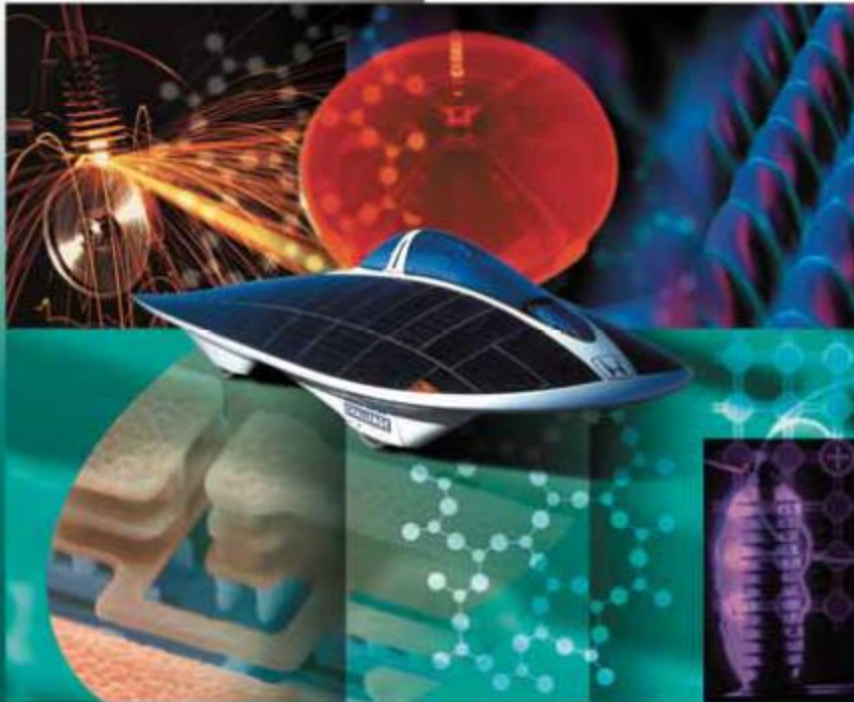


Principles of Electronic Materials and Devices

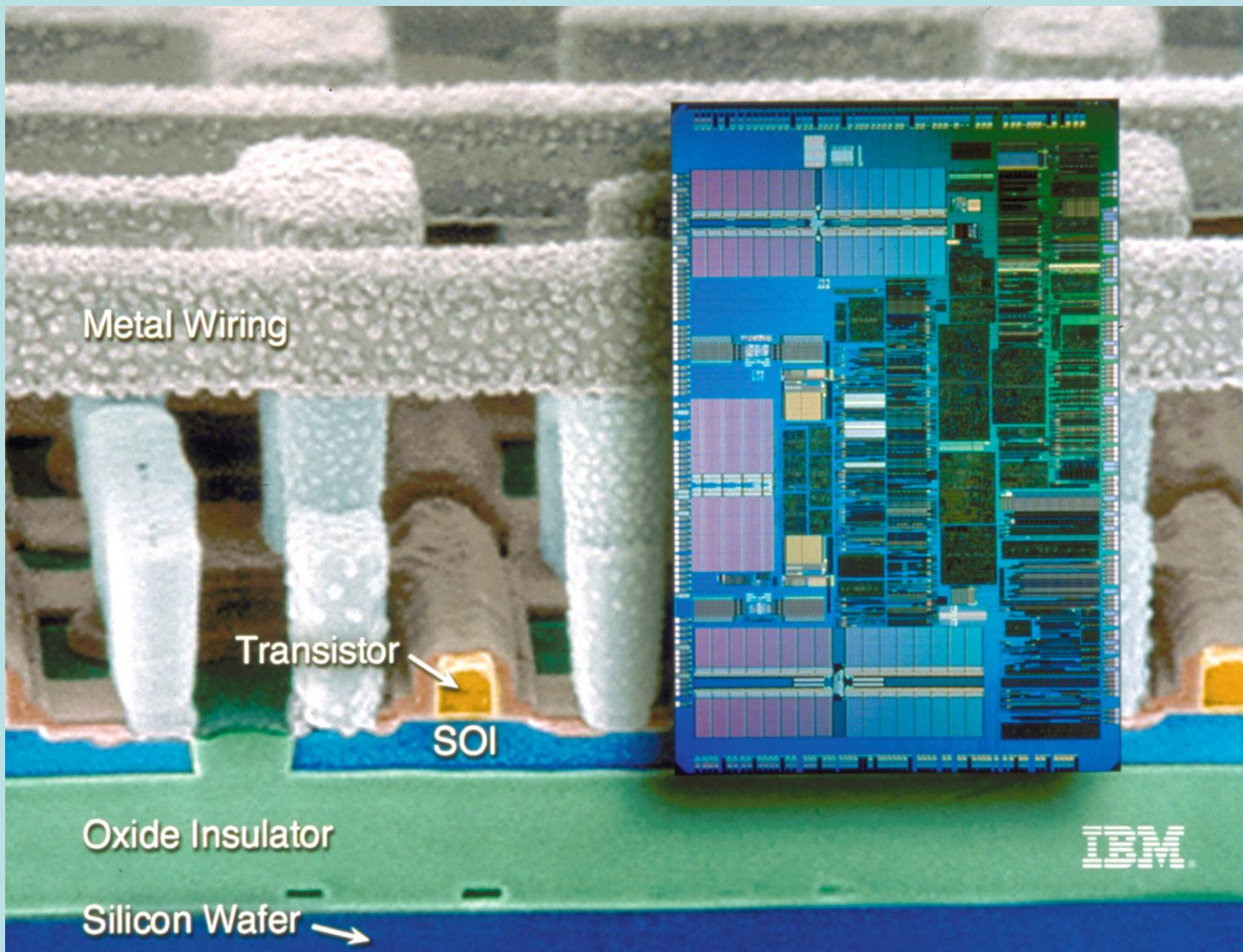
Third Edition



S. O. Kasap

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Silicon is the most important semiconductor in today's electronics

[SOURCE: Courtesy of IBM]

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200 mm and 300 mm Si wafers.

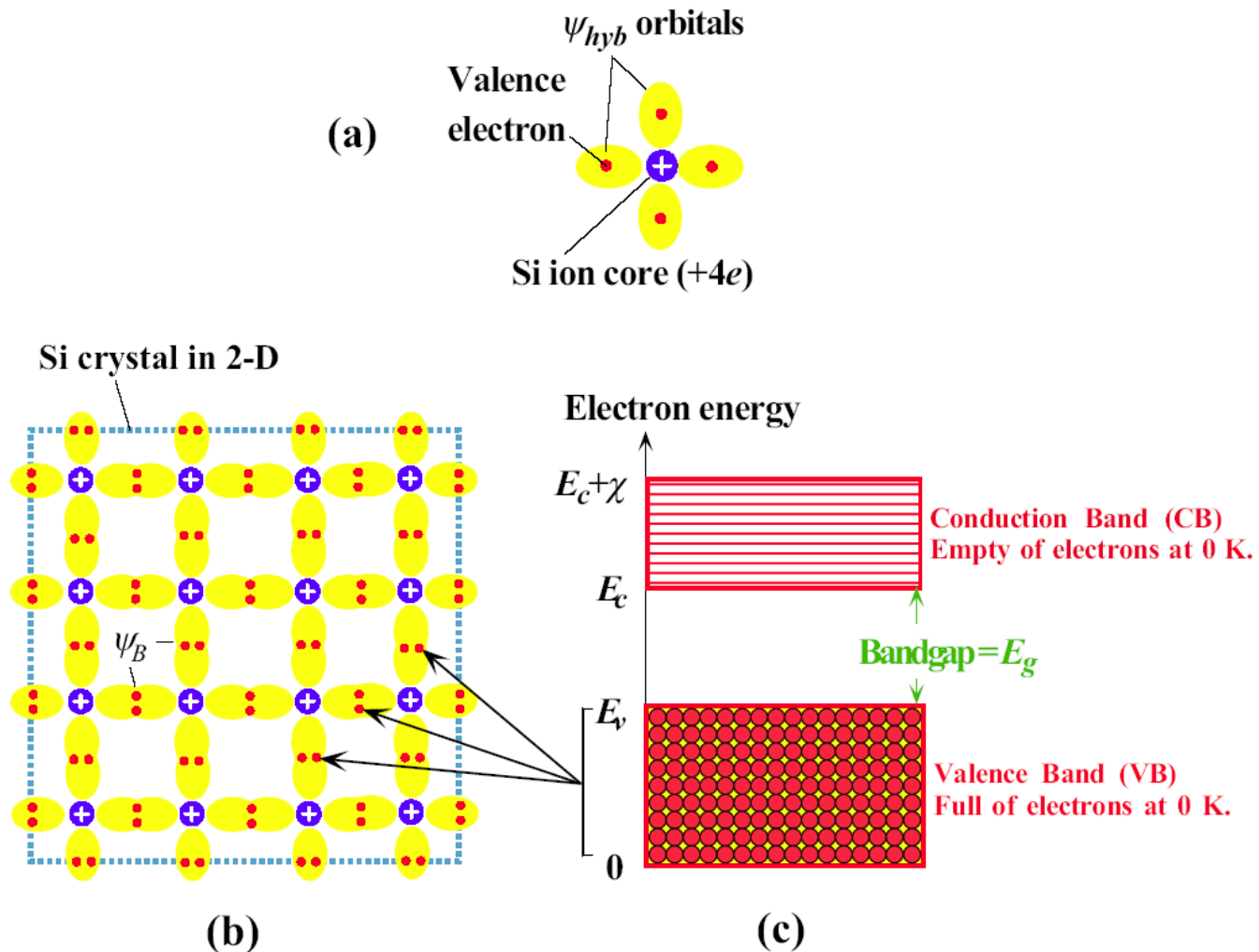
|SOURCE: Courtesy of MEMC, Electronic Materials, Inc.



GaAs ingots and wafers.

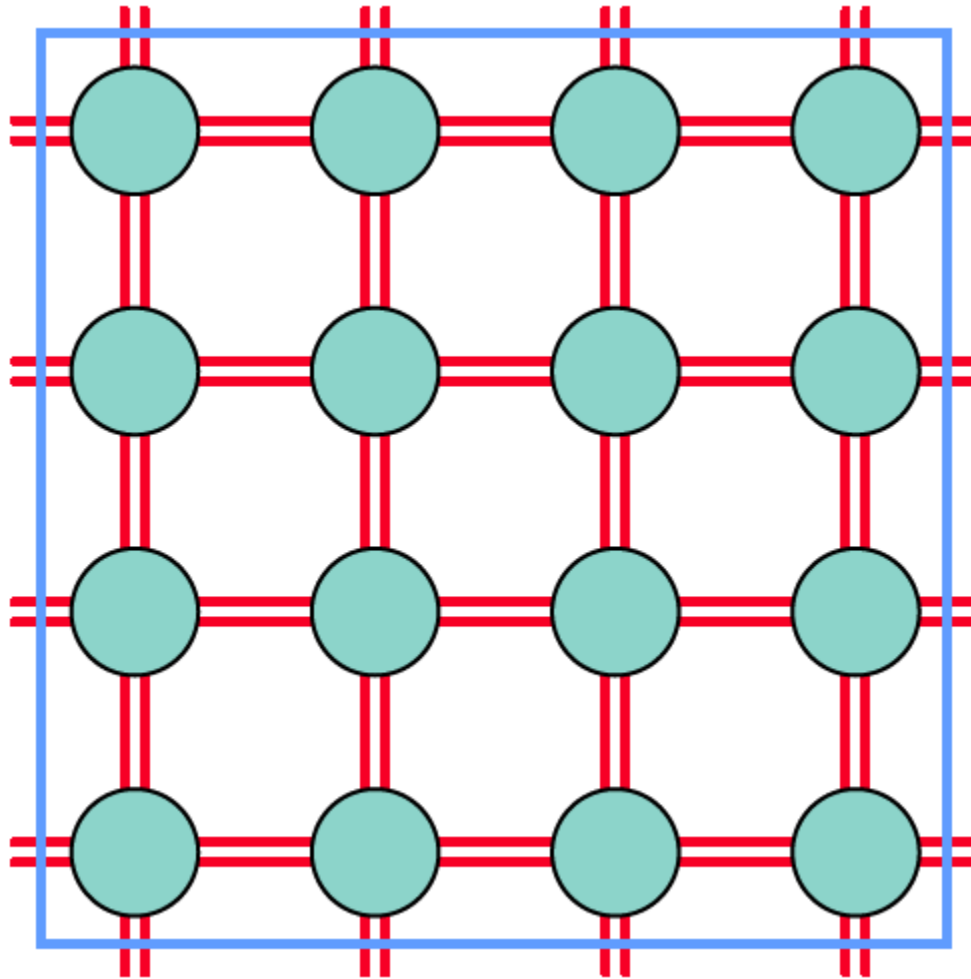
GaAs is used in high speed electronic devices, and optoelectronics.

[SOURCE: Courtesy of Sumitomo Electric Industries, Ltd.



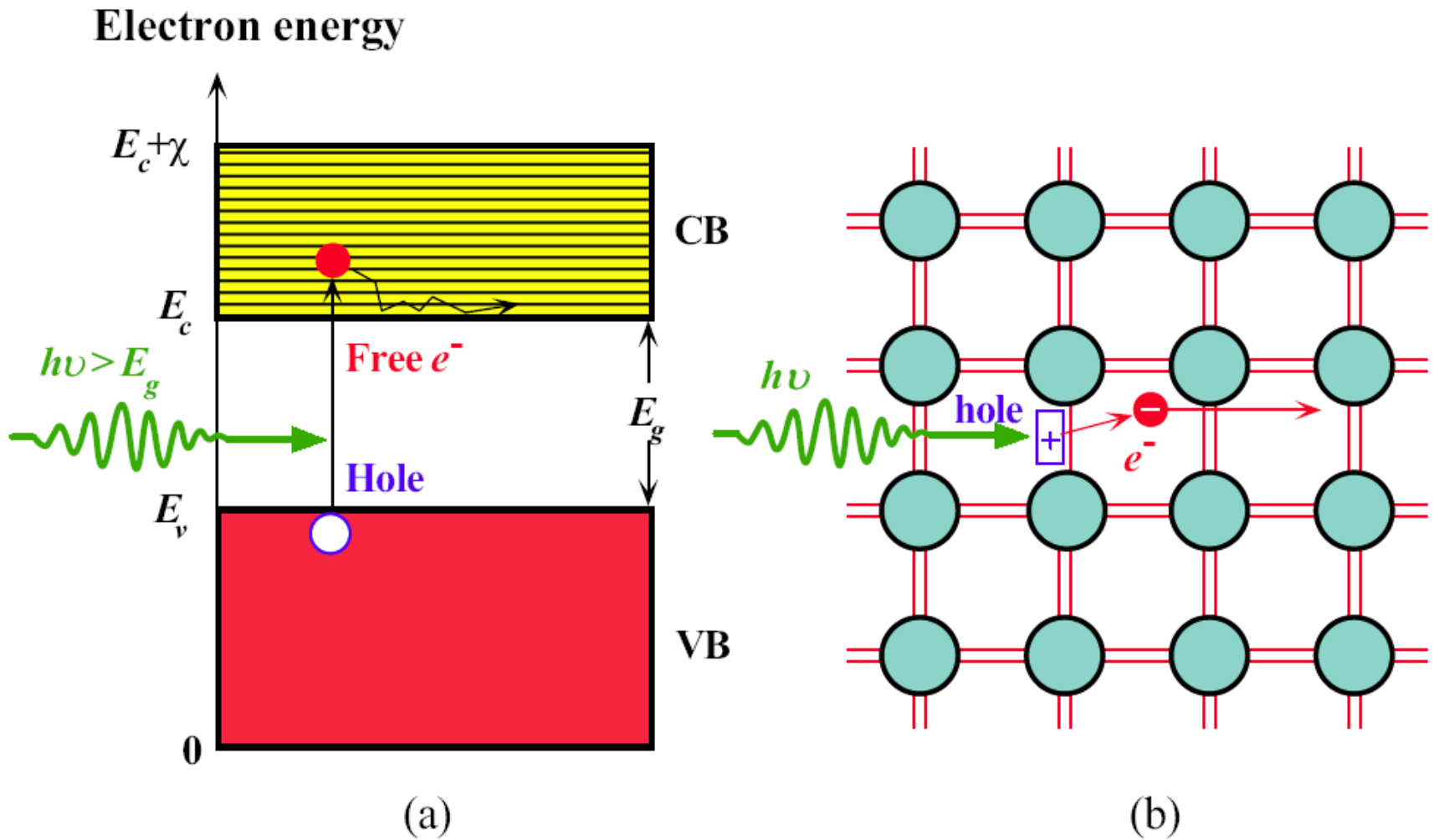
- (a) A simplified two-dimensional illustration of a Si atom with four hybrid orbitals ψ_{hyb} . Each orbital has one electron.
- (b) A simplified two-dimensional view of a region of the Si crystal showing covalent bonds.
- (c) The energy band diagram at absolute zero of temperature.

Fig 5.1



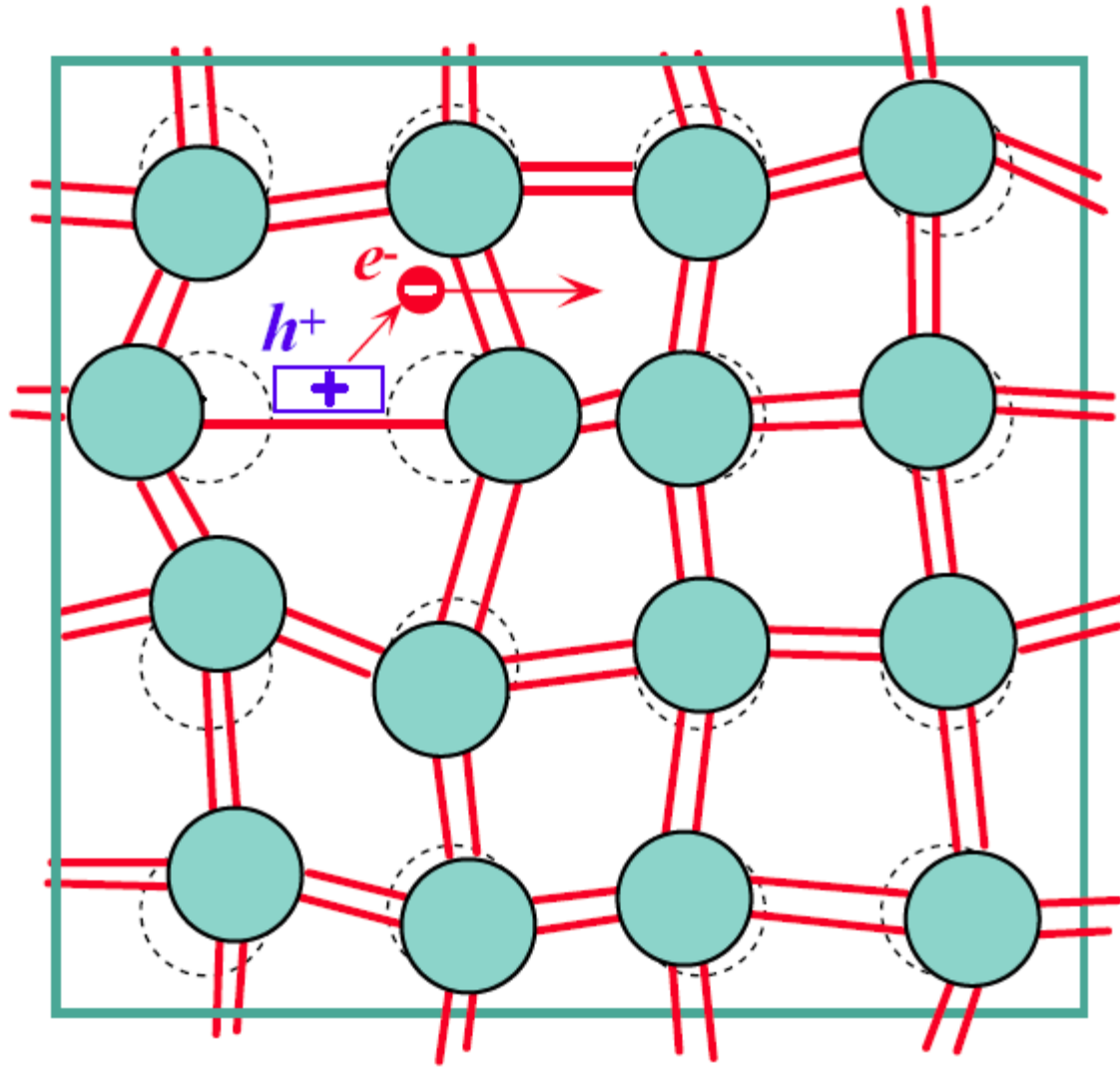
A two-dimensional pictorial view of the Si crystal showing covalent bonds as two lines where each line is a valence electron.

Fig 5.2



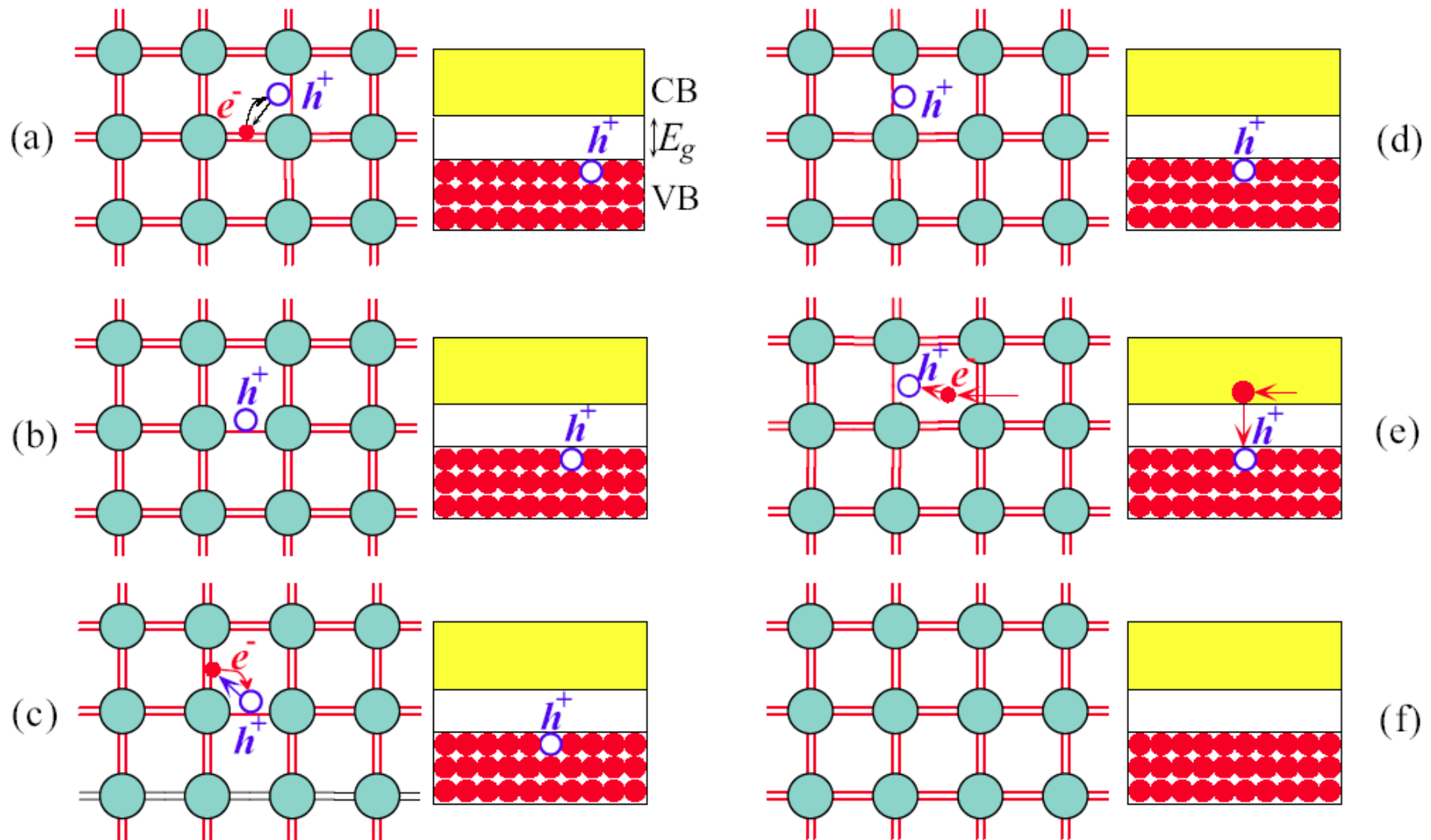
- (a) A photon with an energy greater than E_g can excite an electron from the VB to the CB.
- (b) When a photon breaks a Si-Si bond, a free electron and a hole in the Si-Si bond is created.

Fig 5.3



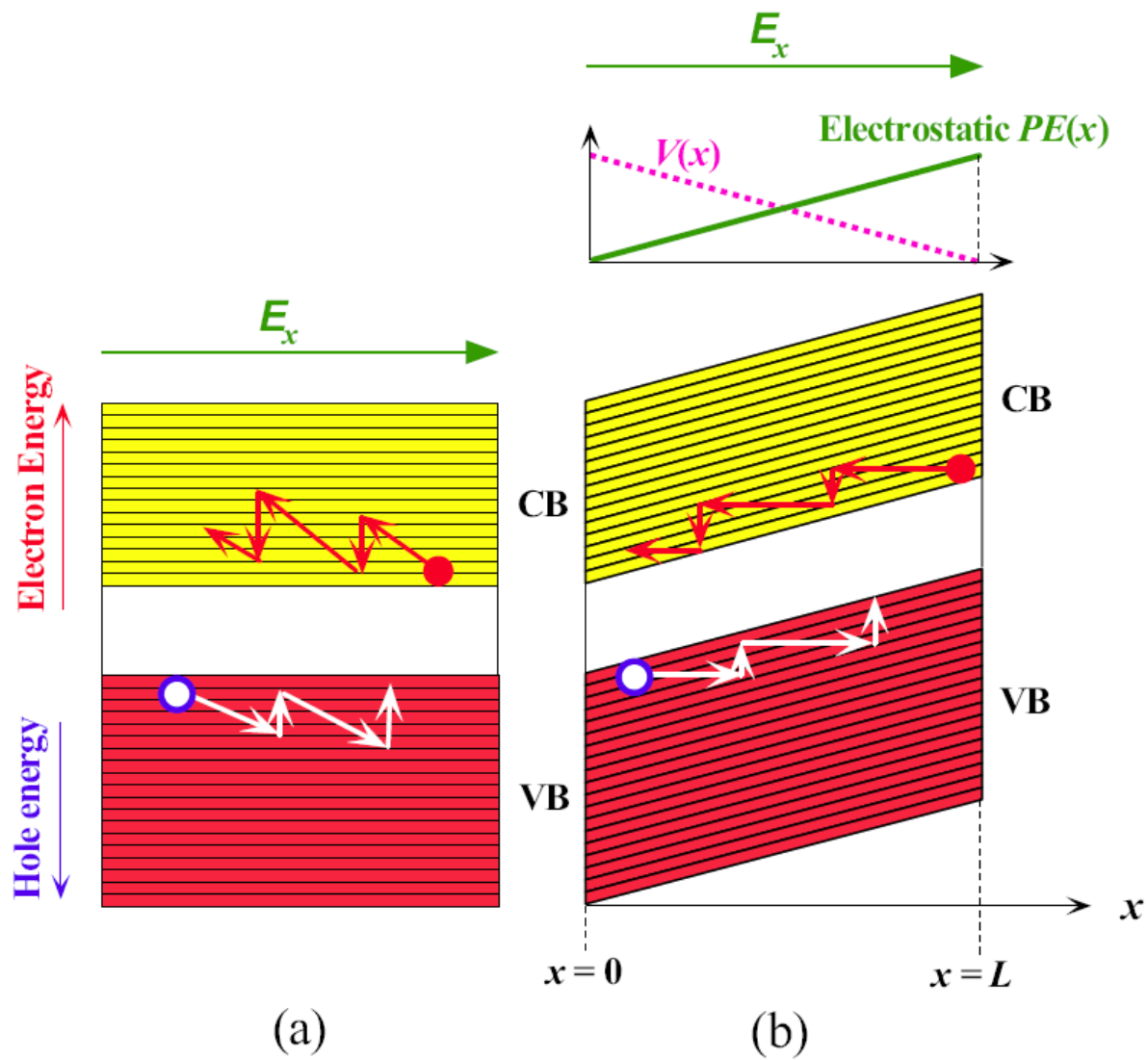
Thermal vibrations of atoms can break bonds and thereby create electron-hole pairs.

Fig 5.4



A pictorial illustration of a hole in the valence band wandering around the crystal due to the tunneling of electrons from neighboring bonds.

Fig 5.5



When an electric field is applied, electrons in the CB and holes in the VB can drift and contribute to the conductivity.

(a) A simplified illustration of drift in E_x .

(b) Applied field bends the energy bands since the electrostatic PE of the electron is $-eV(x)$ and $V(x)$ decreases in the direction of E_x , whereas PE increases.

Fig 5.6

Electron and Hole Drift Velocities

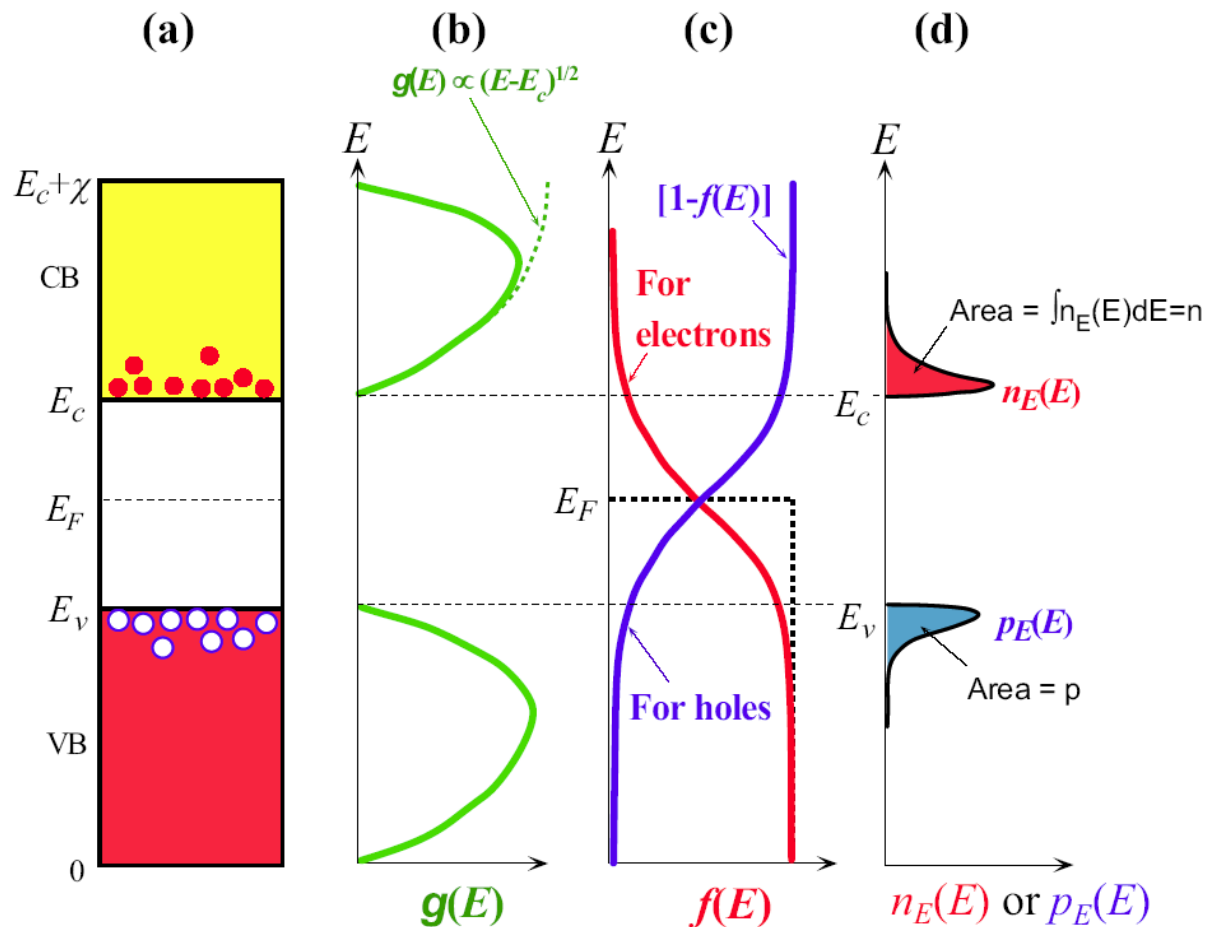
$$v_{de} = \mu_e E_x \quad \text{and} \quad v_{dh} = \mu_h E_x$$

v_{de} = drift velocity of the electrons, μ_e = electron drift mobility, E_x = applied electric field, v_{dh} = drift velocity of the holes, μ_h = hole drift mobility

Conductivity of a Semiconductor

$$\sigma = en\mu_e + ep\mu_h$$

σ = conductivity, e = electronic charge, n = electron concentration in the CB, μ_e = electron drift mobility, p = hole concentration in the VB, μ_h = hole drift mobility



(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 $n_E(E)$ versus E is the electron concentration.

Fig 5.7

Electron Concentration in CB

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

n = electron concentration in the CB, N_c = effective density of states at the CB edge, E_c = conduction band edge, E_F = Fermi energy, k = Boltzmann constant, T = temperature

Effective Density of States at CB Edge

$$N_c = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2}$$

N_c = effective density of states at the CB edge, m_e^* = effective mass of the electron in the CB, k = Boltzmann constant, T = temperature, h = Planck's constant

Hole Concentration in VB

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

p = hole concentration in the VB, N_v = effective density of states at the VB edge, E_F = Fermi energy, E_v = valence band edge, k = Boltzmann constant, T = temperature

Effective Density of States at VB Edge

$$N_v = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}$$

N_v = effective density of states at the VB edge, m_h^* = effective mass of a hole in the VB, k = Boltzmann constant, T = temperature, h = Planck's constant

Mass Action Law

$$np = \underset{\nearrow}{n_i}^2 = N_c N_v \exp\left(-\frac{E_g}{kT}\right)$$

n_i = intrinsic concentration

The np product is a constant, n_i^2 , that depends on the material properties N_c , N_v , E_g , and the temperature. If somehow n is increased (e.g. by doping), p must decrease to keep np constant.

Mass action law applies

in thermal equilibrium

and

in the dark (no illumination)

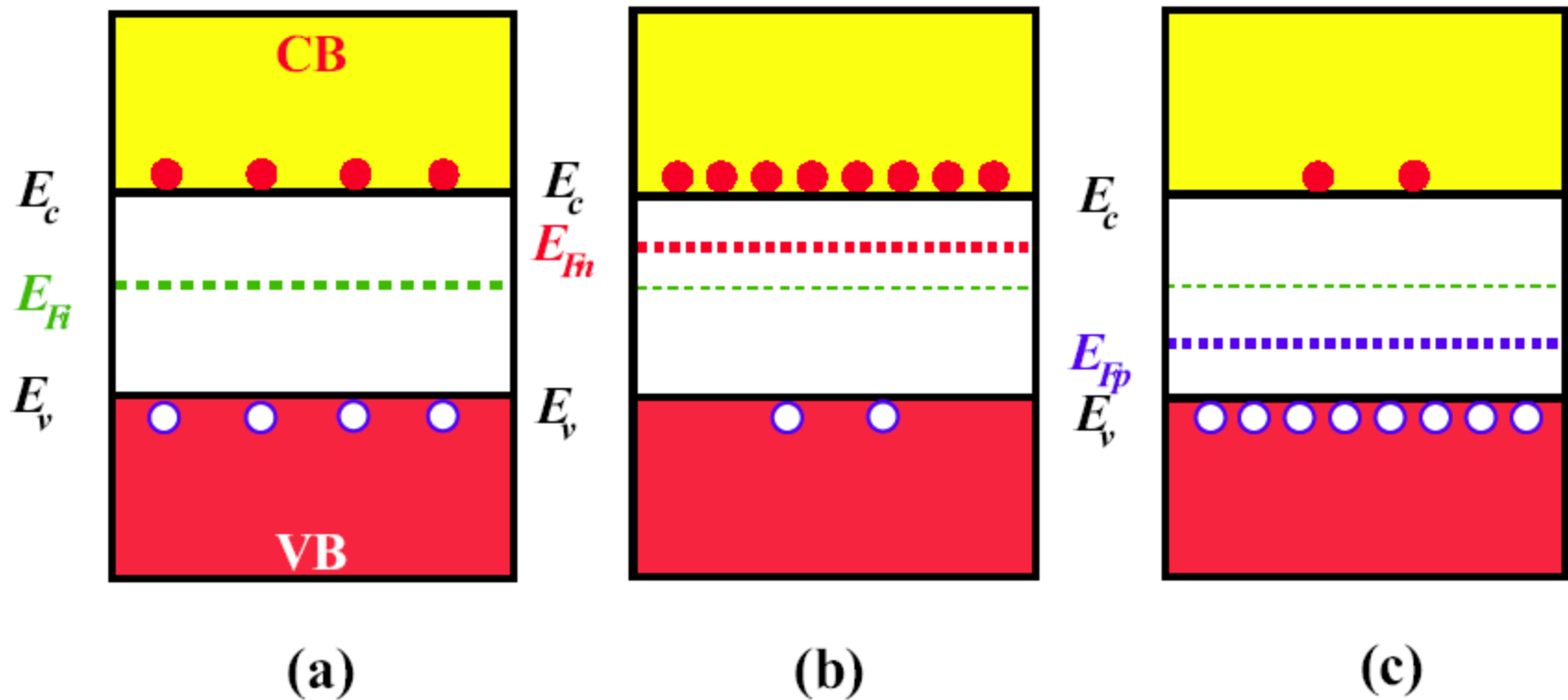
Fermi Energy in Intrinsic Semiconductors

$$E_{Fi} = E_v + \frac{1}{2} E_g - \frac{1}{2} kT \ln \left(\frac{N_c}{N_v} \right)$$

E_{Fi} = Fermi energy in the intrinsic semiconductor, E_v = valence band edge, $E_g = E_c - E_v$ is the bandgap energy, k = Boltzmann constant, T = temperature, N_c = effective density of states at the CB edge, N_v = effective density of states at the VB edge

$$E_{Fi} = E_v + \frac{1}{2} E_g - \frac{3}{4} kT \ln \left(\frac{m_e^*}{m_h^*} \right)$$

m_e^* = electron effective mass (CB), m_h^* = hole effective mass (VB)



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

Fig 5.8

Average Electron Energy in CB

$$\overline{E}_{\text{CB}} = E_c + \frac{3}{2}kT$$

\overline{E}_{CB} = average energy of electrons in the CB, E_c = conduction band edge, k = Boltzmann constant, T = temperature

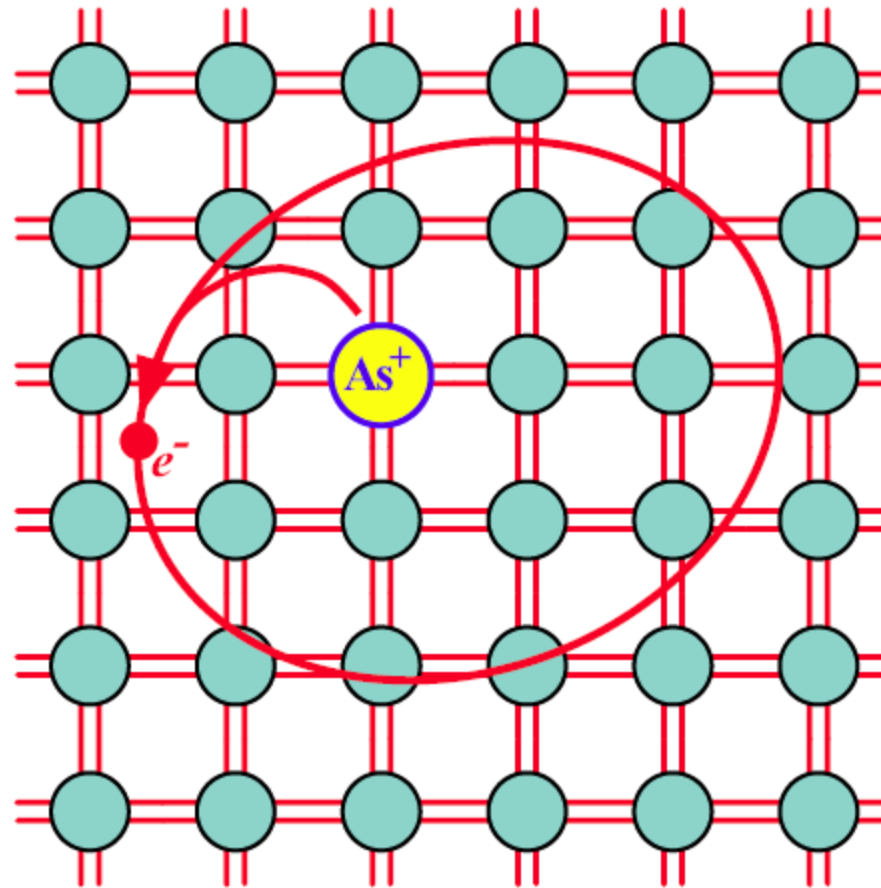
$(3/2)kT$ is also the average kinetic energy per atom in a monatomic gas (kinetic molecular theory) in which the gas atoms move around freely and randomly inside a container.

The electron in the CB behaves as if it were “free” with a mean kinetic energy that is $(3/2)kT$ and an effective mass m_e^* .

Table 5.1 Selected typical properties of Ge, Si, and GaAs at 300 K

	E_g (eV)	χ (eV)	N_c (cm ⁻³)	N_v (cm ⁻³)	n_i (cm ⁻³)	μ_e (cm ² V ⁻¹ s ⁻¹)	μ_h (cm ² V ⁻¹ s ⁻¹)	m_e^*/m_e	m_h^*/m_e	ϵ_r
Ge	0.66	4.13	1.04×10^{19}	6.0×10^{18}	2.3×10^{13}	3900	1900	0.12 <i>a</i> 0.56 <i>b</i>	0.23 <i>a</i> 0.40 <i>b</i>	16
Si	1.10	4.01	2.8×10^{19}	1.2×10^{19}	1.0×10^{10}	1350	450	0.26 <i>a</i> 1.08 <i>b</i>	0.38 <i>a</i> 0.60 <i>b</i>	11.9
GaAs	1.42	4.07	4.7×10^{17}	7×10^{18}	2.1×10^6	8500	400	0.067 <i>a,b</i>	0.40 <i>a</i> 0.50 <i>b</i>	13.1

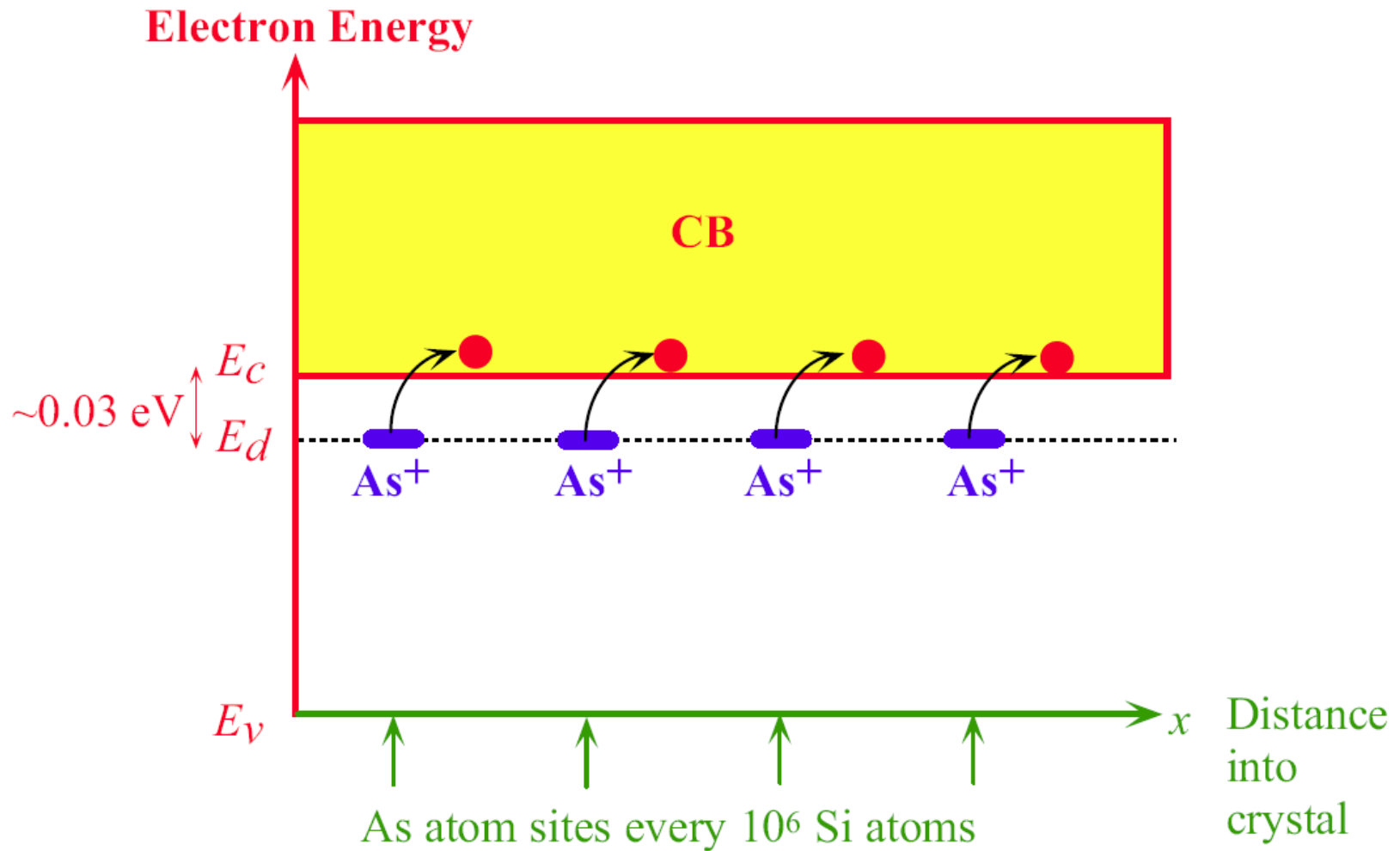
NOTE: Effective mass related to conductivity (labeled *a*) is different than that for density of states (labeled *b*). In numerous textbooks, n_i is taken as 1.45×10^{10} cm⁻³ and is therefore the most widely used value of n_i for Si, though the correct value is actually 1.0×10^{10} cm⁻³. (M. A. Green, *J. Appl. Phys.*, **67**, 2944, 1990.)



Arsenic-doped Si crystal.

The four valence electrons of As allow it to bond just like Si, but the fifth electron is left orbiting the As site. The energy required to release the free fifth electron into the CB is very small.

Fig 5.9



Energy band diagram for an n-type Si doped with 1 ppm As. There are donor energy levels just below E_c around As^+ sites.

Fig 5.10

***n*-Type Conductivity**

$$\sigma = eN_d\mu_e + e\left(\frac{n_i^2}{N_d}\right)\mu_h \approx eN_d\mu_e$$

σ = electrical conductivity

e = electronic charge

N_d = donor atom concentration in the crystal

μ_e = electron drift mobility, n_i = intrinsic concentration,

μ_h = hole drift mobility

Occupation Probability at a Donor

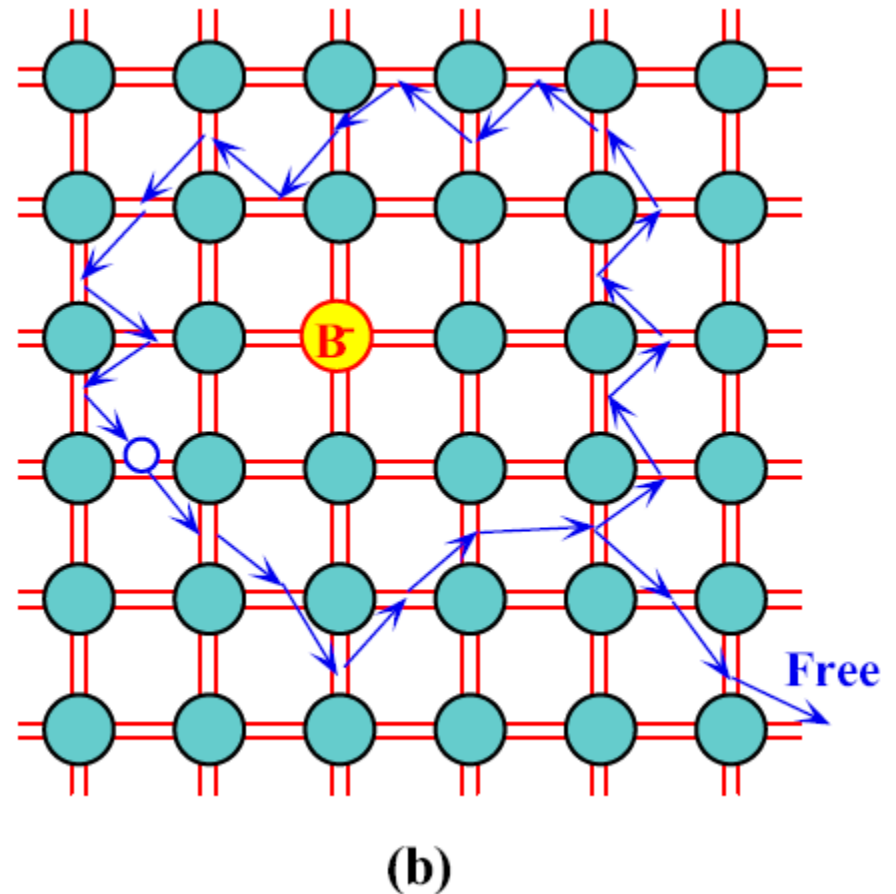
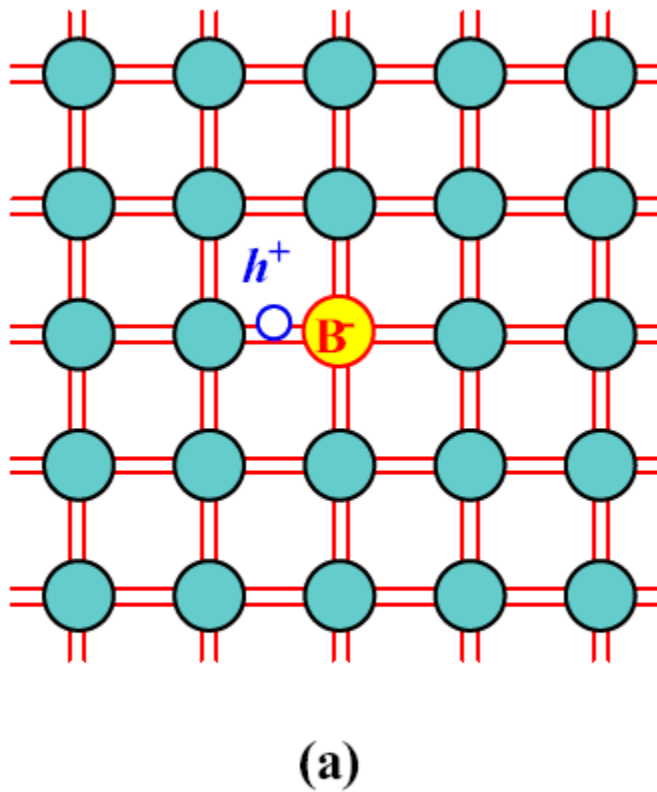
$$f_d(E_d) = \frac{1}{1 + \frac{1}{2} \exp\left[\frac{(E_d - E_F)}{kT}\right]}$$

$f_d(E_d)$ = probability of finding an electron in a state with energy E_d at a donor

E_d = energy level of donor

E_F = Fermi energy

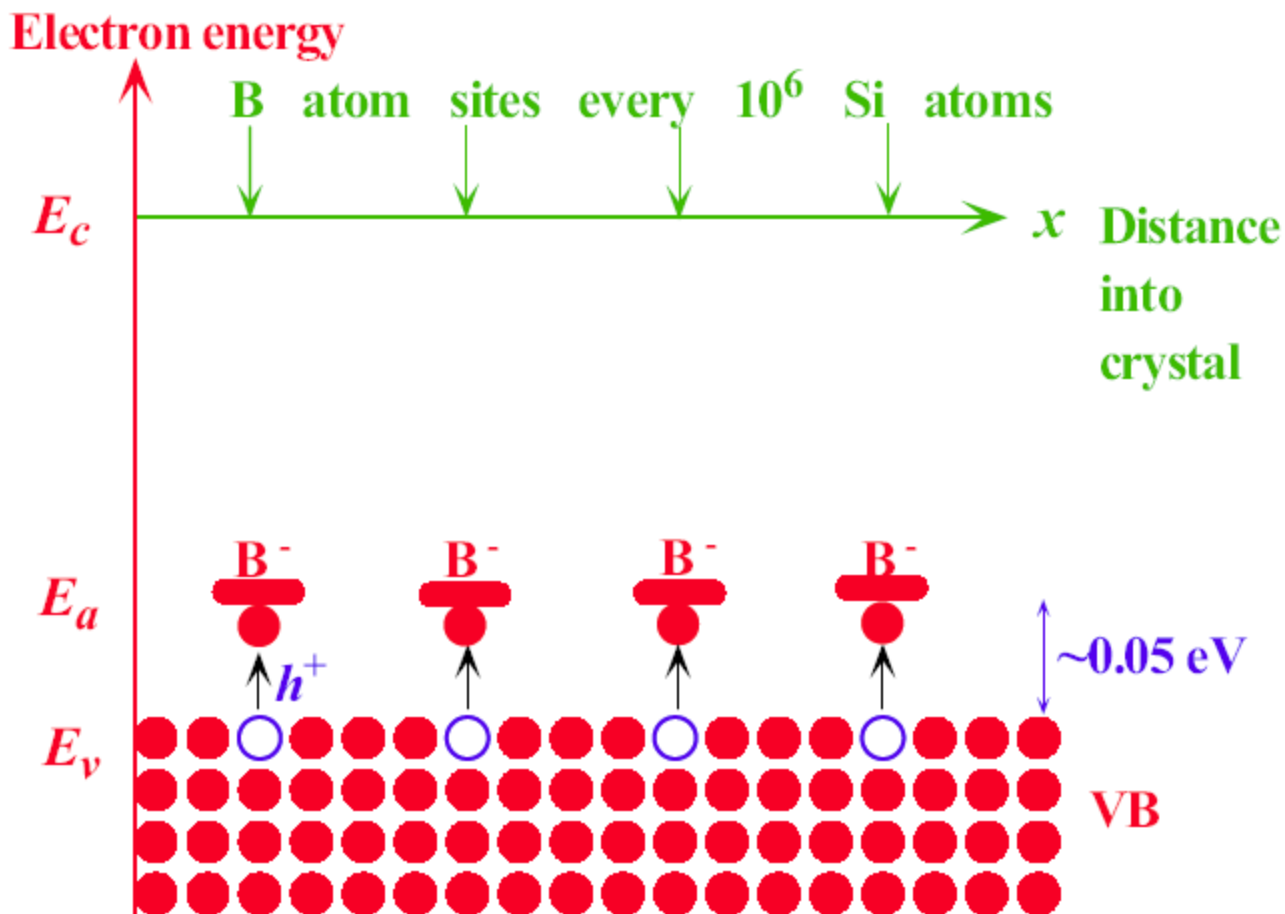
k = Boltzmann constant, T = temperature



Boron-doped Si crystal.

B has only three valence electrons. When it substitutes for a Si atom, one of its bonds has an electron missing and therefore a hole, as shown in (a). The hole orbits around the B⁻ site by the tunneling of electrons from neighboring bonds, as shown in (b). Eventually, thermally vibrating Si atoms provide enough energy to free the hole from the B⁻ site into the VB, as shown.

Fig 5.11



Energy band diagram for a p -type Si doped with 1 ppm B. There are acceptor energy levels E_a just above E_v around B^- sites. These acceptor levels accept electrons from the VB and therefore create holes in the VB.

Fig 5.12

Table 5.2 Examples of donor and acceptor ionization energies (eV) in Si

Donors			Acceptors		
P	As	Sb	B	Al	Ga
0.045	0.054	0.039	0.045	0.057	0.072

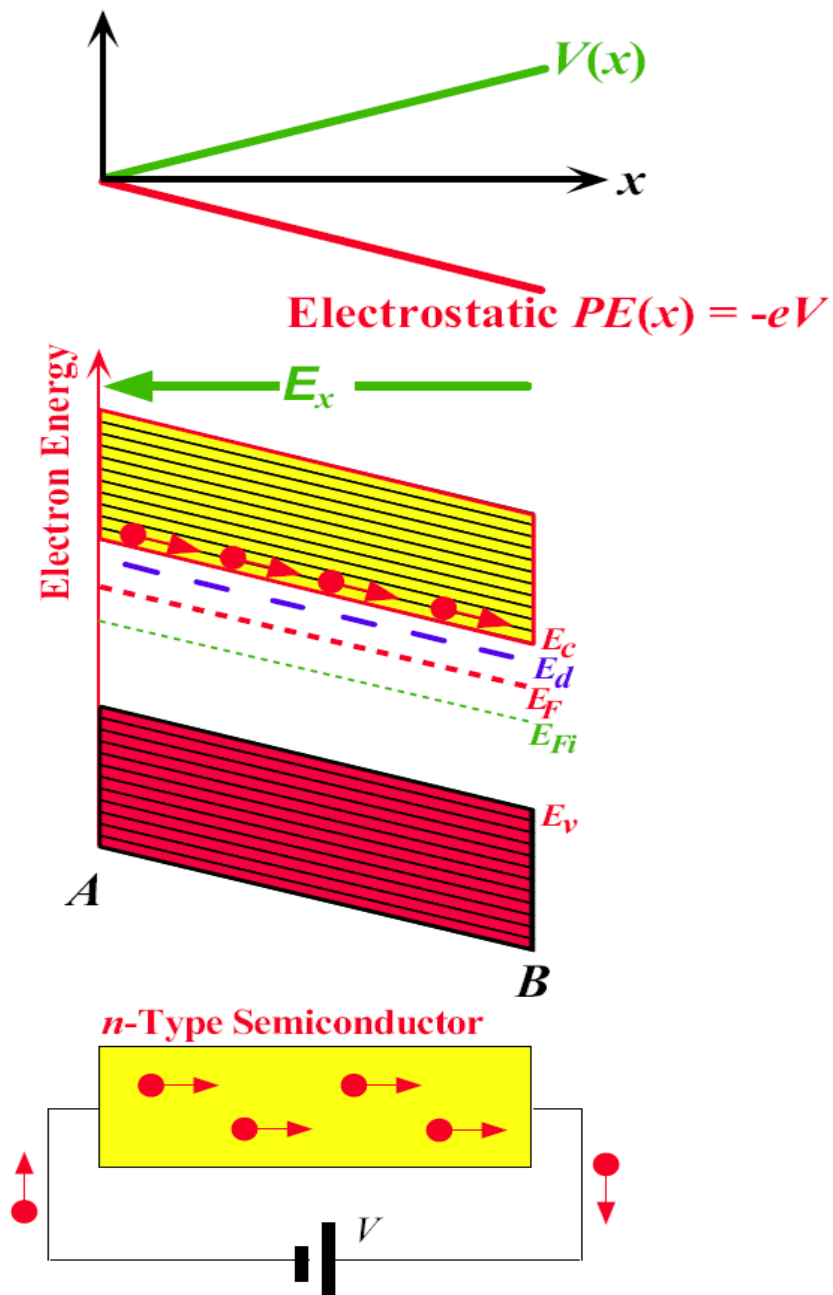
Compensation Doping

More donors than acceptors $N_d - N_a \gg n_i$

$$n = N_d - N_a \qquad p = \frac{n_i^2}{n} = \frac{n_i^2}{N_d - N_a}$$

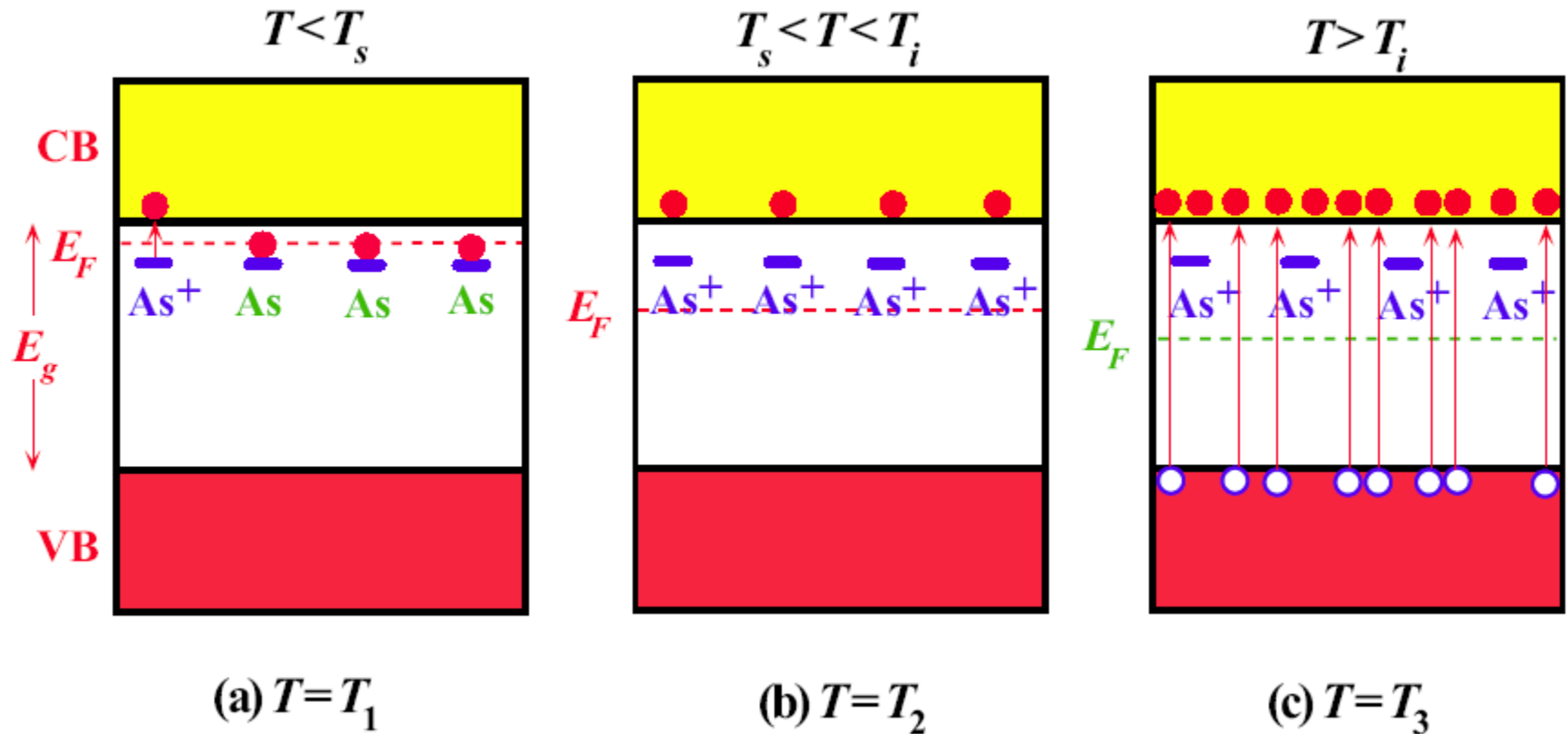
More acceptors than donors $N_a - N_d \gg n_i$

$$p = N_a - N_d \qquad n = \frac{n_i^2}{p} = \frac{n_i^2}{N_a - N_d}$$



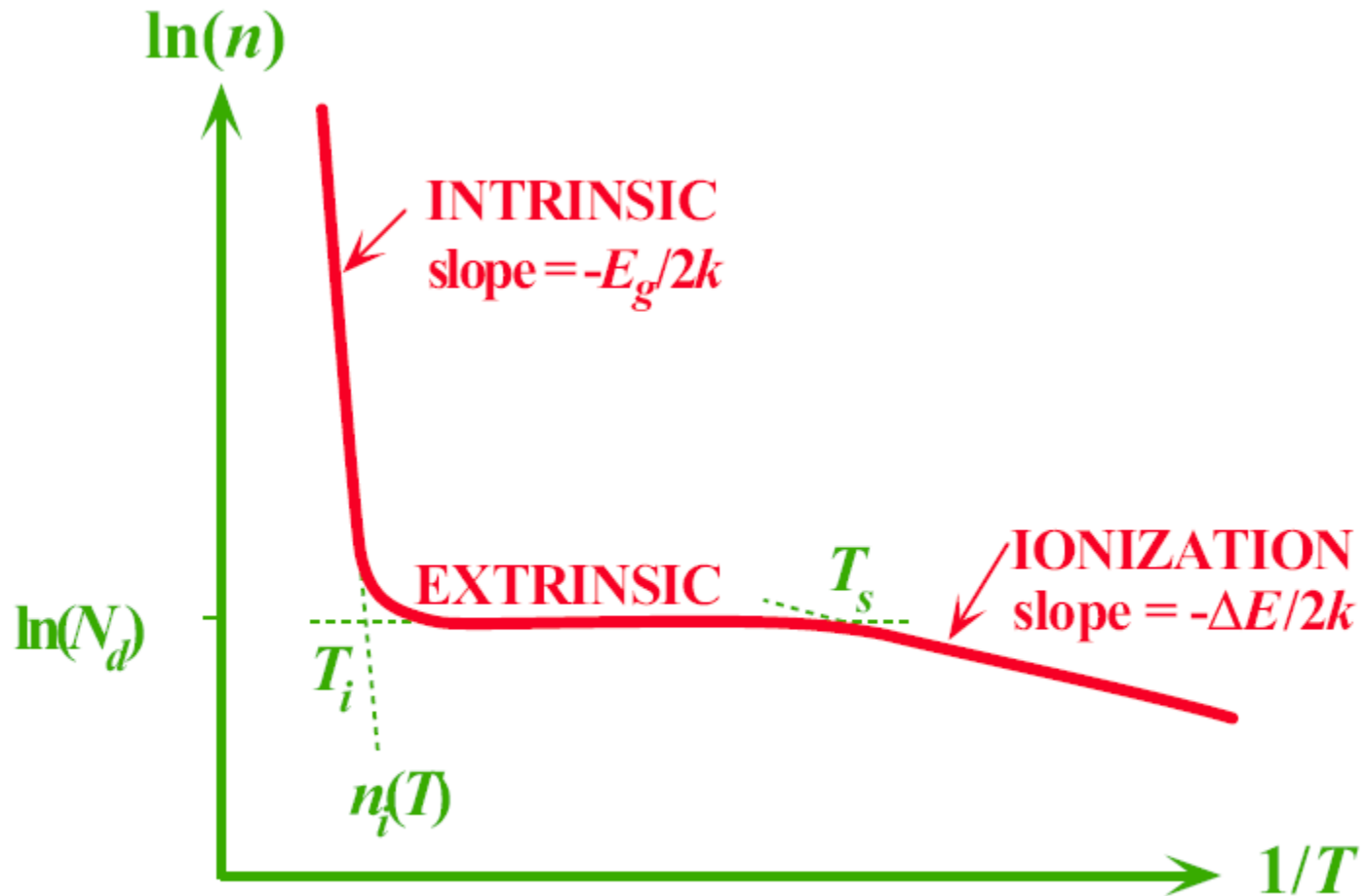
Energy band diagram of an *n*-type semiconductor connected to a voltage supply of V volts. The whole energy diagram tilts because the electron now also has an electrostatic potential energy.

Fig 5.13



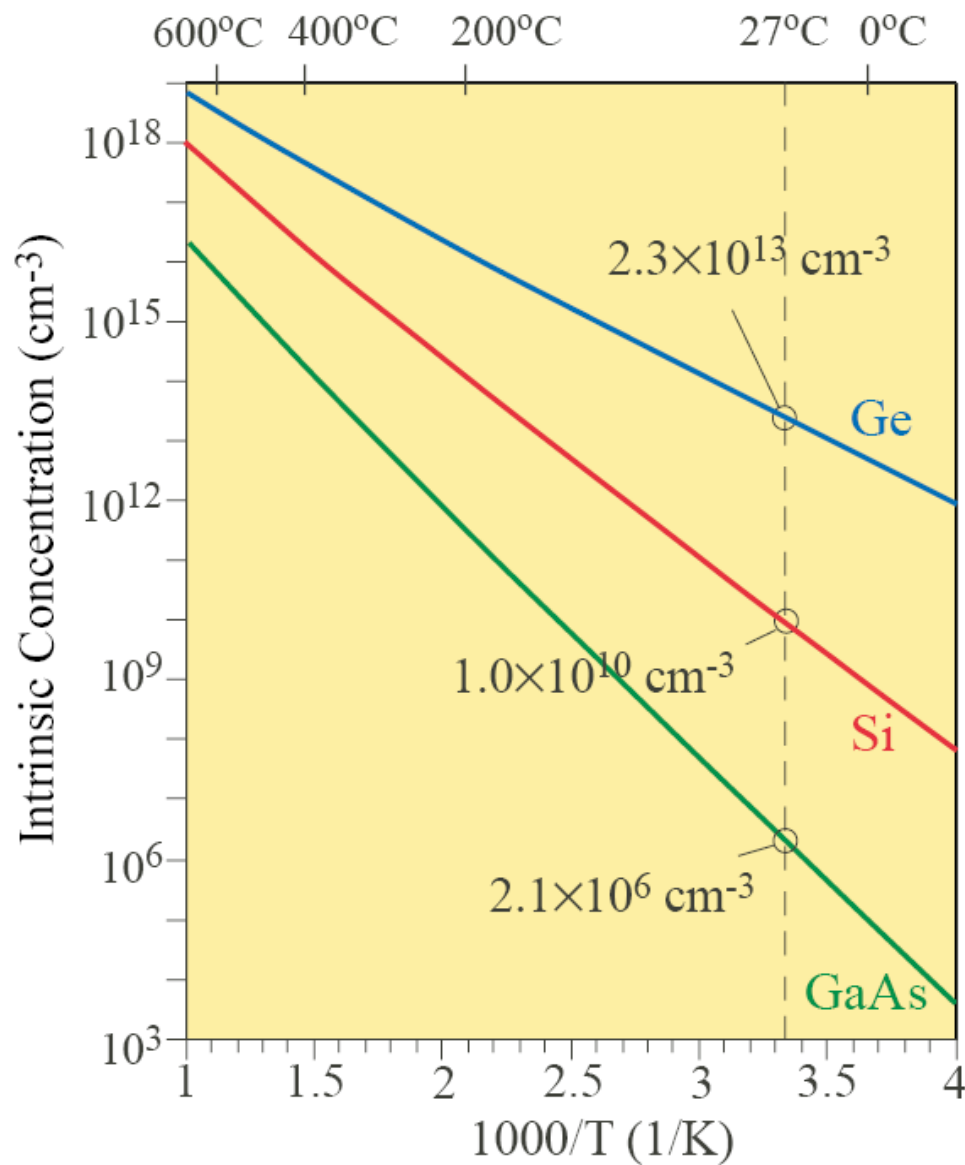
- (a) Below T_s , the electron concentration is controlled by the ionization of the donors.
- (b) Between T_s and T_i , the electron concentration is equal to the concentration of donors since they would all have ionized.
- (c) At high temperatures, thermally generated electrons from the VB exceed the number of electrons from ionized donors and the semiconductor behaves as if intrinsic.

Fig 5.14



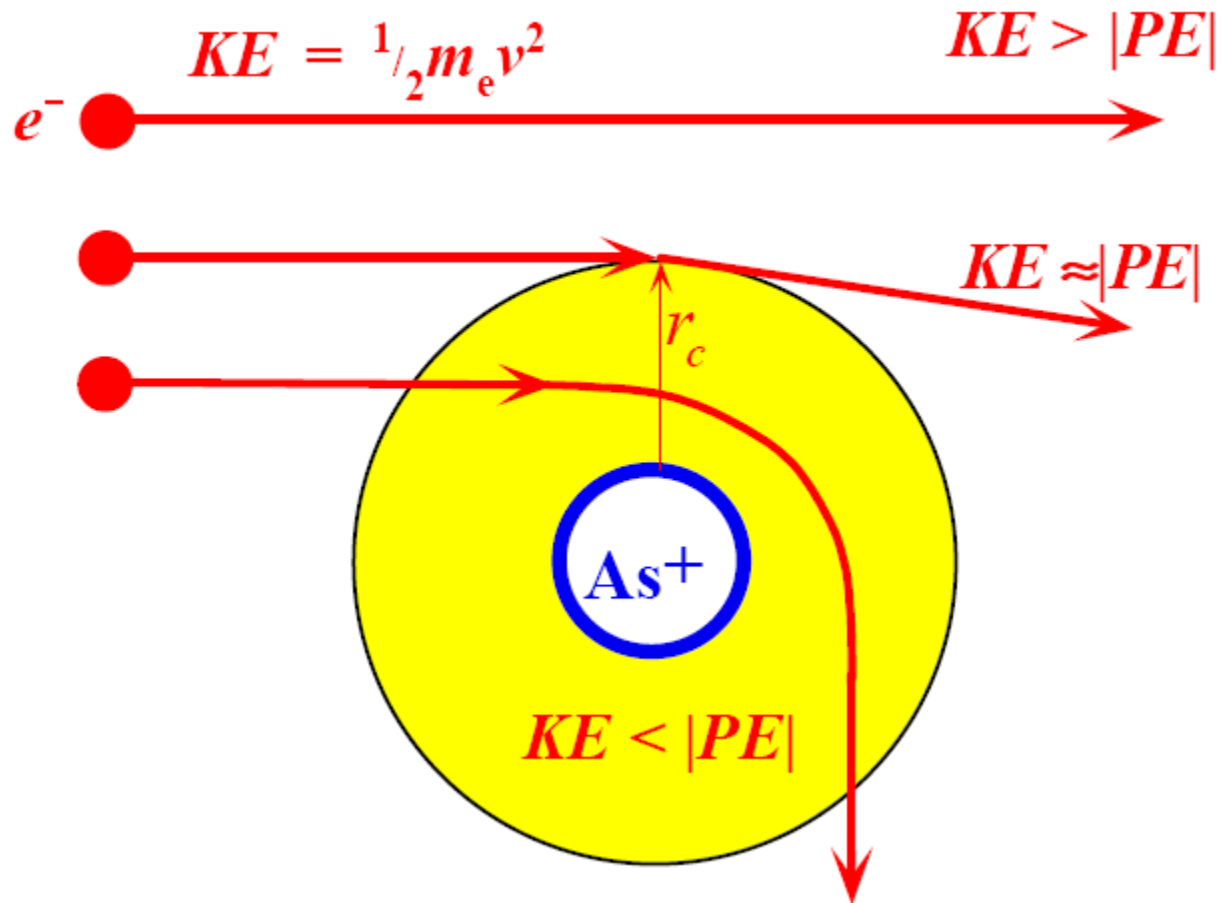
The temperature dependence of the electron concentration in an n -type semiconductor.

Fig 5.15



The temperature dependence of the intrinsic concentration

Fig 5.16



Scattering of electrons by an ionized impurity.

Fig 5.17

Lattice-Scattering-Limited Mobility

$$\mu_L \propto T^{-3/2}$$

μ_L = lattice vibration scattering limited mobility, T = temperature

Ionized Impurity Scattering Limited Mobility

$$\mu_I \propto \frac{T^{3/2}}{N_I}$$

μ_I = ionized impurity scattering limited mobility, N_I = concentration of the ionized impurities (all ionized impurities including donors and acceptors)

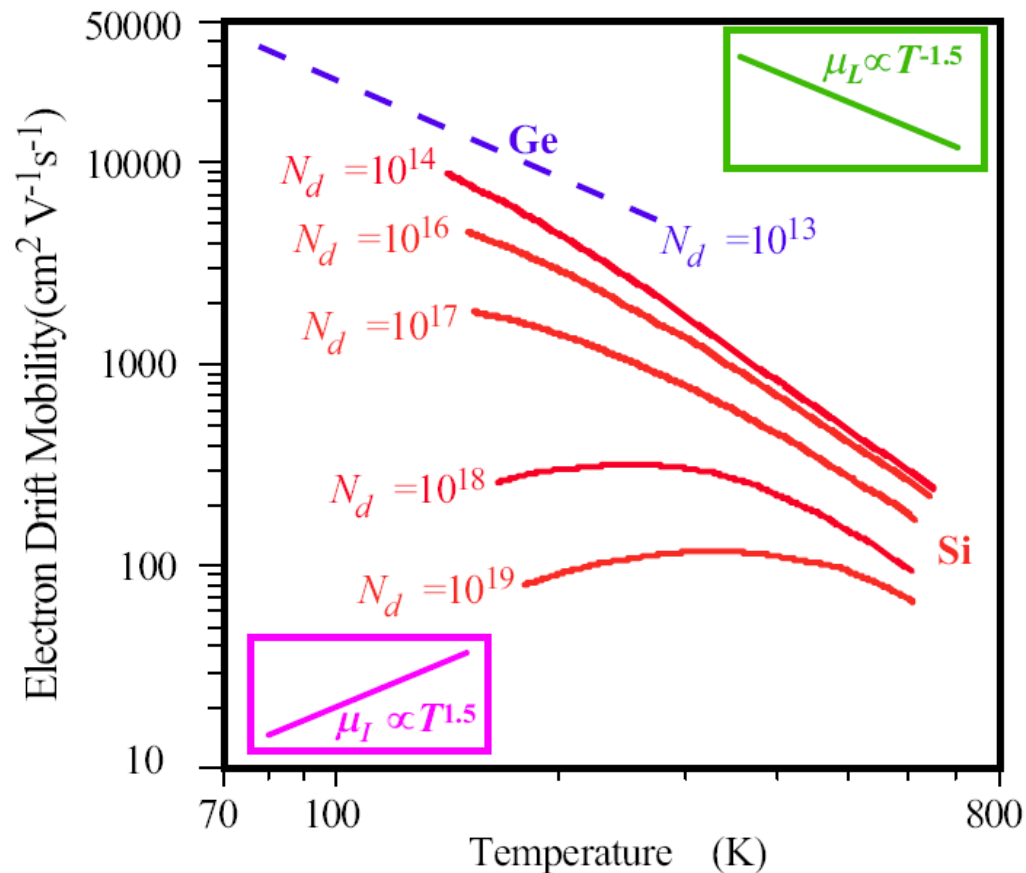
Effective or Overall Mobility

$$\frac{1}{\mu_e} = \frac{1}{\mu_I} + \frac{1}{\mu_L}$$

μ_e = effective drift mobility

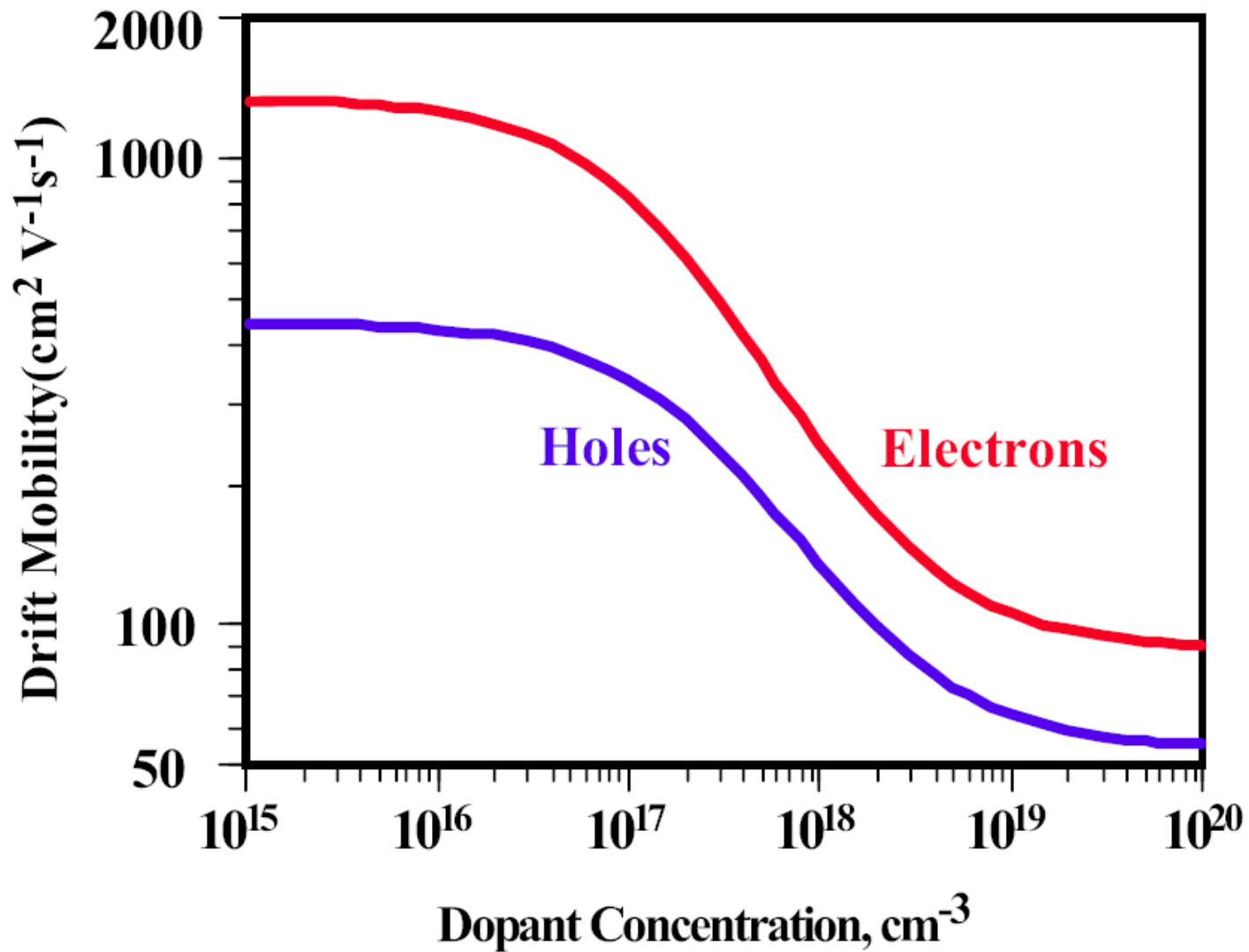
μ_I = ionized impurity scattering limited mobility

μ_L = lattice vibration scattering limited mobility



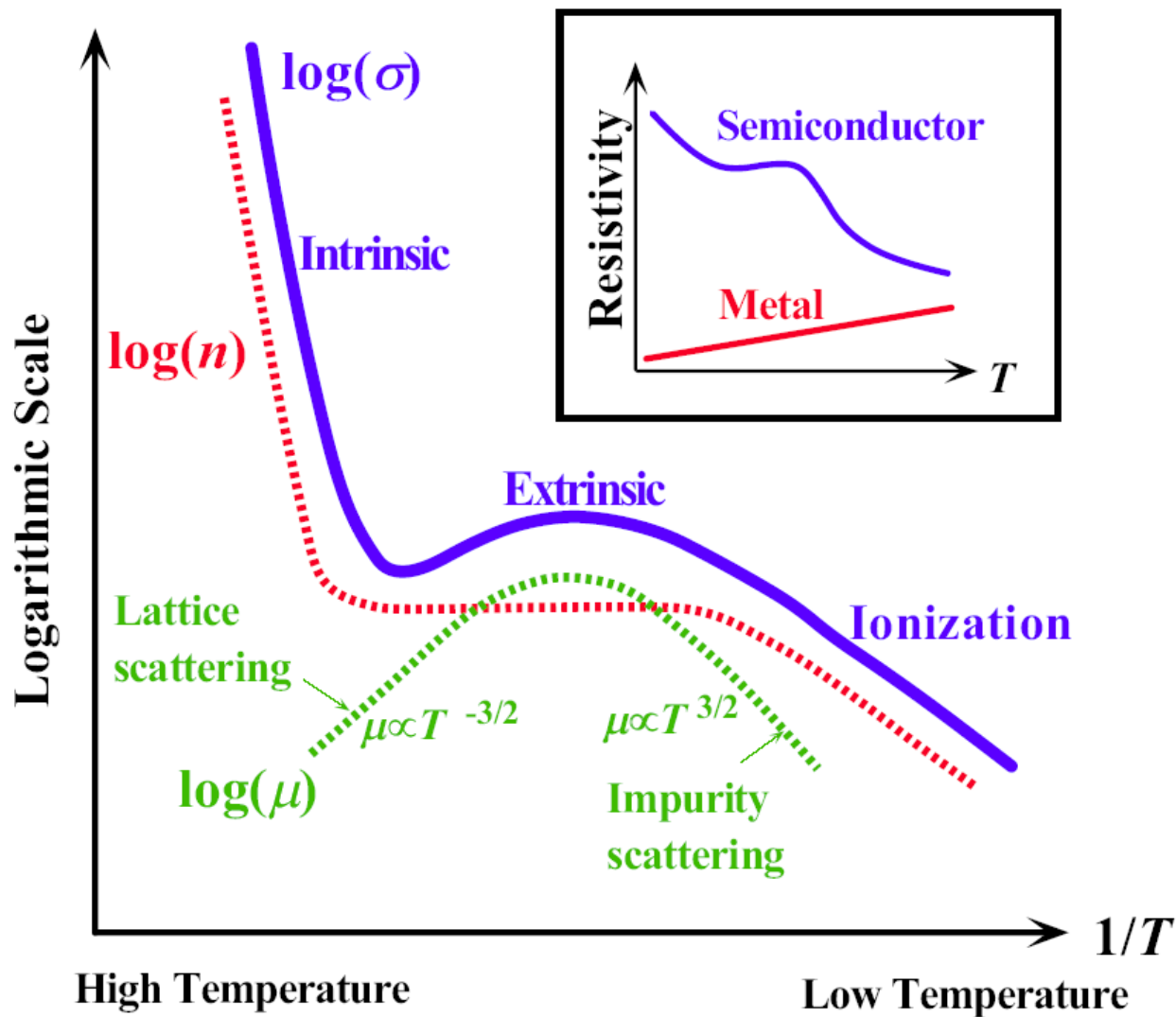
Log-log plot of drift mobility versus temperature for *n*-type Ge and *n*-type Si samples. Various donor concentrations for Si are shown. N_d are in cm^{-3} . The upper right inset is the simple theory for lattice limited mobility, whereas the lower left inset is the simple theory for impurity scattering limited mobility.

Fig 5.18



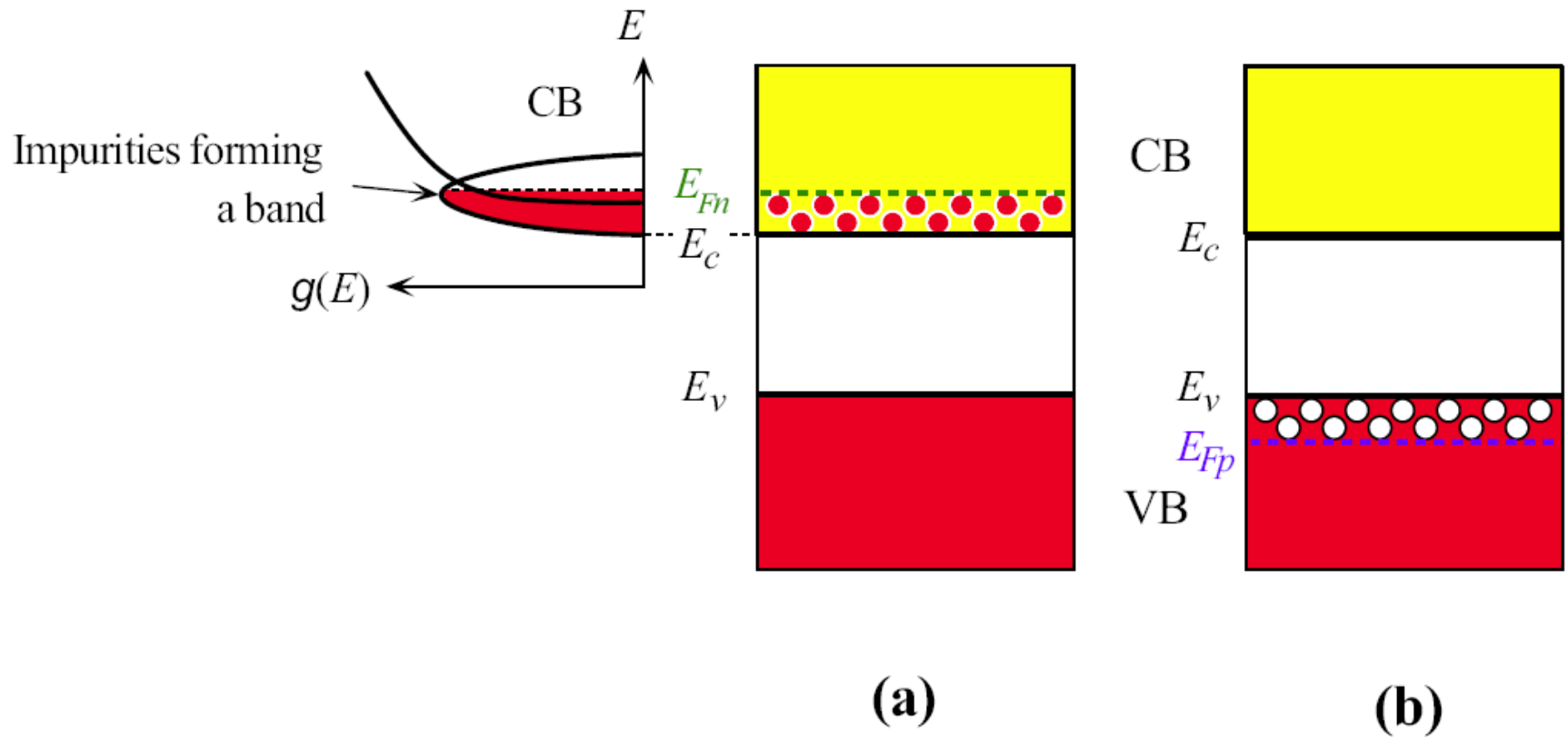
The variation of the drift mobility with dopant concentration in Si for electrons and holes at 300 K.

Fig 5.19



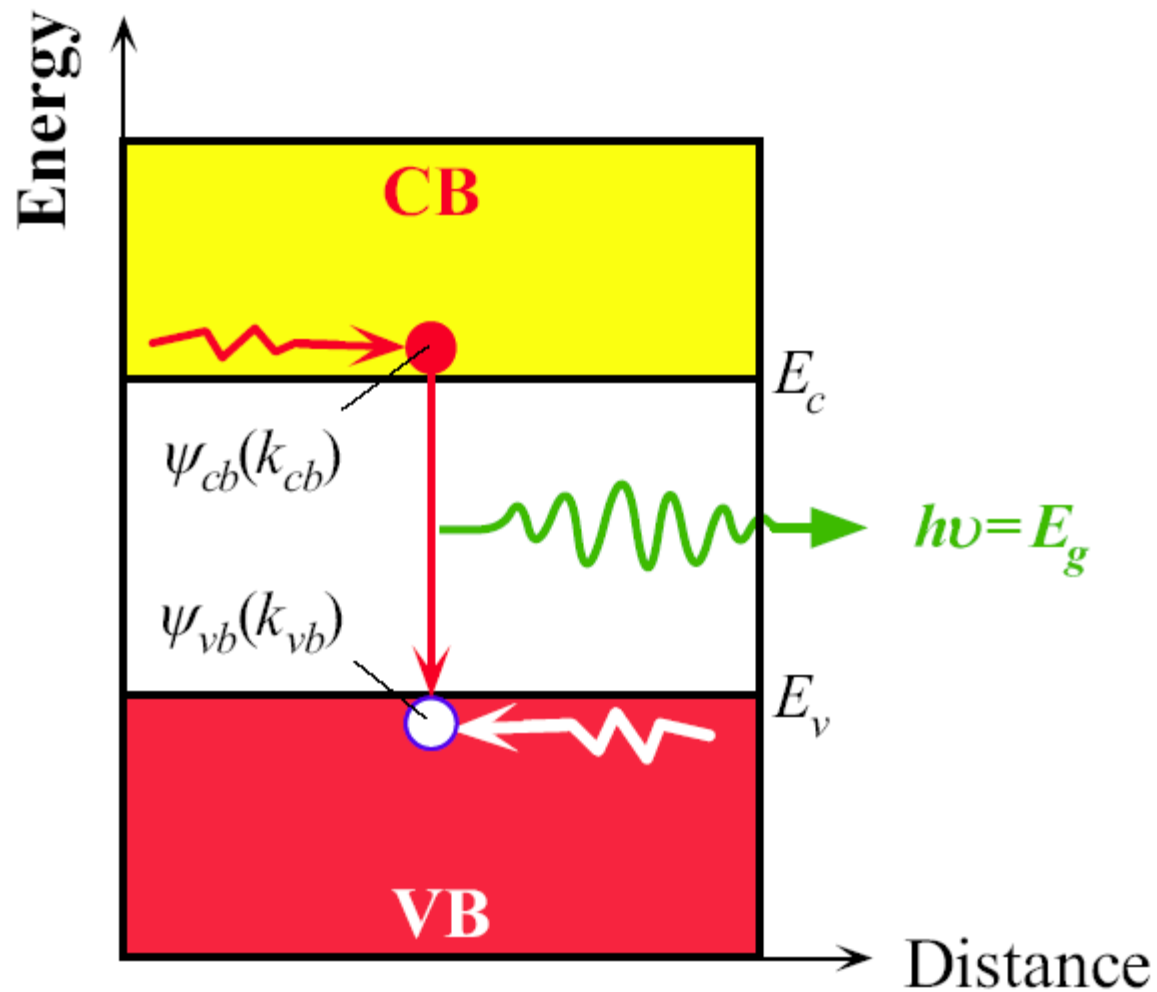
Schematic illustration of the temperature dependence of electrical conductivity for a doped (*n*-type) semiconductor.

Fig 5.20



- (a) Degenerate n -type semiconductor. Large number of donors form a band that overlaps the CB.
- (b) Degenerate p -type semiconductor.

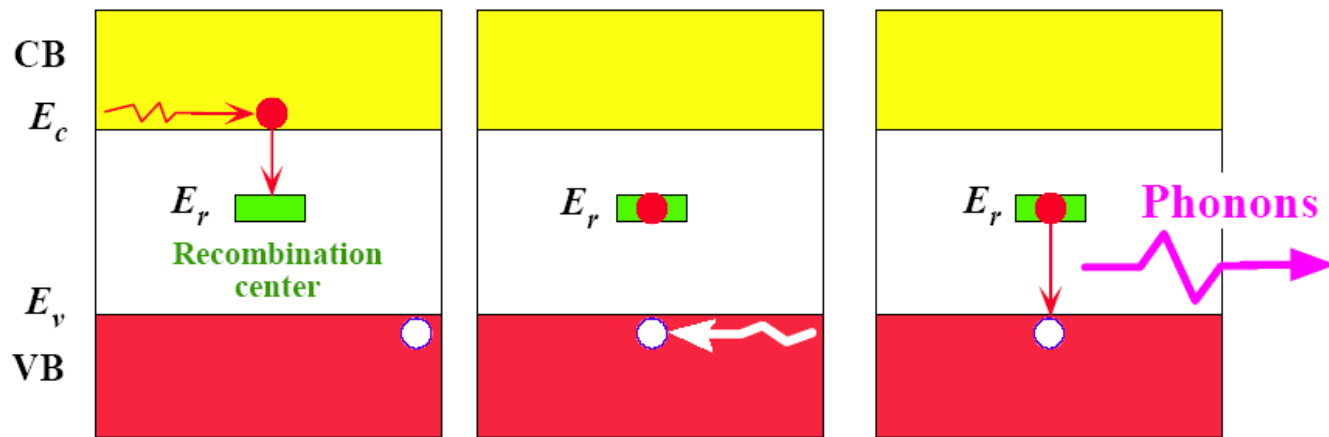
Fig 5.21



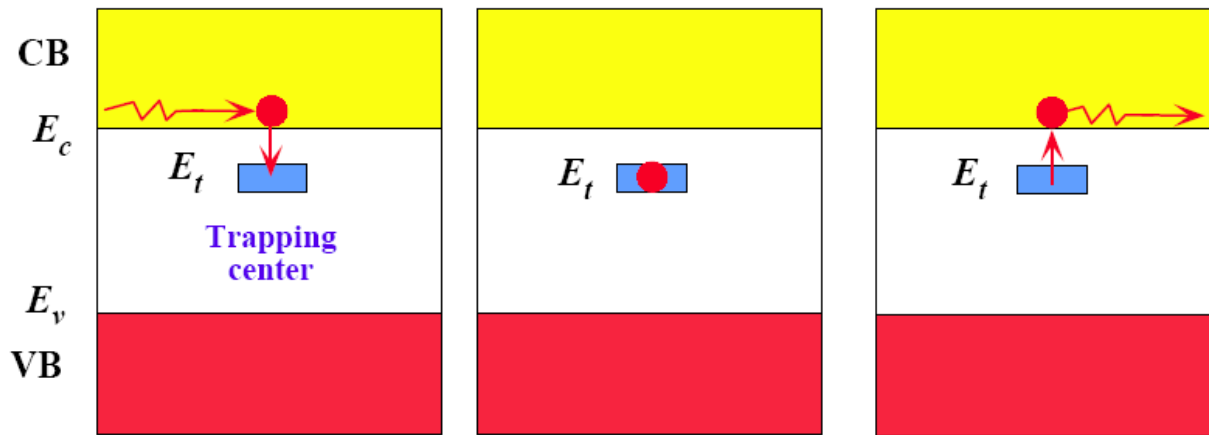
Direct recombination in GaAs.

$k_{cb} = k_{vb}$ so that momentum conservation is satisfied.

Fig 5.22



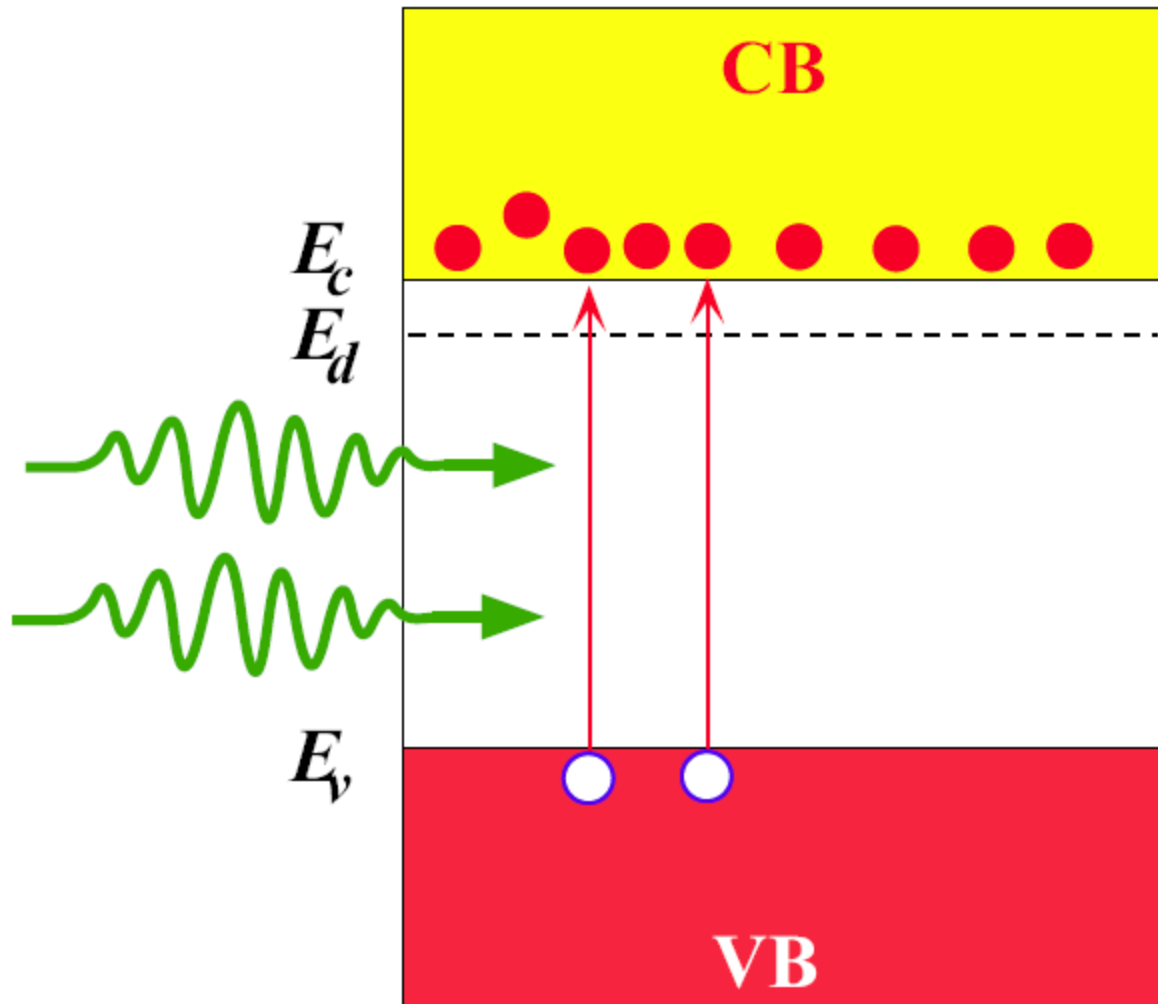
(a) Recombination



(b) Trapping

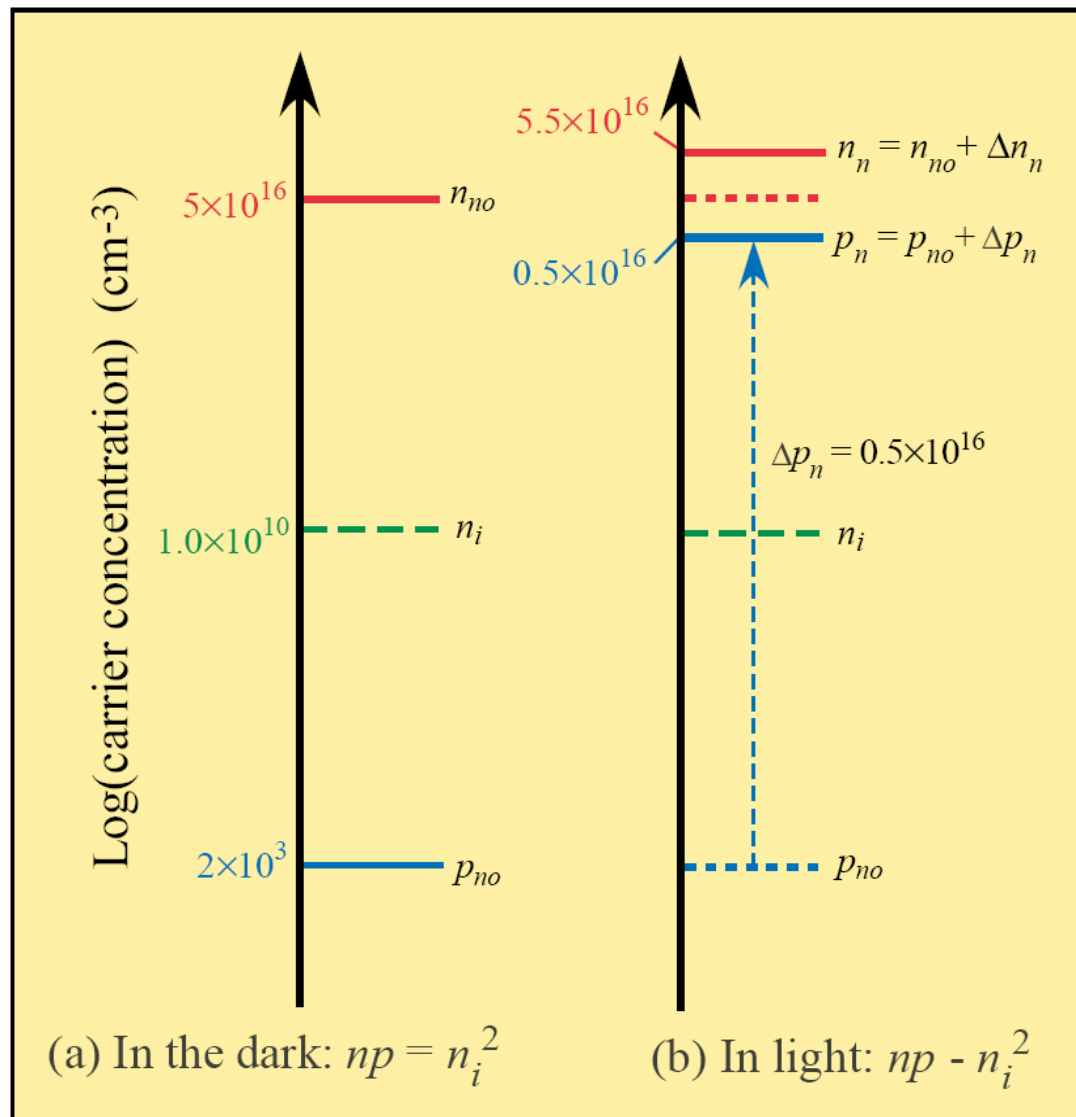
Recombination and trapping. (a) Recombination in Si via a recombination center which has a localized energy level at E_r in the bandgap, usually near the middle. (b) Trapping and detrapping of electrons by trapping centers. A trapping center has a localized energy level in the band gap.

Fig 5.23



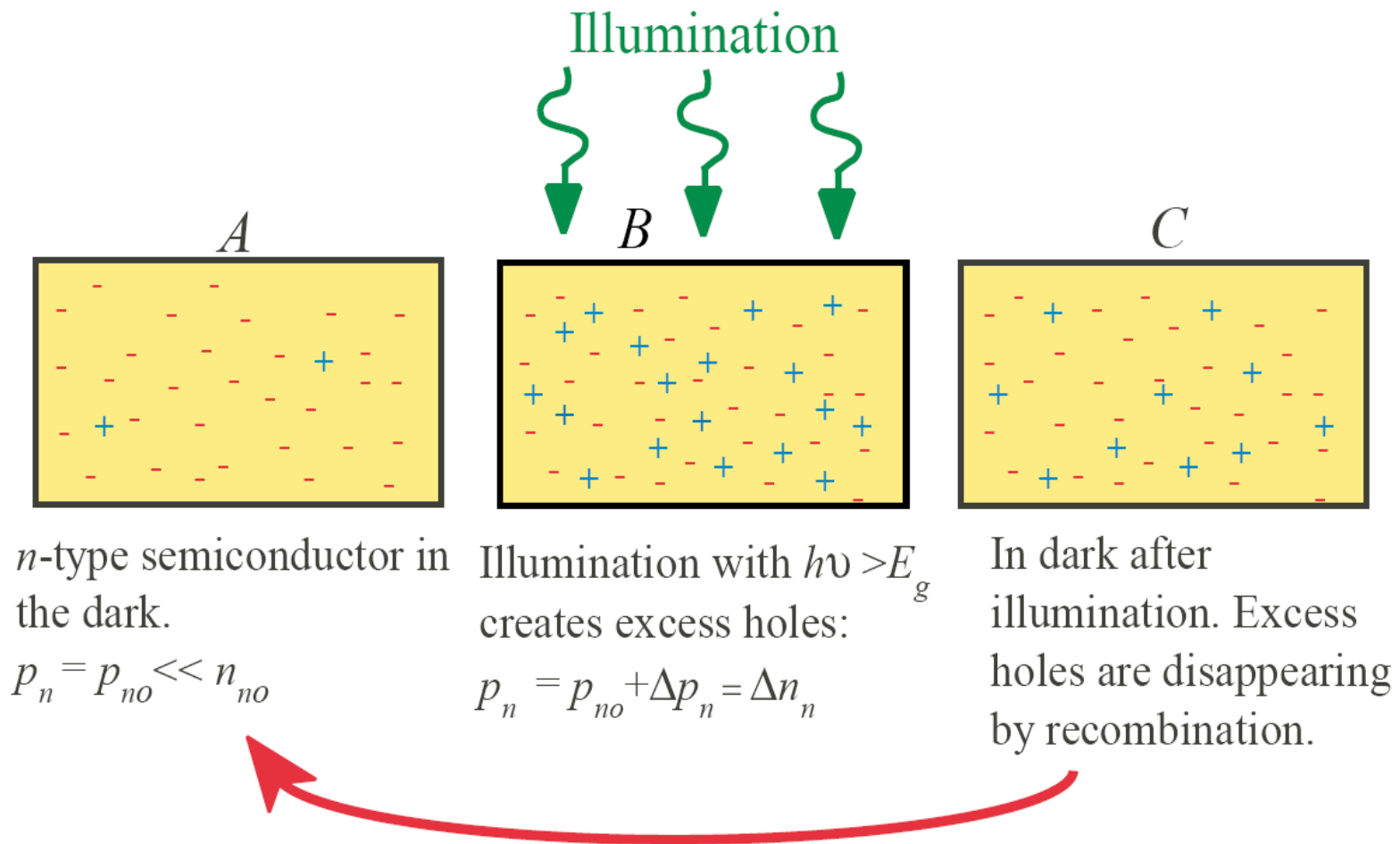
Low-level photoinjection into an n -type semiconductor in which $\Delta n_n > n_0$

Fig 5.24



Low-level injection in an n -type semiconductor does not significantly affect n_n but drastically affects the minority carrier concentration p_n .

Fig 5.25



Illumination of an *n*-type semiconductor results in excess electron and hole concentrations. After the illumination, the recombination process restores equilibrium; the excess electrons and holes simply recombine.

Fig 5.26

Excess Minority Carrier Concentration

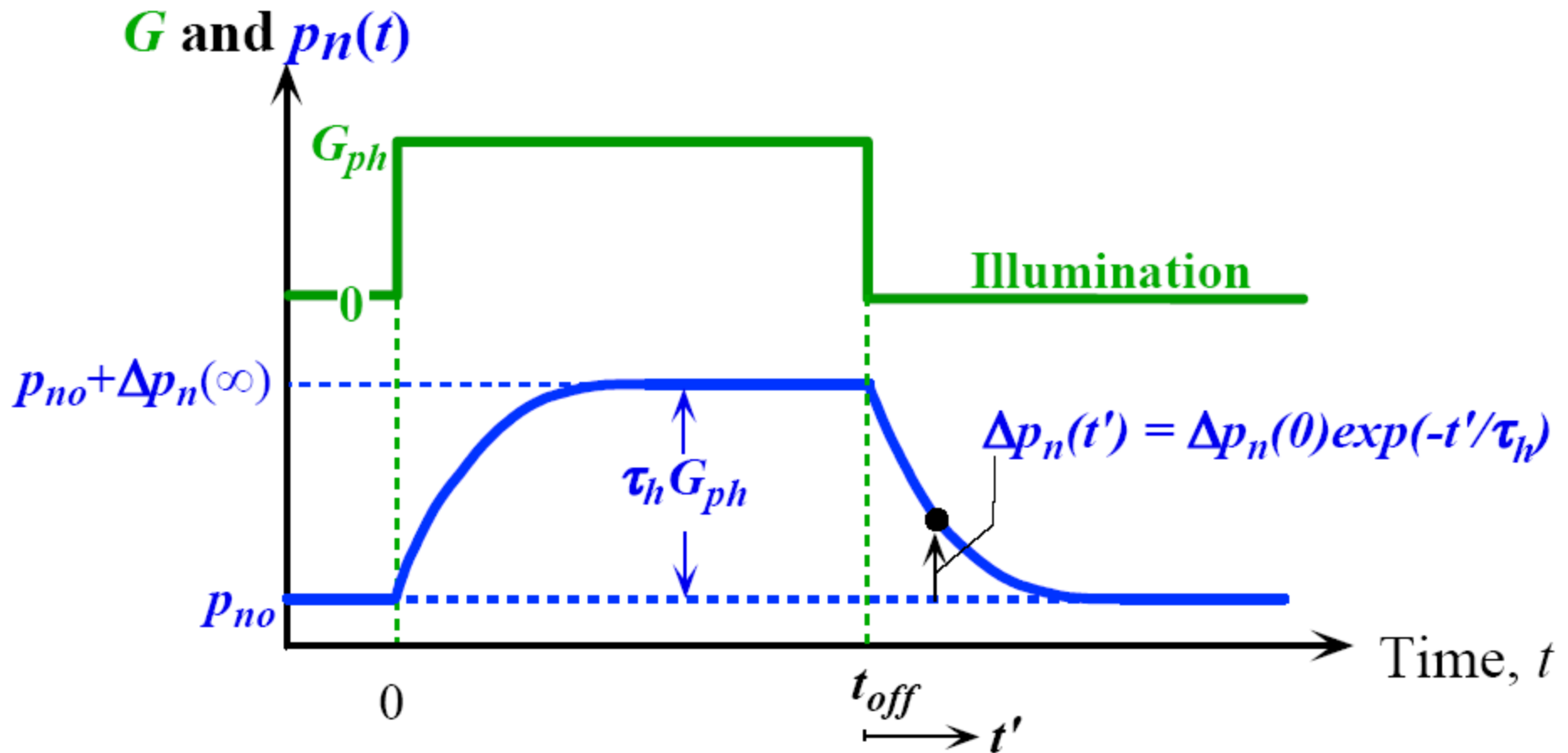
$$\frac{d\Delta p_n}{dt} = G_{\text{ph}} - \frac{\Delta p_n}{\tau_h}$$

Δp_n = excess hole (minority carrier) concentration in n -type

t = time

G_{ph} = rate of photogeneration

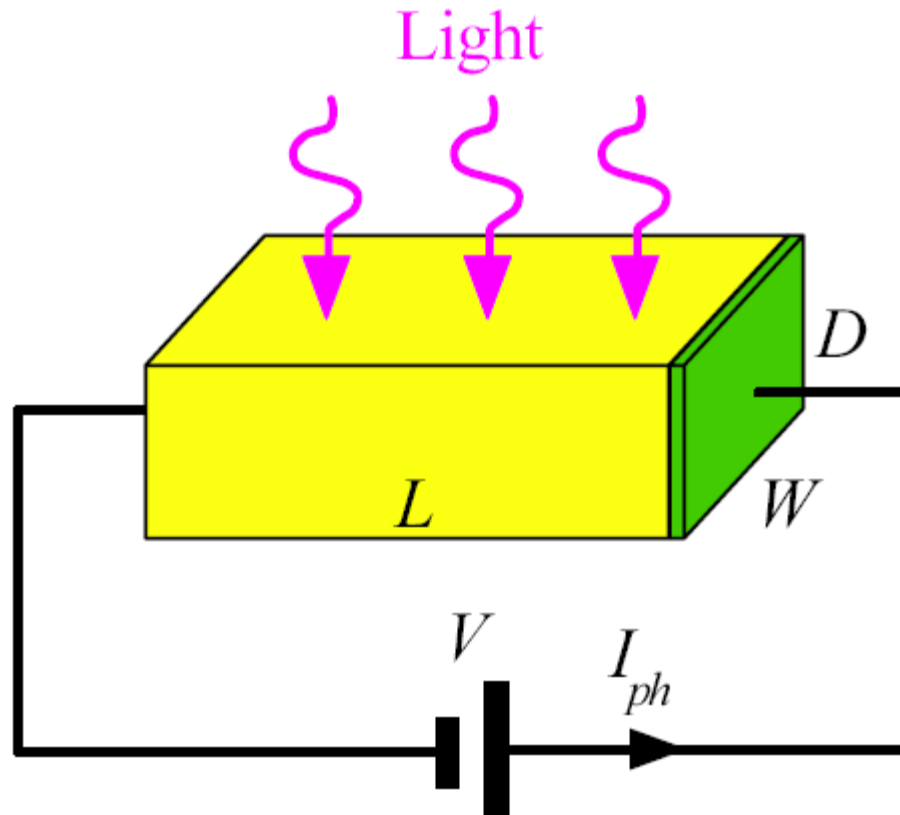
τ_h = minority carrier lifetime (mean recombination time)



Illumination is switched on at time $t = 0$ and then off at $t = t_{off}$.

The excess minority carrier concentration $\Delta p_n(t)$ rises exponentially to its steady-state value with a time constant τ_h . From t_{off} , the excess minority carrier concentration decays exponentially to its equilibrium value.

Fig 5.27



A semiconductor slab of length L , width W , and depth D is illuminated with light of Wavelength λ . I_{ph} is the steady-state photocurrent.

Fig 5.28

Definition of Particle Flux

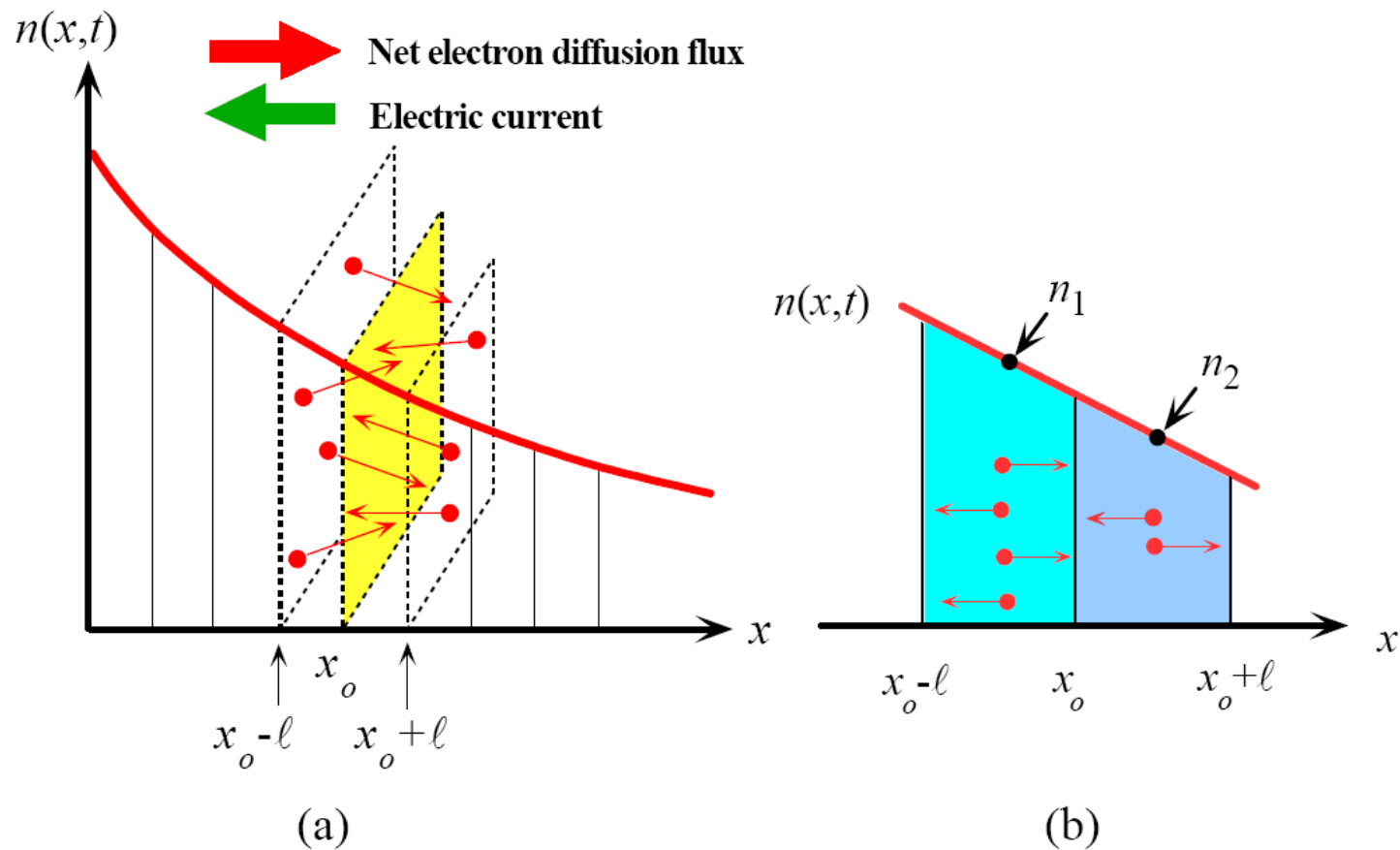
$$\Gamma = \frac{\Delta N}{A \Delta t}$$

Γ = particle flux, ΔN = number of particles crossing A in a time interval Δt , A = area, Δt = time interval

Definition of Current Density

$$J = Q\Gamma$$

J = electric current density, Q = charge of the particle, Γ = particle flux



- (a) Arbitrary electron concentration $n(x, t)$ profile in a semiconductor. There is a net diffusion (flux) of electrons from higher to lower concentrations.
- (b) Expanded view of two adjacent sections at x_0 . There are more electrons crossing x_0 coming from the left ($x_0 - \ell$) than coming from the right ($x_0 + \ell$)

Fig 5.29

Fick's First Law

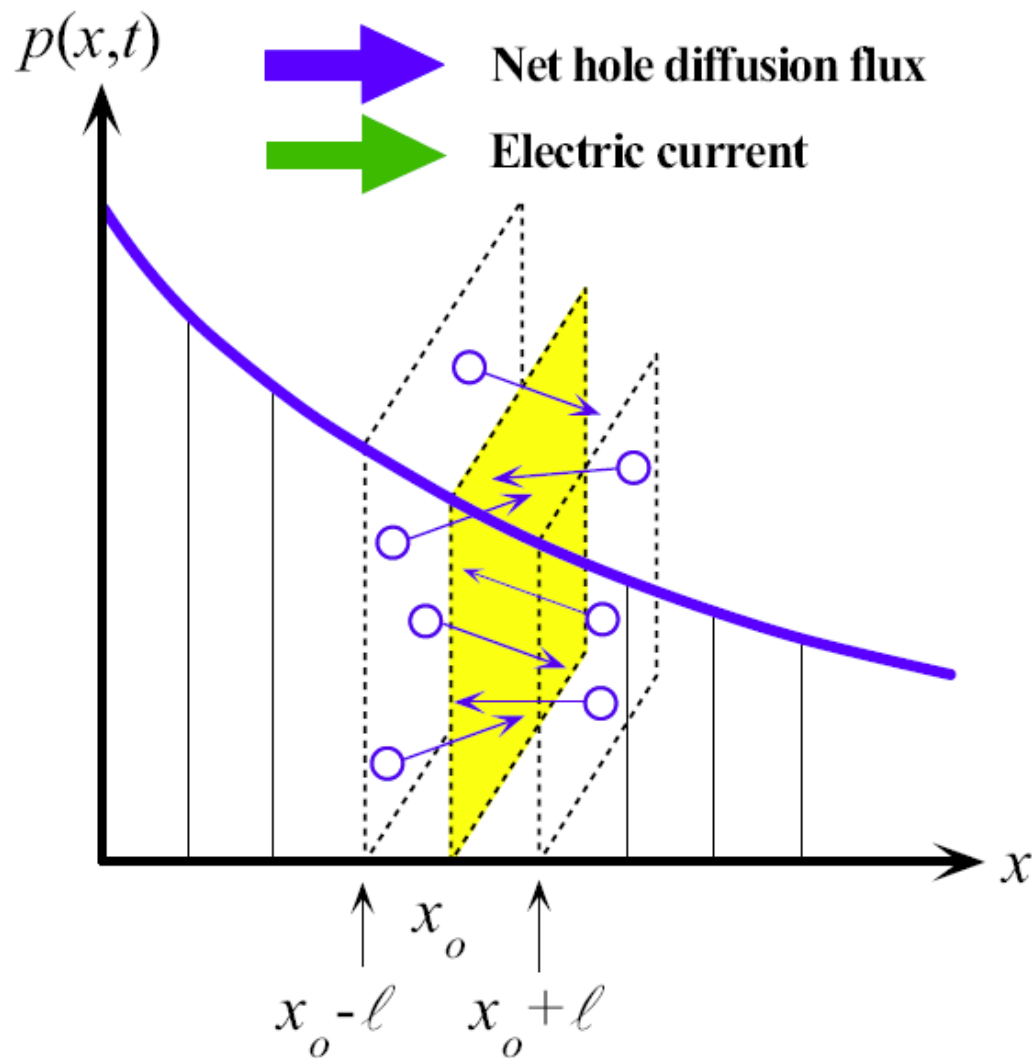
$$\Gamma_e = -D_e \frac{dn}{dx}$$

Γ_e = electron flux, D_e = diffusion coefficient of electrons, dn/dx = electron concentration gradient

Electron Diffusion Current Density

$$J_{D,e} = -e\Gamma_e = eD_e \frac{dn}{dx}$$

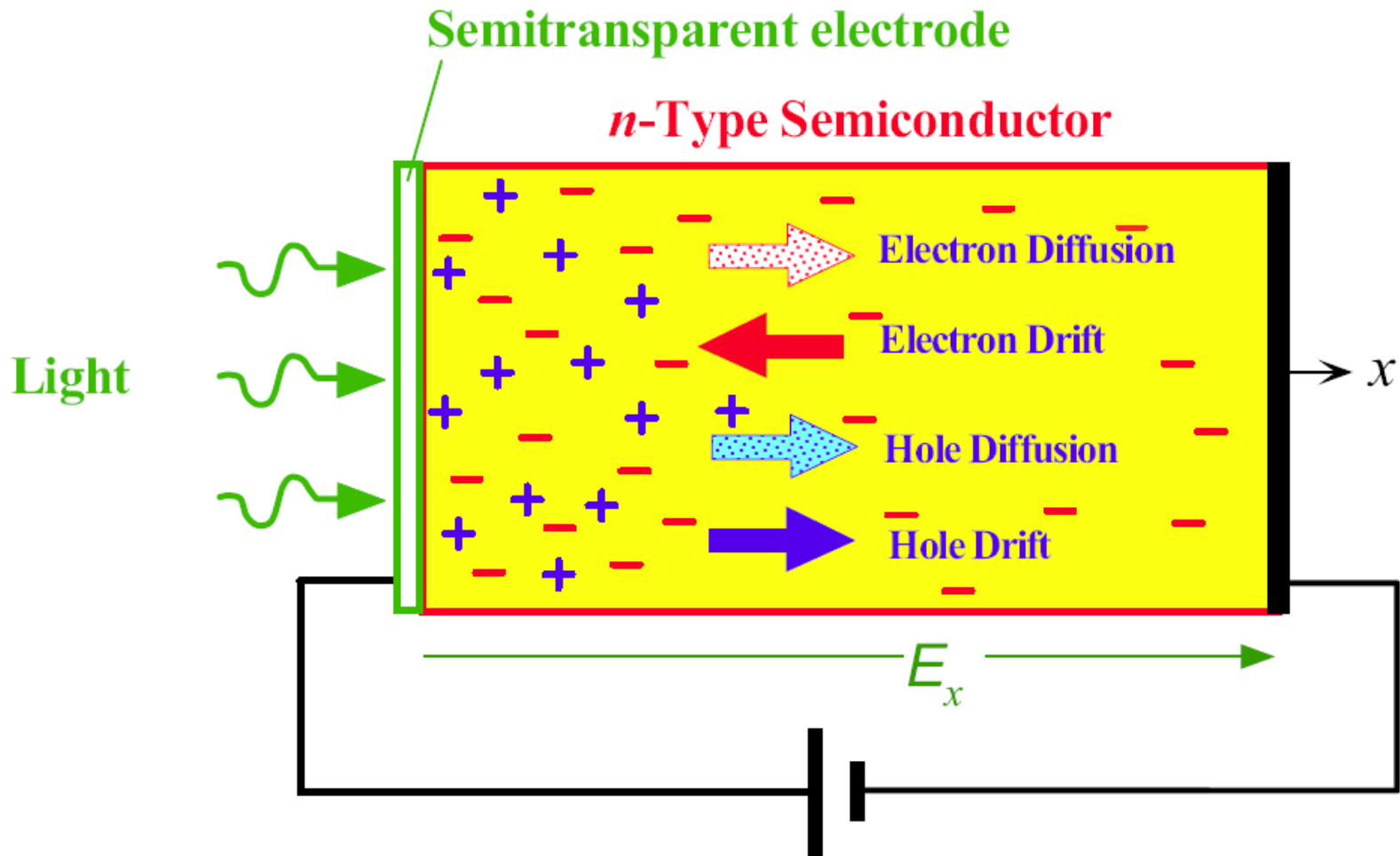
$J_{D,e}$ = electric current density due to electron diffusion, Γ_e = electron flux, e = electronic charge, D_e = diffusion coefficient of electrons, dn/dx = electron concentration gradient



Arbitrary hole concentration $p(x, t)$ profile in a semiconductor.

There is a net diffusion (flux) of holes from higher to lower concentrations. There are more holes crossing x_o coming from the left ($x_o - \ell$) than coming from the right ($x_o + \ell$).

Fig 5.30



When there is an electric field and also a concentration gradient, charge carriers move both by diffusion and drift.

Fig 5.31

Hole Diffusion Current Density

$$J_{D,h} = e\Gamma_h = -eD_h \frac{dp}{dx}$$

$J_{D,h}$ = electric current density due to hole diffusion, e = electronic charge, Γ_h = hole flux, D_h = diffusion coefficient of holes, dp/dx = hole concentration gradient

Total Electron Current Due to Drift and Diffusion

$$J_e = en\mu_e E_x + eD_e \frac{dn}{dx}$$

J_e = electron current due to drift and diffusion, n = electron concentration, μ_e = electron drift mobility, E_x = electric field in the x direction, D_e = diffusion coefficient of electrons, dn/dx = electron concentration gradient

Total Hole Current Due to Drift and Diffusion

$$J_h = ep\mu_h E_x - eD_h \frac{dp}{dx}$$

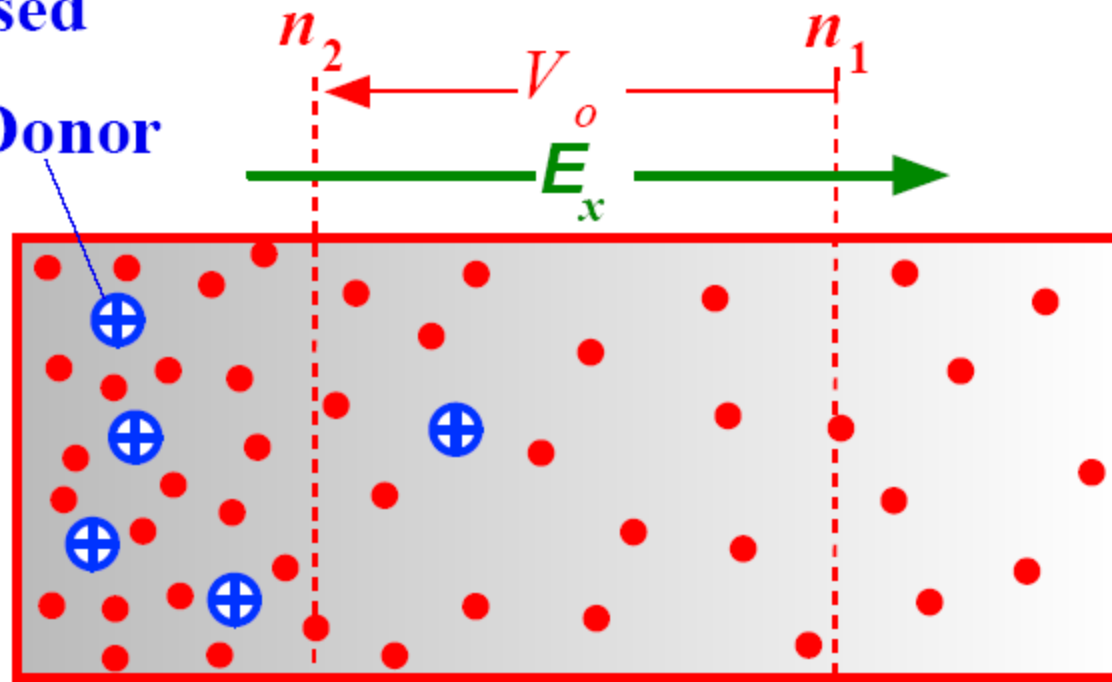
J_h = hole current due to drift and diffusion, p = hole concentration, μ_h = hole drift mobility, E_x = electric field in the x direction, D_h = diffusion coefficient of holes, dp/dx = hole concentration gradient

Einstein Relation

$$\frac{D_e}{\mu_e} = \frac{kT}{e} \qquad \frac{D_h}{\mu_h} = \frac{kT}{e}$$

D_e = diffusion coefficient of electrons, μ_e = electron drift, D_h = diffusion coefficient of the holes, μ_h = hole drift mobility

Exposed
 As^+ Donor



Diffusion Flux
Drift

Net current = 0

Nonuniform doping profile results in electron diffusion toward the less concentrated regions. This exposes positively charged donors and sets up a built-in field E_x . In the steady state, the diffusion of electrons toward the right is balanced by their drift toward the left.

Fig 5.32

Built-In Potential and Concentration

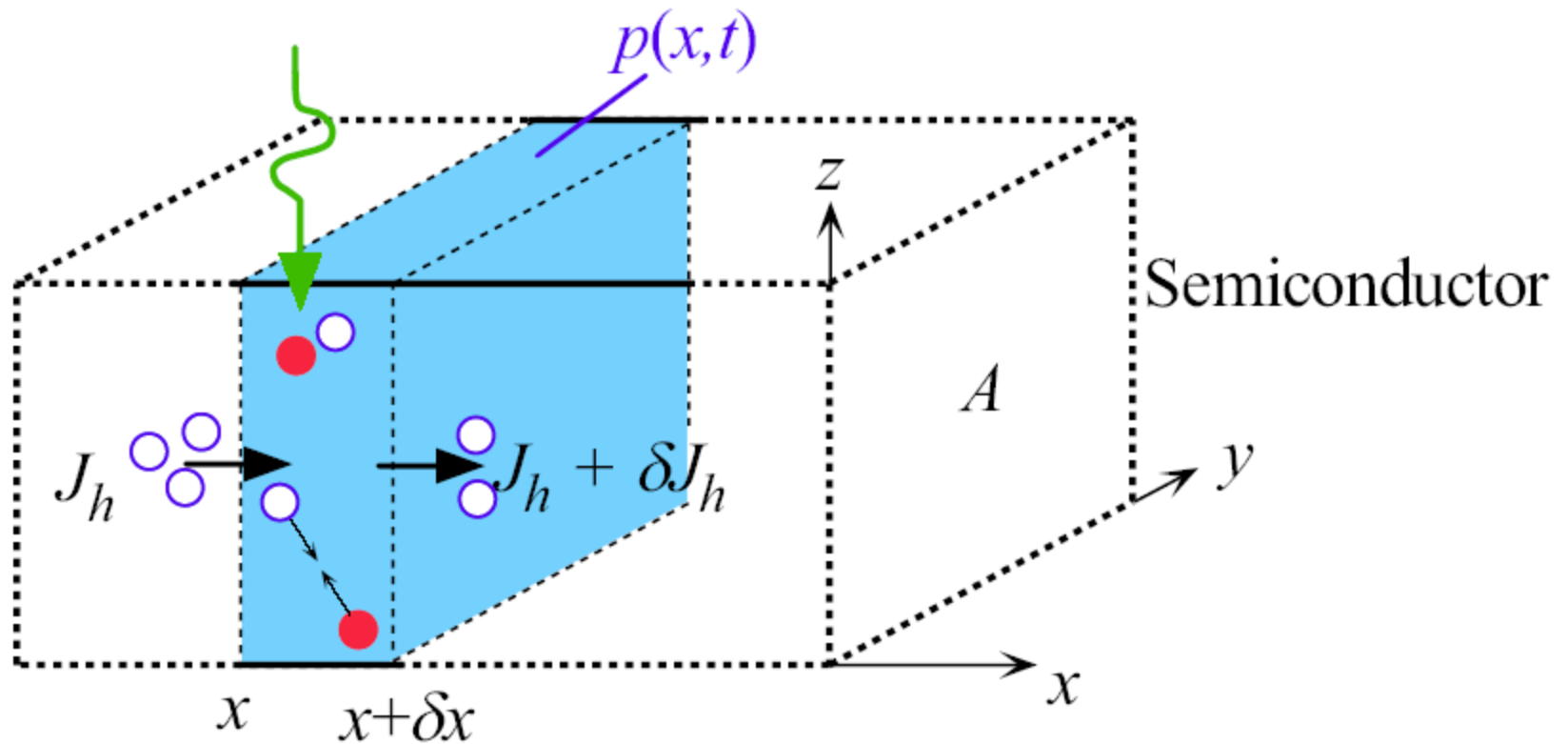
$$V_2 - V_1 = \frac{kT}{e} \ln\left(\frac{n_2}{n_1}\right)$$

V_2 = potential at point 2, V_1 = potential at point 1, k = Boltzmann constant, T = temperature, e = electronic charge, n_2 = electron concentration at point 2, n_1 = electron concentration at point 1

Built-In Field in Nonuniform Doping

$$E_x = \frac{kT}{be}$$

E_x = electric field in the x direction, k = Boltzmann constant, T = temperature, b = characteristic of the exponential doping profile, e = electronic charge .



Consider an elemental volume $A \delta x$ in which the hole concentration is $p(x, t)$

Fig 5.33

Continuity Equation for Holes

$$\frac{\partial p_n}{\partial t} = -\frac{1}{e} \left(\frac{\partial J_h}{\partial x} \right) - \frac{p_n - p_{no}}{\tau_h} + G_{ph}$$

p_n = hole concentration in an n -type semiconductor, p_{no} = equilibrium minority carrier (hole concentration in an n -type semiconductor) concentration, J_h = hole current due to drift and diffusion, τ_h = hole recombination time (lifetime), G_{ph} = photogeneration rate at x at time t , x = position, t = time

Continuity Equation with Uniform Photogeneration

$$\frac{\partial \Delta p_n}{\partial t} = -\frac{\Delta p_n}{\tau_h} + G_{ph}$$

$\Delta p_n = p_n - p_{no}$ is the excess hole concentration

Steady-State Continuity Equation for Holes

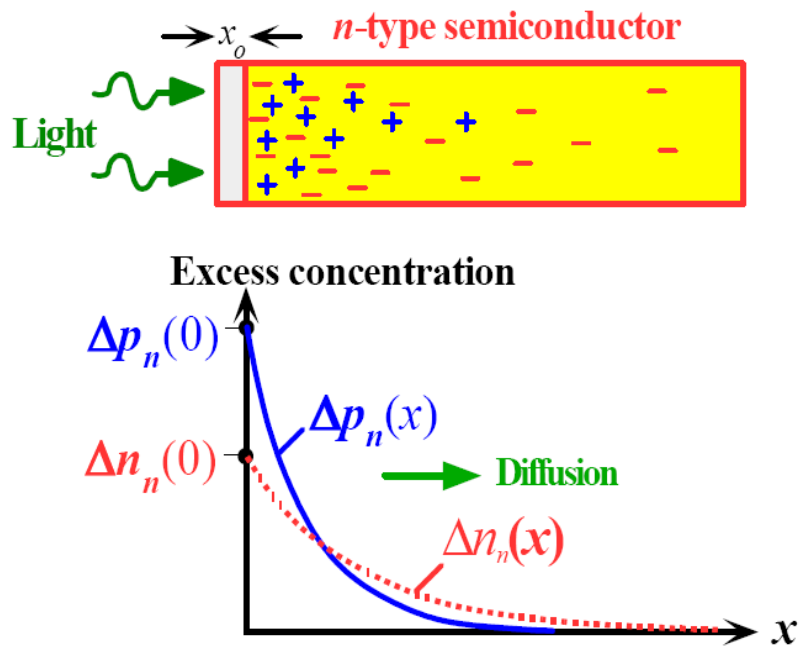
$$\frac{1}{e} \left(\frac{\partial J_h}{\partial x} \right) = - \frac{p_n - p_{no}}{\tau_h}$$

J_h = hole current due to drift and diffusion, p_n = hole concentration in an n -type semiconductor, p_{no} = equilibrium minority carrier (hole concentration in an n -type semiconductor) concentration, τ_h = hole recombination time (lifetime)

Steady-State Continuity Equation with $\mathcal{E} = 0$

$$\frac{d^2 \Delta p_n}{dx^2} = \frac{\Delta p_n}{L_h^2}$$

$\Delta p_n = p_n - p_{no}$ is the excess hole concentration, L_h = diffusion length of the holes

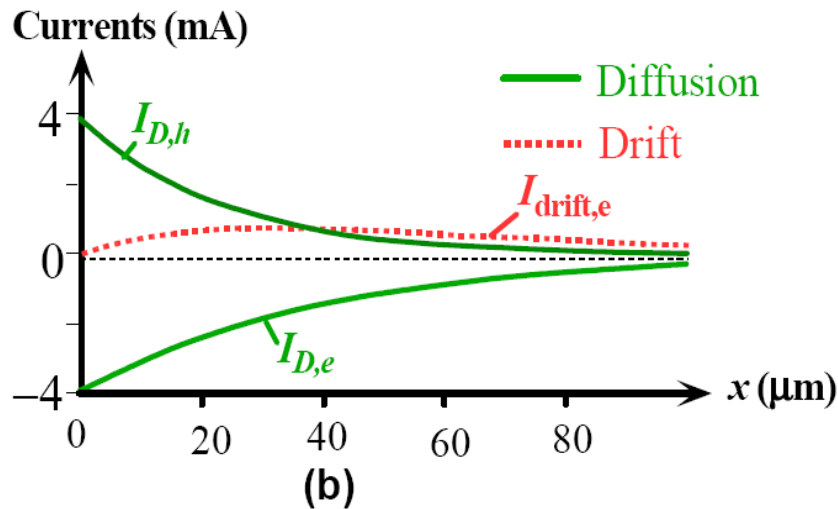


(a)

(a) Steady state excess carrier concentration profiles in an n-type semiconductor that is continuously illuminated at one end.

(b) Majority and minority carrier current components in open circuit.

Total current is zero.



(b)

Fig 5.34

Table 5.3 Currents in an infinite slab illuminated at one end for weak injection near the surface

Currents at	Minority Diffusion $I_{D,h}$ (mA)	Minority Drift $I_{\text{drift},h}$ (mA)	Majority Diffusion $I_{D,e}$ (mA)	Majority Drift $I_{\text{drift},e}$ (mA)	Field \mathcal{E} (V cm ⁻¹)
$x = 0$	3.94	0	-3.94	0	0
$x = L_e$	0.70	0.0022	-1.45	0.75	0.035

Minority Carrier Concentration, Long Bar

$$\Delta p_n(x) = \Delta p_n(0) \exp\left(-\frac{x}{L_h}\right)$$

$\Delta p_n = p_n - p_{no}$ is the excess hole concentration, L_h = diffusion length of the holes

Steady State Hole Diffusion Current

$$I_h \approx I_{D,h} = -AeD_h \frac{dp_n(x)}{dx} = \frac{AeD_h}{L_h} \Delta p_n(0) \exp\left(-\frac{x}{L_h}\right)$$

I_h = hole current, $I_{D,h}$ = hole diffusion current, A = cross-sectional area, D_h = diffusion coefficient of holes, $p_n(x)$ = hole concentration in an n -type semiconductor as a function of position x , L_h = diffusion length of holes, $\Delta p_n = p_n - p_{no}$ is the excess hole concentration

Majority Carrier Concentration, Long Bar

$$\Delta n_n(x) = \Delta n_n(0) \exp\left(-\frac{x}{L_e}\right)$$

$\Delta n_n(x)$ = the excess electron concentration, x = position, L_e = diffusion length of the electrons

Electron Diffusion Current

$$I_{D,e} = AeD_e \frac{dn_n(x)}{dx} = -\frac{AeD_e}{L_e} \Delta n_n(0) \exp\left(-\frac{x}{L_e}\right)$$

$I_{D,e}$ = electron diffusion current, D_e = diffusion coefficient of electrons, $n_n(x)$ = electron concentration in an n -type semiconductor as a function of position x , L_e = diffusion length of the electrons, Δn_n = the excess electron concentration

Electron Drift Current: Use the Open Circuit Condition

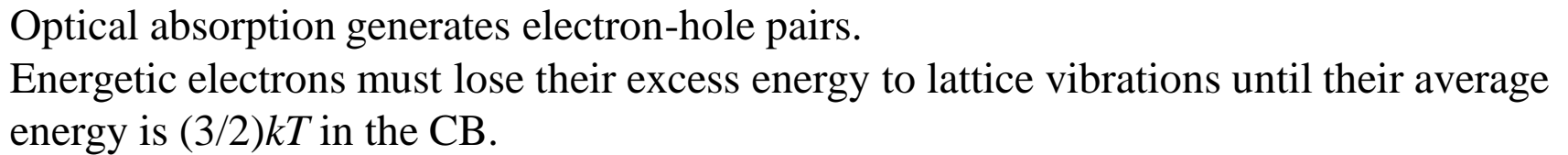
$$I_{\text{drift},e} + I_{D,e} + I_{D,h} = 0$$

$I_{\text{drift},e}$ = electron drift current, $I_{D,e}$ = electron diffusion current, $I_{D,h}$ = hole diffusion current,

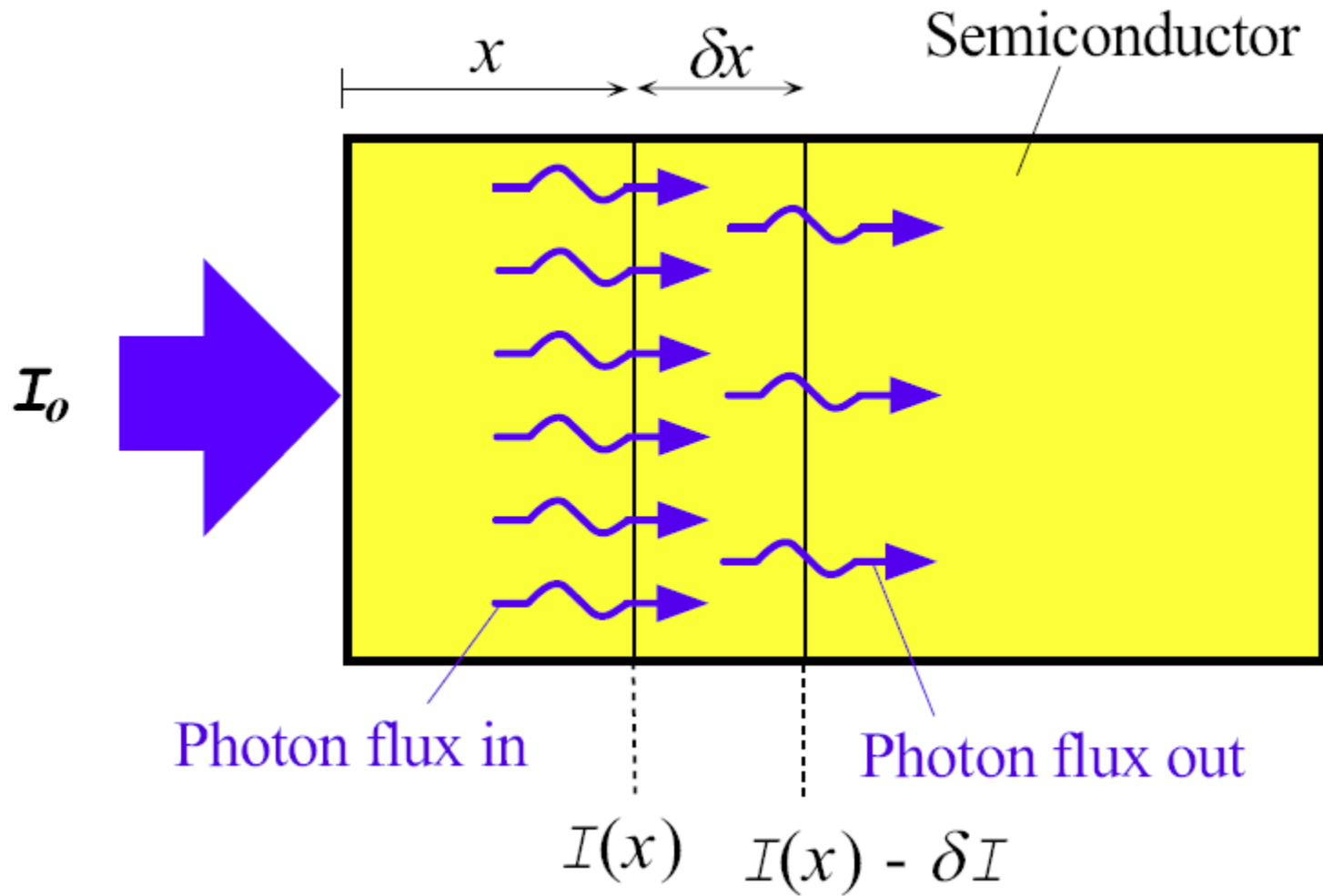
Electric Field

$$\mathcal{E} = \frac{I_{\text{drift},e}}{Aen_{no}\mu_e}$$

\mathcal{E} = electric field, $I_{\text{drift},e}$ = electron drift current, n_{no} = equilibrium majority carrier (electron concentration in an n -type semiconductor) concentration, μ_e = electron drift mobility



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Absorption of photons within a small elemental volume of width δx

Fig 5.36

Definition of Optical Absorption Coefficient

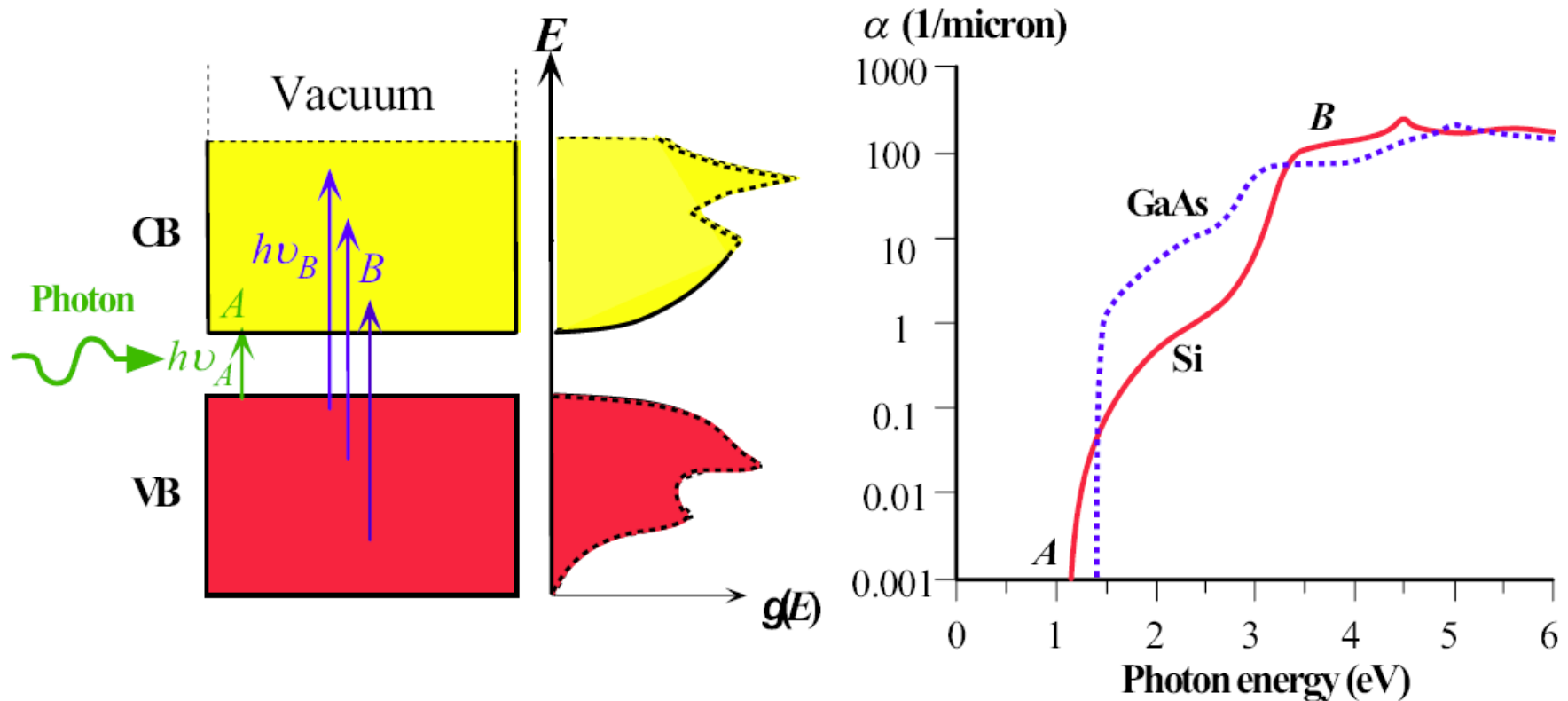
$$\alpha = -\frac{\delta I}{I \delta x}$$

α = absorption coefficient, I = light intensity, δI = change in the light intensity in a small elemental volume of thickness δx at x

Beer-Lambert Law

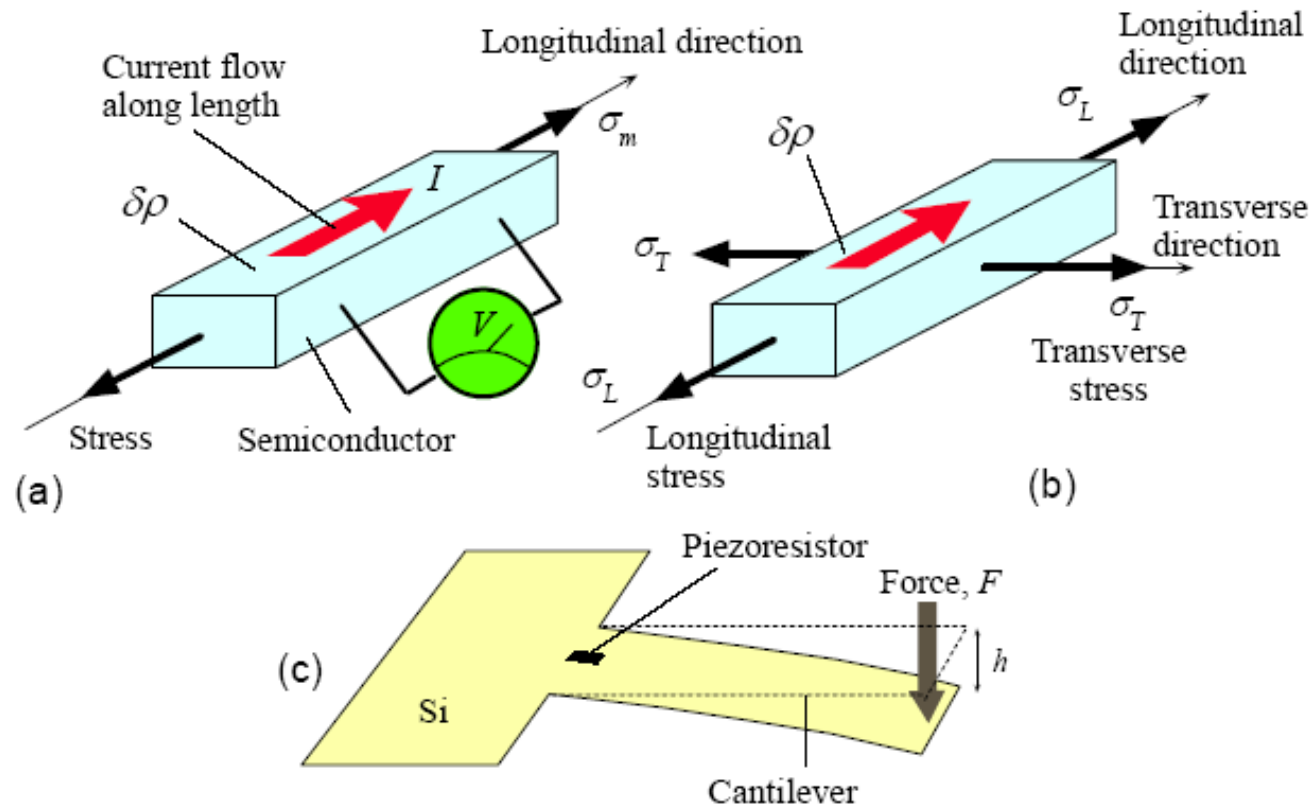
$$I(x) = I_o \exp(-\alpha x)$$

$I(x)$ = light intensity at x , I_o = initial light intensity, α = absorption coefficient, x = distance from the surface (location) where $I = I_o$. Note: Light propagates along x .



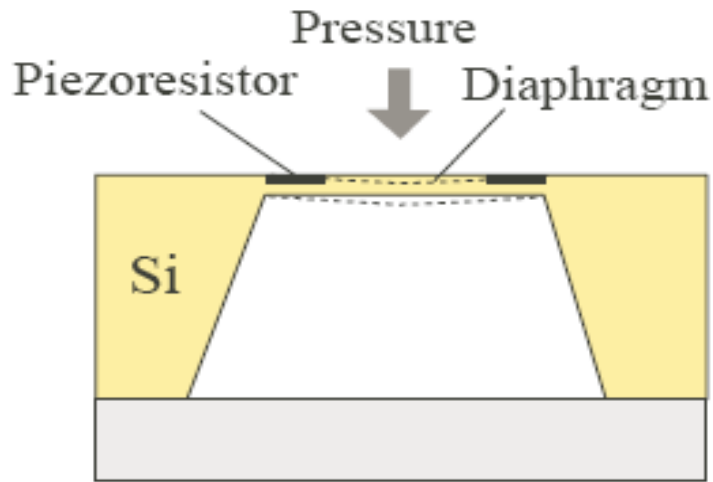
The absorption coefficient α depends on the photon energy $h\nu$ and hence on the wavelength. Density of states increases from band edges and usually exhibits peaks and troughs. Generally α increases with the photon energy greater than E_g because more energetic photons can excite electrons from populated regions of the VB to numerous available states deep in the CB.

Fig 5.37

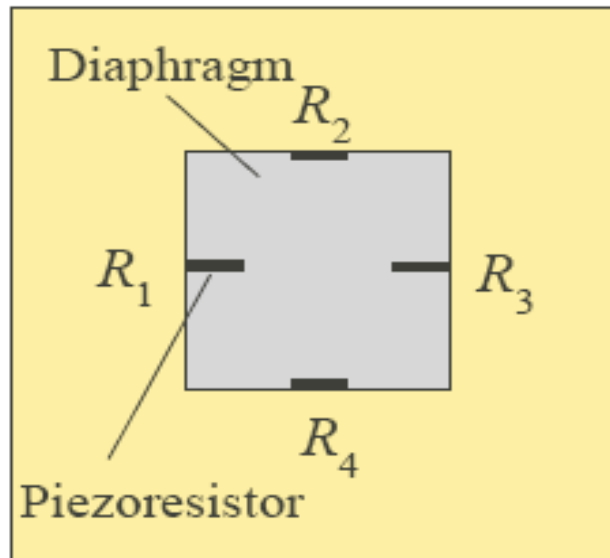


Piezoresistivity and its applications. (a) Stress σ_m along the current (longitudinal) direction changes the resistivity by $\delta\rho$. (b) Stresses σ_L and σ_T cause a resistivity change. (c) A force applied to a cantilever bends it. A piezoresistor at the support end (where the stress is large) measures the stress, which is proportional to the force.

Fig 5.38



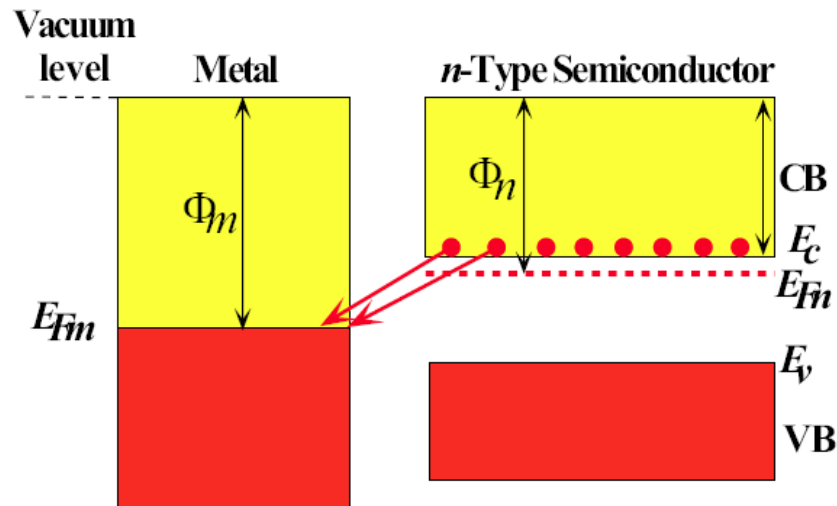
Cross section



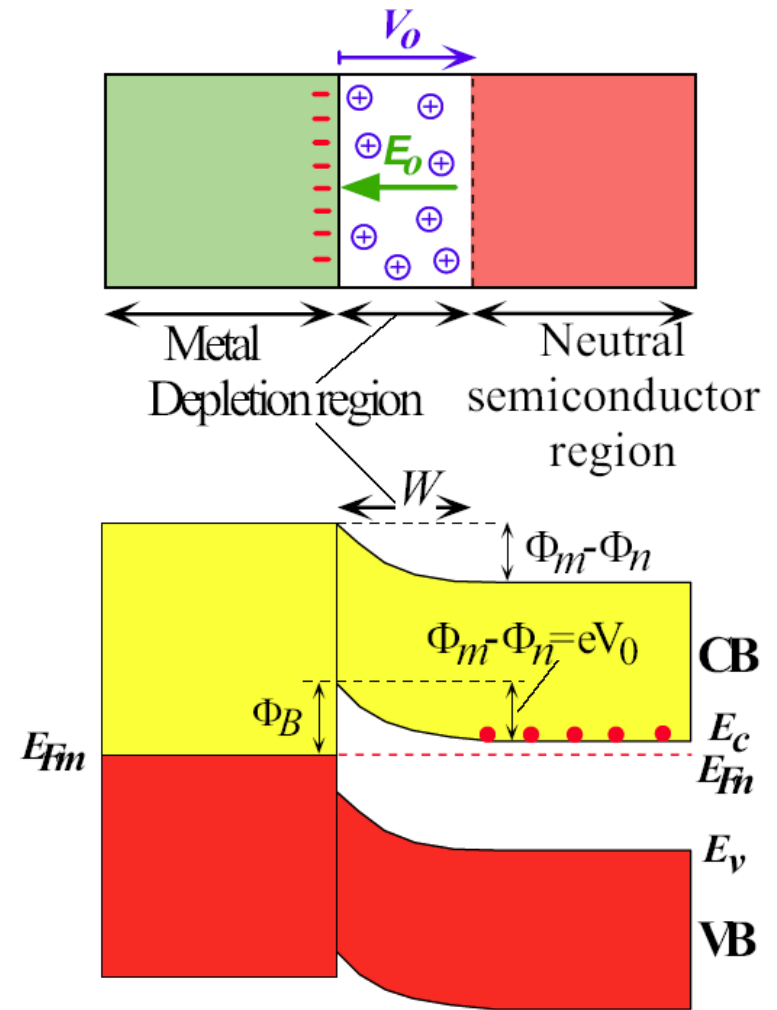
Top view

(d) A pressure sensor has four piezoresistor R_1 , R_2 , R_3 , R_4 embedded in a diaphragm. The pressure bends the diaphragm, which generates stresses that are sensed by the four piezoresistors.

Fig 5.38



Before contact



After contact

Formation of a Schottky junction between a metal and an n -type semiconductor when $\Phi_m > \Phi_n$.

Fig 5.39

Schottky Junction: Metal to n -Type Semiconductor

Built-in potential V_o

$$eV_o = \Phi_m = \Phi_n$$

Work function of the metal

Work function of the semiconductor

Barrier height Φ_B from the metal to the semiconductor

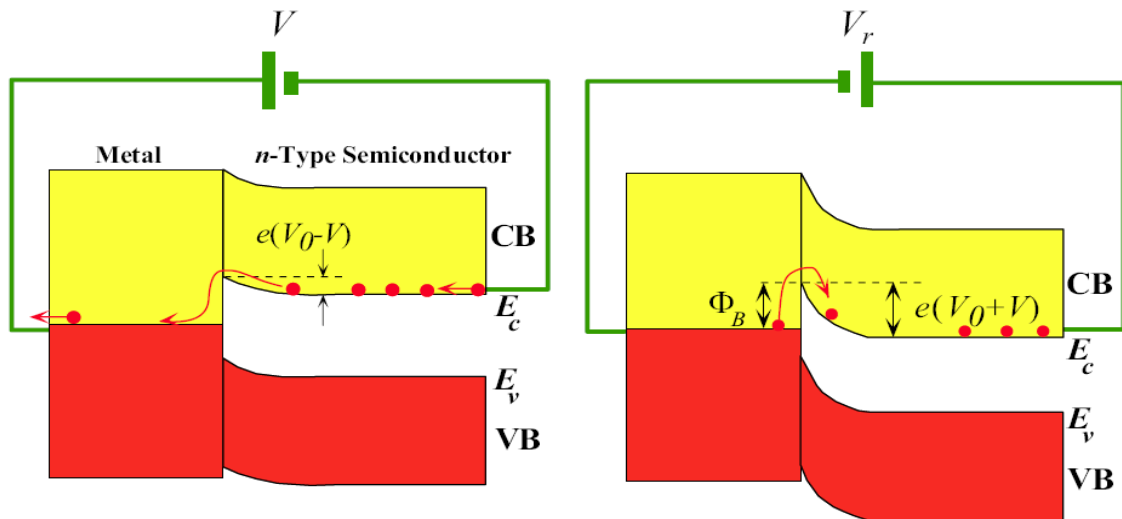
$$\Phi_B = \Phi_m - \chi = eV_o + (E_c - E_{Fn})$$

Work function of metal

Built-in potential

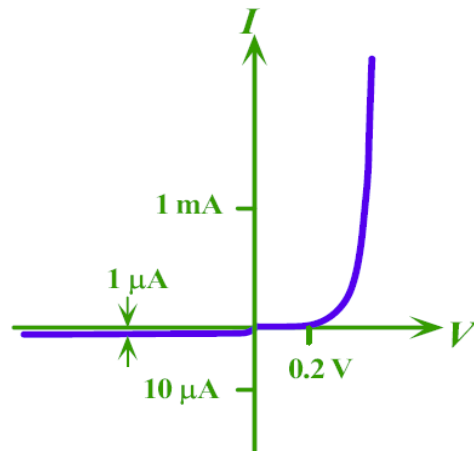
Distance of Fermi level from CB
in the semiconductor

Electron affinity of the semiconductors



(a) Forward biased Schottky junction. Electrons in the CB of the semiconductor can readily overcome the small PE barrier to enter the metal.

(b) Reverse biased Schottky junction. Electrons in the metal can not easily overcome the PE barrier Φ_B to enter the semiconductor.



(c) I - V Characteristics of a Schottky junction exhibits rectifying properties (negative current axis is in microamps)

The Schottky Junction

Fig 5.40

Schottky Junction

$$J = J_o \left[\exp\left(\frac{eV}{kT}\right) - 1 \right]$$

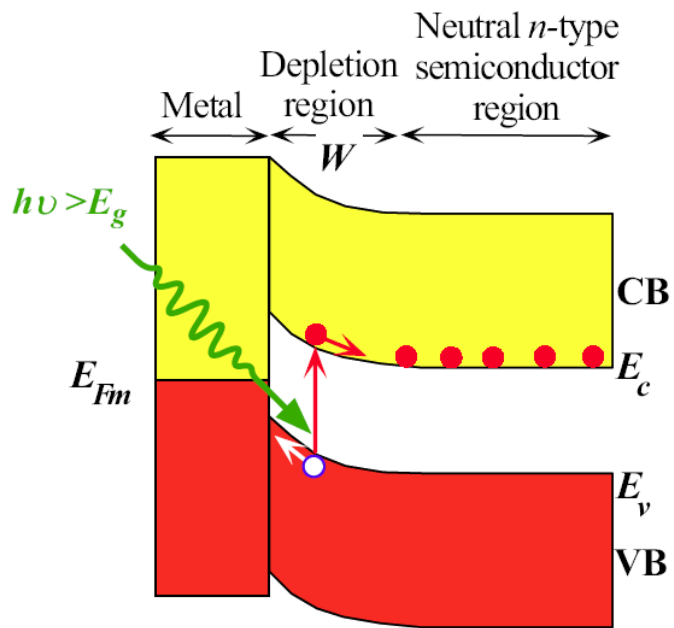
J = current density

J_o = constant that depends on the metal and the semiconductor

e.g. Φ_B , V_o , and *also* on the surface properties

V = voltage, e = electronic charge

k = Boltzmann constant, T = temperature



The principle of the Schottky junction solar cell.

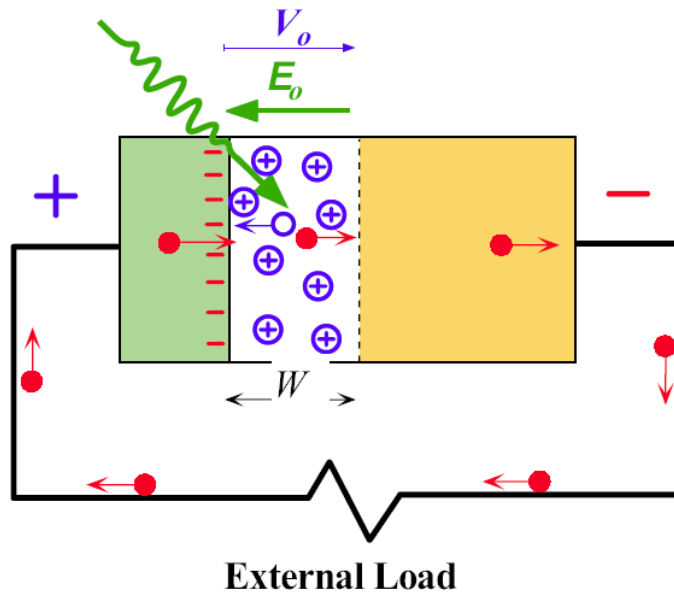
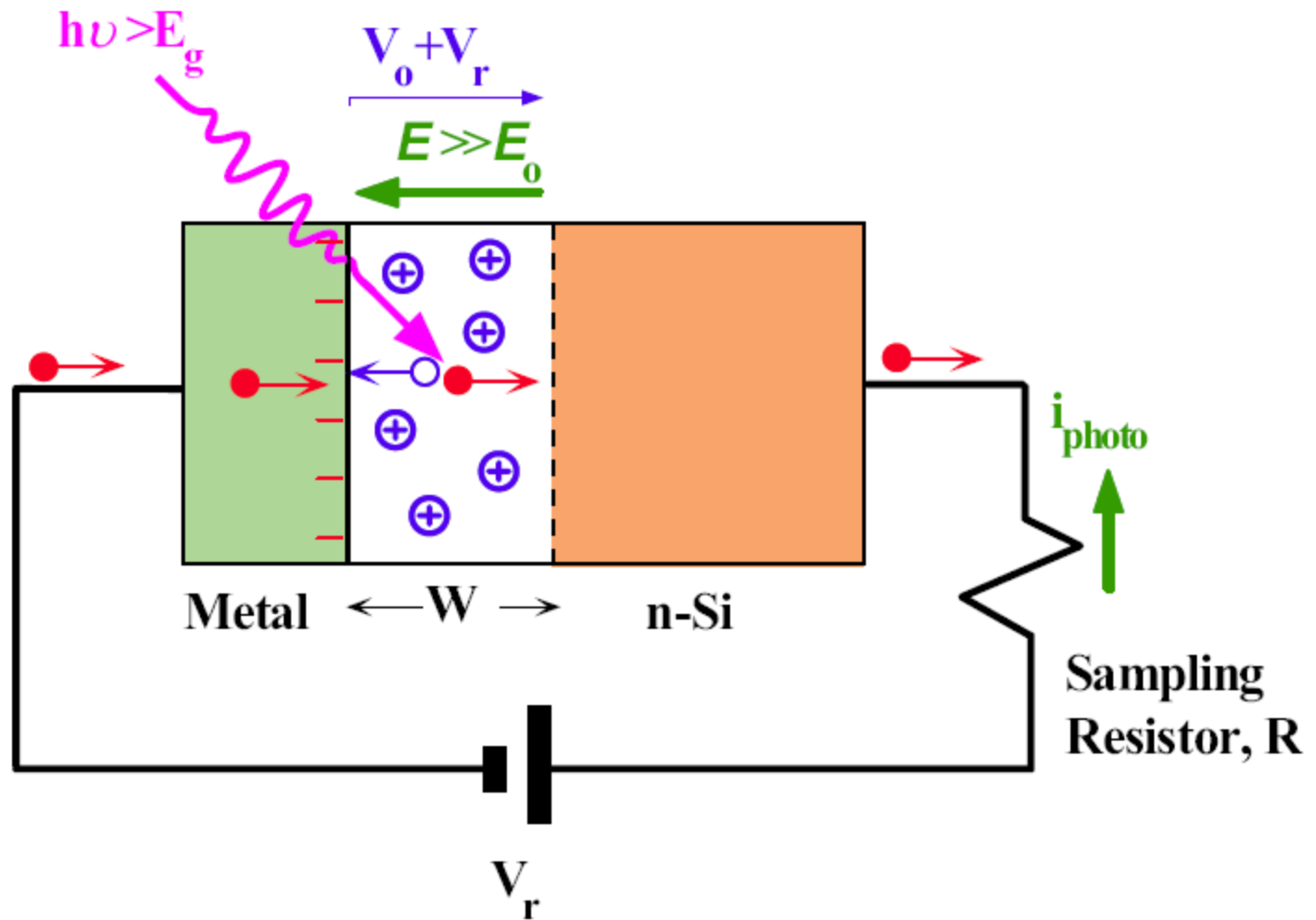
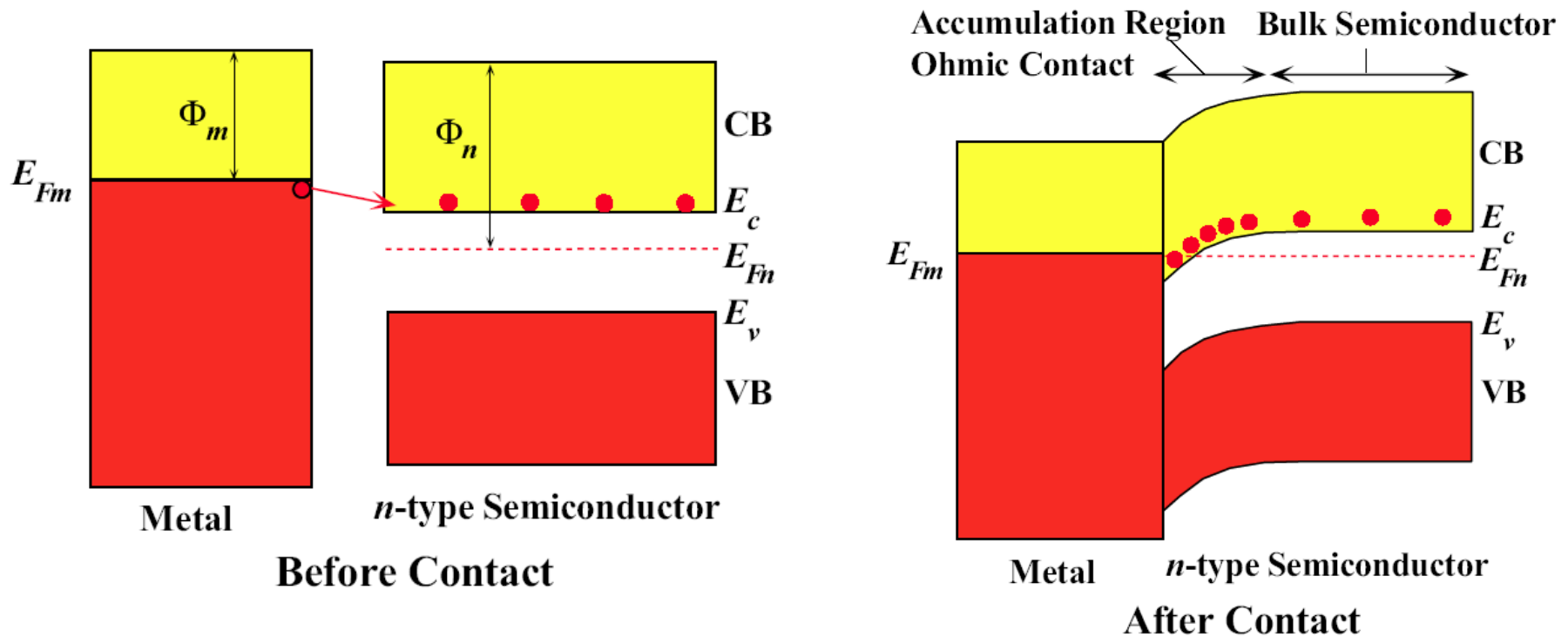


Fig 5.41



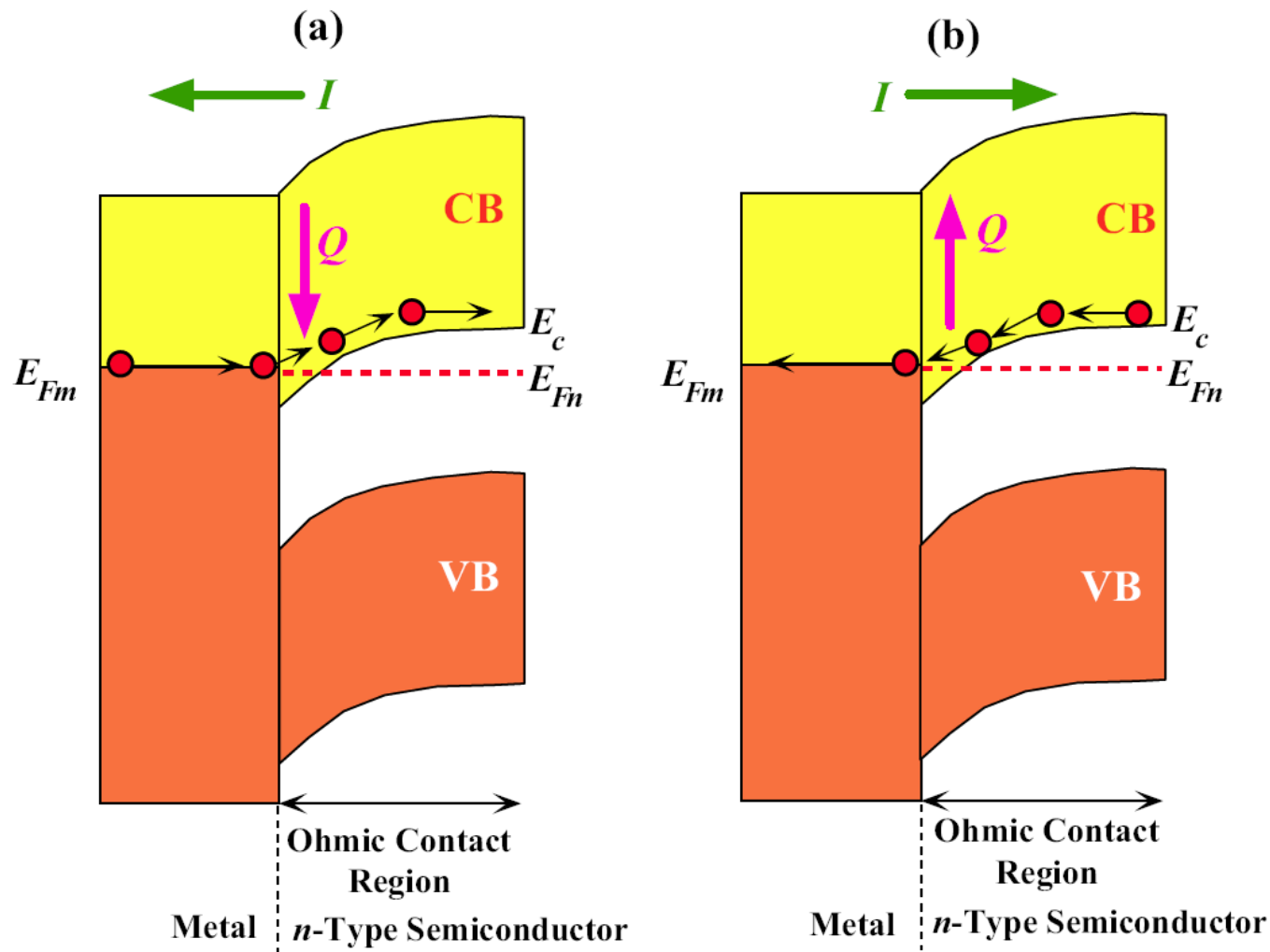
Reverse biased Schottky photodiodes are frequently used as fast photodetectors.

Fig 5.42



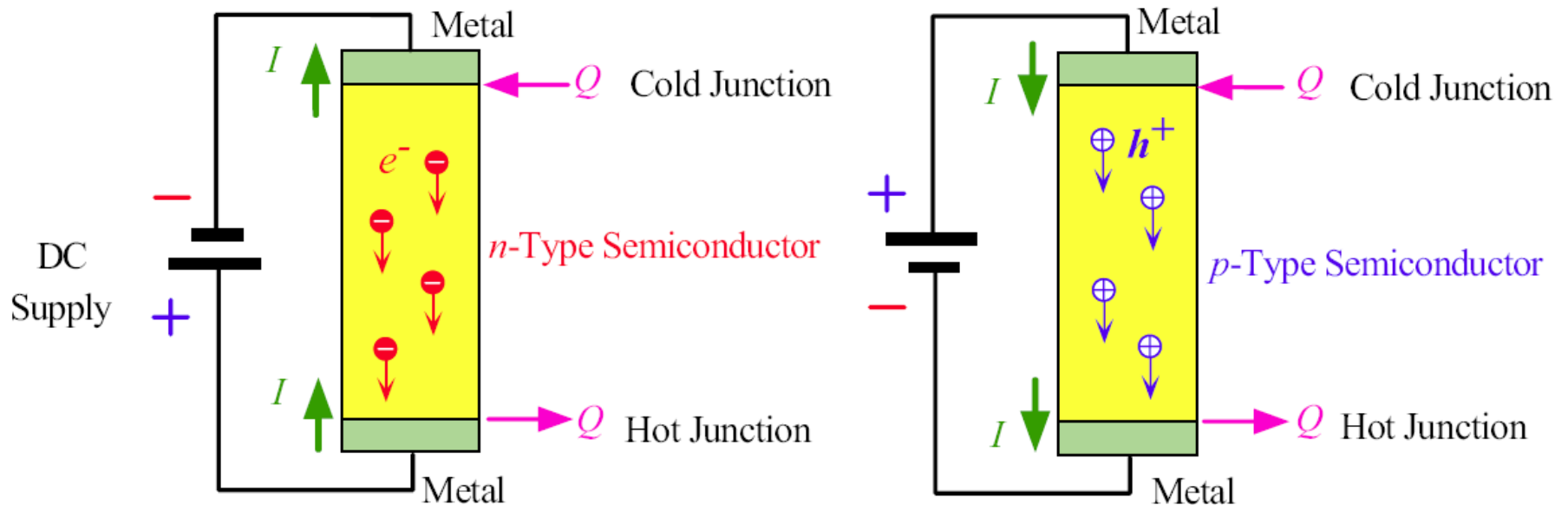
When a metal with a smaller workfunction than an n-type semiconductor are put into contact, The resulting junction is an ohmic contact in the sense that it does not limit the current flow.

Fig 5.43



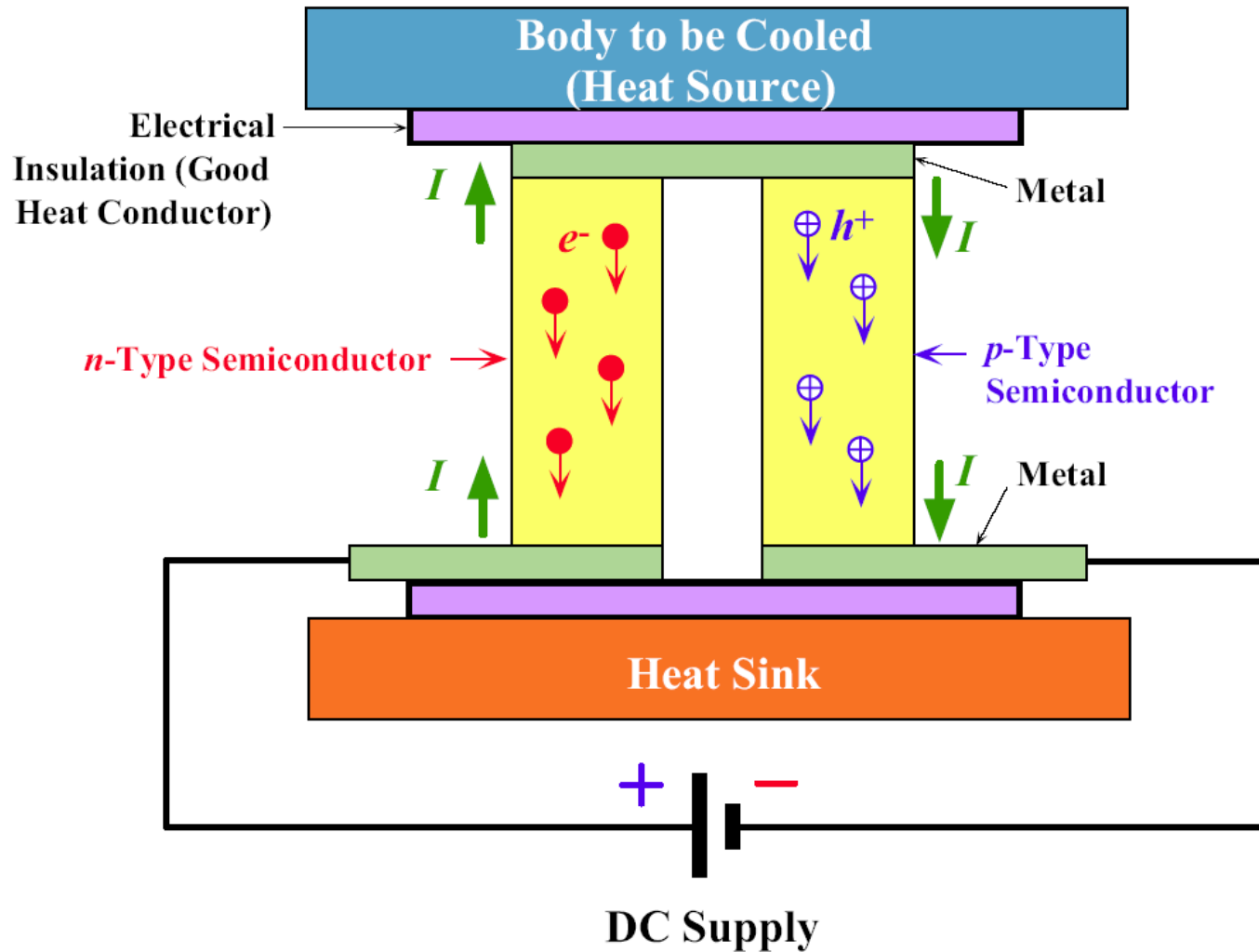
- (a) Current from an n-type semiconductor to the metal results in heat absorption at the junction.
- (b) Current from the metal to an n-type semiconductor results in heat release at the junction.

Fig 5.44



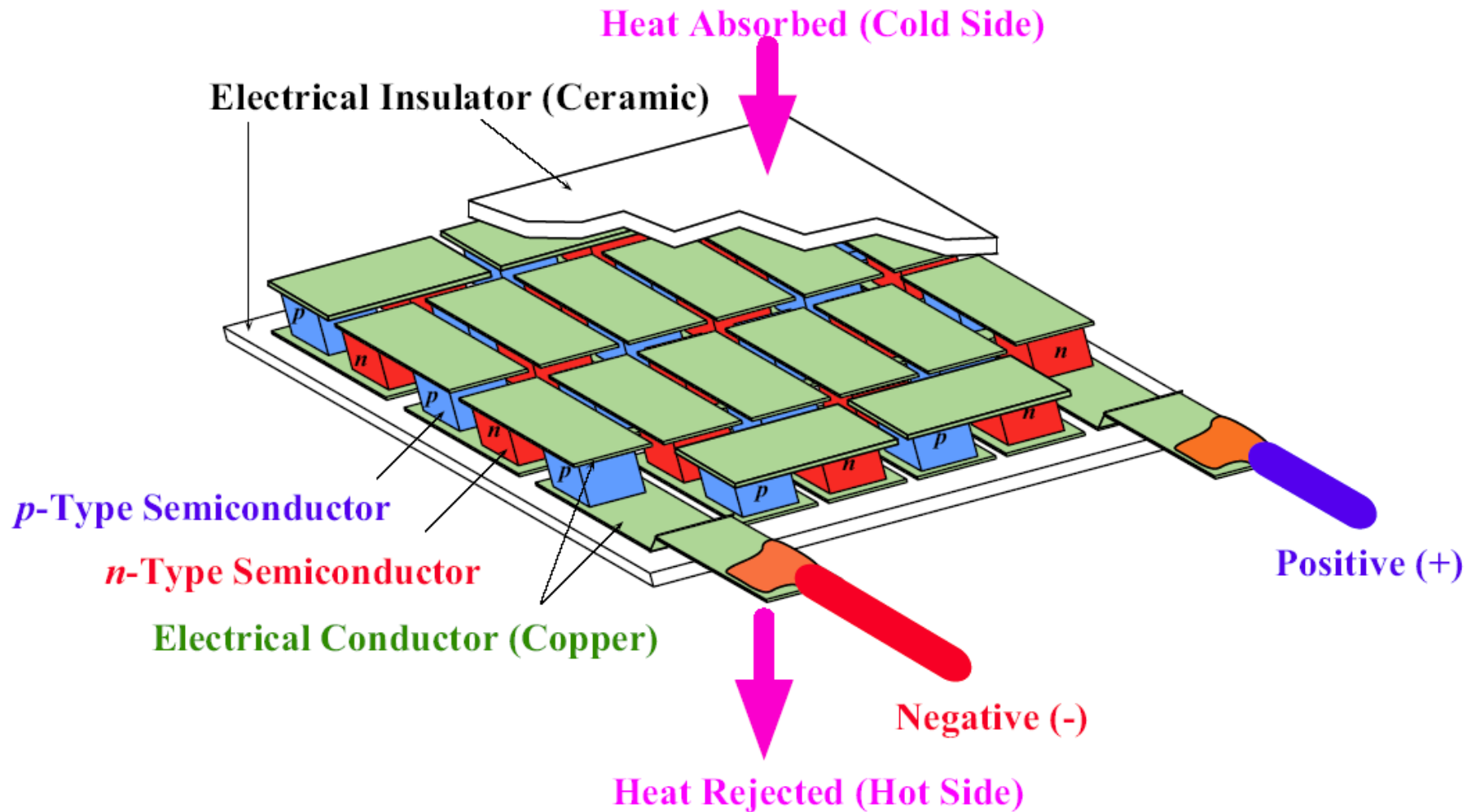
When a dc current is passed through a semiconductor to which metal contacts have been made, one junction absorbs heat and cools (the cold junction) and the other releases heat and warms (the hot junction).

Fig 5.45



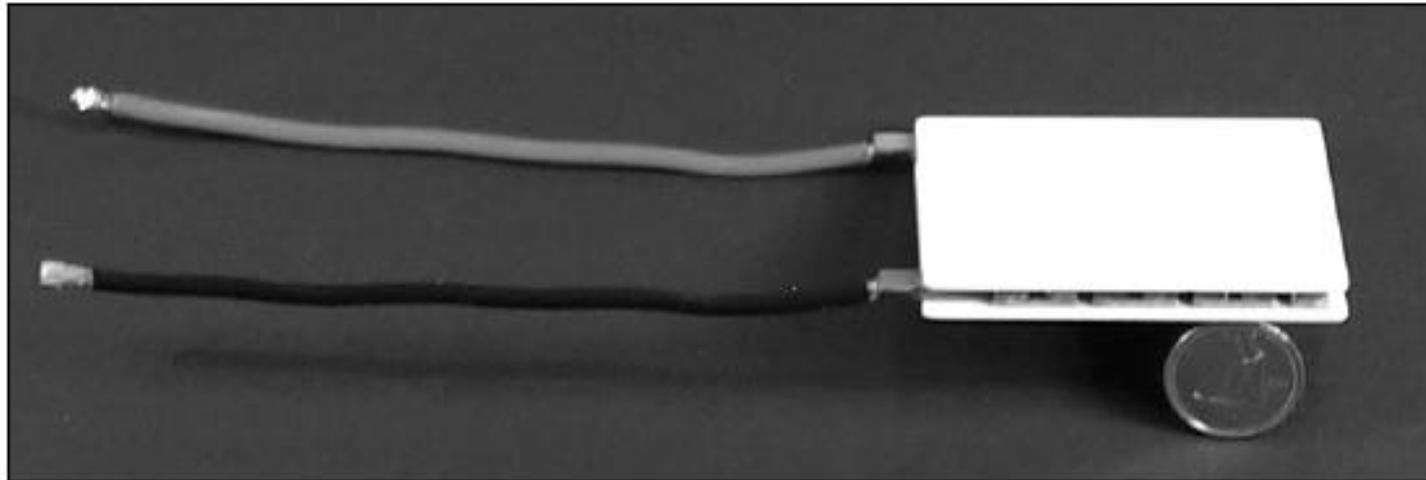
Cross section of a typical thermoelectric cooler.

Fig 5.46

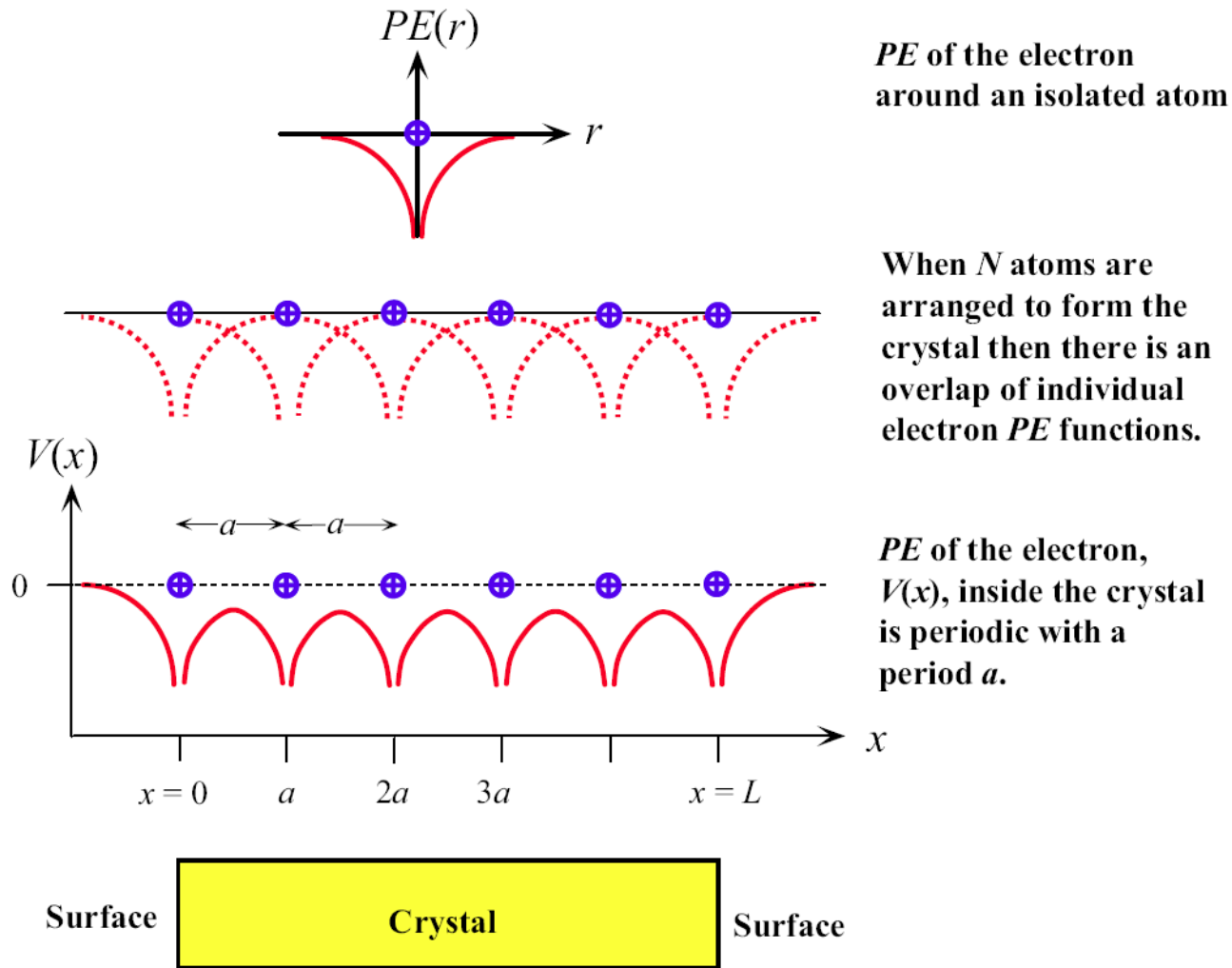


Typical structure of a commercial thermoelectric cooler.

Fig 5.47

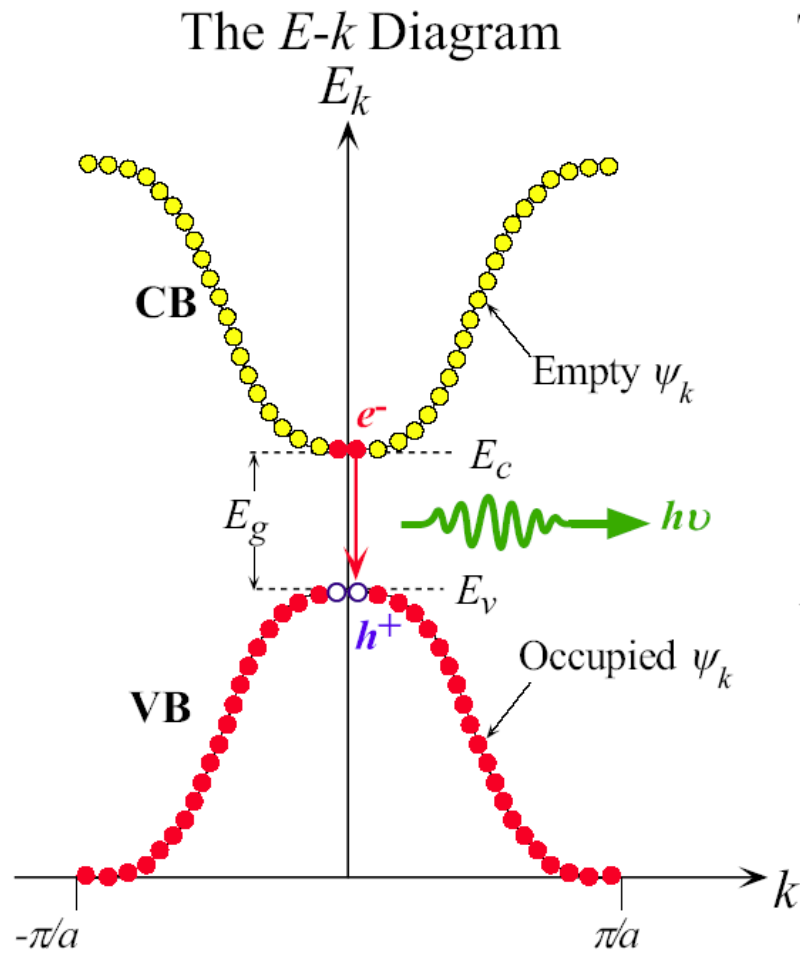


A commercial thermoelectric cooler (by Melcor); an example of the Peltier effect. The device area is $5.5 \text{ cm} \times 5.5 \text{ cm}$ (approximately $2.2 \text{ inches} \times 2.2 \text{ inches}$). Its maximum current is 14 A; maximum heat pump ability is 67 W; maximum temperature difference between the hot and cold surfaces is 67°C .

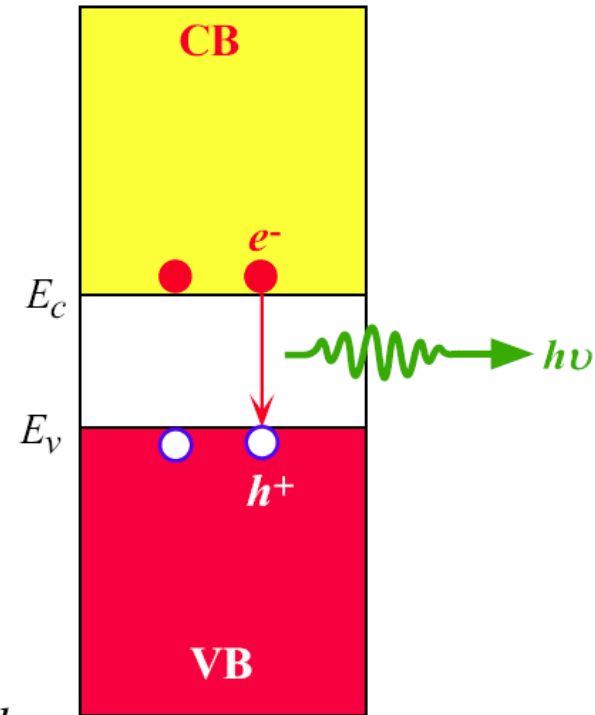


The electron PE , $V(x)$, inside the crystal is periodic with the same periodicity as that of the Crystal, a . Far away outside the crystal, by choice, $V = 0$ (the electron is free and $PE = 0$).

Fig 5.48

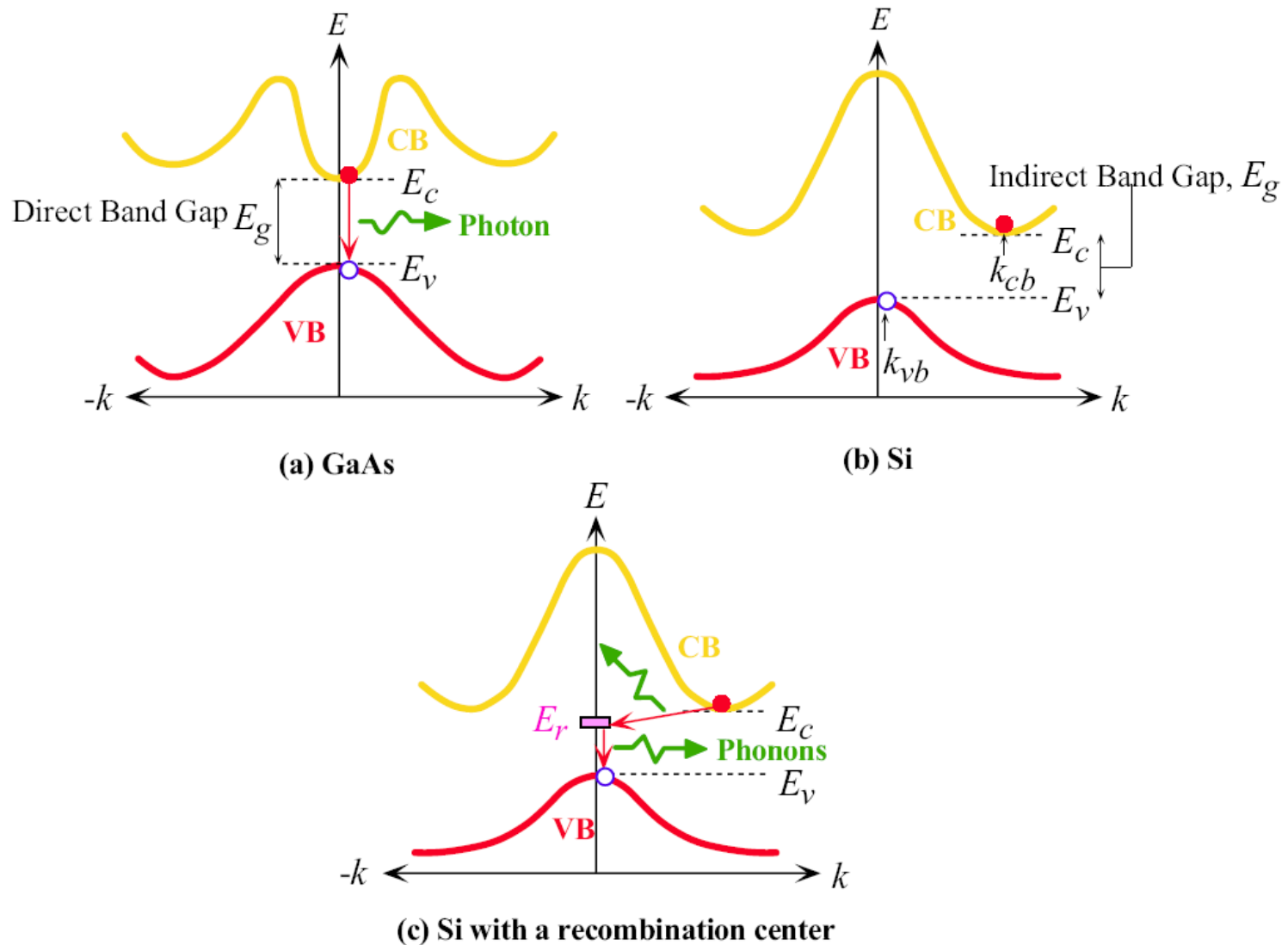


The Energy Band Diagram



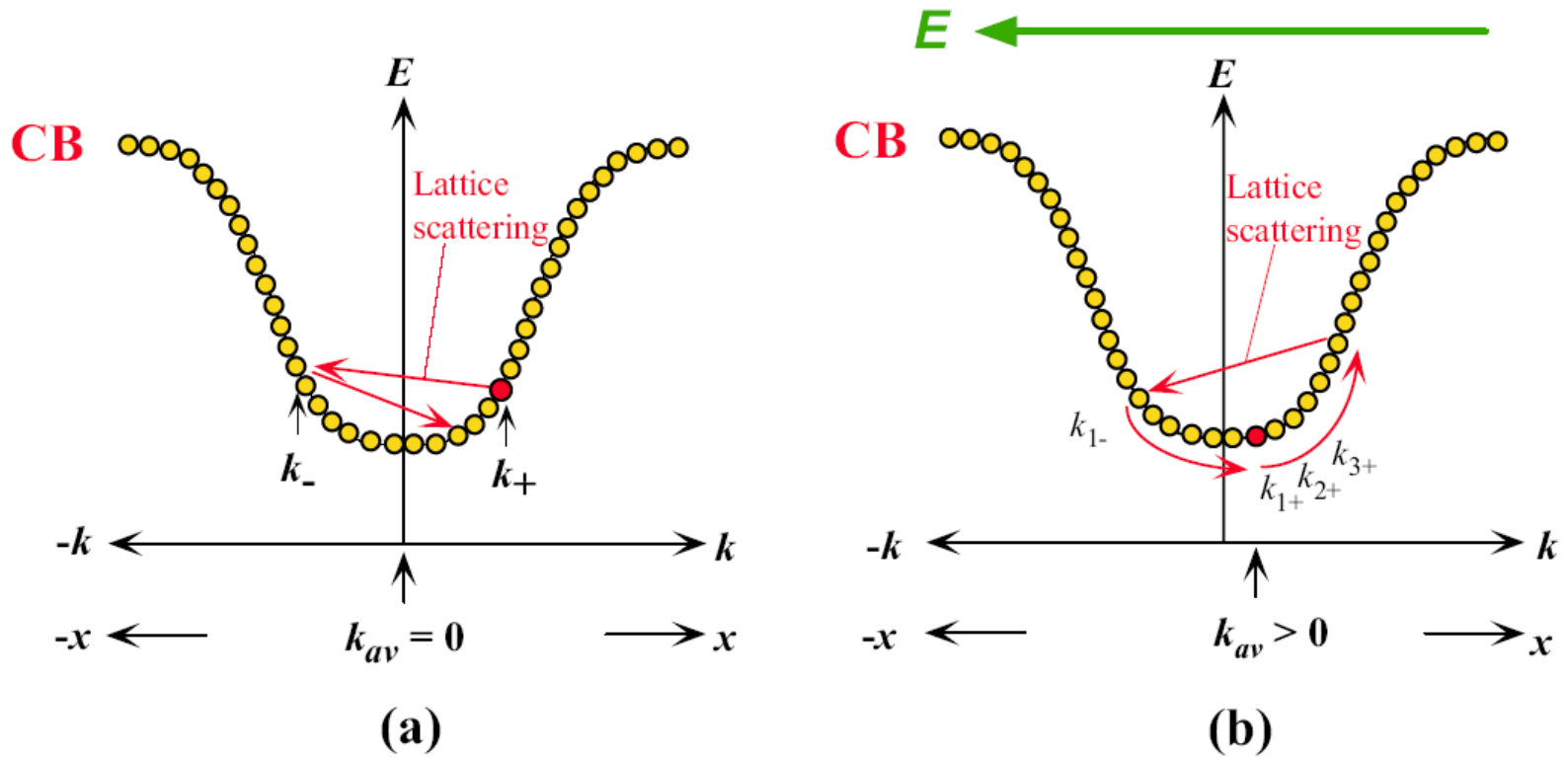
The E - k diagram of a direct bandgap semiconductor such as GaAs. The E - k curve consists of many discrete points each point corresponding to a possible state, wavefunction $\psi_k(x)$ that is allowed to exist in the crystal. The points are so close that we normally draw the E - k relationship as a continuous curve. In the energy range E_v to E_c there are no points ($\psi_k(x)$ solutions).

Fig 5.49



(a) In GaAs the minimum of the CB is directly above the maximum of the VB. GaAs is therefore a direct band gap semiconductor. (b) In Si, the minimum of the CB is displaced from the maximum of the VB and Si is an indirect band gap semiconductor. (c) Recombination of an electron and a hole in Si involves a recombination center.

Fig 5.50



- (a) In the absence of a field, over a long time, average of all k values is zero, there is no net momentum in any one direction.
- (b) In the presence of a field E in the $-x$ direction, the electron accelerates in the $+x$ direction increasing its k value along x until it is scattered to a random k value. Over a long time, average of all k values is along the $+x$ direction. Thus the electron drifts along $+x$.

Fig 5.51

Electron's group velocity

$$v_g = \frac{1}{\hbar} \frac{dE}{dk}$$

v_g = group velocity, E = electron energy, k = electron's wavevector

External force and acceleration

$$F_{\text{ext}} = \frac{\hbar^2}{\left[\frac{d^2 E}{dk^2} \right]} a$$

F_{ext} = externally applied force, a = acceleration

Effective Mass

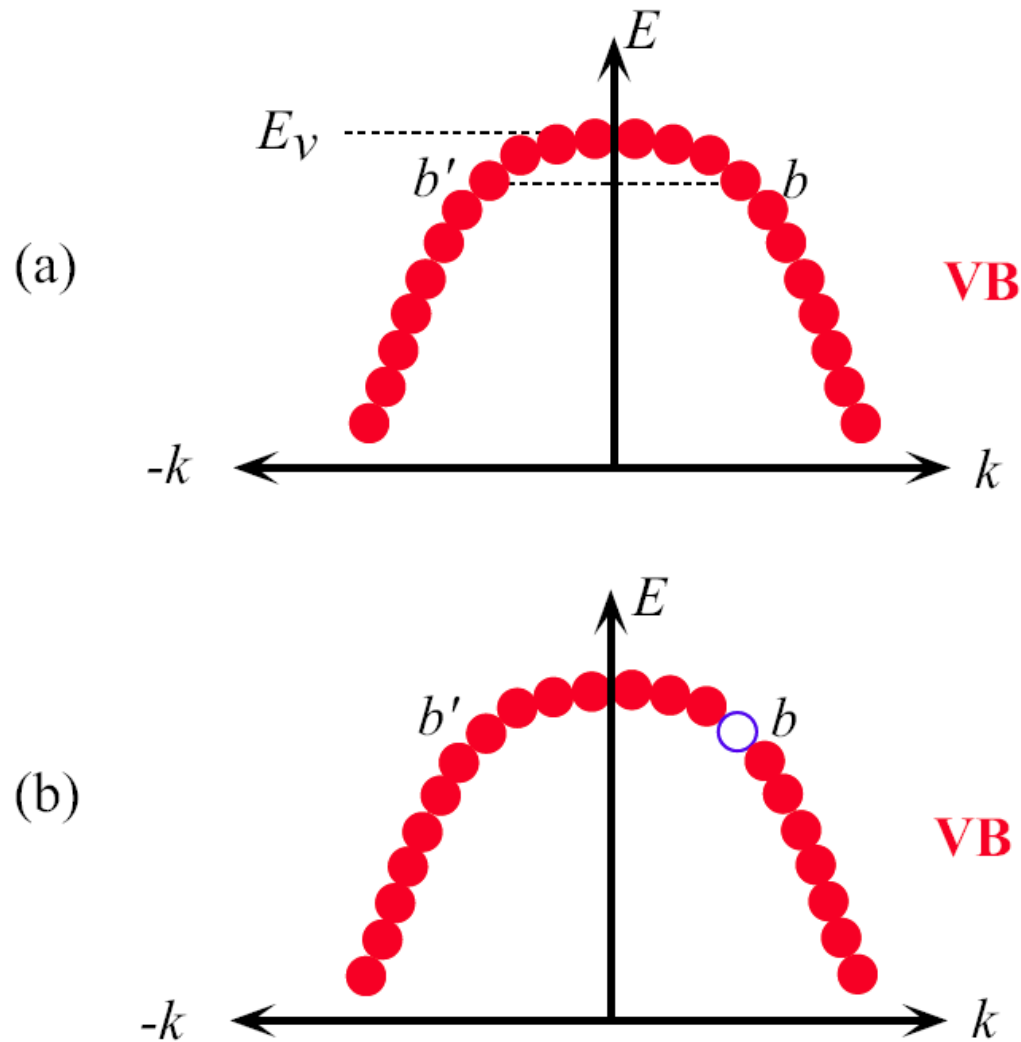
$$m_e^* = \hbar^2 \left[\frac{d^2 E}{dk^2} \right]^{-1}$$

m_e^* = effective mass of the electron inside the crystal

Effective mass depends on the curvature of the E - k curve.

Sharp (large) curvature gives a small effective mass

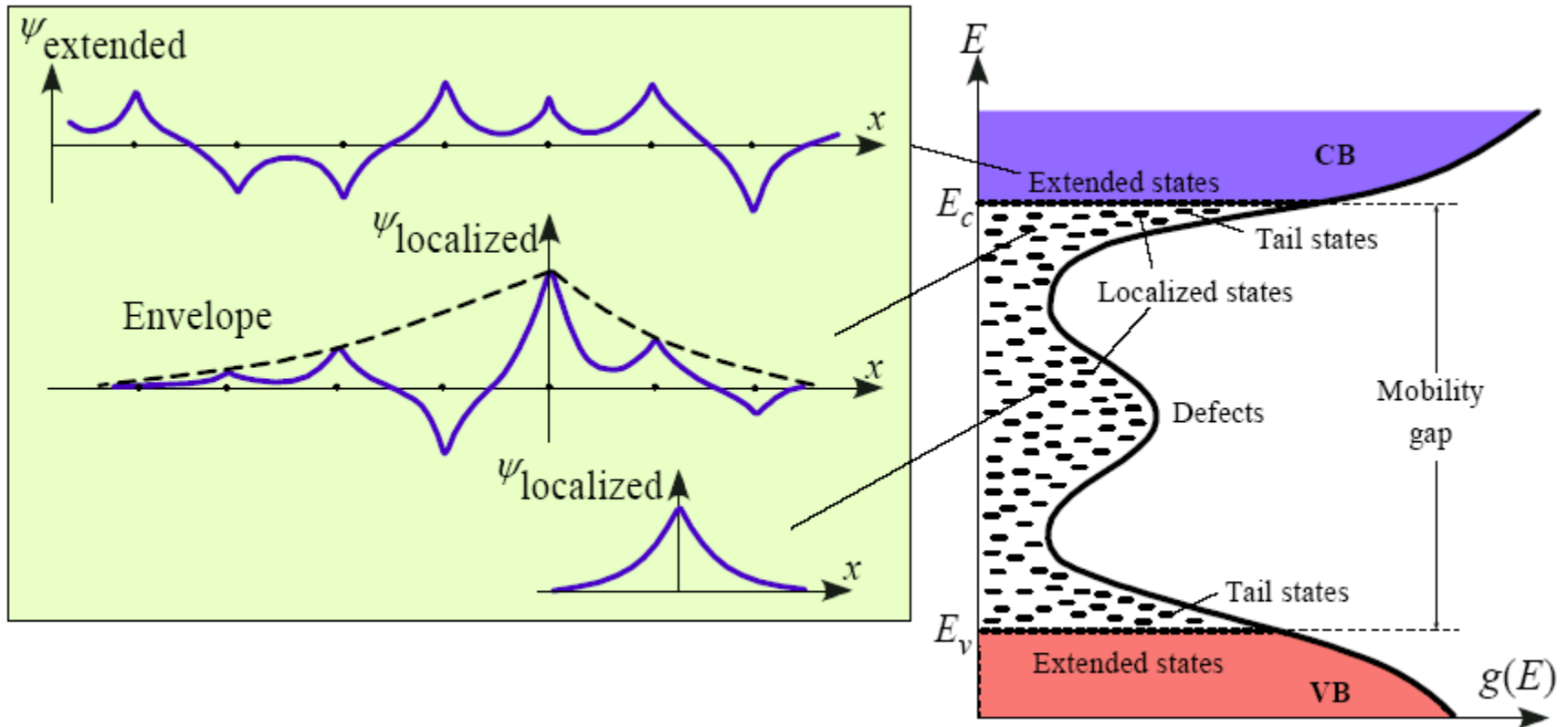
Broad (small) curvature gives a large effective mass



(a) In a full valence band there is no net contribution to the current. There are equal numbers of electrons (e.g. at b and b') with opposite momenta.

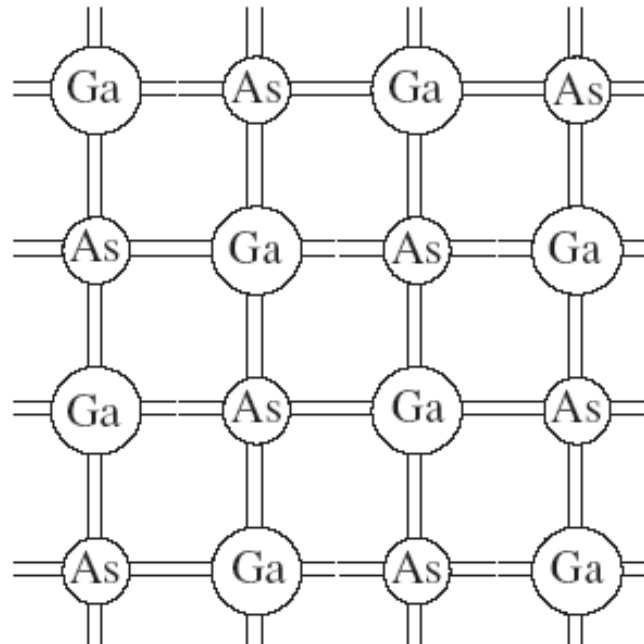
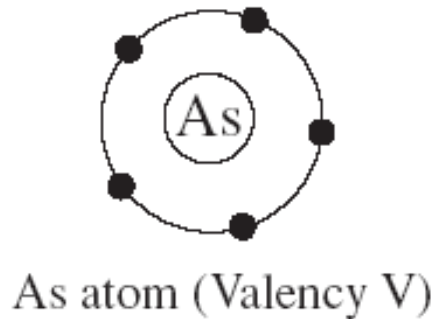
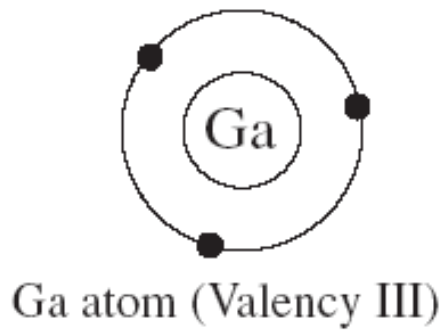
(b) If there is an empty state (hole) at b at the top of the band then the electron at b' contributes to the current.

Fig 5.52



Schematic representation of the density of states $g(E)$ vs. energy E for an amorphous semiconductor and the associated electron wavefunctions for an electron in the extended and localized states.

Fig 5.53



The GaAs crystal structure in two dimensions. Average number of valence electrons per atom is four. Each Ga atom covalently bonds with four neighboring As atoms and vice versa.

Fig 5.54

Table 5.4 Hall effect in selected semiconductors

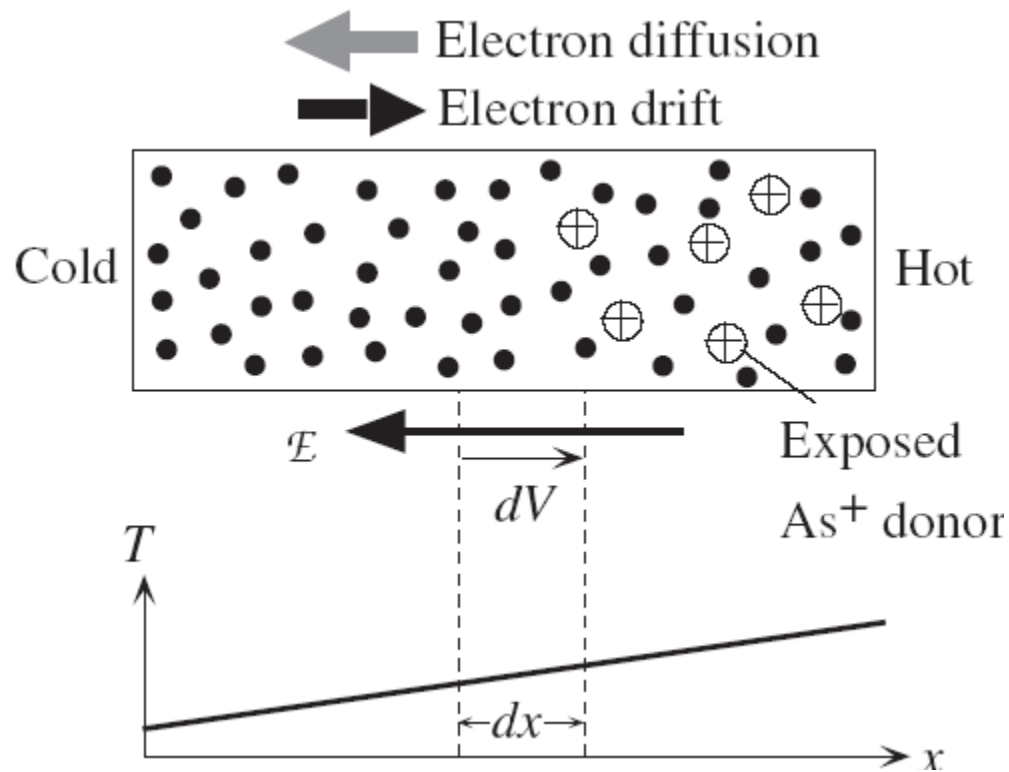
	$E_g(\text{eV})$	$n_i(\text{cm}^{-3})$	$\mu_e (\text{cm}^2 \text{V}^{-1} \text{s}^{-1})$	$\mu_e (\text{cm}^2 \text{V}^{-1} \text{s}^{-1})$	b	$R_H (\text{m}^3 \text{A}^{-1} \text{s}^{-1})$
Si	1.10	1×10^{10}	1,350	450	3	-312
GaAs	1.42	2×10^6	8,500	400	?	?
InAs	0.36	1×10^{15}	33,000	460	?	?
InSb	0.17	2×10^{16}	78,000	850	?	?

Table 5.5 Work functions in eV

Cs	Li	Al	Au
1.8	2.5	4.25	5.0

Table 5.6

Material	Π (V)	ρ (Ω m)	κ ($\text{W m}^{-1} \text{K}^{-1}$)	FOM
<i>n</i> -Bi ₂ Te ₃	6.0×10^{-2}	10^{-5}	1.70	
<i>p</i> -Bi ₂ Te ₃	7.0×10^{-2}	10^{-5}	1.45	
Cu	5.5×10^{-4}	1.7×10^{-8}	390	
W	3.3×10^{-4}	5.5×10^{-8}	167	



In the presence of a temperature gradient, there is an internal field and a voltage difference. The Seebeck coefficient is defined as dV/dT , the potential difference per unit temperature difference.

Fig 5.55