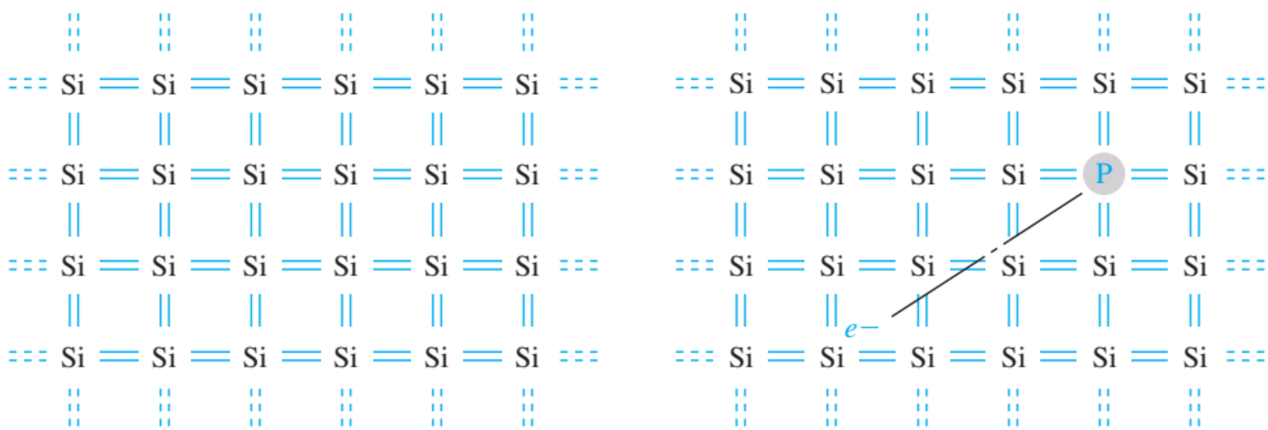
<u>Extrinsic semiconductor</u>

This is done by adding impurity atoms to the intrinsic material. This process is called **<u>doping</u>**. The advantage of doping is to change the <u>electrical properties</u> of the material. Two types of extrinsic (impure) semiconductor materials: ***n-type*** and ***p-type***.

- **<u>n-type semiconductor</u>**

A group V element, such as phosphorus, is added to the intrinsic material, such as Si or Ge. 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 Figure 21. We refer to the fifth valence electron as a donor electron.



(a) Pure Si (b) impurity Si

Figure 21.

The phosphorus atom without the donor electron is positively charged. At very low temperatures, the donor electron is bound to the phosphorus atom. However, If a small amount of energy, such as thermal energy, is added to the donor electron, it can be elevated into the conduction band, leaving behind a positively charged phosphorus ion. The electron in the conduction band can now move through the crystal generating a current, while the positively charged ion is fixed in the crystal.

This type of impurity atom donates an electron to the conduction band and so is called a *donor impurity atom.* The donor impurity atoms add electrons to the conduction band without creating holes in the valence band. Figure 22 shows the energy-band diagram that we would expect. The energy level, E_d, is the energy state of the donor electron.

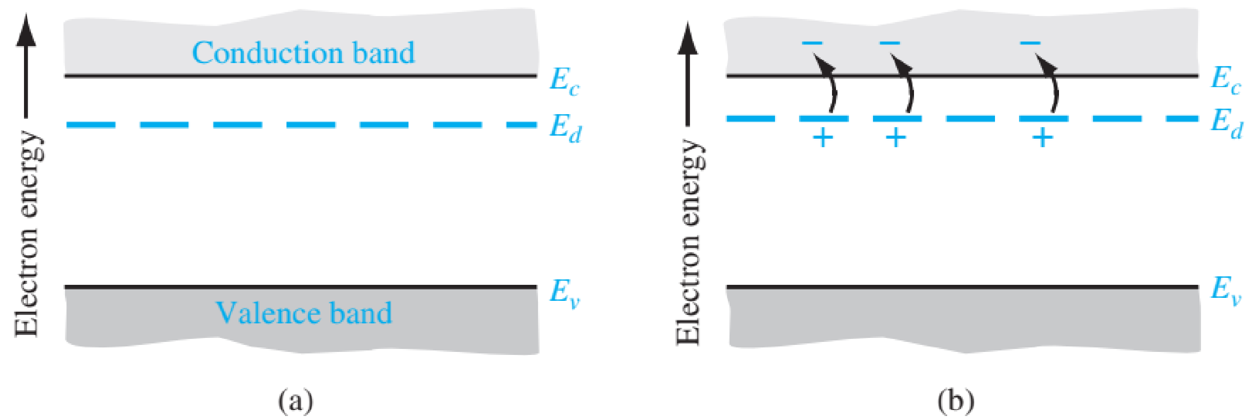


Figure 22 : *The energy-band diagram showing (a) the discrete donor energy state and (b) the effect of a donor state being ionized.*

- **<u>p-type semiconductor</u>**

It is adding a group III element, such as boron, to silicon. The group III element has three valence electrons, which are all taken up in the covalent bonding. As shown in Figure 23a, one covalent bonding position appears to be empty. So, with small energy, electron in the valence band occupies the empty. Figure 23b shows how valence electrons may gain a small amount of thermal energy and move about in the crystal. The “empty” position associated with the boron atom becomes occupied, and other valence electron positions become vacated.

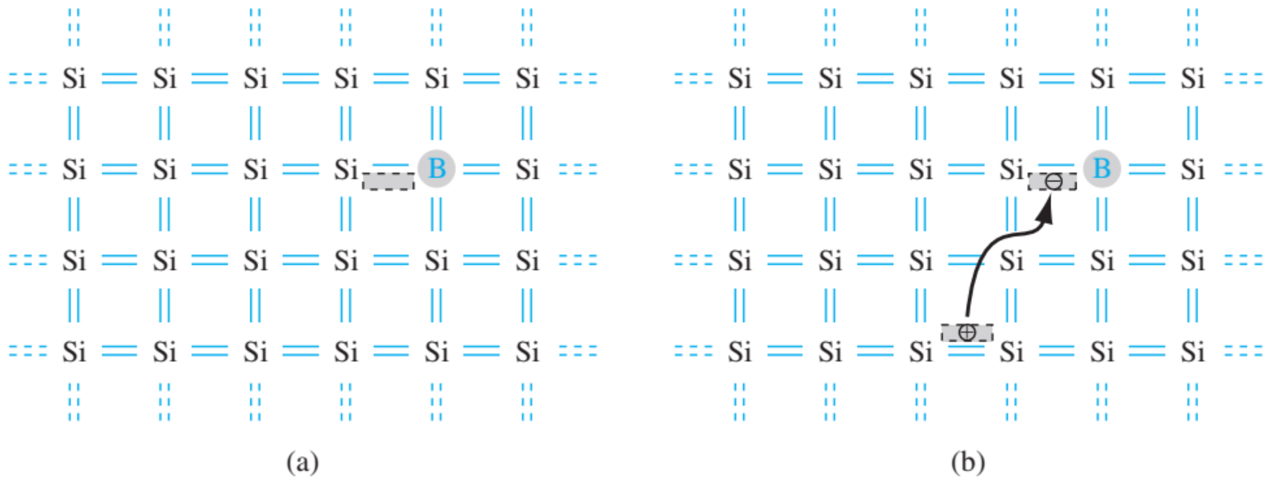


Figure 23.

Figure 24 shows the expected energy state of the "empty" position and also the formation of a hole in the valence band. If an electron were to occupy this "empty" position, it needs energy. Therefore, the electron occupying this "empty" position does not have sufficient energy to be in the conduction band, so its energy is far smaller than the conduction-band energy. The hole can move through the crystal generating a current, while the negatively charged boron atom is fixed in the crystal. The group III atom accepts an electron from the valence band and so is referred to as an *acceptor impurity atom*. The acceptor atom can generate holes in the valence band without generating electrons in the conduction band.

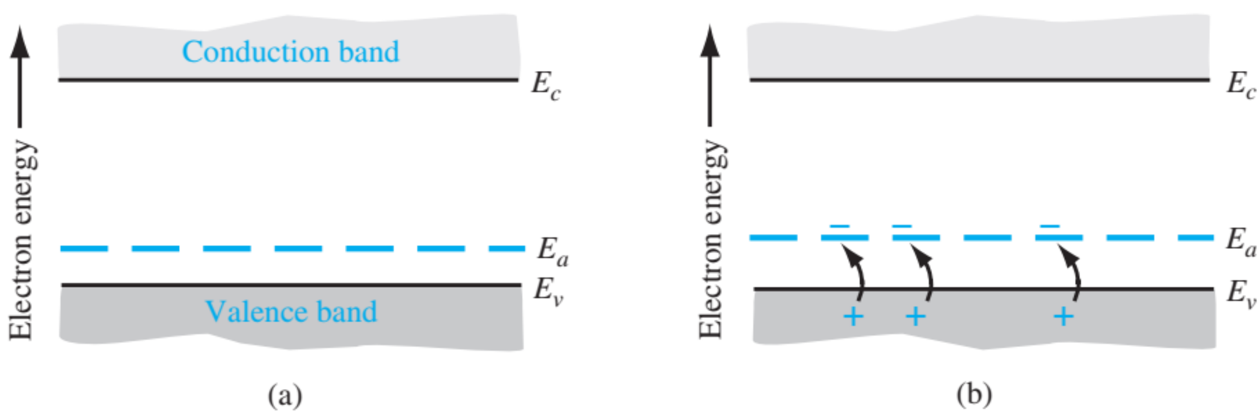


Figure 24.

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. Figure 25a shows when $E_F > E_{Fi}$, the electron concentration is larger than the hole concentration, and Figure 25b shows 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. When the density of holes is greater than the density of electrons, the semiconductor is p-type.

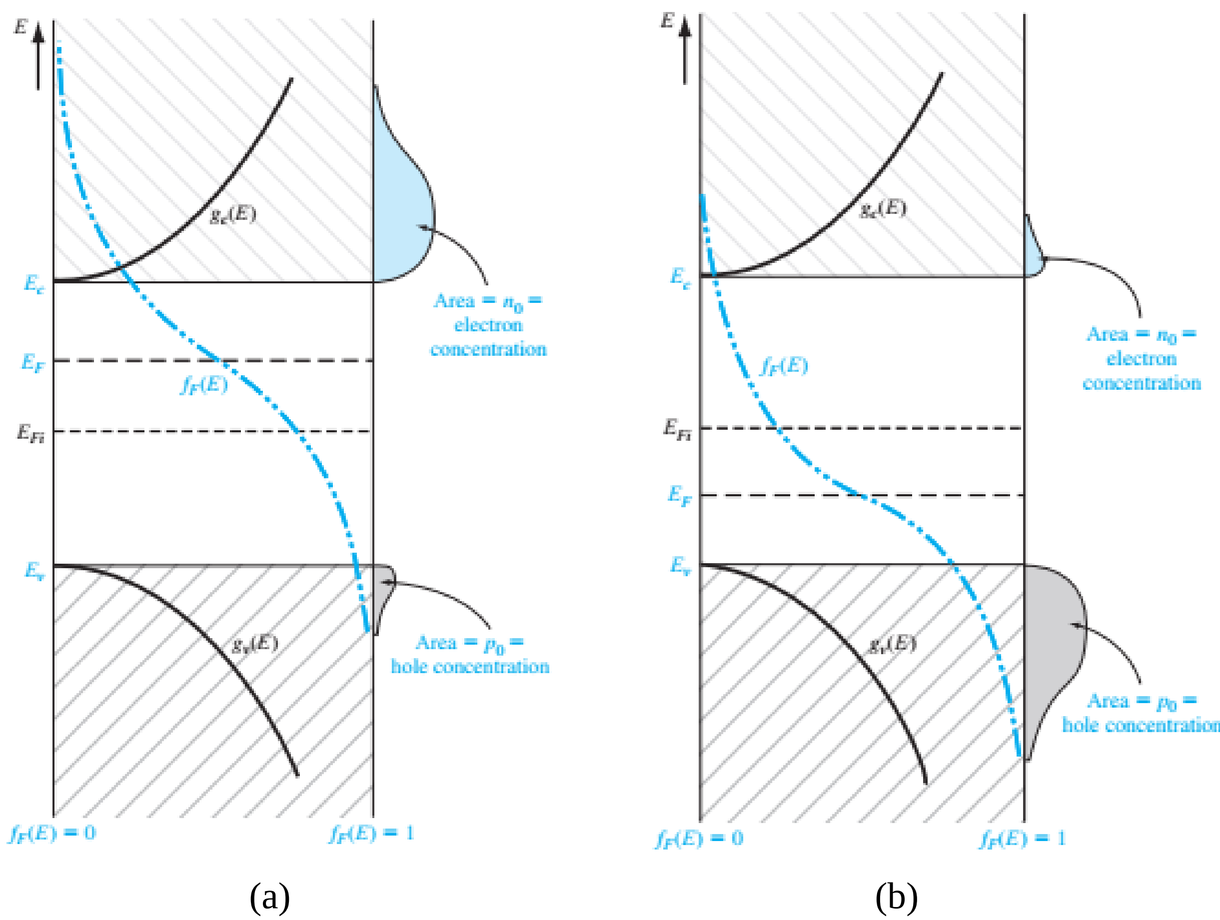


Figure 25.

The concentration of carries in terms of the Fermi energy is

$$n_o = N_c . exp\left(\frac{-(E_c - E_F)}{kT}\right) \dots\dots\dots (1)$$

$$p_o = N_v . exp\left(\frac{-(E_F - E_v)}{kT}\right) \dots\dots\dots (2)$$

<u>Note:</u> In an n-type semiconductor, electrons are referred to as the majority carrier and holes as the minority carrier. Similarly, in a p-type semiconductor, holes are the majority carrier and electrons are the minority carrier.

We may derive another form of the equations for the thermal-equilibrium concentrations of electrons and holes. If we add and subtract an intrinsic Fermi energy in the exponent of Equation (1), we can write

$$n_o = N_c . exp\left(\frac{-(E_c - E_{Fi}) + (E_F - E_{Fi})}{kT}\right)$$

$$n_o = N_c . exp\left(\frac{-(E_c - E_{Fi})}{kT}\right) . exp\left(\frac{(E_F - E_{Fi})}{kT}\right)$$

The intrinsic carrier concentration is given by Equation

$$n_i^2 = n_o p_o$$

Because number of electrons is equal to number of holes,

$$n_i = N_c . exp\left(\frac{-(E_c - E_{Fi})}{kT}\right)$$

So,

$$\boxed{n_o = n_i \, exp\left(\frac{(E_F - E_{Fi})}{kT}\right)} \dots\dots\dots (3)$$

Similarly, if we add and subtract an intrinsic Fermi energy in the exponent of Equation (2), we will obtain

$$p_o = n_i \, exp\left(\frac{-(E_F - E_{Fi})}{kT}\right) \ldots\ldots\ldots..(4)$$

The $n_o\ p_o$ Product

From Equations (1) and (2), we have

$$n_o\ p_o = N_c\ N_v\ exp\left(\frac{-(E_c - E_F)}{kT}\right)\ exp\left(\frac{-(E_F - E_v)}{kT}\right)$$

$$n_o\ p_o = N_c\ N_v\ exp\left(\frac{-E_g}{kT}\right) \ldots\ldots\ldots..(5)$$

For the semiconductor in thermal equilibrium,

$$n_o\ p_o = n_i^2 \ldots\ldots\ldots..(6)$$

Equation (6) states that the product of n_o and p_o is always a constant for a given semiconductor material at a given temperature.