Chapter 41

1. (a) The probability that a state with energy E is occupied is given by

$$P(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

where E_F is the Fermi energy, T is the temperature on the Kelvin scale, and k is the Boltzmann constant. If energies are measured from the top of the valence band, then the energy associated with a state at the bottom of the conduction band is E = 1.11 eV. Furthermore,

$$kT = (8.62 \times 10^{-5}\ \text{eV/K})(300\ \text{K}) = 0.02586\ \text{eV}.$$

For pure silicon, E_F = 0.555 eV and

$$(E - E_F)/kT = (0.555\ \text{eV})/(0.02586\ \text{eV}) = 21.46.$$

Thus,

$$P(E) = \frac{1}{e^{21.46} + 1} = 4.79 \times 10^{-10}.$$

(b) For the doped semiconductor,

$$(E - E_F)/kT = (0.11\ \text{eV})/(0.02586\ \text{eV}) = 4.254$$

and

$$P(E) = \frac{1}{e^{4.254} + 1} = 1.40 \times 10^{-2}.$$

(c) The energy of the donor state, relative to the top of the valence band, is 1.11 eV – 0.15 eV = 0.96 eV. The Fermi energy is 1.11 eV – 0.11 eV = 1.00 eV. Hence,

$$(E - E_F)/kT = (0.96\ \text{eV} - 1.00\ \text{eV})/(0.02586\ \text{eV}) = -1.547$$

and

$$P(E) = \frac{1}{e^{-1.547} + 1} = 0.824.$$

16. Equation 41-5 gives

$$N(E) = \frac{8\sqrt{2}\pi m^{3/2}}{h^3} E^{1/2}$$

for the density of states associated with the conduction electrons of a metal. This can be written

$$N(E) = CE^{1/2}$$

where

$$C = \frac{8\sqrt{2}\pi m^{3/2}}{h^3} = \frac{8\sqrt{2}\pi (9.109\times10^{-31}\,\mathrm{kg})^{3/2}}{(6.626\times10^{-34}\,\mathrm{J\cdot s})^3} = 1.062\times10^{56}\,\mathrm{kg}^{3/2}/\mathrm{J}^3\cdot\mathrm{s}^3$$
$$= 6.81\times10^{27}\,\mathrm{m}^{-3}\cdot(\mathrm{eV})^{-3/2}.$$

Thus,

$$N(E) = CE^{1/2} = \left[6.81\times10^{27}\,\mathrm{m}^{-3}\cdot(\mathrm{eV})^{-3/2}\right](7.0\,\mathrm{eV})^{1/2} = 1.8\times10^{28}\,\mathrm{m}^{-3}\cdot\mathrm{eV}^{-1}\ .$$

This is consistent with that shown in Fig. 41-6.

21. The valence band is essentially filled and the conduction band is essentially empty. If an electron in the valence band is to absorb a photon, the energy it receives must be sufficient to excite it across the band gap. Photons with energies less than the gap width are not absorbed and the semiconductor is transparent to this radiation. Photons with energies greater than the gap width are absorbed and the semiconductor is opaque to this radiation. Thus, the width of the band gap is the same as the energy of a photon associated with a wavelength of 350 nm. Noting that $hc = 1240\,\text{eV}\cdot\text{nm}$, we obtain

$$E_{\text{gap}} = \frac{1240\,\text{eV}\cdot\text{nm}}{\lambda} = \frac{1240\,\text{eV}\cdot\text{nm}}{350\,\text{nm}} = 3.54\,\text{eV}.$$

34. (a) The semiconductor is *n*-type, since each phosphorus atom has one more valence electron than a silicon atom.

(b) The added charge carrier density is

$$n_P = 10^{-6}\, n_{Si} = 10^{-6}\,(5 \times 10^{28}\ \text{m}^{-3}) = 5 \times 10^{22}\ \text{m}^{-3}.$$

(c) The ratio is

$$(5 \times 10^{22}\ \text{m}^{-3})/[2(5 \times 10^{15}\ \text{m}^{-3})] = 5 \times 10^{6}.$$

Here the factor of 2 in the denominator reflects the contribution to the charge carrier density from *both* the electrons in the conduction band *and* the holes in the valence band.

28. The probability P_h that a state is occupied by a hole is the same as the probability the state is unoccupied by an electron. Since the total probability that a state is either occupied or unoccupied is 1, we have $P_h + P = 1$. Thus,

$$P_h = 1 - \frac{1}{e^{(E-E_F)/kT}+1} = \frac{e^{(E-E_F)/kT}}{1+e^{(E-E_F)/kT}} = \frac{1}{e^{-(E-E_F)/kT}+1} .$$