Solid State Electronics EC210
Arab Academy for Science and Technology
AAST – Cairo
Spring 2015

Lecture 12:

Electron-Hole Statistics

Lecture Notes Prepared by:
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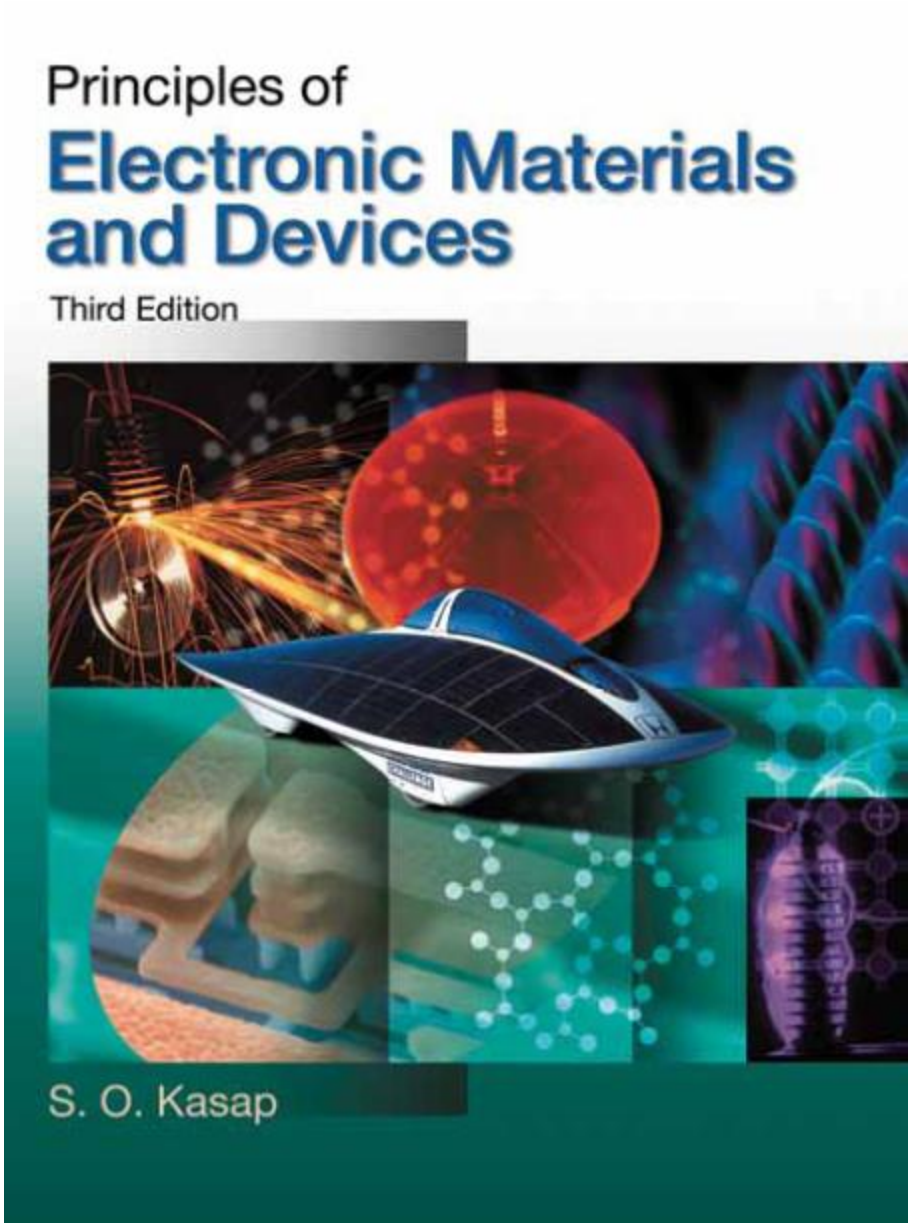

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Pages

- Kasap: p380-401

Free Carriers

- (Free Conduction Electrons and Free Valence Holes)

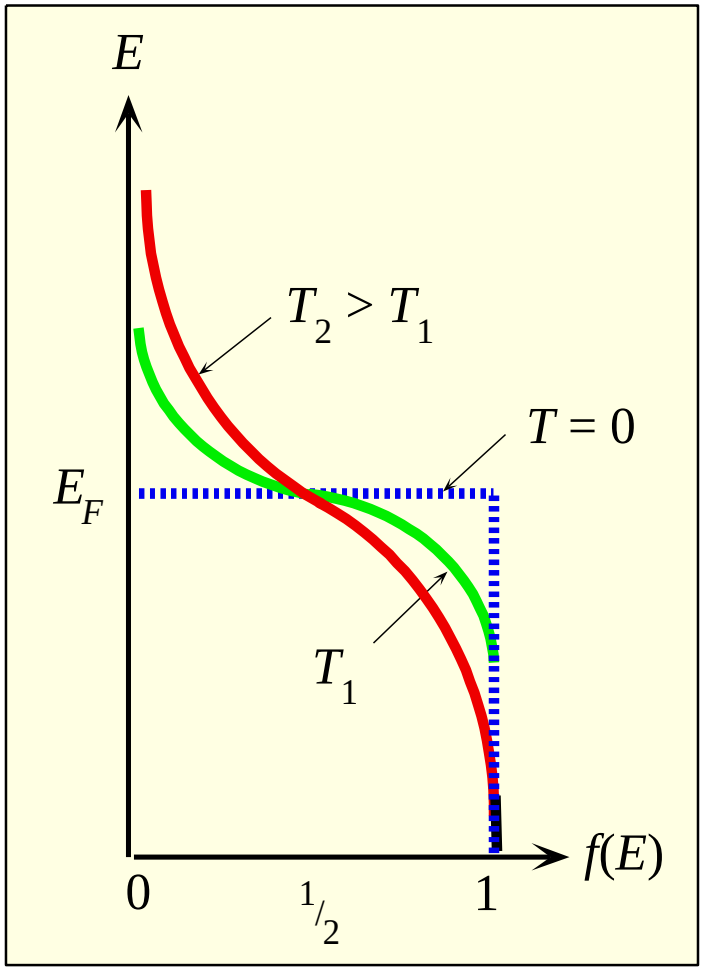
Concentration of carriers

Density of States

Distribution of carriers (Fermi Dirac Distribution)

Fermi Level (EF), Intrinsic Energy Level (Ei) and Fermi- Dirac Distribution

$$F(E) = \frac{1}{e^{(E-E_F)/k_B T} + 1}$$



The Fermi-Dirac function, *f*(*E*), describes the statistics of electrons in a solid. The electrons interact with each other and the environment so that they obey the Pauili Exclusion Principle.

Maxwell-Boltzmann Distribution

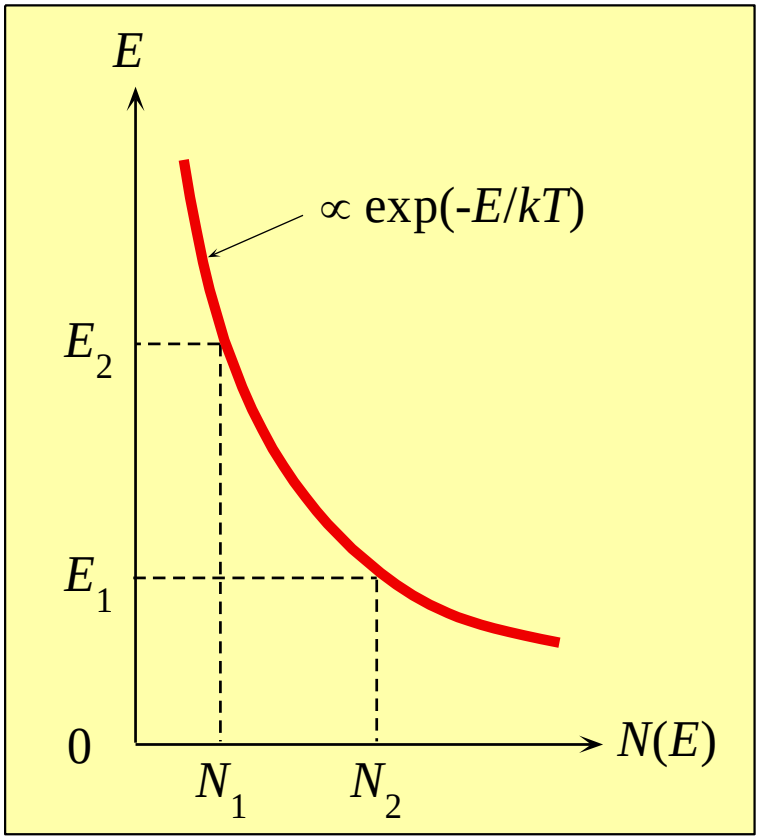
Replaces Fermi-Dirac Distribution when

$(E - EF)/kT > 3$

$$\Rightarrow \exp\left[\frac{E-EF}{k_B T}\right] \gg 1$$

$$\Rightarrow f_{FD} \sim fMB$$

$$= \exp\left[-\frac{E - EF}{k_B T}\right]$$

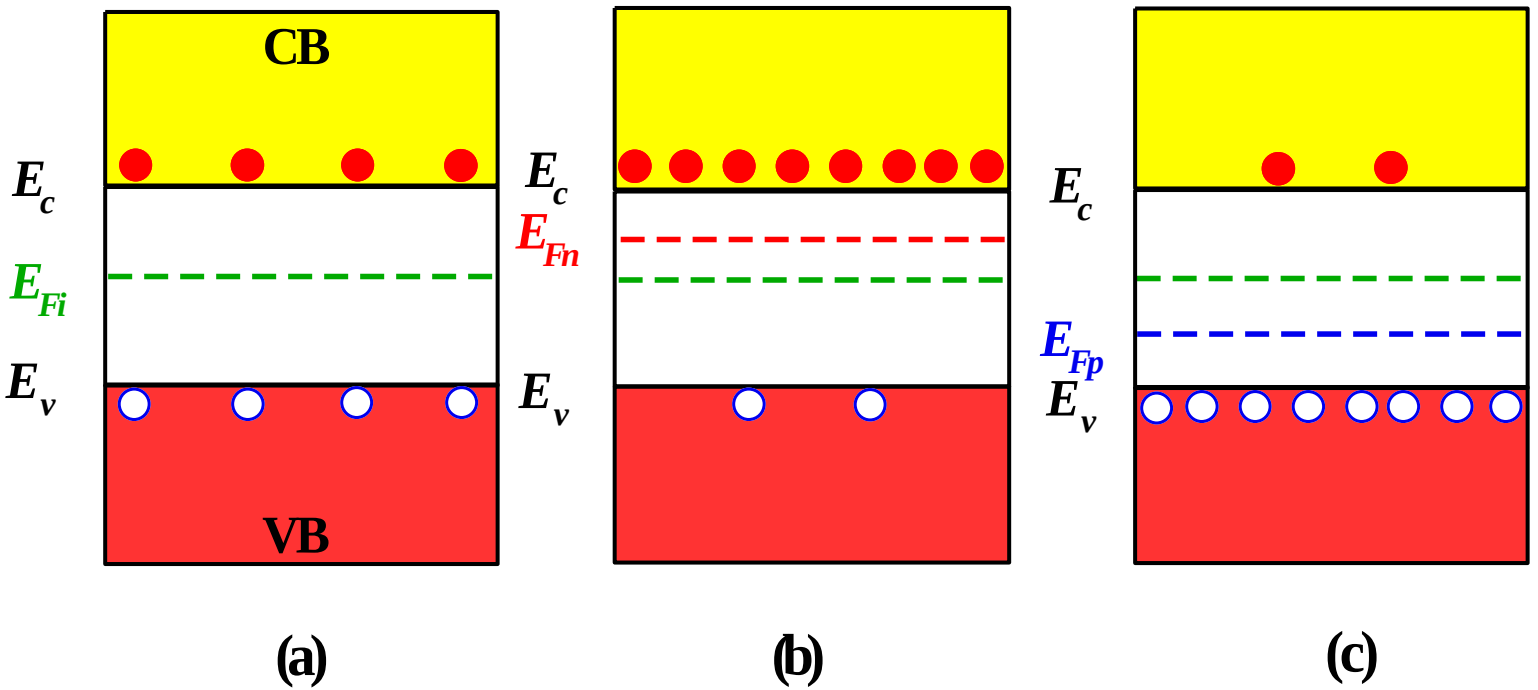


The Boltzmann energy distribution describes the statistics of particles, e.g. electrons, when the particles do not interact with each other, i.e. when there are very few electrons compared with the number of available states.

Fig 4.25

From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

Fermi Level for Intrinsic, n-type and p-type Semiconductor

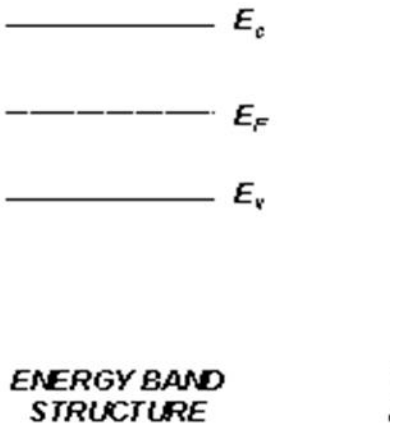


Energy band diagrams for (a) intrinsic (b) *n*-type and (c) p-type semiconductors. In all cases, $np = n_i^2$

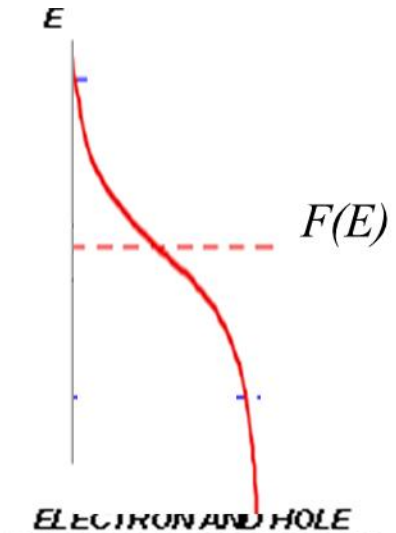
Fig 5.8

f_{F-D} Positioning in Energy Band

Intrinsic Semiconductors



ENERGY BAND STRUCTURE

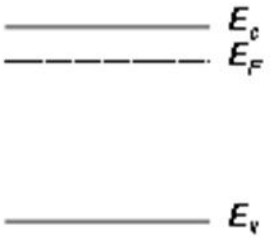


ELECTRON AND HOLE FERMI-DIRAC FUNCTIONS

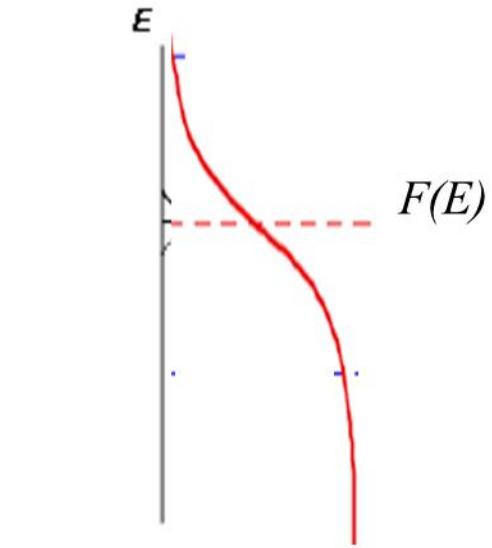
$n=p=n_i$

f_{F-D} Positioning in Energy Band

n Type Semiconductors



ENERGY BAND STRUCTURE



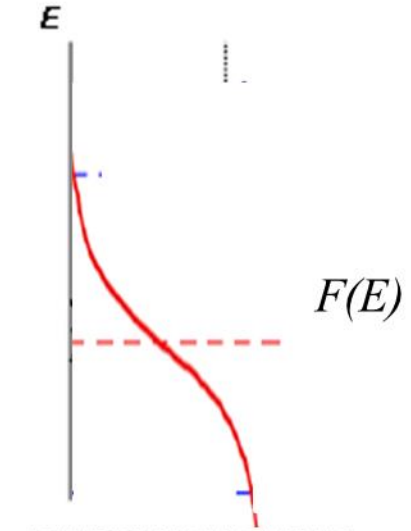
ELECTRON AND HOLE FERMI-DIRAC FUNCTIONS

n > p

f_{F-D} Positioning in Energy Band

p Type Semiconductors

ENERGY BAND STRUCTURE



ELECTRON AND HOLE FERMI-DIRAC FUNCTIONS

p > n

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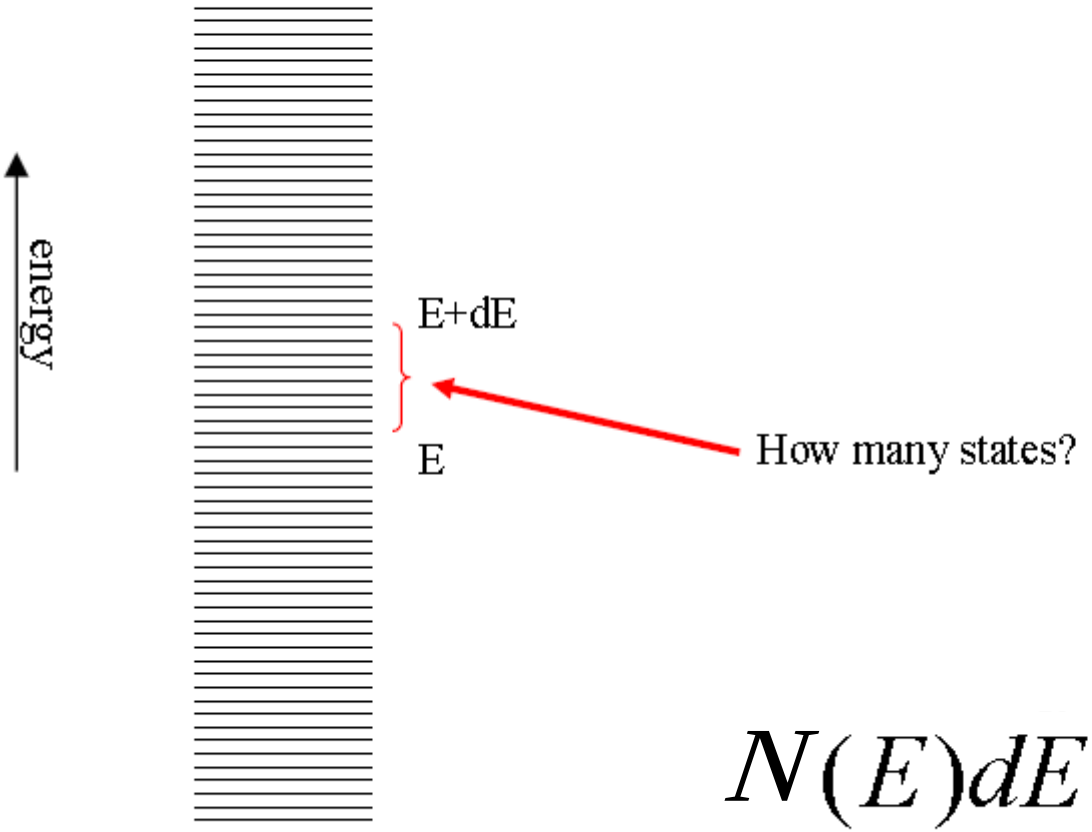
Density of states:



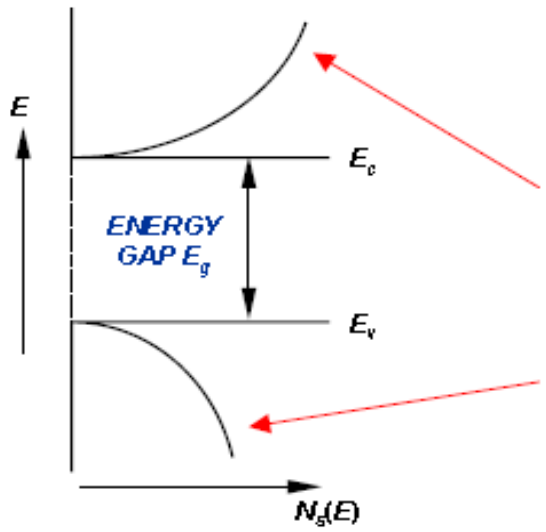
$$N(E)dE = ?$$

Number of states with energy between E and E + dE *per volume*.

Density of States in Conduction and Valence Bands

- Within the FORBIDDEN energy gap the density of states is required to VANISH completely

- It is usually assumed that at energies relatively CLOSE to the gap the density of states in both bands follows the FREE ELECTRON form



$$N_s(E) = \frac{1}{2\pi^2}\left[\frac{2m}{\hbar^2}\right]^{3/2} E^{1/2}$$

$$N_{sc}(E \geq E_c) = \frac{1}{2\pi^2}\left[\frac{2m_n^*}{\hbar^2}\right]^{3/2} (E - E_c)^{1/2}$$

CONDUCTION BAND

$$N_{sv}(E \leq E_v) = \frac{1}{2\pi^2}\left[\frac{2m_p^*}{\hbar^2}\right]^{3/2} (E_v - E)^{1/2}$$

VALENCE BAND

Free Carrier Concentration

• Using the density of states and the Fermi function we may calculate the CONCENTRATION of carriers present in the conduction and valence bands at any given temperature

  * We do this by INTEGRATING the density of OCCUPIED states over the range of energies relevant to either band

•

N. of Electrons in Conduction Band per unit volume:

$$n = \int_{E_c}^{E_{ctop}} N_{sc}(E) f(E) dE \qquad (4.1)$$

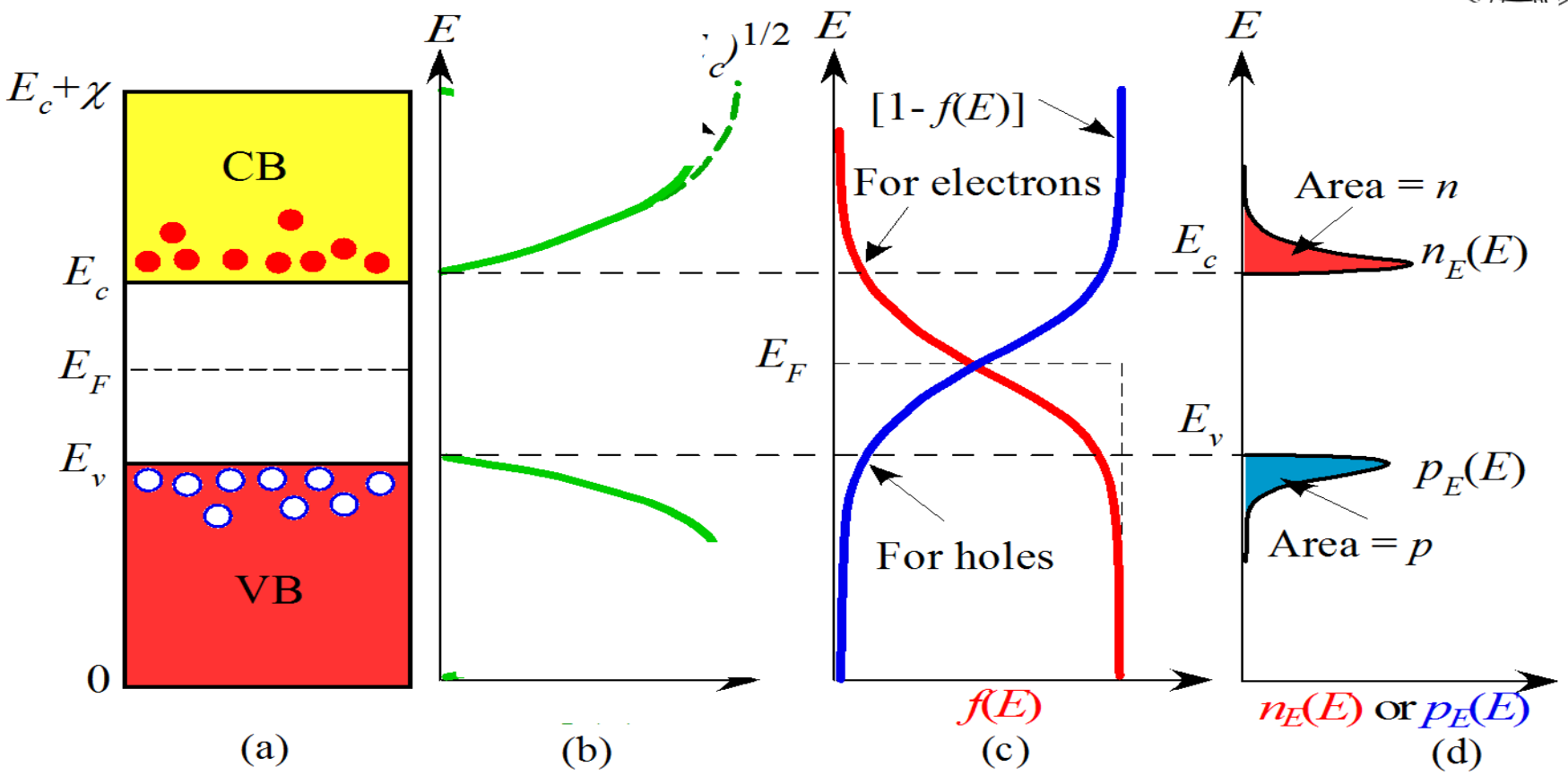
N. of Holes in Valence Band per unit volume:

$$p = \int_{E_{vbottom}}^{E_v} N_{sv}(E)\left[1 - f(E)\right] dE \qquad (4.2)$$

⇒ Note here how we write the probability for occupation of HOLE states as 1-*f*(*E*)

⇒ By substituting the expressions for the electron and hole densities of states into these integrals we may calculate *n* and *p* for any given *T* and E_F

Carriers in Conduction and Valence Bands: Intrinsic Case ($n=p=n_i$)



(a) Energy band diagram. (b) Density of states (number of states per unit energy per unit volume). (c) Fermi-Dirac probability function (probability of occupancy of a state). (d) The product of $g(E)$ and $f(E)$ is the energy density of electrons in the CB (number of electrons per unit energy per unit volume). The area under $n_E(E)$ vs. E is the electron concentration in the conduction band.