University of Anbar
College of Science – Dept. of Physics

Lectures of Semiconductors #1

for 3th level of physics students

Lecture 8 : The Semiconductor in Equilibrium/1

by
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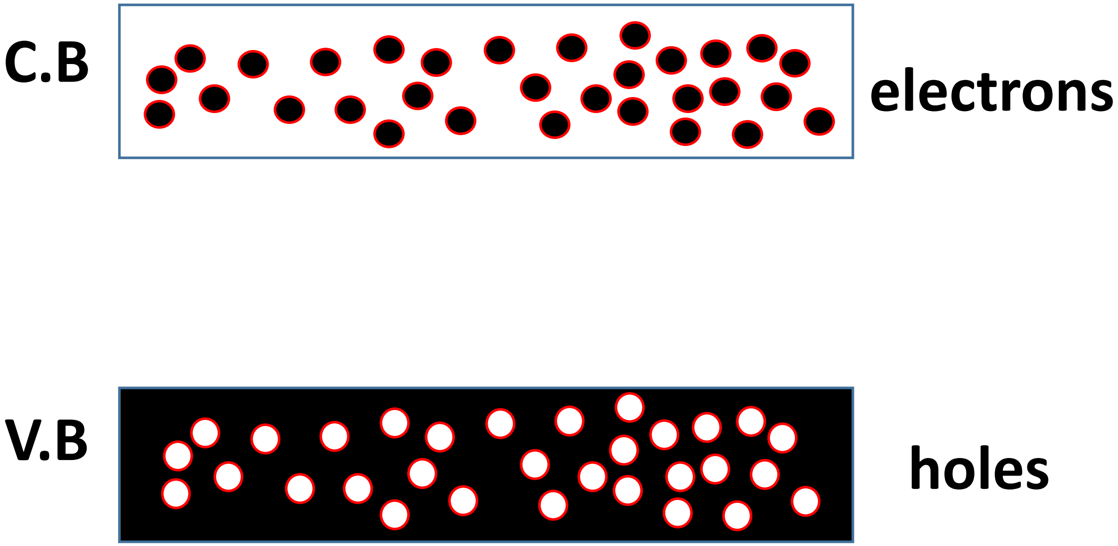
4.1 | CHARGE CARRIERS IN SEMICONDUCTORS

contribution to a current of the semiconductors

electron **hole**



- **To determine the concentration of electrons and holes**

The Fermi–Dirac probability

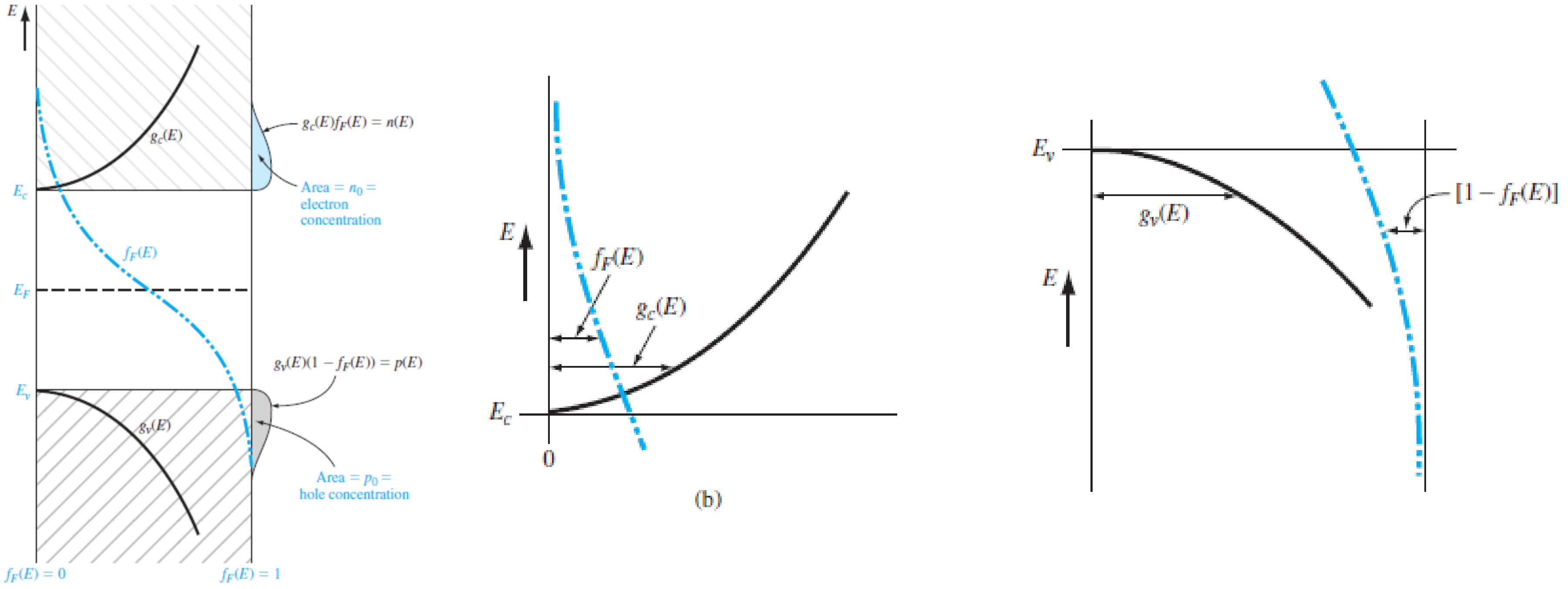
$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

4.1.1 Equilibrium Distribution of Electrons and Holes

- **The distribution of electrons in the conduction band** $n(E) = g_c(E) f_F(E)$ **....(1)**
- **The distribution of electrons in the conduction band** $p(E) = g_v(E)[1 - f_F(E)]$ **....(2)**

where $f_F(E)$ is the Fermi–Dirac probability function and $g_c(E)$ is the density of quantum states in the conduction band.

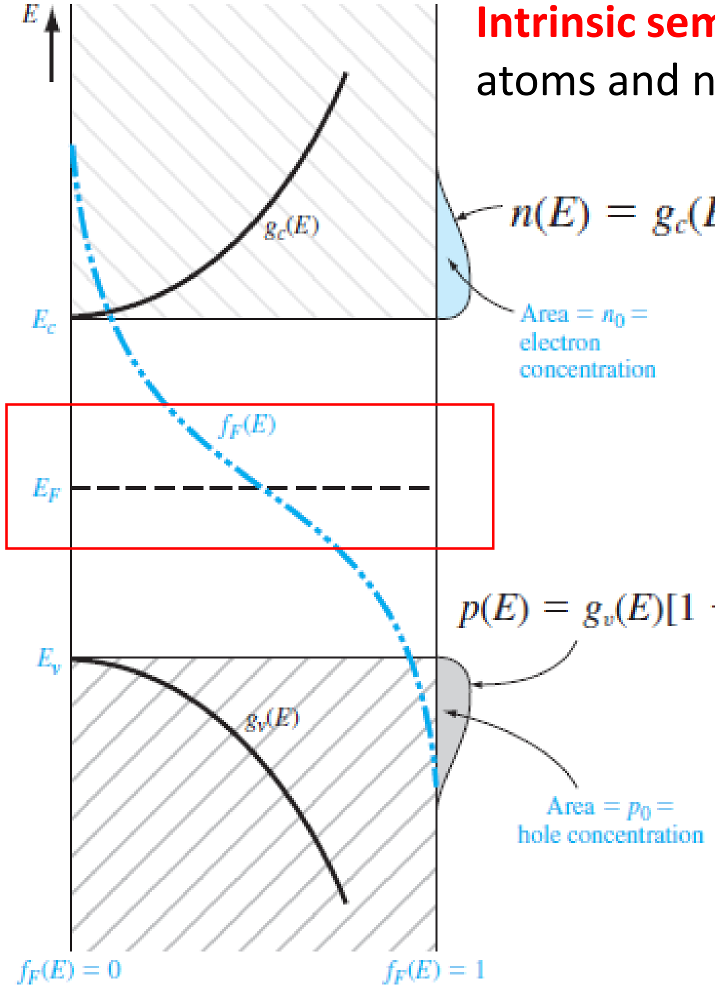
The total hole concentration per unit volume is found by integrating this function over the entire valence-band energy.

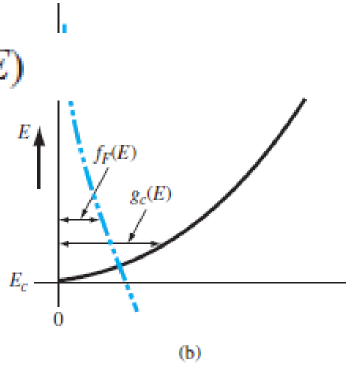


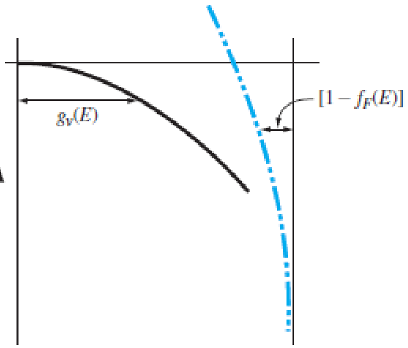
To find the thermal-equilibrium electron and hole concentrations, we need to determine the position of the Fermi energy E_F with respect to the bottom of the conduction-band energy E_c and the top of the valence-band energy E_v.

Here we will initially consider an intrinsic semiconductor.

Intrinsic semiconductor is a pure semiconductor with no impurity atoms and no lattice defects in the crystal







- if $g_c(E)$ and $g_v(E)$ are symmetrical, the Fermi energy must be at the mid-gap energy in order to obtain equal electron and hole concentrations.
- If the effective masses of the electron and hole are not exactly equal, then the effective density of states functions $g_c(E)$ and $g_v(E)$ will not be exactly symmetrical about the midgap energy. The Fermi level for the intrinsic semiconductor will then shift slightly from the midgap energy in order to obtain equal electron and hole concentrations.

4.1.2 The n_o and p_o Equations

$$n_o = \int g_C(E)\, f_F(E) dE \quad \ldots\ldots(3) \quad , \qquad g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E - E_c}$$

If E_f be found in band gap, $E > E_c$, and $E_c - E_f$>>kT, then $E - E_f$>>kT

so that the Fermi probability function reduces to the Boltzmann approximation, which is

$$f_F(E) = \frac{1}{1 + \exp\frac{(E - E_F)}{kT}} \approx \exp\left[\frac{-(E - E_F)}{kT}\right] \tag{4.4}$$

$$n_0 = \int_{E_c}^{\infty} \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E - E_c}\,\exp\left[\frac{-(E - E_F)}{kT}\right] dE \tag{4.5}$$

$$\eta = \frac{E - E_c}{kT} \quad \text{and} \quad N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

in the same way, we get the holes concentration

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

$$p_0 = N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

Example: Calculate the probability that a quantum state in the conduction band at $E = E_c + kT/2$ is occupied by an electron, and calculate the thermal-equilibrium electron concentration in silicon at $T = 300$ K.

Assume the Fermi energy is 0.25 eV below the conduction band. The value of N_c for silicon at $T = 300$ K is $N_c = 2.8 \times 10^{19}$ cm^{-3} (see Appendix B).

■ **Solution**

The probability that a quantum state at $E = E_c + kT/2$ is occupied by an electron is given by

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \cong \exp\left[\frac{-(E - E_F)}{kT}\right] = \exp\left[\frac{-(E_c + (kT/2) - E_F)}{kT}\right]$$

or

$$f_F(E) = \exp\left[\frac{-(0.25 + (0.0259/2))}{0.0259}\right] = 3.90 \times 10^{-5}$$

The electron concentration is given by

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] = (2.8 \times 10^{19}) \exp\left[\frac{-0.25}{0.0259}\right]$$

or

$$n_0 = 1.80 \times 10^{15} \text{ cm}^{-3}$$

4.1.3 The Intrinsic Carrier Concentration

For an intrinsic semiconductor, the concentration of electrons in the conduction band is equal to the concentration of holes in the valence band

$$n_i = p_i = n_o = p_o$$

The Fermi energy level for the intrinsic semiconductor is called the intrinsic Fermi energy, or $E_F = E_{Fi}$

$$n_0 = n_i = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right]$$

If we take the product of Equations

$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] \cdot \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right]$$

$$p_0 = p_i = n_i = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right]$$

$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_v)}{kT}\right] = N_c N_v \exp\left[\frac{-E_g}{kT}\right]$$

where E_g is the bandgap energy. For a given semiconductor material at a constant temperature, the value of n_i is a constant, and independent of the Fermi energy.

Table 4.1 | Effective density of states function and density of states effective mass values

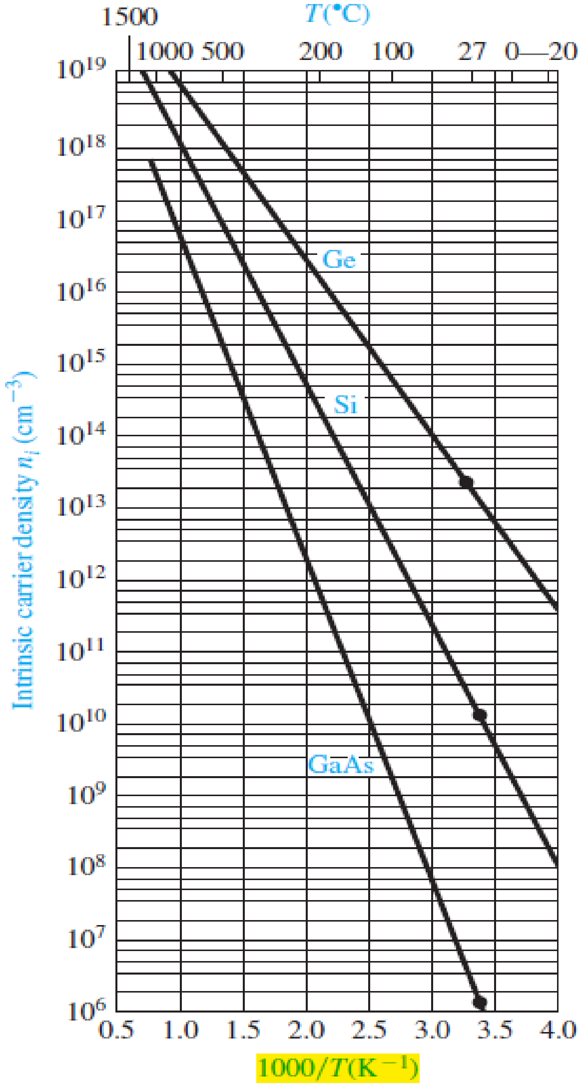
	N_c (cm^{-3})	N_v (cm^{-3})	m_n^*/m_0	m_p^*/m_0
Silicon	2.8×10^{19}	1.04×10^{19}	1.08	0.56
Gallium arsenide	4.7×10^{17}	7.0×10^{18}	0.067	0.48
Germanium	1.04×10^{19}	6.0×10^{18}	0.55	0.37

Table 4.2 | Commonly accepted values of n_i at $T = 300$ K

Silicon	$n_i = 1.5 \times 10^{10}$ cm^{-3}
Gallium arsenide	$n_i = 1.8 \times 10^{6}$ cm^{-3}
Germanium	$n_i = 2.4 \times 10^{13}$ cm^{-3}

Example: Calculate the intrinsic carrier concentration in silicon at $T = 250$ K and at $T = 400$ K.

The values of N_c and N_v for silicon at $T = 300$ K are 2.8×10^{19} cm^{-3} and 1.04×10^{19} cm^{-3}, respectively. Both N_c and N_v vary as $T^{3/2}$. Assume the bandgap energy of silicon is 1.12 eV and does not vary over this temperature range.



■ **Solution**

$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_v)}{kT}\right] = N_c N_v \exp\left[\frac{-E_g}{kT}\right]$$

$$n_i^2 = (2.8 \times 10^{19})(1.04 \times 10^{19})\left(\frac{250}{300}\right)^3 \exp\left[\frac{-1.12}{(0.0259)(250/300)}\right]$$

$$= 4.90 \times 10^{15}$$

or

$$n_i = 7.0 \times 10^7 \text{ cm}^{-3}$$

At $T = 400$ K, we find

$$n_i^2 = (2.8 \times 10^{19})(1.04 \times 10^{19})\left(\frac{400}{300}\right)^3 \exp\left[\frac{-1.12}{(0.0259)(400/300)}\right]$$

$$= 5.67 \times 10^{24}$$

or

$$n_i = 2.38 \times 10^{12} \text{ cm}^{-3}$$