The Fermi energy in an intrinsic semiconductor, $E_i = E_F$, is given by

$$E_i = \frac{E_V + E_C}{2} + \frac{kT}{2} \ln\left(\frac{N_V}{N_C}\right) \tag{3.19}$$

which is typically very close to the middle of the band gap. The intrinsic carrier concentration is typically very small compared to the densities of states and typical doping densities ($n_i \approx 10^{10}$ cm^{-3} in Si) and intrinsic semiconductors behave very much like insulators; that is, they are not very useful as conductors of electricity.

The number of electrons and holes in their respective bands, and hence the conductivity of the semiconductor, can be controlled through the introduction of specific impurities, or dopants, called *donors* and *acceptors*. For example, when semiconductor silicon is doped with phosphorous, one electron is donated to the conduction band for each atom of phosphorous introduced. From Table 3.1, it can be seen that phosphorous is in column V of the periodic table of elements and thus has five valence electrons. Four of these are used to satisfy the four covalent bonds of the silicon lattice and the fifth is available to fill an empty state in the conduction band. If silicon is doped with boron (valency of three, since it is in column III), each boron atom accepts an electron from the valence band, leaving behind a hole. All impurities introduce additional localized electronic states into the band structure, often within the forbidden band between E_C and E_V, as illustrated in Figure 3.5. If the energy of the state, E_D, introduced by a donor atom is sufficiently close to the conduction bandedge (within a few kT), there will be sufficient thermal energy to allow the extra electron to occupy a state in the conduction band. The donor state will then be positively charged (ionized) and must be considered when analyzing the electrostatics of the situation. Similarly, an acceptor atom will introduce a negatively charged (ionized) state at energy E_A. The controlled introduction of donor and acceptor impurities into a semiconductor allows the creation of the n-type (electrons are the primary source of electrical conduction) and p-type (holes are the primary source of electrical conduction) semiconductors, respectively. This is the basis for the construction of all semiconductor devices, including solar cells. The number of ionized donors and acceptors are given by [7]

$$N_D^+ = \frac{N_D}{1 + g_D e^{(E_F - E_D)/kT}} = \frac{N_D}{1 + e^{(E_F - E_D')/kT}} \tag{3.20}$$

and

$$N_A^- = \frac{N_A}{1 + g_A e^{(E_A - E_F)/kT}} = \frac{N_A}{1 + e^{(E_A' - E_F)/kT}} \tag{3.21}$$

where g_D and g_A are the donor and acceptor site degeneracy factors. Typically, $g_D = 2$ and $g_A = 4$. These factors are normally combined into the donor and the acceptor energies so that $E_D' = E_D - kT \ln g_D$ and $E_A' = E_A + kT \ln g_A$. Often, the donors and acceptors are assumed to be completely ionized so that $n_o \simeq N_D$ in n-type material and $p_o = N_A$ in p-type material. The Fermi energy can then be written as

$$E_F = E_i + kT \ln \frac{N_D}{n_i} \tag{3.22}$$