the valence band into the impurity level within the band gap; no free electron is introduced into the conduction band.

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18.28 Nitrogen will act as a donor in Si. Since it (N) is from group VA of the periodic table (Figure 2.6), and an N atom has one more valence electron than an Si atom.

Boron will act as an acceptor in Ge. Since it (B) is from group IIIA of the periodic table, a B atom has one less valence electron than a Ge atom.

Sulfur will act as a donor in InSb. Since S is from group VIA of the periodic table, it will substitute for Sb; also, an S atom has one more valence electron than an Sb atom.

Indium will act as a donor in CdS. Since In is from group IIIA of the periodic table, it will substitute for Cd; and, an In atom has one more valence electron than a Cd atom.

Arsenic will act as an acceptor in ZnTe. Since As is from group VA of the periodic table, it will substitute for Te; furthermore, an As atom has one less valence electron than a Te atom.

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18.29 (a) In this problem, for a Si specimen, we are given values for p $(2.0 \text{ x } 10^{22} \text{ m}^{-3})$ and σ $[500 \, (\Omega\text{-m})^{-1}]$, while values for μ_h and μ_e (0.05 and 0.14 m^2/V-s, respectively) are found in Table 18.3. In order to solve for n we must use Equation 18.13, which, after rearrangement, leads to

$$n = \frac{\sigma - p|e|\mu_h}{|e|\mu_e}$$

$$= \frac{500 \, (\Omega - \text{m})^{-1} - (2.0 \text{ x } 10^{22} \text{ m}^{-3})(1.602 \text{ x } 10^{-19} \text{ C})(0.05 \text{ m}^2/\text{V-s})}{(1.602 \text{ x } 10^{-19} \text{ C})(0.14 \text{ m}^2/\text{V-s})}$$

$$= 2.97 \text{ x } 10^{20} \text{ m}^{-3}$$

(b) This material is p-type extrinsic since p $(2.0 \text{ x } 10^{22} \text{ m}^{-3})$ is greater than n $(2.97 \text{ x } 10^{20} \text{ m}^{-3})$.

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18.30 (a) This germanium material to which has been added 10^{24} m^{-3} As atoms is *n*-type since As is a donor in Ge. (Arsenic is from group VA of the periodic table--Ge is from group IVA.)

(b) Since this material is *n*-type extrinsic, Equation 18.16 is valid. Furthermore, each As atom will donate a single electron, or the electron concentration is equal to the As concentration since all of the As atoms are ionized at room temperature; that is $n = 10^{24}$ m^{-3}, and, as given in the problem statement, $\mu_e = 0.1$ m^2/V-s. Thus

$$\sigma = n|e|\mu_e$$

$$= (10^{24}\ \text{m}^{-3})(1.602\ \text{x}\ 10^{-19}\ \text{C})(0.1\ \text{m}^2/\text{V-s})$$

$$= 1.6\ \text{x}\ 10^{4}\ (\Omega\text{-m})^{-1}$$

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18.31 In order to solve for the electron and hole mobilities for GaSb, we must write conductivity expressions for the two materials, of the form of Equation 18.13—i.e.,

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

For the intrinsic material

$$8.9 \times 10^4\ (\Omega\text{-m})^{-1} = (8.7 \times 10^{23}\ \text{m}^{-3})(1.602 \times 10^{-19}\ \text{C})\,\mu_e$$
$$+ (8.7 \times 10^{23}\ \text{m}^{-3})(1.602 \times 10^{-19}\ \text{C})\,\mu_h$$

which reduces to

$$0.639 = \mu_e + \mu_h$$

Whereas, for the extrinsic GaSb

$$2.3 \times 10^5\ (\Omega\text{-m})^{-1} = (7.6 \times 10^{22}\ \text{m}^{-3})(1.602 \times 10^{-19}\ \text{C})\,\mu_e$$
$$+ (1.0 \times 10^{25}\ \text{m}^{-3})(1.602 \times 10^{-19}\ \text{C})\,\mu_h$$

which may be simplified to

$$0.1436 = 7.6 \times 10^{-3}\,\mu_e + \mu_h$$

Thus, we have two independent expressions with two unknown mobilities. Upon solving these equations simultaneously, we get $\mu_e = 0.50\ \text{m}^2/\text{V-s}$ and $\mu_h = 0.14\ \text{m}^2/\text{V-s}$.

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The Temperature Dependence of Carrier Concentration

18.32 In order to estimate the electrical conductivity of intrinsic silicon at 80°C, we must employ Equation 18.15. However, before this is possible, it is necessary to determine values for n_i, μ_e, and μ_h. According to Figure 18.16, at 80°C (353 K), $n_i = 1.5 \times 10^{18}$ m^{-3}, whereas from the "$<10^{20}$ m^{-3}" curves of Figures 18.19a and 18.19b, at 80ºC (353 K), $\mu_e = 0.10$ m^2/V-s and $\mu_h = 0.035$ m^2/V-s (realizing that the mobility axes of these two plot are scaled logarithmically). Thus, the conductivity at 80°C is

$$\sigma = n_i |e| (\mu_e + \mu_h)$$

$$\sigma = (1.5 \text{ x } 10^{18} \text{ m}^{-3})(1.602 \text{ x } 10^{-19} \text{ C})(0.10 \text{ m}^2/\text{V-s} + 0.035 \text{ m}^2/\text{V-s})$$

$$= 0.032\ (\Omega\text{-m})^{-1}$$

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18.33 This problem asks for us to assume that electron and hole mobilities for intrinsic Ge are temperature-dependent, and proportional to $T^{-3/2}$ for temperature in K. It first becomes necessary to solve for C in Equation 18.36 using the room-temperature (298 K) conductivity [2.2 (Ω-m)$^{-1}$] (Table 18.3). This is accomplished by taking natural logarithms of both sides of Equation 18.36 as

$$\ln \sigma = \ln C - \frac{3}{2}\ln T - \frac{E_g}{2kT}$$

and after rearranging and substitution of values for E_g (0.67 eV, Table 18.3), and the room-temperature conductivity, we get

$$\ln C = \ln \sigma + \frac{3}{2}\ln T + \frac{E_g}{2kT}$$

$$= \ln (2.2) + \frac{3}{2}\ln (298) + \frac{0.67 \text{ eV}}{(2)(8.62 \times 10^{-5} \text{ eV/K})(298 \text{ K})}$$

$$= 22.38$$

Now, again using Equation 18.36, we are able to compute the conductivity at 448 K (175°C)

$$\ln \sigma = \ln C - \frac{3}{2}\ln T - \frac{E_g}{2kT}$$

$$= 22.38 - \frac{3}{2}\ln (448 \text{ K}) - \frac{0.67 \text{ eV}}{(2)(8.62 \times 10^{-5} \text{ eV/K})(448 \text{ K})}$$

$$= 4.548$$

which leads to

$$\sigma = e^{4.548} = 94.4 \ (\Omega\text{-m})^{-1}.$$

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18.34 This problem asks that we determine the temperature at which the electrical conductivity of intrinsic Ge is 40 $(\Omega\text{-m})^{-1}$, using Equation 18.36 and the results of Problem 18.33. First of all, taking logarithms of Equation 18.36

$$\ln \sigma = \ln C - \frac{3}{2}\ln T - \frac{E_g}{2kT}$$

And, from Problem 18.33 the value of ln *C* was determined to be 22.38. Using this and σ = 40 $(\Omega\text{-m})^{-1}$, the above equation takes the form

$$\ln 40 = 22.38 - \frac{3}{2}\ln T - \frac{0.67 \text{ eV}}{(2)(8.62 \text{ x } 10^{-5} \text{ eV/K})(T)}$$

In order to solve for *T* from the above expression it is necessary to use an equation solver. For some solvers, the following set of instructions may be used:

ln(40) = 22.38 –1.5*ln(T) – 0.67/(2*8.62*10^-5*T)

The resulting solution is *T* = 400, which value is the temperature in K; this corresponds to *T*(ºC) = 400 – 273 = 127°C.

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18.35 This problem asks that we estimate the temperature at which GaAs has an electrical conductivity of 1.6 x 10^{-3} (Ω-m)$^{-1}$ assuming that the conductivity has a temperature dependence as shown in Equation 18.36. From the room temperature (298 K) conductivity [10^{-6} (Ω-m)$^{-1}$] and band gap energy (1.42 eV) of Table 18.3 we determine the value of *C* (Equation 18.36) by taking natural logarithms of both sides of the equation, and after rearrangement as follows:

$$\ln C = \ln \sigma + \frac{3}{2} \ln T + \frac{E_g}{2kT}$$

$$= \ln \left[10^{-6} \, (\Omega - \text{m})^{-1}\right] + \frac{3}{2} \ln \, (298 \text{ K}) + \frac{1.42 \text{ eV}}{(2)(8.62 \text{ x } 10^{-5} \text{ eV/K})(298 \text{ K})}$$

$$= 22.37$$

Now we substitute this value into Equation 18.36 in order to determine the value of *T* for which σ = 1.6 x 10^{-3} (Ω-m)$^{-1}$, thus

$$\ln \sigma = \ln C - \frac{3}{2} \ln T - \frac{E_g}{2kT}$$

$$\ln \left[1.6 \text{ x } 10^{-3} \, (\Omega \text{ - m})^{-1}\right] = 22.37 - \frac{3}{2} \ln T - \frac{1.42 \text{ eV}}{(2)(8.62 \times 10^{-5} \text{ eV/K})(T)}$$

This equation may be solved for *T* using an equation solver. For some solvers, the following set of instructions may be used:

ln(1.6*10^–3) = 22.37 – 1.5*ln(T) – 1.42/(2*8.62*10^–5*T)

The resulting solution is *T* = 417; this value is the temperature in K which corresponds to *T*(ºC) = 417 K – 273 = 144°C.

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18.36 This question asks that we compare and then explain the difference in temperature dependence of the electrical conductivity for metals and intrinsic semiconductors.

For metals, the temperature dependence is described by Equation 18.10 (and converting from resistivity to conductivity using Equation 18.4), as

$$\sigma = \frac{1}{\rho_0 + aT}$$

That is, the electrical conductivity decreases with increasing temperature.

Alternatively, from Equation 18.8, the conductivity of metals is equal to

$$\sigma = n|e|\mu_e$$

As the temperature rises, n will remain virtually constant, whereas the mobility (μ_e) will decrease, because the thermal scattering of free electrons will become more efficient. Since $|e|$ is independent of temperature, the net result will be diminishment in the magnitude of σ.

For intrinsic semiconductors, the temperature-dependence of conductivity is just the opposite of that for metals—i.e, conductivity increases with rising temperature. One explanation is as follows: Equation 18.15 describes the conductivity; i.e.,

$$\sigma = n|e|(\mu_e + \mu_h) = p|e|(\mu_e + \mu_h)$$
$$= n_i|e|(\mu_e + \mu_h)$$

Both n and p increase dramatically with rising temperature (Figure 18.16), since more thermal energy becomes available for valence band-conduction band electron excitations. The magnitudes of μ_e and μ_h will diminish somewhat with increasing temperature (per the upper curves of Figures 18.19a and 18.19b), as a consequence of the thermal scattering of electrons and holes. However, this reduction of μ_e and μ_h will be overwhelmed by the increase in n and p, with the net result is that σ increases with temperature.

An alternative explanation is as follows: for an intrinsic semiconductor the temperature dependence is represented by an equation of the form of Equation 18.36. This expression contains two terms that involve temperature—a preexponential one (in this case $T^{-3/2}$) and the other in the exponential. With rising temperature the preexponential term decreases, while the exp ($-E_g/2kT$) parameter increases. With regard to relative magnitudes, the exponential term increases much more rapidly than the preexponential one, such that the electrical conductivity of an intrinsic semiconductor increases with rising temperature.

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Factors That Affect Carrier Mobility

18.37 This problems asks that we determine the room-temperature electrical conductivity of silicon that has been doped with 10^{23} m^{-3} of arsenic atoms. Inasmuch as As is a group VA element in the periodic table (Figure 2.6) it acts as a donor in silicon. Thus, this material is *n*-type extrinsic, and it is necessary to use Equation 18.16), with n = 10^{23} m^{-3} since at room temperature all of the As donor impurities are ionized. The electron mobility, from Figure 18.18 at an impurity concentration of 10^{23} m^{-3}, is 0.065 m^2/V-s. Therefore, the conductivity is equal to

$$\sigma = n\,|e|\,\mu_e = \left(10^{23}\ \mathrm{m}^{-3}\right)\left(1.602 \times 10^{-19}\ \mathrm{C}\right)\left(0.065\ \mathrm{m}^2/\mathrm{V-s}\right) = 1040\ (\Omega-\mathrm{m})^{-1}$$

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18.38 Here we are asked to calculate the room-temperature electrical conductivity of silicon that has been doped with 2 x 10^{24} m^{-3} of boron atoms. Inasmuch as B is a group IIIA element in the periodic table (Figure 2.6) it acts as an acceptor in silicon. Thus, this material is *p*-type extrinsic, and it is necessary to use Equation 18.17, with p = 2 x 10^{24} m^{-3} since at room temperature all of the B acceptor impurities are ionized. The hole mobility, from Figure 18.18 at an impurity concentration of 2 x 10^{24} m^{-3}, is 0.0065 m^2/V-s. Therefore, the conductivity is equal to

$$\sigma = p|e|\mu_e = (2 \times 10^{24}\ \mathrm{m}^{-3})(1.602 \times 10^{-19}\ \mathrm{C})(0.0065\ \mathrm{m}^2/\mathrm{V-s}) = 2080\ (\Omega - \mathrm{m})^{-1}$$

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18.39 In this problem we are to estimate the electrical conductivity, at 75°C, of silicon that has been doped with 10^{22} m^{-3} of phosphorous atoms. Inasmuch as P is a group VA element in the periodic table (Figure 2.6) it acts as a donor in silicon. Thus, this material is *n*-type extrinsic, and it is necessary to use Equation 18.16; *n* in this expression is 10^{22} m^{-3} since at 75°C all of the P donor impurities are ionized. The electron mobility is determined using Figure 18.19a. From the 10^{22} m^{-3} impurity concentration curve and at 75°C (348 K), μ_e = 0.08 m^2/V-s. Therefore, the conductivity is equal to

$$\sigma = n|e|\mu_e = (10^{22}\ \text{m}^{-3})(1.602 \times 10^{-19}\ \text{C})(0.08\ \text{m}^2/\text{V-s}) = 128\ (\Omega\text{-m})^{-1}$$

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18.40 In this problem we are to estimate the electrical conductivity, at 135°C, of silicon that has been doped with 10^{24} m^{-3} of aluminum atoms. Inasmuch as Al is a group IIIA element in the periodic table (Figure 2.6) it acts as an acceptor in silicon. Thus, this material is *p*-type extrinsic, and it is necessary to use Equation 18.17; *p* in this expression is 10^{24} m^{-3} since at 135°C all of the Al acceptor impurities are ionized. The hole mobility is determined using Figure 18.19b. From the 10^{24} m^{-3} impurity concentration curve and at 135°C (408 K,) μ_h = 0.007 m^2/V-s. Therefore, the conductivity is equal to

$$\sigma = p|e|\mu_h = (10^{24}\ \text{m}^{-3})(1.602 \times 10^{-19}\ \text{C})(0.007\ \text{m}^2/\text{V-s}) = 1120\ (\Omega\text{-m})^{-1}$$

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The Hall Effect

18.41 (a) This portion of the problem calls for us to determine the electron mobility for some hypothetical metal using the Hall effect. This metal has an electrical resistivity of 3.3 x 10^{-8} (Ω-m), while the specimen thickness is 15 mm, I_x = 25 A and B_z = 0.95 tesla; under these circumstances a Hall voltage of –2.4 x 10^{-7} V is measured. It is first necessary to convert resistivity to conductivity (Equation 18.4). Thus

$$\sigma = \frac{1}{\rho} = \frac{1}{3.3 \text{ x} 10^{-8} \ (\Omega - \text{m})} = 3.0 \text{ x } 10^{7} \ (\Omega\text{ - m})^{-1}$$

The electron mobility may be determined using Equation 18.20b; and upon incorporation of Equation 18.18, we have

$$\mu_e = |R_\text{H}|\sigma$$

$$= \frac{|V_\text{H}|\, d\, \sigma}{I_x B_z}$$

$$= \frac{\left(\left|-2.4 \text{ x } 10^{-7} \text{ V}\right|\right)(15 \text{ x } 10^{-3} \text{ m})\left[3.0 \text{ x } 10^{7} \ (\Omega - \text{m})^{-1}\right]}{(25 \text{ A})(0.95 \text{ tesla})}$$

$$= 0.0045 \ \text{m}^2/\text{V - s}$$

(b) Now we are to calculate the number of free electrons per cubic meter. From Equation 18.8 we have

$$n = \frac{\sigma}{|e|\, \mu_e}$$

$$= \frac{3.0 \text{ x } 10^{7} \ (\Omega\text{ - m})^{-1}}{(1.602 \text{ x } 10^{-19} \text{ C})(0.0045 \ \text{m}^2/\text{V - s})}$$

$$= 4.17 \text{ x } 10^{28} \ \text{m}^{-3}$$

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18.42 In this problem we are asked to determine the magnetic field required to produce a Hall voltage of -3.5×10^{-7} V, given that $\sigma = 1.2 \times 10^{7}$ $(\Omega\text{-m})^{-1}$, μ_e = 0.0050 m^2/V-s, I_x = 40 A, and d = 35 mm. Combining Equations 18.18 and 18.20b, and after solving for B_z, we get

$$B_z = \frac{|V_H|\sigma d}{I_x \mu_e}$$

$$= \frac{\left(\left|-3.5 \text{ x } 10^{-7} \text{ V}\right|\right)\left[1.2 \text{ x } 10^{7} \; (\Omega - \text{m})^{-1}\right](35 \text{ x } 10^{-3} \text{ m})}{(40 \text{ A})(0.0050 \text{ m}^2/\text{V-s})}$$

$$= 0.74 \text{ tesla}$$

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Semiconducting Devices

18.43 The explanations called for are found in Section 18.15.

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18.44 The energy generated by the electron-hole annihilation reaction, Equation 18.21, is dissipated as heat.

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18.45 In an electronic circuit, a transistor may be used to (1) amplify an electrical signal, and (2) act as a switching device in computers.

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18.46 The differences in operation and application for junction transistors and MOSFETs are described in Section 18.15.

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Conduction in Ionic Materials

18.47 We are asked in this problem to determine the electrical conductivity for the nonstoichiometric $Fe_{(1-x)}O$, given x = 0.040 and that the hole mobility is 1.0 x 10^{-5} m^2/V-s. It is first necessary to compute the number of vacancies per cubic meter for this material. For this determination let us use as our basis 10 unit cells. For the sodium chloride crystal structure there are four cations and four anions per unit cell. Thus, in ten unit cells of FeO there will normally be forty O^{2-} and forty Fe^{2+} ions. However, when x = 0.04, (0.04)(40) = 1.6 of the Fe^{2+} sites will be vacant. (Furthermore, there will be 3.2 Fe^{3+} ions in these ten unit cells inasmuch as two Fe^{3+} ions are created for every vacancy). Therefore, each unit cell will, on the average contain 0.16 vacancies. Now, the number of vacancies per cubic meter is just the number of vacancies per unit cell divided by the unit cell volume; this volume is just the unit cell edge length (0.437 nm) cubed. Thus

$$\frac{\#\ \text{vacancies}}{\text{m}^3} = \frac{0.16\ \text{vacancies/unit cell}}{(0.437 \times 10^{-9}\ \text{m})^3}$$

$$= 1.92 \text{ x } 10^{27} \text{ vacancies/m}^3$$

Inasmuch as it is assumed that the vacancies are saturated, the number of holes (p) is also 1.92 x 10^{27} m^{-3}. It is now possible, using Equation 18.17, to compute the electrical conductivity of this material as

$$\sigma = p|e|\mu_h$$

$$= (1.92 \times 10^{27}\ \text{m}^{-3})(1.602 \times 10^{-19}\ \text{C})(1.0 \times 10^{-5}\ \text{m}^2/\text{V-s}) = 3076\ (\Omega\text{-m})^{-1}$$

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18.48 For this problem, we are given, for NaCl, the activation energy (173,000 J/mol) and preexponential (4.0×10^{-4} m^2/s) for the diffusion coefficient of Na^+ and are asked to compute the mobility for a Na^+ ion at 873 K. The mobility, μ_{Na^+}, may be computed using Equation 18.23; however, this expression also includes the diffusion coefficient D_{Na^+}, which is determined using Equation 5.8 as

$$D_{Na^+} = D_0 \exp\left(-\frac{Q_d}{RT}\right)$$

$$= \left(4.0 \times 10^{-4} \text{ m}^2/\text{s}\right) \exp\left[-\frac{173{,}000 \text{ J/mol}}{(8.31 \text{ J/mol-K})(873 \text{ K})}\right]$$

$$= 1.76 \times 10^{-14} \text{ m}^2/\text{s}$$

Now solving for μ_{Na^+} yields

$$\mu_{Na^+} = \frac{n_{Na^+} e D_{Na^+}}{kT}$$

$$= \frac{(1)\left(1.602 \times 10^{-19} \text{ C/atom}\right)\left(1.76 \times 10^{-14} \text{ m}^2/\text{s}\right)}{\left(1.38 \times 10^{-23} \text{ J/atom-K}\right)(873 \text{ K})}$$

$$= 2.34 \times 10^{-13} \text{ m}^2/\text{V-s}$$

(Note: the value of n_{Na^+} is unity, since the valence for sodium is one.)

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Capacitance

18.49 We want to compute the plate spacing of a parallel-plate capacitor as the dielectric constant is increased form 2.2 to 3.7, while maintaining the capacitance constant. Combining Equations 18.26 and 18.27 yields

$$C = \frac{\varepsilon_r \varepsilon_0 A}{l}$$

Now, let us use the subscripts 1 and 2 to denote the initial and final states, respectively. Since $C_1 = C_2$, then

$$\frac{\varepsilon_{r1} \varepsilon_0 A}{l_1} = \frac{\varepsilon_{r2}\, \varepsilon_0 A}{l_2}$$

And, solving for l_2

$$l_2 = \frac{\varepsilon_{r2} l_1}{\varepsilon_{r1}} = \frac{(3.7)(2 \text{ mm})}{2.2} = 3.36 \text{ mm}$$

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18.50 This problem asks for us to ascertain which of the materials listed in Table 18.5 are candidates for a parallel-plate capacitor that has dimensions of 38 mm by 65 mm, a plate separation of 1.3 mm so as to have a minimum capacitance of 7 x 10^{-11} F, when an ac potential of 1000 V is applied at 1 MHz. Upon combining Equations 18.26 and 18.27 and solving for the dielectric constant ε_r we get

$$\varepsilon_r = \frac{lC}{\varepsilon_0 A}$$

$$= \frac{(1.3 \text{ x } 10^{-3}\,\text{m})(7 \text{ x } 10^{-11}\,\text{F})}{(8.85 \text{ x } 10^{-12}\,\text{F/m})(38 \text{ x } 10^{-3}\,\text{m})(65 \text{ x } 10^{-3}\,\text{m})}$$

$$= 4.16$$

Thus, the minimum value of ε_r to achieve the desired capacitance is 4.16 at 1 MHz. Of those materials listed in the table, titanate ceramics, mica, steatite, soda-lime glass, porcelain, and phenol-formaldehyde are candidates.

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18.51 In this problem we are given, for a parallel-plate capacitor, its area (3225 mm^2), the plate separation (1 mm), and that a material having an ε_r of 3.5 is positioned between the plates.

(a) We are first asked to compute the capacitance. Combining Equations 18.26 and 18.27, and solving for C yields

$$C = \frac{\varepsilon_r \varepsilon_0 A}{l}$$

$$= \frac{(3.5)(8.85 \times 10^{-12}\ \text{F/m})(3225\ \text{mm}^2)(1\ \text{m}^2/10^6\ \text{mm}^2)}{10^{-3}\ \text{m}}$$

$$= 10^{-10}\ \text{F} = 100\ \text{pF}$$

(b) Now we are asked to compute the electric field that must be applied in order that 2 x 10^{-8} C be stored on each plate. First we need to solve for V in Equation 18.24 as

$$V = \frac{Q}{C} = \frac{2 \times 10^{-8}\ \text{C}}{10^{-10}\ \text{F}} = 200\ \text{V}$$

The electric field E may now be determined using Equation 18.6; thus

$$E = \frac{V}{l} = \frac{200\ \text{V}}{10^{-3}\ \text{m}} = 2.0 \times 10^5\ \text{V/m}$$

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18.52 This explanation is found in Section 18.19.

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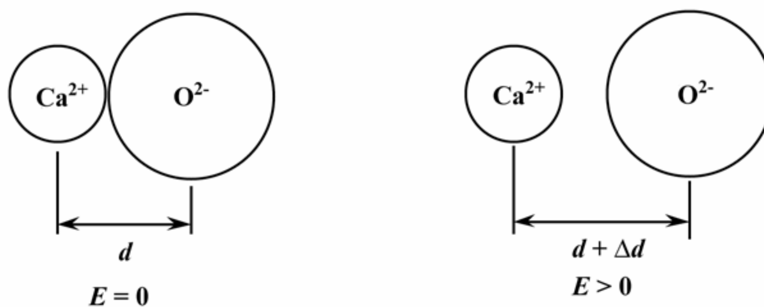
Field Vectors and Polarization

Types of Polarization

18.53 Shown below are the relative positions of Ca^{2+} and O^{2-} ions, without and with an electric field present.



Now,

$$d = r_{Ca^{2+}} + r_{O^{2-}} = 0.100 \text{ nm} + 0.140 \text{ nm} = 0.240 \text{ nm}$$

and

$$\Delta d = 0.05\, d = (0.05)(0.240 \text{ nm}) = 0.0120 \text{ nm} = 1.20 \times 10^{-11} \text{ m}$$

From Equation 18.28, the dipole moment, p, is just

$$p = q\,\Delta d$$

$$= (1.602 \times 10^{-19} \text{ C})(1.20 \times 10^{-11} \text{ m})$$

$$= 1.92 \times 10^{-30} \text{ C-m}$$

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18.54 (a) In order to solve for the dielectric constant in this problem, we must employ Equation 18.32, in which the polarization and the electric field are given. Solving for ε_r from this expression gives

$$\varepsilon_r = \frac{P}{\varepsilon_0 E} + 1$$

$$= \frac{4.0 \text{ x } 10^{-6} \text{ C/m}^2}{(8.85 \text{ x } 10^{-12} \text{ F/m})(1 \text{ x } 10^5 \text{ V/m})} + 1$$

$$= 5.52$$

(b) The dielectric displacement may be determined using Equation 18.31, as

$$D = \varepsilon_0 E + P$$

$$= (8.85 \text{ x } 10^{-12} \text{ F/m})(1 \text{ x } 10^5 \text{ V/m}) + 4.0 \text{ x } 10^{-6} \text{ C/m}^2$$

$$= 4.89 \text{ x } 10^{-6} \text{ C/m}^2$$

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18.55 (a) We want to solve for the voltage when $Q = 2.0 \times 10^{-10}$ C, $A = 650$ mm^2, $l = 4.0$ mm, and $\varepsilon_r = 3.5$. Combining Equations 18.24, 18.26, and 18.27 yields

$$C = \frac{Q}{V} = \varepsilon \frac{A}{l} = \varepsilon_r \varepsilon_0 \frac{A}{l}$$

Or

$$\frac{Q}{V} = \varepsilon_r \varepsilon_0 \frac{A}{l}$$

And, solving for V, and incorporating values provided in the problem statement, leads to

$$V = \frac{Q\,l}{\varepsilon_r \varepsilon_0 A}$$

$$= \frac{(2.0 \times 10^{-10}\ \text{C})(4.0 \times 10^{-3}\ \text{m})}{(3.5)(8.85 \times 10^{-12}\ \text{F/m})(650\ \text{mm}^2)(1\ \text{m}^2/10^6\ \text{mm}^2)}$$

$$= 39.7\ \text{V}$$

(b) For this same capacitor, if a vacuum is used

$$V = \frac{Q\,l}{\varepsilon_0 A}$$

$$= \frac{(2.0 \times 10^{-10}\ \text{C})(4.0 \times 10^{-3}\ \text{m})}{(8.85 \times 10^{-12}\ \text{F/m})(650 \times 10^{-6}\ \text{m}^2)}$$

$$= 139\ \text{V}$$

(c) The capacitance for part (a) is just

$$C = \frac{Q}{V} = \frac{2.0 \times 10^{-10}\ \text{C}}{39.7\ \text{V}} = 5.04 \times 10^{-12}\ \text{F}$$

While for part (b)

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$$C = \frac{Q}{V} = \frac{2.0 \times 10^{-10}\ \text{C}}{139\ \text{V}} = 1.44 \times 10^{-12}\ \text{F}$$

(d) The dielectric displacement may be computed by combining Equations 18.31, 18.32 and 18.6, as

$$D = \varepsilon_0 E + P = \varepsilon_0 E + \varepsilon_0(\varepsilon_r - 1)E = \varepsilon_0\varepsilon_r E = \frac{\varepsilon_0\varepsilon_r V}{l}$$

And incorporating values for ε_r and l provided in the problem statement, as well as the value of V computed in part (a)

$$D = \frac{(8.85 \times 10^{-12}\ \text{F/m})(3.5)(39.7\ \text{V})}{4.0 \times 10^{-3}\ \text{m}}$$

$$= 3.07 \times 10^{-7}\ \text{C/m}^2$$

(e) The polarization is determined using Equations 18.32 and 18.6 as

$$P = \varepsilon_0(\varepsilon_r - 1)E = \varepsilon_0(\varepsilon_r - 1)\frac{V}{l}$$

$$= \frac{(8.85 \times 10^{-12}\ \text{F/m})(3.5 - 1)(39.7\ \text{V})}{4.0 \times 10^{-3}\ \text{m}}$$

$$= 2.20 \times 10^{-7}\ \text{C/m}^2$$

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18.56 (a) For electronic polarization, the electric field causes a net displacement of the center of the negatively charged electron cloud relative to the positive nucleus. With ionic polarization, the cations and anions are displaced in opposite directions as a result of the application of an electric field. Orientation polarization is found in substances that possess permanent dipole moments; these dipole moments become aligned in the direction of the electric field.

(b) Only electronic polarization is to be found in gaseous argon; being an inert gas, its atoms will not be ionized nor possess permanent dipole moments.

Both electronic and ionic polarizations will be found in solid LiF, since it is strongly ionic. In all probability, no permanent dipole moments will be found in this material.

Both electronic and orientation polarizations are found in liquid H_2O. The H_2O molecules have permanent dipole moments that are easily oriented in the liquid state.

Only electronic polarization is to be found in solid Si; this material does not have molecules with permanent dipole moments, nor is it an ionic material.

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18.57 (a) This portion of the problem asks that we compute the magnitude of the dipole moment associated with each unit cell of $BaTiO_3$, which is illustrated in Figure 18.35. The dipole moment *p* is defined by Equation 18.28 as $p = qd$ in which *q* is the magnitude of each dipole charge, and *d* is the distance of separation between the charges. Each Ti^{4+} ion has four units of charge associated with it, and thus $q = (4)(1.602 \times 10^{-19}\text{ C}) = 6.41 \times 10^{-19}\text{ C}$. Furthermore, *d* is the distance the Ti^{4+} ion has been displaced from the center of the unit cell, which is just 0.006 nm + 0.006 nm = 0.012 nm [Figure 18.35(b)]. Hence

$$p = qd = (6.41 \text{ x } 10^{-19}\text{ C})(0.012 \text{ x } 10^{-9}\text{ m})$$

$$= 7.69 \text{ x } 10^{-30}\text{ C-m}$$

(b) Now it becomes necessary to compute the maximum polarization that is possible for this material. The maximum polarization will exist when the dipole moments of all unit cells are aligned in the same direction. Furthermore, it is computed by dividing the above value of *p* by the volume of each unit cell, which is equal to the product of three unit cell edge lengths, as shown in Figure 18.35. Thus

$$P = \frac{p}{V_C}$$

$$= \frac{7.69 \text{ x } 10^{-30}\text{ C}-\text{m}}{(0.403 \text{ x } 10^{-9}\text{ m})(0.398 \text{ x } 10^{-9}\text{ m})(0.398 \text{ x } 10^{-9}\text{ m})}$$

$$= 0.121\text{ C/m}^2$$

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Frequency Dependence of the Dielectric Constant

18.58 For this soda-lime glass, in order to compute the fraction of the dielectric constant at low frequencies that is attributed to ionic polarization, we must determine the ε_r within this low-frequency regime; such is tabulated in Table 18.5, and at 1 MHz its value is 6.9. Thus, this fraction is just

$$\text{fraction} = \frac{\varepsilon_r(\text{low}) - \varepsilon_r(\text{high})}{\varepsilon_r(\text{low})}$$

$$= \frac{6.9 - 2.3}{6.9} = 0.67$$

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Ferroelectricity

18.59 The ferroelectric behavior of $BaTiO_3$ ceases above its ferroelectric Curie temperature because the unit cell transforms from tetragonal geometry to cubic; thus, the Ti^{4+} is situated at the center of the cubic unit cell, there is no charge separation, and no net dipole moment.

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DESIGN PROBLEMS

Electrical Resistivity of Metals

18.D1 This problem asks that we calculate the composition of a copper-nickel alloy that has a room temperature resistivity of 2.5 x 10^{-7} Ω-m. The first thing to do is, using the 90 Cu-10 Ni resistivity data, determine the impurity contribution, and, from this result, calculate the constant *A* in Equation 18.11. Thus,

$$\rho_{\text{total}} = 1.90 \times 10^{-7}\ (\Omega\text{-m}) = \rho_i + \rho_t$$

From Table 18.1, for pure copper, and using Equation 18.4

$$\rho_t = \frac{1}{\sigma} = \frac{1}{6.0 \times 10^7\ (\Omega - \text{m})^{-1}} = 1.67 \times 10^{-8}\ (\Omega\text{-m})$$

Thus, for the 90 Cu-10 Ni alloy

$$\rho_i = \rho_{\text{total}} - \rho_t = 1.90 \times 10^{-7} - 1.67 \times 10^{-8}$$

$$= 1.73 \times 10^{-7}\ (\Omega\text{-m})$$

In the problem statement, the impurity (i.e., nickel) concentration is expressed in weight percent. However, Equation 18.11 calls for concentration in atom fraction (i.e., atom percent divided by 100). Consequently, conversion from weight percent to atom fraction is necessary. (Note: we now choose to denote the atom fraction of nickel as c'_{Ni}, and the weight percents of Ni and Cu by C_{Ni} and C_{Cu}, respectively.) Using these notations, this conversion may be accomplished by using a modified form of Equation 4.6a as

$$c'_{\text{Ni}} = \frac{C'_{\text{Ni}}}{100} = \frac{C_{\text{Ni}}A_{\text{Cu}}}{C_{\text{Ni}}A_{\text{Cu}} + C_{\text{Cu}}A_{\text{Ni}}}$$

Here A_{Ni} and A_{Cu} denote the atomic weights of nickel and copper (which values are 58.69 and 63.55 g/mol, respectively). Thus

$$c'_{\text{Ni}} = \frac{(10\ \text{wt\%})(63.55\ \text{g/mol})}{(10\ \text{wt\%})(63.55\ \text{g/mol}) + (90\ \text{wt\%})(58.69\ \text{g/mol})}$$

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$$= 0.107$$

Now, solving for *A* in Equation 18.11

$$A = \frac{\rho_i}{c'_{\mathrm{Ni}}\left(1 - c'_{\mathrm{Ni}}\right)}$$

$$= \frac{1.73 \times 10^{-7}\,(\Omega-\mathrm{m})}{(0.107)(1 - 0.107)} = 1.81 \times 10^{-6}\ (\Omega\text{ - m})$$

Now it is possible to compute the c'_{Ni} to give a room temperature resistivity of 2.5 x 10^{-7} Ω-m. Again, we must determine ρ_i as

$$\rho_i = \rho_{\mathrm{total}} - \rho_t$$

$$= 2.5 \times 10^{-7} - 1.67 \times 10^{-8} = 2.33 \times 10^{-7}\ (\Omega\text{ - m})$$

If Equation 18.11 is expanded, then

$$\rho_i = A\,c'_{\mathrm{Ni}} - A\,c'^{\,2}_{\mathrm{Ni}}$$

Or, rearranging this equation, we have

$$A\,c'^{\,2}_{\mathrm{Ni}} - A\,c'_{\mathrm{Ni}} + \rho_i = 0$$

Now, solving for c'_{Ni} (using the quadratic equation solution)

$$c'_{\mathrm{Ni}} = \frac{A \pm \sqrt{A^2 - 4A\rho_i}}{2A}$$

Again, from the above

$A = 1.81 \times 10^{-6}$ (Ω-m)
$\rho_i = 2.33 \times 10^{-7}$ (Ω-m)

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which leads to

$$c'_{\text{Ni}} = \frac{1.81 \text{ x } 10^{-6} \pm \sqrt{(1.81 \text{ x } 10^{-6})^2 - (4)(1.81 \text{ x } 10^{-6})(2.33 \text{ x } 10^{-7})}}{(2)(1.81 \text{ x } 10^{-6})}$$

And, taking the negative root,

$$c'_{\text{Ni}} = 0.152$$

Or, in terms of atom percent,

$$C'_{\text{Ni}} = 100c'_{\text{Ni}} = (100)(0.152) = 15.2 \text{ at\%}$$

While the concentration of copper is

$$C'_{\text{Cu}} = 100 - C'_{\text{Ni}} = 100 - 15.2 = 84.8 \text{ at\%}$$

Now, converting this composition to weight percent Ni, requires that we use Equation 4.7a as

$$C_{\text{Ni}} = \frac{C'_{\text{Ni}} A_{\text{Ni}}}{C'_{\text{Ni}} A_{\text{Ni}} + C'_{\text{Cu}} A_{\text{Cu}}} \text{ x } 100$$

$$= \frac{(15.2 \text{ at\%})(58.69 \text{ g/mol})}{(15.2 \text{ at\%})(58.69 \text{ g/mol}) + (84.8 \text{ at\%})(63.55 \text{ g/mol})} \text{ x } 100$$

$$= 14.2 \text{ wt\%}$$

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18.D2 This problem asks that we determine the electrical conductivity of an 85 wt% Cu-15 wt% Zn alloy at –100°C using information contained in Figures 18.8 and 18.37. In order to solve this problem it is necessary to employ Equation 18.9 which is of the form

$$\rho_{\text{total}} = \rho_t + \rho_i$$

since it is assumed that the alloy is undeformed. Let us first determine the value of ρ_i at room temperature (25°C) which value will be independent of temperature. From Figure 18.8, at 25°C and for pure Cu, $\rho_t(25) = 1.75 \times 10^{-8}$ Ω-m. Now, since it is assumed that the curve in Figure 18.37 was generated also at room temperature, we may take ρ as $\rho_{\text{total}}(25)$ at 85 wt% Cu-15 wt% Zn which has a value of 4.7×10^{-8} Ω-m. Thus

$$\rho_i = \rho_{\text{total}}(25) - \rho_t(25)$$

$$= 4.7 \times 10^{-8}\ \Omega\text{-m} - 1.75 \times 10^{-8}\ \Omega\text{-m} = 2.95 \times 10^{-8}\ \Omega\text{-m}$$

Finally, we may determine the resistivity at –100°C, $\rho_{\text{total}}(-100)$, by taking the resistivity of pure Cu at –100°C from Figure 18.8, which gives us $\rho_t(-100) = 0.90 \times 10^{-8}$ Ω-m. Therefore

$$\rho_{\text{total}}(-100) = \rho_i + \rho_t(-100)$$

$$= 2.95 \times 10^{-8}\ \Omega\text{-m} + 0.90 \times 10^{-8}\ \Omega\text{-m} = 3.85 \times 10^{-8}\ \Omega\text{-m}$$

And, using Equation 18.4 the conductivity is calculated as

$$\sigma = \frac{1}{\rho} = \frac{1}{3.85 \times 10^{-8}\ \Omega-\text{m}} = 2.60 \times 10^{7}\ (\Omega\text{-m})^{-1}$$

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18.D3 To solve this problem, we want to consult Figures 7.16(b) and 18.9 in order to determine the Ni concentration ranges over which the yield strength is greater than 130 MPa (19,000 psi) and the conductivity exceeds 4.0 x 10^6 (Ω-m)$^{-1}$.

From Figure 7.16(b), a Ni concentration greater than about 23 wt% is necessary for a yield strength in excess of 130 MPa. In Figure 18.9 is plotted the resistivity versus the Ni content. Since conductivity is the reciprocal of resistivity, the resistivity must be less than 25 x 10^{-8} Ω-m--i.e., $\frac{1}{4.0 \times 10^6 \ (\Omega - \text{m})^{-1}}$. According to the figure, this will be the case for Ni concentrations less than 17 wt%.

Hence, it is *not* possible to prepare an alloy meeting the criteria; for the stipulated yield strength the required Ni content must be greater than 23 wt%, whereas for the required conductivity, less than 17 wt% Ni is necessary.

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Extrinsic Semiconduction

Factors That Affect Carrier Mobility

18.D4 First of all, those elements which, when added to silicon render it *n*-type, lie one group to the right of silicon in the periodic table; these include the group VA elements (Figure 2.6)--i.e., nitrogen, phosphorus, arsenic, and antimony.

Since this material is extrinsic and *n*-type, $n >> p$, and the electrical conductivity is a function of the hole concentration according to Equation 18.16. Also, the number of free electrons is about equal to the number of donor impurities, N_d. That is

$$n \sim N_d$$

From Equation 18.16, the conductivity is a function of both the electron concentration (n) and the electron mobility (μ_e). Furthermore, the room-temperature electron mobility is dependent on impurity concentration (Figure 18.18). One way to solve this problem is to use an iterative approach—i.e., assume some donor impurity concentration (which will also equal the value of n), then determine a "calculated" electron mobility from Equation 18.16—i.e.,

$$\mu_e = \frac{\sigma}{n\,|e|}$$

and, finally, compare this mobility with the "measured" value from Figure 18.18, taken at the assumed n (i.e., N_d) value.

Let us begin by assuming that $N_d = 10^{22}$ m^{-3}. Thus, the "calculated" mobility value is

$$\mu_e = \frac{\sigma}{n|e|} = \frac{200\ (\Omega - \text{m})^{-1}}{\left(10^{22}\ \text{m}^{-3}\right)\left(1.602 \text{ x } 10^{-19}\ \text{C}\right)} = 0.125\ \text{m}^2/\text{V}-\text{s}$$

From Figure 18.18, at an impurity concentration of 10^{22} m^{-3} the "measured" electron mobility is 0.10 m^2/V-s, which is slightly lower than the "calculated" value.

For our next choice, let us assume a higher impurity concentration, say 10^{23} m^{-3}. At this higher concentration there will be a reduction of both "calculated" and "measured" electron mobilities. The "calculated" value is just

$$\mu_e = \frac{\sigma}{n\,|e|} = \frac{200\ (\Omega - \text{m})^{-1}}{\left(10^{23}\ \text{m}^{-3}\right)\left(1.602 \text{ x } 10^{-19}\ \text{C}\right)} = 0.0125\ \text{m}^2/\text{V}-\text{s}$$

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Whereas, Figure 18.18 yields a "measured" μ_e of 0.06 m^2/V-s, which is higher than the "calculated" value. Therefore, the correct impurity concentration will lie somewhere between 10^{22} and 10^{23} m^{-3} probably closer to the lower of these two values. At 1.3 x 10^{22} m^{-3}, both "measured" and "calculated" μ_e values are about equal (0.095 m^2/V-s).

It next becomes necessary to calculate the concentration of donor impurities in atom percent. This computation first requires the determination of the number of silicon atoms per cubic meter, N_{Si}, using Equation 4.2, which is as follows

$$N_{\text{Si}} = \frac{N_{\text{A}} \rho'_{\text{Si}}}{A_{\text{Si}}}$$

$$= \frac{(6.023 \text{ x } 10^{23} \text{ atoms/mol})(2.33 \text{ g/cm}^3)(10^6 \text{ cm}^3/\text{m}^3)}{28.09 \text{ g/mol}}$$

$$= 5 \text{ x } 10^{28} \text{ m}^{-3}$$

(Note: in the above discussion, the density of silicon is represented by ρ'_{Si} in order to avoid confusion with resistivity, which is designated by ρ.)

The concentration of donor impurities in atom percent (C'_d) is just the ratio of N_d and (N_d + N_{Si}) multiplied by 100 as

$$C'_d = \frac{N_d}{N_d + N_{\text{Si}}} \text{ x } 100$$

$$= \frac{1.3 \text{ x } 10^{22} \text{ m}^{-3}}{(1.3 \text{ x } 10^{22} \text{ m}^{-3}) + (5 \text{ x } 10^{28} \text{ m}^{-3})} \text{ x } 100 = 2.6 \text{ x } 10^{-5} \text{ at\%}$$

Now, conversion to weight percent (C_d) is possible using Equation 4.7a as

$$C_d = \frac{C'_d A_d}{C'_d A_d + C'_{\text{Si}} A_{\text{Si}}} \text{ x } 100$$

where A_d and A_{Si} are the atomic weights of the donor and silicon, respectively. Thus, the concentration in weight percent will depend on the particular donor type. For example, for nitrogen

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$$C_N = \frac{C'_N A_N}{C'_N A_N + C'_{Si} A_{Si}} \times 100$$

$$= \frac{(2.6 \times 10^{-5} \text{ at\%})(14.01 \text{ g/mol})}{(2.6 \times 10^{-5} \text{ at\%})(14.01 \text{ g/mol}) + (99.999974 \text{ at\%})(28.09 \text{ g/mol})} \times 100$$

$$= 1.3 \times 10^{-5} \text{ wt\%}$$

Similar calculations may be carried out for the other possible donor impurities which yield

$$C_P = 2.87 \times 10^{-5} \text{ wt\%}$$

$$C_{As} = 6.93 \times 10^{-5} \text{ wt\%}$$

$$C_{Sb} = 1.127 \times 10^{-4} \text{ wt\%}$$

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18.D5 This problem asks for us to determine the temperature at which boron is to be diffused into high-purity silicon in order to achieve a room-temperature electrical conductivity of 1000 $(\Omega\text{-m})^{-1}$ at a distance 0.2 μm from the surface if the B concentration at the surface is maintained at 1.0 x 10^{25} m^{-3}. It is first necessary for us to compute the hole concentration (since B is an acceptor in Si) at this 0.2 μm location.

From Equation 18.17, the conductivity is a function of both the hole concentration (p) and the hole mobility (μ_h). Furthermore, the room-temperature hole mobility is dependent on impurity concentration (Figure 18.18). One way to solve this problem is to use an iterative approach—i.e., assume some boron concentration, N_B (which will also equal the value of p), then determine a "calculated" hole mobility from Equation 18.17—i.e.,

$$\mu_h = \frac{\sigma}{p|e|}$$

and then compare this mobility with the "measured" value from Figure 18.18, taken at the assumed p (i.e., N_B).

Let us begin by assuming that $N_B = 10^{24}$ m^{-3}. Thus, the "calculated" mobility value is

$$\mu_h = \frac{\sigma}{p|e|} = \frac{1000\ (\Omega - \text{m})^{-1}}{(10^{24}\ \text{m}^{-3})(1.602 \text{ x } 10^{-19}\ \text{C})} = 0.0062\ \text{m}^2/\text{V}-\text{s}$$

From Figure 18.18, at an impurity concentration of 10^{24} m^{-3} the "measured" hole mobility is 0.01 m^2/V-s, which is higher than the "calculated" value.

For our next choice, let us assume a lower boron concentration, say 10^{23} m^{-3}. At this lower concentration there will be an increase of both "calculated" and "measured" hole mobilities. The "calculated" value is just

$$\mu_h = \frac{\sigma}{p|e|} = \frac{1000\ (\Omega - \text{m})^{-1}}{(10^{23}\ \text{m}^{-3})(1.602 \text{ x } 10^{-19}\ \text{C})} = 0.062\ \text{m}^2/\text{V}-\text{s}$$

Whereas, Figure 18.18 yields a "measured" μ_h of 0.024 m^2/V-s, which is lower than the "calculated" value. Therefore, the correct impurity concentration will lie somewhere between 10^{23} and 10^{24} m^{-3}. At 4.0 x 10^{23} m^{-3}, "measured" and "calculated" values are about equal (0.015 m^2/V-s).

With regard to diffusion, the problem is one involving the nonsteady-state diffusion of B into the Si, wherein we have to solve for temperature. Temperature is incorporated into the diffusion coefficient expression given in the problem. But we must first employ the solution to Fick's second law for constant surface composition boundary conditions, Equation 5.5; in this expression C_0 is taken to be zero inasmuch as the problem stipulates that the initial boron concentration may be neglected. Thus,

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$$\frac{C_x - C_0}{C_s - C_0} = 1 - \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

$$\frac{4.0 \text{ x } 10^{23}\,\mathrm{m}^{-3} - 0}{1.0 \text{ x } 10^{25}\,\mathrm{m}^{-3} - 0} = 1 - \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

which reduces to

$$0.9600 = \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

In order to solve this expression for a value $\frac{x}{2\sqrt{Dt}}$ of it is necessary to interpolate using data in Table 5.1. Thus

z	erf(z)
1.4	0.9523
z	0.9600
1.5	0.9661

$$\frac{z - 1.4}{1.5 - 1.4} = \frac{0.9600 - 0.9523}{0.9661 - 0.9523}$$

From which, $z = 1.4558$; which is to say

$$1.4558 = \frac{x}{2\sqrt{Dt}}$$

Inasmuch as there are 3600 s/h (= t) and $x = 0.2$ µm (= 2 x 10^{-7} m) the above equation becomes

$$1.4558 = \frac{2 \text{ x } 10^{-7}\,\mathrm{m}}{2\sqrt{(D)(3600\,\mathrm{s})}}$$

which, when solving for the value of D, leads to

$$D = \frac{1}{3600\,\mathrm{s}}\left[\frac{2 \times 10^{-7}\,\mathrm{m}}{(2)(1.4558)}\right]^2 = 1.31 \times 10^{-18}\,\mathrm{m}^2/\mathrm{s}$$

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Now, equating this value to the expression for *D* given in the problem gives

$$D = 1.31 \text{ x } 10^{-18} \text{ m}^2/\text{s} = \left(2.4 \text{ x } 10^{-4}\right) \exp\left[-\frac{347{,}000 \text{ J/mol}}{(8.31 \text{ J/mol-K})(T)}\right]$$

To solve for *T*, let us take the natural logarithms of both sides of the above equation; this leads to

$$\ln\left(1.31 \text{ x } 10^{-18}\right) = \ln\left(2.4 \text{ x } 10^{-4}\right) - \frac{347{,}000}{8.31T}$$

$$-41.176 = -8.335 - \frac{4.176 \text{ x } 10^4}{T}$$

which yields a value for *T* of 1271 K (998°C).

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Conduction in Ionic Materials

18.D6 This problem asks, for the nonstoichiometric $Fe_{(1-x)}O$, given the electrical conductivity [1200 $(\Omega\text{-m})^{-1}$] and hole mobility (1.0×10^{-5} m^2/V-s) that we determine the value of x. It is first necessary to compute the number of holes per unit volume (p) using Equation 18.17. Thus

$$p = \frac{\sigma}{|e|\mu_h}$$

$$= \frac{1200\ (\Omega - \text{m})^{-1}}{(1.602 \times 10^{-19}\ \text{C})(1.0 \times 10^{-5}\ \text{m}^2/\text{V-s})} = 7.49 \times 10^{26}\ \text{holes/m}^3$$

Inasmuch as it is assumed that the acceptor states are saturated, the number of vacancies is also 7.49×10^{26} m^{-3}. Next, it is possible to compute the number of vacancies per unit cell by taking the product of the number of vacancies per cubic meter times the volume of a unit cell. This volume is just the unit cell edge length (0.437 nm) cubed:

$$\frac{\#\ \text{vacancies}}{\text{unit cell}} = (7.49 \times 10^{26}\ \text{m}^{-3})(0.437 \times 10^{-9}\ \text{m})^3 = 0.0625$$

A unit cell for the sodium chloride structure contains the equivalence of four cations and four anions. Thus, if we take as a basis for this problem 10 unit cells, there will be 0.625 vacancies, 40 O^{2-} ions, and 39.375 iron ions (since 0.625 of the iron sites is vacant). (It should also be noted that since two Fe^{3+} ions are created for each vacancy, that of the 39.375 iron ions, 38.125 of them are Fe^{2+} and 1.25 of them are Fe^{3+}). In order to find the value of $(1-x)$ in the chemical formula, we just take the ratio of the number of total Fe ions (39.375) and the number of total Fe ion sites (40). Thus

$$(1 - x) = \frac{39.375}{40} = 0.984$$

Or the formula for this nonstoichiometric material is $Fe_{0.984}O$.

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Semiconductor Devices

18.D7 (a) In this portion of the problem we are asked to determine the time required to grow a layer of SiO_2 that is 100 nm (i.e., 0.100 μm) thick on the surface of a silicon chip at 1000°C, in an atmosphere of O_2 (oxygen pressure = 1 atm). Thus, using Equation 18.37, it is necessary to solve for the time *t*. However, before this is possible, we must calculate the value of *B* from Equation 18.38a as follows:

$$B = 800 \exp\left(-\frac{1.24 \text{ eV}}{kT}\right) = (800)\exp\left[-\frac{1.24 \text{ eV}}{(8.62 \times 10^{-5} \text{ eV/atom-K})(1000 + 273 \text{ K})}\right]$$

$$= 0.00990 \ \mu\text{m}^2/\text{h}$$

Now, solving for *t* from Equation 18.37 using the above value for *B* and that $x = 0.100$ μm, we have

$$t = \frac{x^2}{B} = \frac{(0.100 \ \mu\text{m})^2}{0.00990 \ \mu\text{m}^2/\text{h}}$$

$$= 1.01 \text{ h}$$

Repeating the computation for *B* at 700°C:

$$B = (800)\exp\left[-\frac{1.24 \text{ eV}}{(8.62 \times 10^{-5} \text{ eV/atom-K})(700 + 273 \text{ K})}\right]$$

$$= 3.04 \times 10^{-4} \ \mu\text{m}^2/\text{h}$$

And solving for the oxidation time as above

$$t = \frac{(0.100 \ \mu\text{m})^2}{3.04 \times 10^{-4} \ \mu\text{m}^2/\text{h}} = 32.9 \text{ h}$$

(b) This part of the problem asks for us to compute the heating times to form an oxide layer 100 nm thick at the same two temperatures (1000°C and 700°C) when the atmosphere is water vapor (1 atm pressure). At 1000°C, the value of *B* is determined using Equation 18.38b, as follows:

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$$B = 215 \exp\left(-\frac{0.70 \text{ eV}}{kT}\right) = (215) \exp\left[-\frac{0.70 \text{ eV}}{(8.62 \times 10^{-5} \text{ eV/atom-K})(1000 + 273 \text{ K})}\right]$$

$$= 0.365 \ \mu\text{m}^2/\text{h}$$

And computation of the time t from the rearranged form of Equation 18.37, leads to

$$t = \frac{x^2}{B} = \frac{(0.100 \ \mu\text{m})^2}{0.365 \ \mu\text{m}^2/\text{h}}$$

$$= 0.0274 \text{ h} = 98.6 \text{ s}$$

And at 700°C, the value of B is

$$B = (215) \exp\left[-\frac{0.70 \text{ eV}}{(8.62 \times 10^{-5} \text{ eV/atom-K})(700 + 273 \text{ K})}\right] = 0.0510 \ \mu\text{m}^2/\text{h}$$

Whereas the time required to grow the 100 nm oxide layer is

$$t = \frac{x^2}{B} = \frac{(0.100 \ \mu\text{m})^2}{0.0510 \ \mu\text{m}^2/\text{h}}$$

$$= 0.196 \text{ h} = 706 \text{ s}$$

From the above computations, it is very apparent (1) that the 100 nm oxide layer forms more rapidly at 1000°C (than at 700°C) in both O_2 and H_2O gaseous atmospheres, and (2) that the oxide layer formation is more rapid in water vapor than in oxygen.

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18.D8 We are asked to compare silicon and gallium arsenide semiconductors relative to properties and applications.

The following are the characteristics and applications for Si: (1) being an elemental semiconductor, it is cheaper to grow in single-crystalline form; (2) because of its electron band structure, it is best used in transistors; (3) electronic processes are relatively slow due to the low mobilities for electrons and holes (Table 18.3).

For GaAs: (1) it is much more expensive to produce inasmuch as it is a compound semiconductor; (2) because of its electron band structure it is best used in light-emitting diodes and semiconducting lasers; (3) its band gap may be altered by alloying; (4) electronic processes are more rapid than in Si due to the greater mobilities for electrons and holes; (5) absorption of electromagnetic radiation is greater in GaAs, and therefore, thinner layers are required for solar cells.

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