2.14 (a) Determine the temperature at which the intrinsic carrier concentration in (i) Si and (ii) GaAs are equal to the room temperature (300 K) intrinsic carrier concentration of Ge.

(b) Semiconductor A has a band gap of 1 eV, while semiconductor B has a band gap of 2 eV. What is the ratio of the intrinsic carrier concentrations in the two materials (n_{iA}/n_{iB}) at 300 K. Assume any differences in the carrier effective masses may be neglected.

2.16 Concentration questions with a twist.

(a) A silicon wafer is uniformly doped p-type with $N_A = 10^{15}/\text{cm}^3$. At $T \simeq 0$ K, what are the equilibrium hole and electron concentrations?

(b) A semiconductor is doped with an impurity concentration N such that $N \gg n_i$ and all the impurities are ionized. Also, $n = N$ and $p = n_i^2/N$. Is the impurity a donor or an acceptor? Explain.

(c) The electron concentration in a piece of Si maintained at 300 K under equilibrium conditions is $10^5/\text{cm}^3$. What is the hole concentration?

(d) For a silicon sample maintained at $T = 300$ K, the Fermi level is located 0.259 eV above the intrinsic Fermi level. What are the hole and electron concentrations?

(e) In a nondegenerate germanium sample maintained under equilibrium conditions near room temperature, it is known that $n_i = 10^{13}/\text{cm}^3$, $n = 2p$, and $N_A = 0$. Determine n and N_D.

2.17 Determine the equilibrium electron and hole concentrations inside a uniformly doped sample of Si under the following conditions:

(a) $T = 300$ K, $N_A \ll N_D$, $N_D = 10^{15}/\text{cm}^3$.

(b) $T = 300$ K, $N_A = 10^{16}/\text{cm}^3$, $N_D \ll N_A$.

(c) $T = 300$ K, $N_A = 9 \times 10^{15}/\text{cm}^3$, $N_D = 10^{16}/\text{cm}^3$.

(d) $T = 450$ K, $N_A = 0$, $N_D = 10^{14}/\text{cm}^3$.

(e) $T = 650$ K, $N_A = 0$, $N_D = 10^{14}/\text{cm}^3$.

2.18 (a to e) For each of the conditions specified in Problem 2.17, determine the position of E_i, compute $E_F - E_i$, and draw a carefully dimensioned energy band diagram for the Si sample. NOTE: $E_G(\text{Si}) = 1.08$ eV at 450 K and 1.015 eV at 650 K.

2.22 GaAs considerations.

(a) Make a sketch similar to Fig. 2.14 that is specifically appropriate for GaAs. Be sure to take into account the fact that $m_n^* \ll m_p^*$ in GaAs.

(b) Based on your answer to part (a), would you expect E_i in GaAs to lie above or below midgap? Explain.

(c) Determine the precise position of the intrinsic Fermi level in GaAs at room temperature (300 K).

(d) Determine the maximum nondegenerate donor and acceptor doping concentrations in GaAs at room temperature.

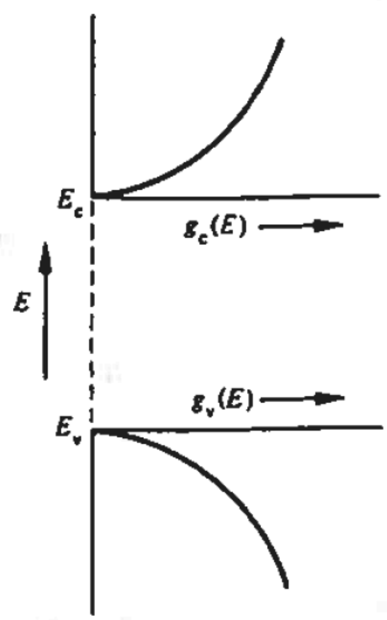

Figure 2.14 General energy dependence of $g_c(E)$ and $g_v(E)$ near the band edges. $g_c(E)$ and $g_v(E)$ are the density of states in the conduction and valence bands, respectively.

Table 2.1 Density of States Effective Masses at 300 K.

Material	m_n^*/m_0	m_p^*/m_0
Si	1.18	0.81
Ge	0.55	0.36
GaAs	0.066	0.52

$$\left.\begin{aligned} n_i &\simeq 2 \times 10^6/\text{cm}^3 && \text{in GaAs} \\ &\simeq 1 \times 10^{10}/\text{cm}^3 && \text{in Si} \\ &\simeq 2 \times 10^{13}/\text{cm}^3 && \text{in Ge} \end{aligned}\right\} \text{at room temperature}$$

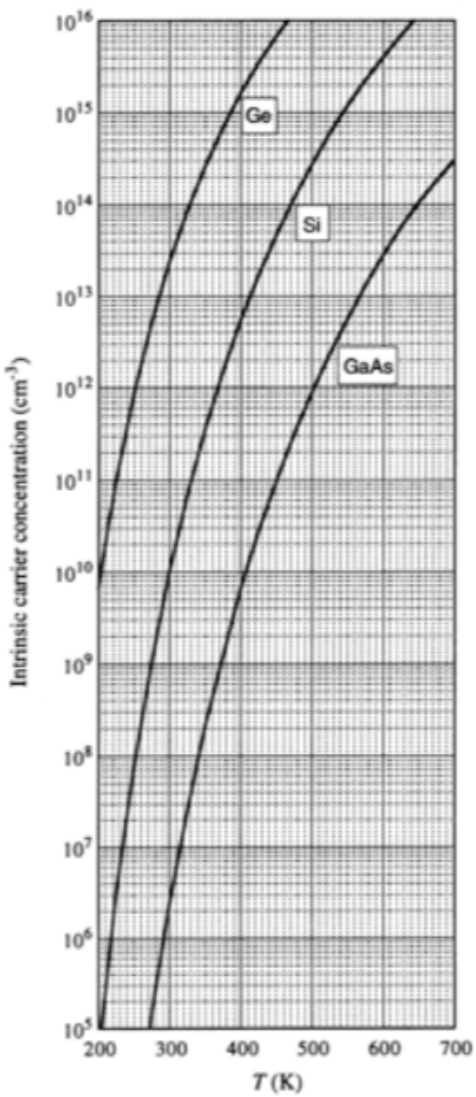

Table 2.4 Carrier Modeling Equation Summary.

Density of States and Fermi Function

$$g_c(E) = \frac{m_n^* \sqrt{2m_n^*(E - E_c)}}{\pi^2 \hbar^3}, \quad E \geq E_c$$

$$g_v(E) = \frac{m_p^* \sqrt{2m_p^*(E_v - E)}}{\pi^2 \hbar^3}, \quad E \leq E_v$$

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

Carrier Concentration Relationships

$$n = N_C \frac{2}{\sqrt{\pi}} F_{1/2}(\eta_c) \qquad N_C = 2\left[\frac{m_n^* kT}{2\pi\hbar^2}\right]^{3/2}$$

$$p = N_V \frac{2}{\sqrt{\pi}} F_{1/2}(\eta_v) \qquad N_V = 2\left[\frac{m_p^* kT}{2\pi\hbar^2}\right]^{3/2}$$

$$n = N_C e^{(E_F - E_c)/kT}$$

$$p = N_V e^{(E_v - E_F)/kT}$$

$$n = n_i e^{(E_F - E_i)/kT}$$

$$p = n_i e^{(E_i - E_F)/kT}$$

n_i, np-Product, and Charge Neutrality

$$n_i = \sqrt{N_C N_V} e^{-E_G/2kT} \qquad np = n_i^2 \qquad p - n + N_D - N_A = 0$$

n, p, and Fermi Level Computational Relationships

$$n = \frac{N_D - N_A}{2} + \left[\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2\right]^{1/2}$$

$$E_i = \frac{E_c + E_v}{2} + \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right)$$

$$\left.\begin{array}{l} n \simeq N_D \\ p \simeq n_i^2/N_D \end{array}\right\} \quad N_D \gg N_A,\ N_D \gg n_i$$

$$E_F - E_i = kT\ln(n/n_i) = -kT\ln(p/n_i)$$

$$\left.\begin{array}{l} p \simeq N_A \\ n \simeq n_i^2/N_A \end{array}\right\} \quad N_A \gg N_D,\ N_A \gg n_i$$

$$E_F - E_i = kT\ln(N_D/n_i) \quad N_D \gg N_A,\ N_D \gg n_i$$

$$E_i - E_F = kT\ln(N_A/n_i) \quad N_A \gg N_D,\ N_A \gg n_i$$

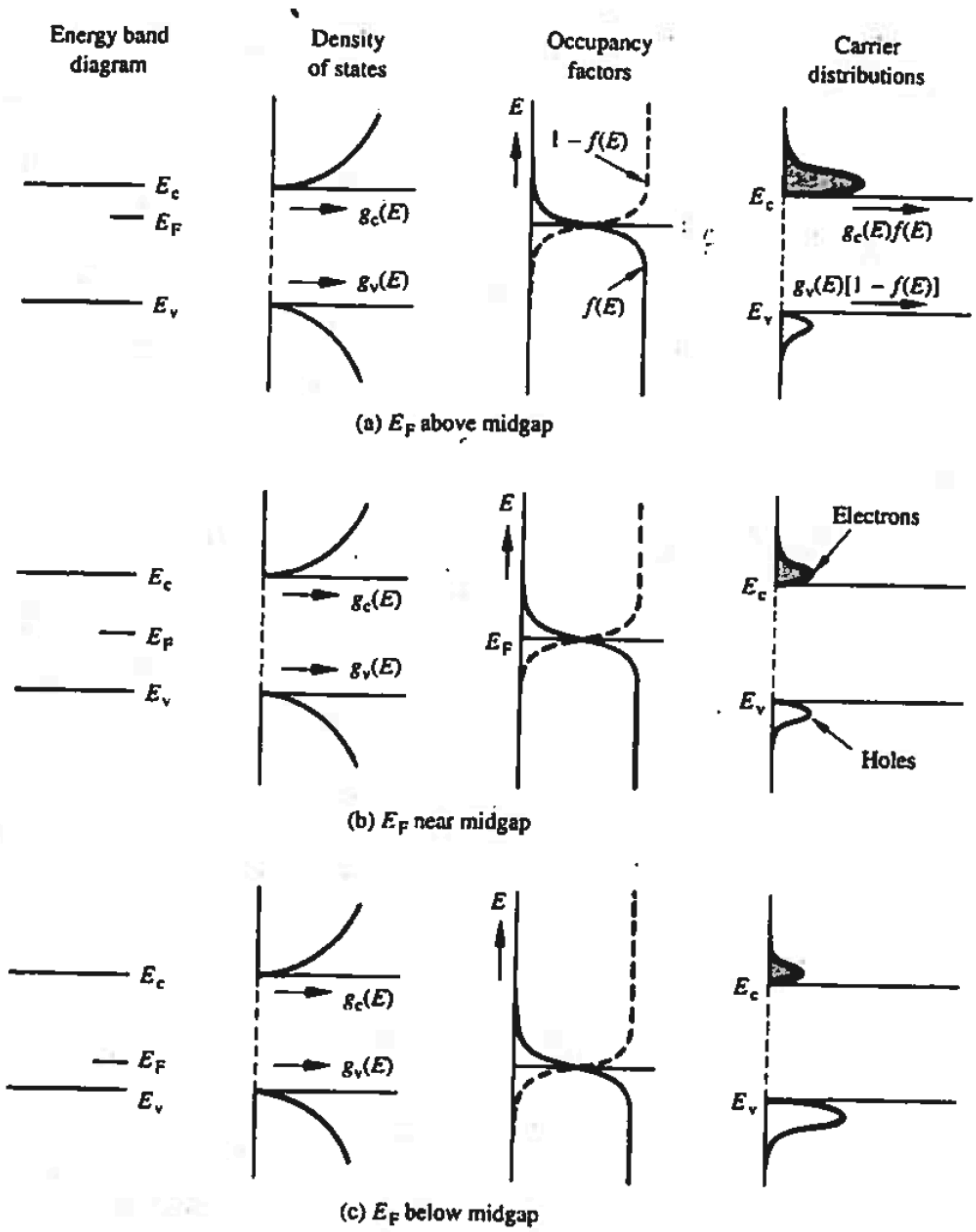

Figure 2.16 Carrier distributions (not drawn to scale) in the respective bands when the Fermi level is positioned (a) above midgap, (b) near midgap, and (c) below midgap. Also shown in each case are coordinated sketches of the energy band diagram, density of states, and the occupancy factors (the Fermi function and one minus the Fermi function).