Fermi Level in Semiconductor

BPT: 401: Electronics and Modern Physics

Tutorial - 3

Fermi level in Intrinsic Semiconductor

$$f(E)_{\text{Fermi-Dirac}} = \frac{1}{e^{(E-E_F)/kT}+1}$$

The probability that a particle will have energy E

At absolute zero, fermions will fill up all available energy states below a level E_F called the Fermi energy with one (and only one) particle. They are constrained by the Pauli exclusion principle. At higher temperatures, some are elevated to levels above the Fermi level.

See the Maxwell-Boltzmann distribution for a general discussion of the exponential term.

For low temperatures, those energy states below the Fermi energy E_F have a probability of essentially 1, and those above the Fermi energy essentially zero.

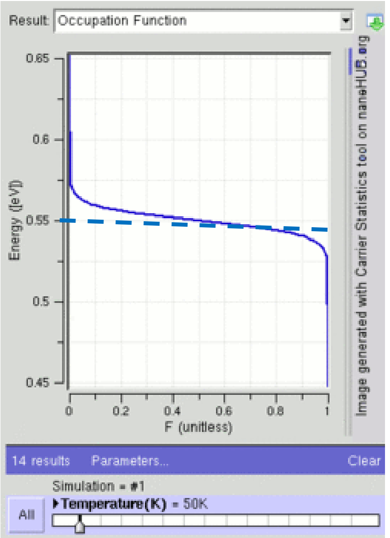
The quantum difference which arises from the fact that the particles are indistinguishable.

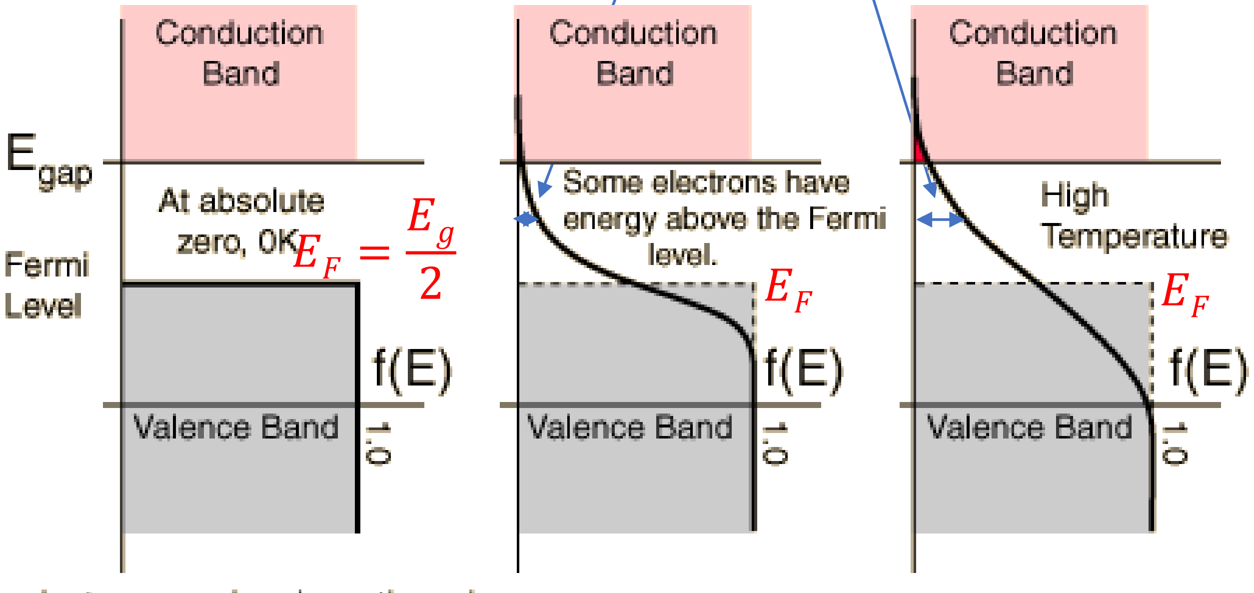
Probability of free electron occupancy on the energy level above E_F increases with increasing temperature

$$f(E) = \begin{cases} 1 & \text{For } E \le E_F \\ 0 & \text{for } E > E_F \end{cases}$$

$$f(E_F) = \frac{1}{1+e^{(E_F-E_F)/kT}} = \frac{1}{1+1} = \frac{1}{2}$$

Fermi level is the highest occupied energy level of free electrons at 0 K (highest possible Quantum state of free electrons at 0 K) and **Fermi energy** is the energy of electrons in Fermi level



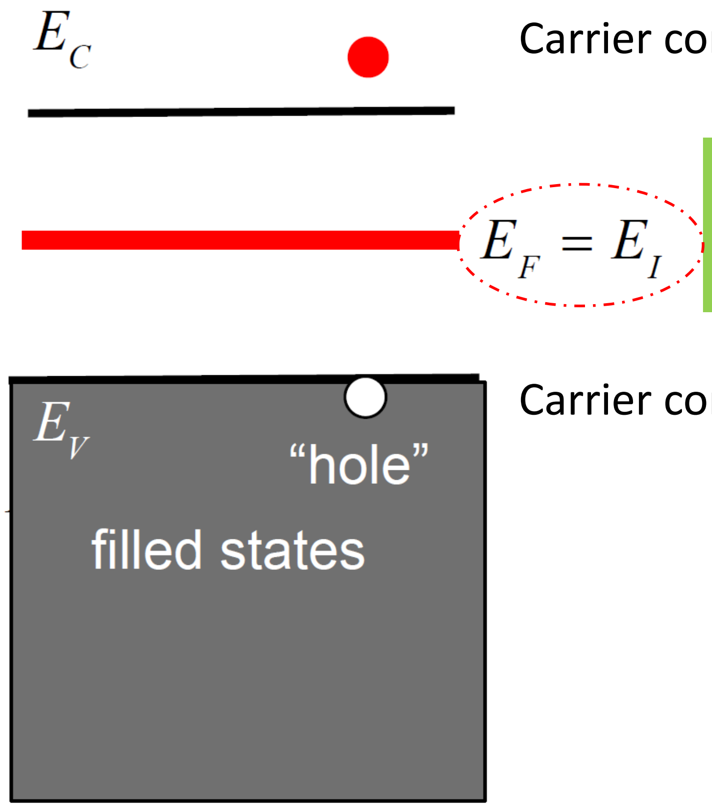


No electrons can be above the valence band at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

At high temperatures, some electrons can reach the conduction band and contribute to electric current.

Intrinsic Semiconductor and Law of Mass Action

$No.\,of\ free\ electrons\ in\ CB\ =\ No.\,of\ holes\ in\ VB\ (T > 0\ K)$ Carrier generation by **thermal excitation**;



Carrier concentration in CB, $\boldsymbol{n = n_i}$ ***(free electrons)***

E_F – Fermi level

E_i – Fermi level of intrinsic semiconductor

Carrier concentration in VB, $\boldsymbol{p = n_i}$ ***(holes)***

Law of Mass Action

$$np = n_i^2$$

$$n_i(300\,K) \approx 10^{10}\ \text{cm}^{-3}$$

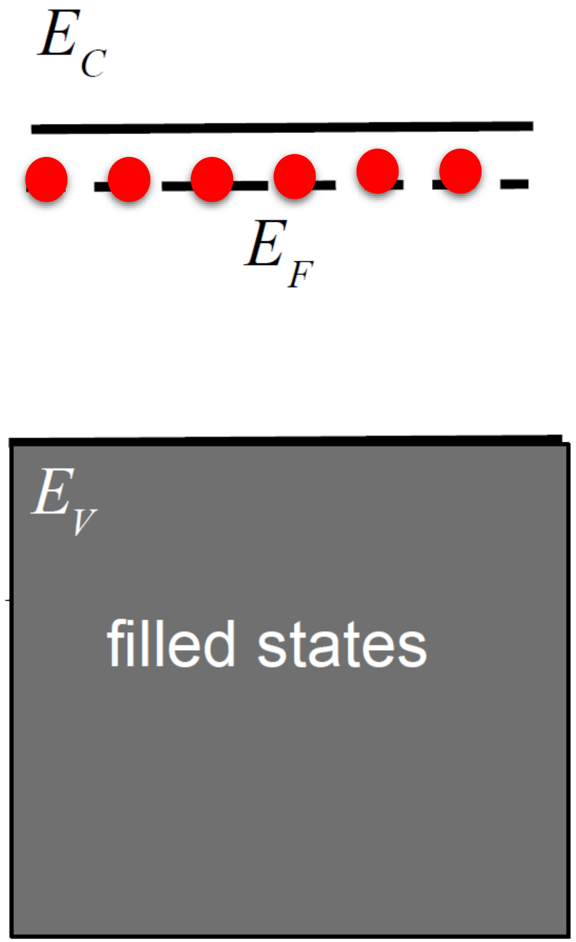
n → electron concentration, p →holes concentration , n_i →intrinsic charge carrier concentration

Fermi level in N type and P type Semiconductor

N type

$$n_{0N} \approx N_D^+$$

At 0K, No. of free e⁻s = No. of donor ions



At T = 0 K

$$f_0(E) = \frac{1}{1 + e^{(E-E_F)/k_B T}}$$

$$E = E_F \rightarrow f_0(E) = \frac{1}{2}$$

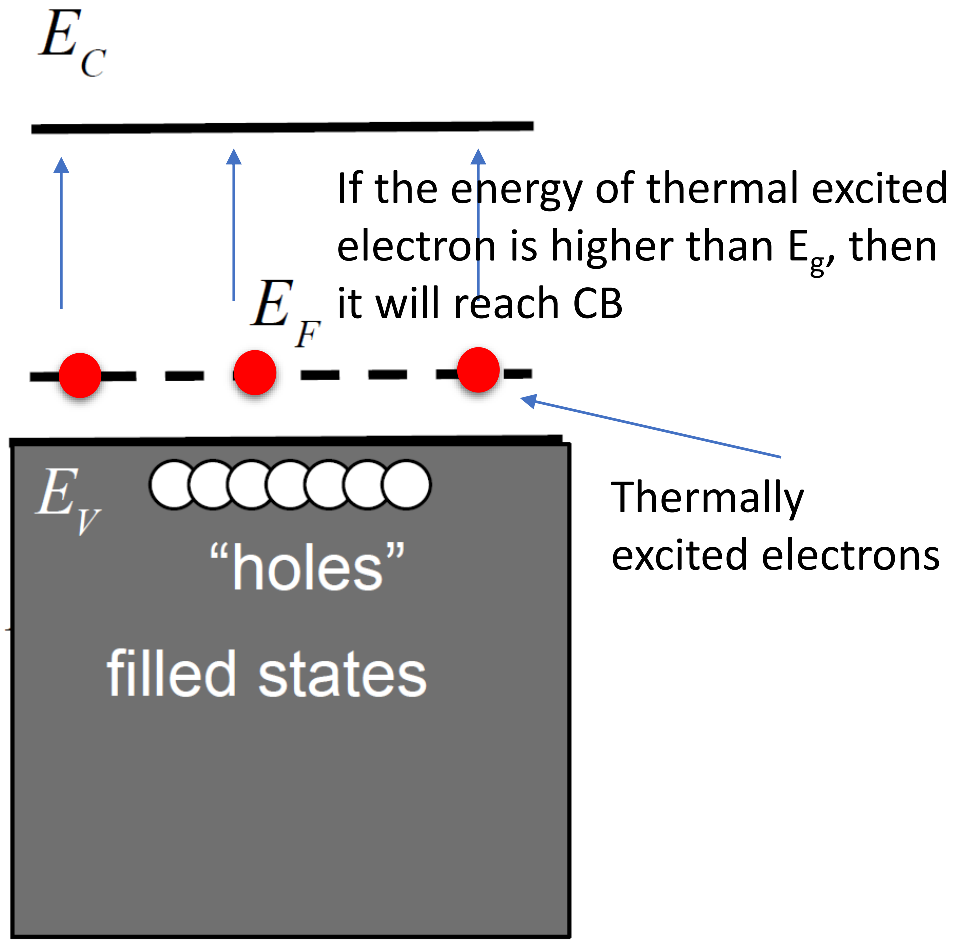
$$E << E_F \rightarrow f_0(E) = 1$$

$$E >> E_F \rightarrow f_0(E) = 0$$

P type

$$p_{0P} \approx N_A^-$$

At 0K, No. of holes in VB = No. of acceptor ions



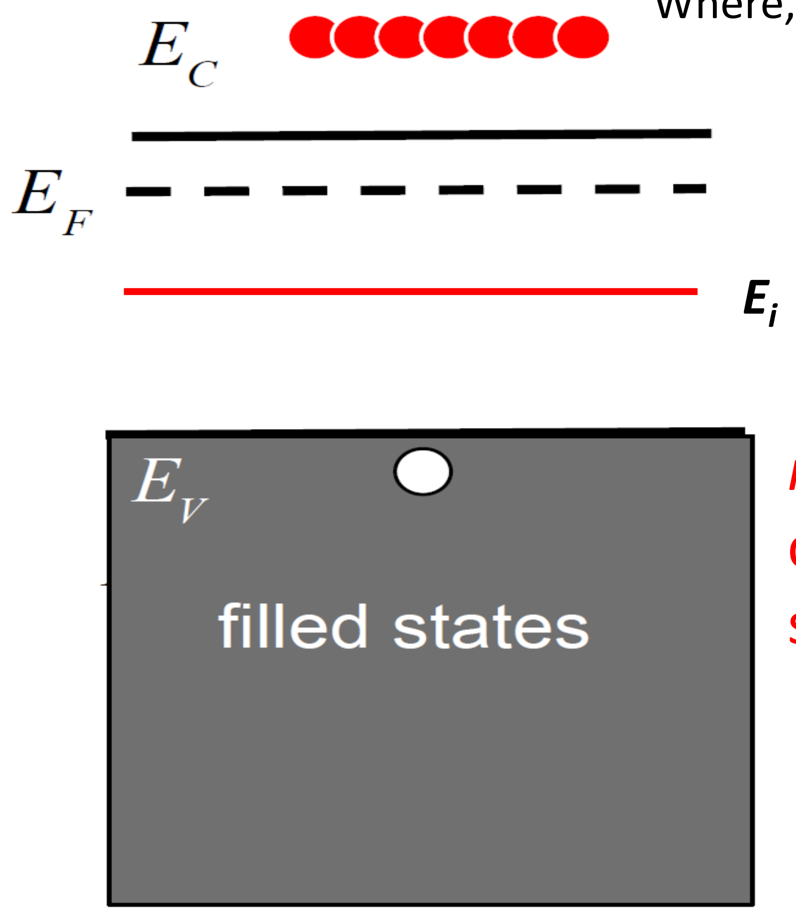
N type Semiconductor (free electrons concentration)

N_D is the density of pentavalent or donor atoms (e.g. Phosphor)

$$n_{0N} \approx N_D^+$$

$$E_{F\,(n\text{-}type)} = E_I + K_BT\ ln(N_D/n_i)$$

Where, E_I is the Fermi energy of intrinsic semiconductor



$$N_D/n_i = \exp\left(\frac{E_F - Ei}{K_BT}\right)$$

$$N_D = n_0 = n_i \exp\left(\frac{E_F - Ei}{K_BT}\right)$$

n_0 is free electrons concentration in N type semiconductor

$$n_0 \approx N_D^+$$

$$n_0\, p_0 = n_i^2$$

$$p_0 = n_i^2 / N_D^+$$

$$n_0 = N_D \approx 10^{17}\ \text{cm}^{-3}$$

$$n_i(300\,K) \approx 10^{10}\ \text{cm}^{-3}$$

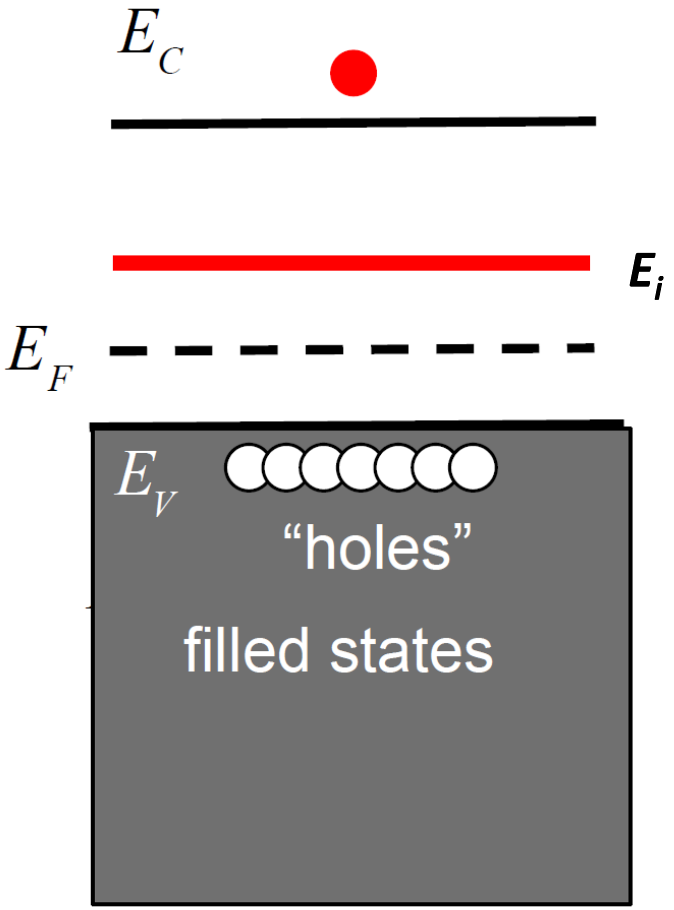
$$p_0 \approx 10^{3}\ \text{cm}^{-3}$$

P type Semiconductor (holes concentration)

N_A is the density of trivalent or acceptor atoms (e.g. Boron)

$$\boldsymbol{E_{F\,(p\text{-}type)} = E_i - K_B T \ln(N_A/n_i)}$$

Where, E_I is the Fermi energy of intrinsic semiconductor



$$N_A/n_i = \exp\left(\frac{E_i - EF}{K_B T}\right)$$

$$p_0 = n_i \exp\left(\frac{E_i - EF}{K_B T}\right)$$

p_0 is the hole concentration in VB

$$p_0 \approx N_A^-$$

$$n_0 p_0 = n_i^2$$

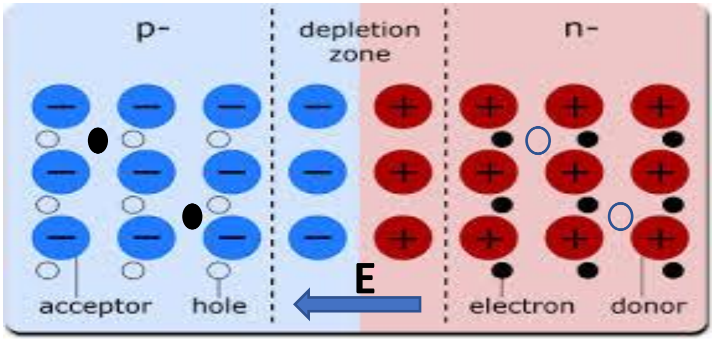
$$n_0 = n_i^2 / N_A^-$$

$$p_0 = N_A \approx 10^{17} \text{ cm}^{-3}$$

$$n_i(300K) \approx 10^{10} \text{ cm}^{-3}$$

$$n_0 \approx 10^3 \text{ cm}^{-3}$$

Formation of PN junction



Electrons diffusion (J_n diff)

Holes diffusion (J_p diff)

Charge concentration gradient

J_n **diff = q**$D\frac{\partial n}{\partial x}$

$\frac{\partial n}{\partial x}$ *is the concentration gradient*

D is the diffusion coefficient

q is the carrier charge

J_n **drift = q**μ_n**nE**

μ_n – Carrier mobility

n – charge carrier concentration

E- is the built-in electric field

As election diffuses from N to P type material (due to concentration gradient), it leaves positive charges (holes) in the N type and vice versa. Once a majority carrier crosses the junction, it becomes a minority carrier. It will continue to diffuse away from the junction and can travel a distance on average equal to the diffusion length before it recombines with opposite charges. The current caused by the diffusion of carriers across the junction is called a **diffusion current**. As a result an electric field (E) is developed in the junction (depleted region). This built-up electric field push the minority charge carriers, due to which a **drift current** is developed in the direction opposite to that of the direction of diffusion current. Under equilibrium, the drift current is equal and opposite to that of the diffusion current so there won't be further movement of charge carriers and the net current is zero. The electron drift current and electron diffusion current exactly balance out. Similarly, the hole current also balance out.

$J = J_p + J_n = 0$

$J_p = J_{p\ drift} + J_{p\ diff} = 0$

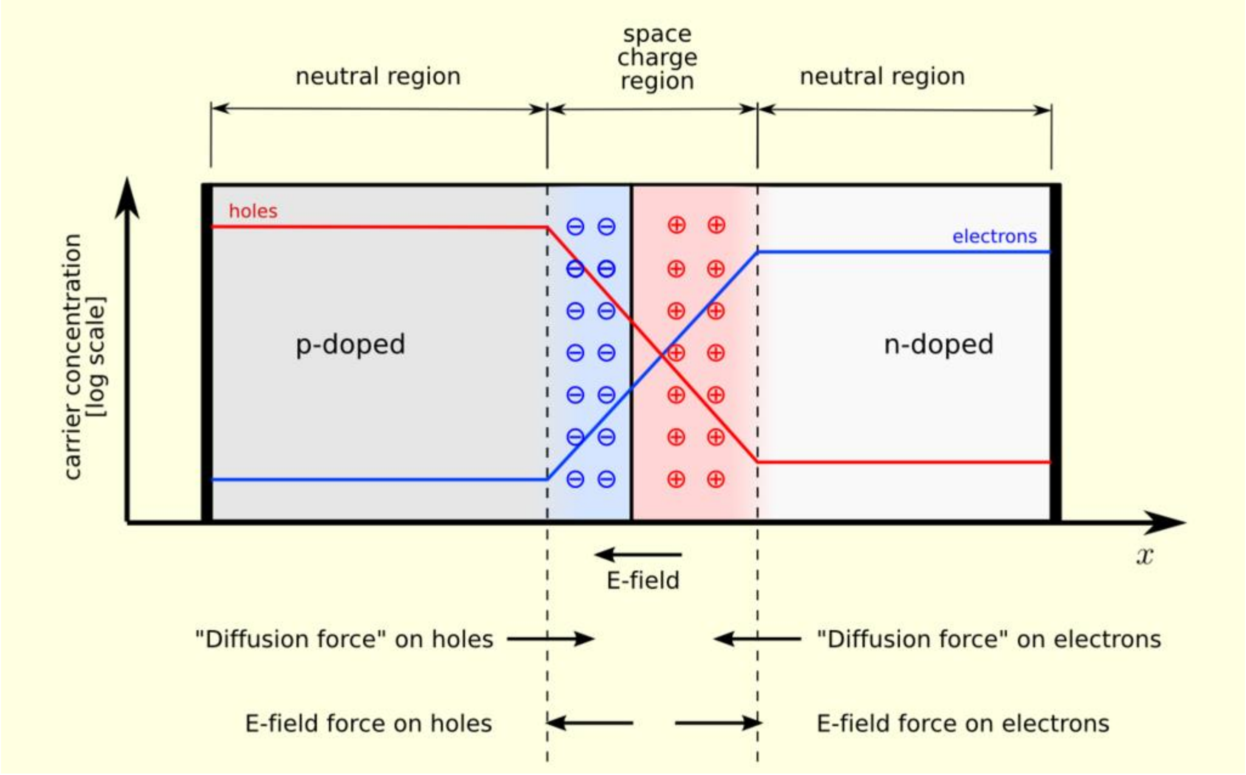
$J_n = J_{n\ drift} + J_{n\ diff} = 0$

Diffusion current – majority charge carrier

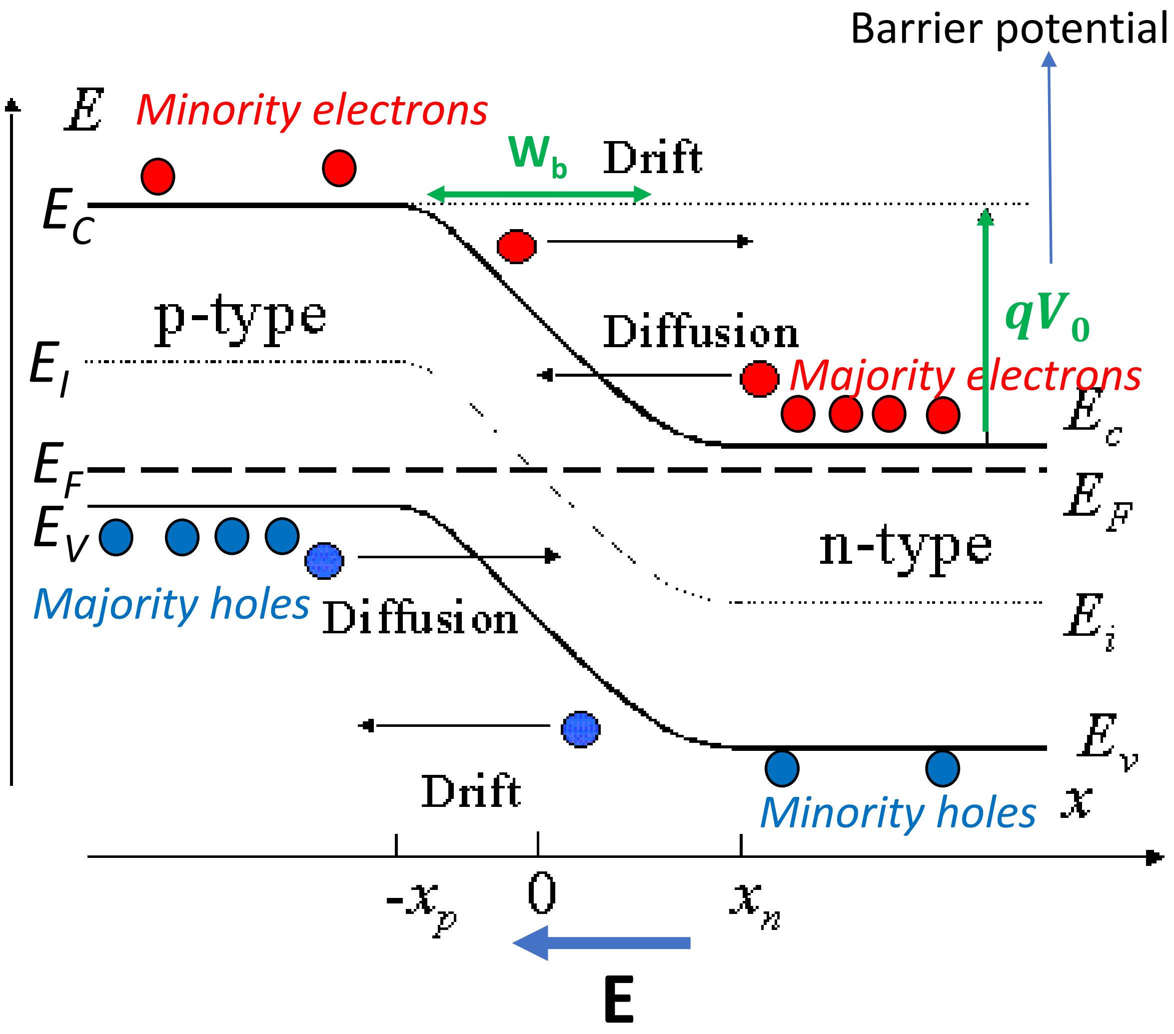
Drift current – minority charge carrier

J - total current density, J_p – hole current density, J_n – electron current density

Energy Band diagram of PN junction

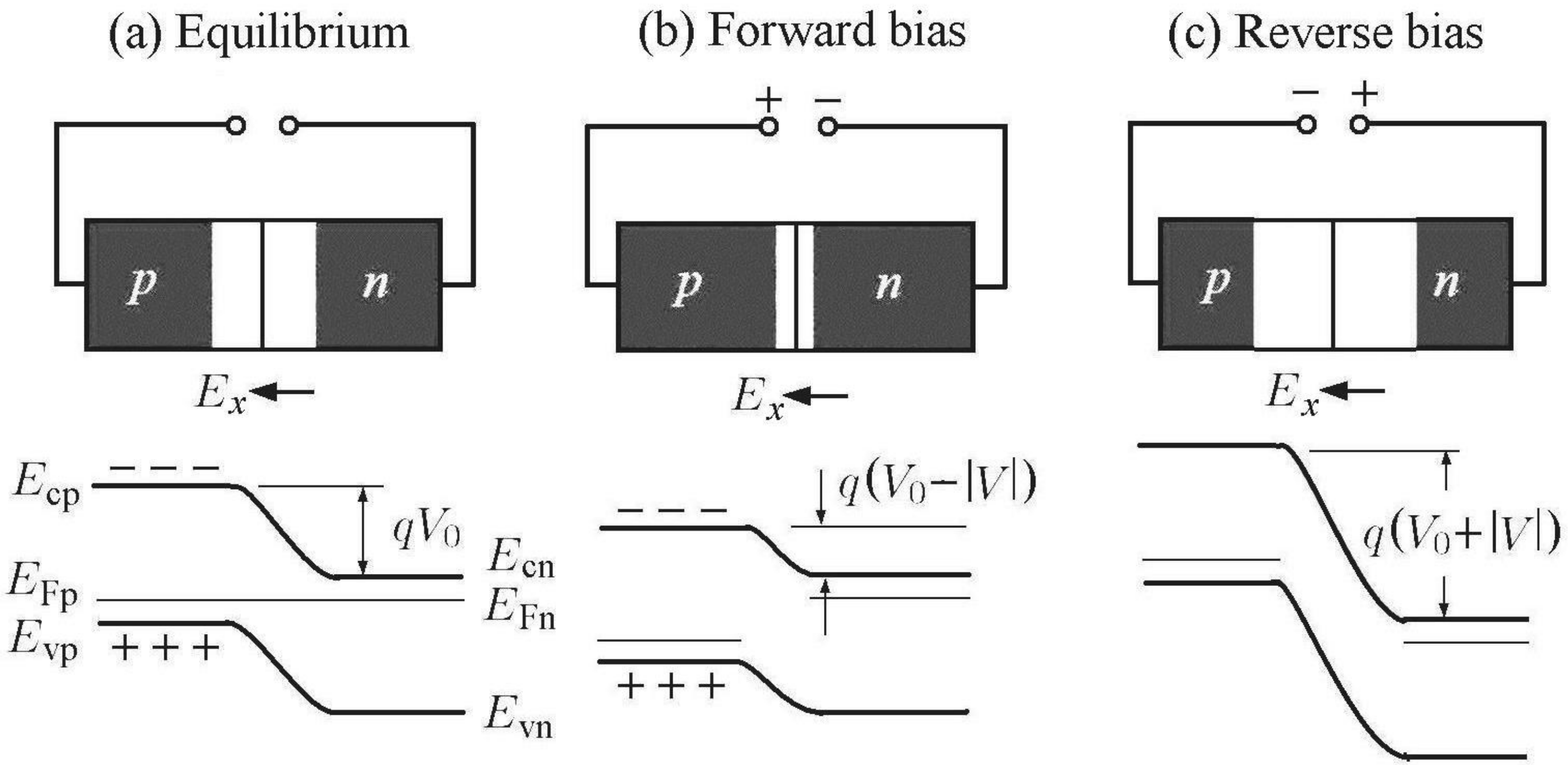


PN junction formation



Energy Band diagram of PN junction

Effect of bias in a *PN* junction



(a) At equilibrium, without external bias, the diffusion current and the drift current cancel each other. (b) A positive bias voltage pushes the holes to the *n*-side and the free electrons to the *p*-side. The potential barrier is reduced. Both diffusion currents of holes and free electrons are increased. The drift currents, depending on the available carriers, are unchanged. The net current is nonzero. (c) By applying a reversed bias, the holes are pushed further back into the *p*-region and the free electrons are pushed further back into the *n*-region. The diffusion current is reduced. Only the drift current persists.