Objective *To calculate the intrinsic carrier concentration in gallium arsenide at $T = 300$ K and $T = 450$ K.*

The values of N_c and N_v at 300 K for gallium arsenide are 4.7×10^{17} cm^{-3} and 7.0×10^{18} cm^{-3}, respectively. Both N_c and N_v vary as $T^{3/2}$. Assume the bandgap energy of gallium arsenide is 1.42 eV and does not vary with temperature over this range. The value of kT at 450 K is

$$kT = (0.0259)\left(\frac{450}{300}\right) = 0.03885 \text{ eV}$$

Using Eq. (3.28), we find for $T = 300$ K

$$n_i^2 = (4.7 \times 10^{17})(7.0 \times 10^{18}) \exp\left(\frac{-1.42}{0.0259}\right) = 2.00 \times 10^{12}$$

so that

$$n_i = 2.24 \times 10^{6} \text{ cm}^{-3}$$

For $T = 450$ K, we find

$$n_i^2 = (4.7 \times 10^{17})(7.0 \times 10^{18})\left(\frac{450}{300}\right)^3 \exp\left(\frac{-1.42}{0.03885}\right) = 1.30 \times 10^{15}$$

so that

$$n_i = 3.85 \times 10^{7} \text{ cm}^{-3}$$

---

[1] Values elsewhere may be slightly different, which affects the intrinsic carrier concentration at room temperature. In general, these differences are between 0.1×10^{6} and 1.5×10^{6} cm^{-3}. This difference is, in most cases, not significant.

Comment We may note from this example that the intrinsic carrier concentration increased by over 4 orders of magnitude as the temperature increased by 150°C.

Figure 3.10 is a plot of n_i from Eq. (3.28) for silicon, gallium arsenide, and germanium as a function of temperature. As seen in the figure, the value of n_i for these semiconductors may easily vary over several orders of magnitude as the temperature changes over a reasonable range.

3.2.4 The Intrinsic Fermi-Level Position

We have qualitatively argued that the Fermi energy level is located near the center of the forbidden bandgap for the intrinsic semiconductor. We can specifically calculate the intrinsic Fermi-level position. Since the electron and hole concentrations are equal, setting Eqs (3.25) and (3.26) equal to each other, we have

$$N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right] \tag{3.29}$$

If we take the natural log of both sides of this equation and solve for E_{Fi}, we obtain

$$E_{Fi} = \frac{1}{2}(E_c + E_v) + \frac{1}{2}kT \ln\left(\frac{N_v}{N_c}\right) \tag{3.30}$$

From the definitions for N_c and N_v given by Eqs (3.15) and (3.23), respectively, Eq. (3.30) may be written as

$$E_{Fi} = \frac{1}{2}(E_c + E_v) + \frac{3}{4}kT \ln\left(\frac{m_p^*}{m_n^*}\right) \tag{3.31a}$$

The first term, $\frac{1}{2}(E_c + E_v)$, is the energy exactly midway between E_c and E_v, or the midgap energy. We can define

$$\frac{1}{2}(E_c + E_v) = E_{\text{midgap}}$$

so that

$$\boxed{E_{Fi} - E_{\text{midgap}} = \frac{3}{4}kT \ln\left(\frac{m_p^*}{m_n^*}\right)} \tag{3.31b}$$

If the electron and hole effective masses are equal so that $m_p^* = m_n^*$, then the intrinsic Fermi level is exactly in the center of the bandgap. If $m_p^* > m_n^*$, the intrinsic Fermi level is slightly above the center, and if $m_p^* < m_n^*$, it is slightly below the center of the bandgap. The density of states function is directly related to the carrier effective mass; thus a larger effective mass means a larger density of states function. The intrinsic Fermi level must shift away from the band with the larger density of states in order to maintain equal numbers of electrons and holes.

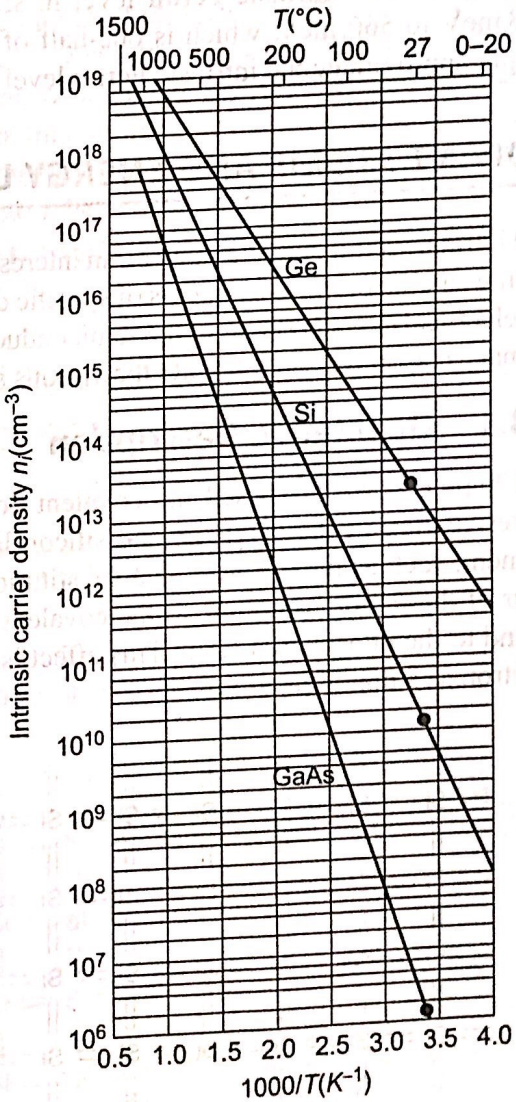

Fig. 3.10 *The intrinsic carrier concentration of Ge, Si, and GaAs as a function of temperature (From Sze [13])*

Example 3.9

Objective *To calculate the position of the intrinsic Fermi level with respect to the center of the bandgap in silicon at T = 300 K.*

The density of states effective carrier masses in silicon are $m_n^* = 1.08m_0$ and $m_p^* = 0.56m_0$.

The intrinsic Fermi level with respect to the center of the bandgap is

$$E_{Fi} - E_{\text{midgap}} = \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right) = \frac{3}{4}(0.0259)\ln\left(\frac{0.56}{1.08}\right)$$

or

$$E_{Fi} - E_{\text{midgap}} = -0.0128 \text{ eV} = -12.8 \text{ meV}$$

Comment The intrinsic Fermi level in silicon is 12.8 meV below the midgap energy. If we compare 12.8 meV to 560 meV, which is one-half of the bandgap energy of silicon, we can, in many applications, simply approximate the intrinsic Fermi level to be in the center of the bandgap.

DOPANT ATOMS AND ENERGY LEVELS 3.3

The intrinsic semiconductor may be an interesting material, but the real power of semiconductors is realized by adding small, controlled amounts of specific dopant, or impurity, atoms. This doping process, can greatly alter the electrical characteristics of the semiconductor. The doped semiconductor, called an *extrinsic* material, is the primary reason we can fabricate the various semiconductor devices that we will consider in later chapters.

3.3.1 Qualitative Description

In Chapter 2, we discussed the covalent bonding of silicon and considered the simple two-dimensional representation of the single-crystal silicon lattice as shown in Fig. 3.11. Now consider adding a group V element, such as phosphorus, as a substitutional impurity. The group V element has five valence electrons. Four of these will contribute to the covalent bonding with the silicon atoms, leaving the fifth more loosely bound to the phosphorus atom. This effect is schematically shown in Fig. 3.12. We refer to the fifth valence electron as a donor electron.

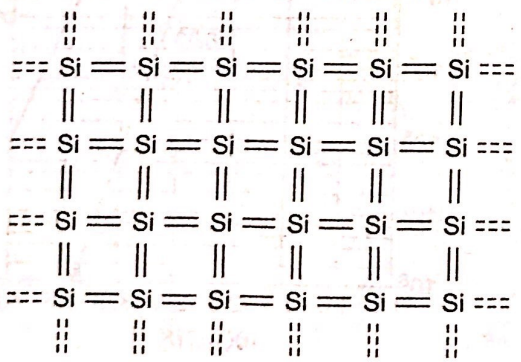

Fig. 3.11 *Two-dimensional representation of the intrinsic silicon lattice*

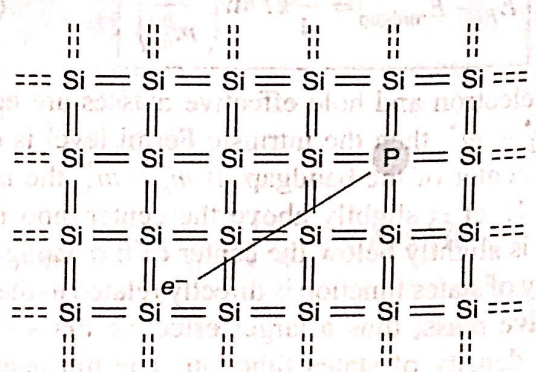

Fig. 3.12 *Two-dimensional representation of the silicon lattice doped with a phosphorus atom*

Donors		
Phosphorus	0.045	0.012
Arsenic	0.05	0.0127
Acceptors		
Boron	0.045	0.0104
Aluminum	0.06	0.0102

Group IV elements, such as silicon and germanium, can also be impurity atoms in gallium arsenide. If a silicon atom replaces a gallium atom, the silicon impurity will act as a donor, but if the silicon atom replaces an arsenic atom, then the silicon impurity will act as an acceptor. The same is true for germanium as an impurity atom. Such impurities are called *amphoteric*. Experimentally in gallium arsenide, it is found that germanium is predominantly an acceptor and silicon is predominantly a donor. Table 3.4 lists the ionization energies for the various impurity atoms in gallium arsenide.

THE EXTRINSIC SEMICONDUCTOR 3.4

We defined an intrinsic semiconductor as a material with no impurity atoms present in the crystal. An *extrinsic semiconductor* is defined as a semiconductor in which controlled amounts of specific dopant or impurity atoms have been added so that the thermal-equilibrium electron and hole concentrations are different from the intrinsic carrier concentration. One type of carrier will predominate in an extrinsic semiconductor.

3.4.1 Equilibrium Distribution of Electrons and Holes

Adding donor or acceptor impurity atoms to a semiconductor will change the distribution of electrons and holes in the material. Since the Fermi energy is related to the distribution function, the Fermi energy will change as dopant atoms are added. If the Fermi energy changes from near the midgap value, the density of electrons in the conduction band and the density of holes in the valence band will change. These effects are shown in Fig. 3.16 and 3.17. Figure 3.16 shows the case for $E_F > E_{Fi}$ and Fig. 3.17 shows the case for $E_F < E_{Fi}$. When $E_F > E_{Fi}$, the electron concentration is larger than the hole concentration, and when $E_F < E_{Fi}$, the hole concentration is larger than the electron concentration. When the density of electrons is greater than the density of holes, the semiconductor is n type; donor impurity atoms have been added. When the density of holes is greater than the density of electrons, the semiconductor is p type; acceptor impurity atoms have been added. The Fermi energy level in a semiconductor changes as the electron and hole concentrations change and, again, the Fermi energy changes as donor or acceptor impurities are added. The change in the Fermi level as a function of impurity concentrations will be considered in Section 3.6.

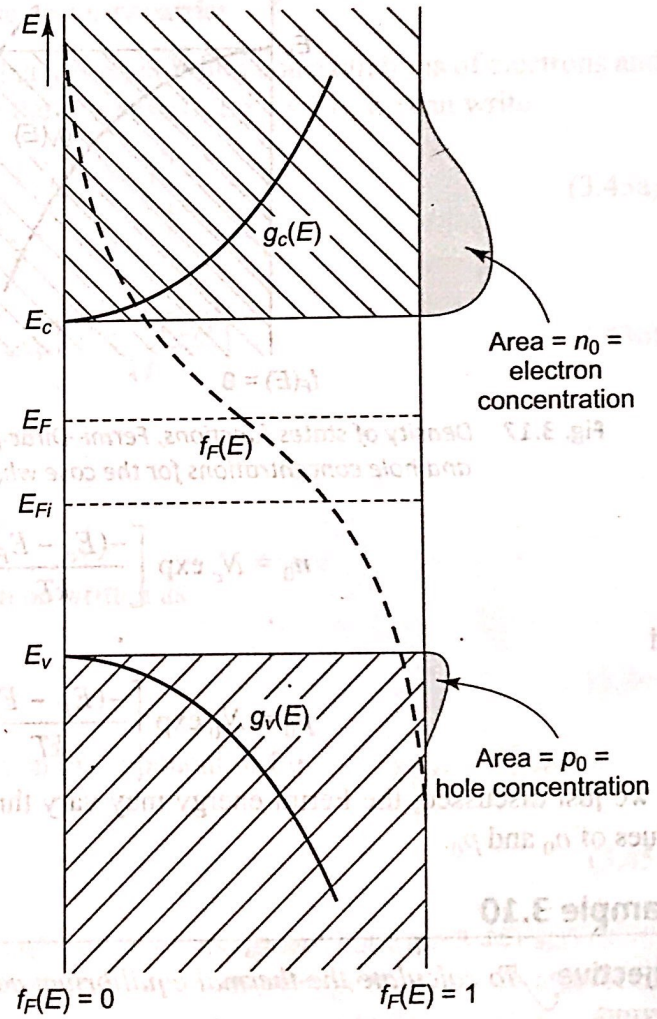

Fig. 3.16 *Density of states functions, Fermi–Dirac probability function, and areas representing electron and hole concentrations for the case when E_F is above the intrinsic Fermi energy.*

The expressions previously derived for the thermal-equilibrium concentration of electrons and holes, given by Eqs (3.16) and (3.24) are general equations for n_0 and p_0 in terms of the Fermi energy. These equations are again given as