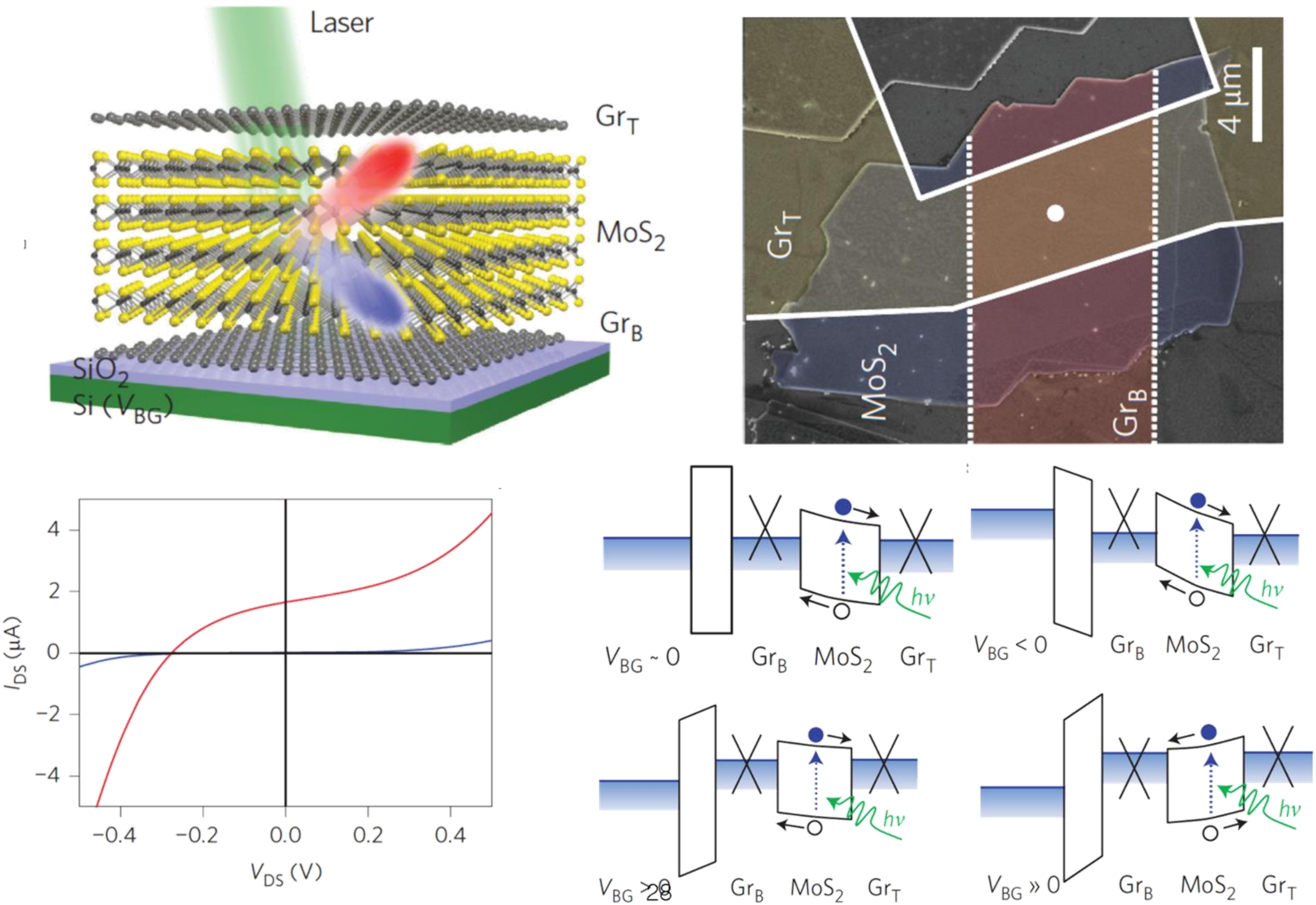
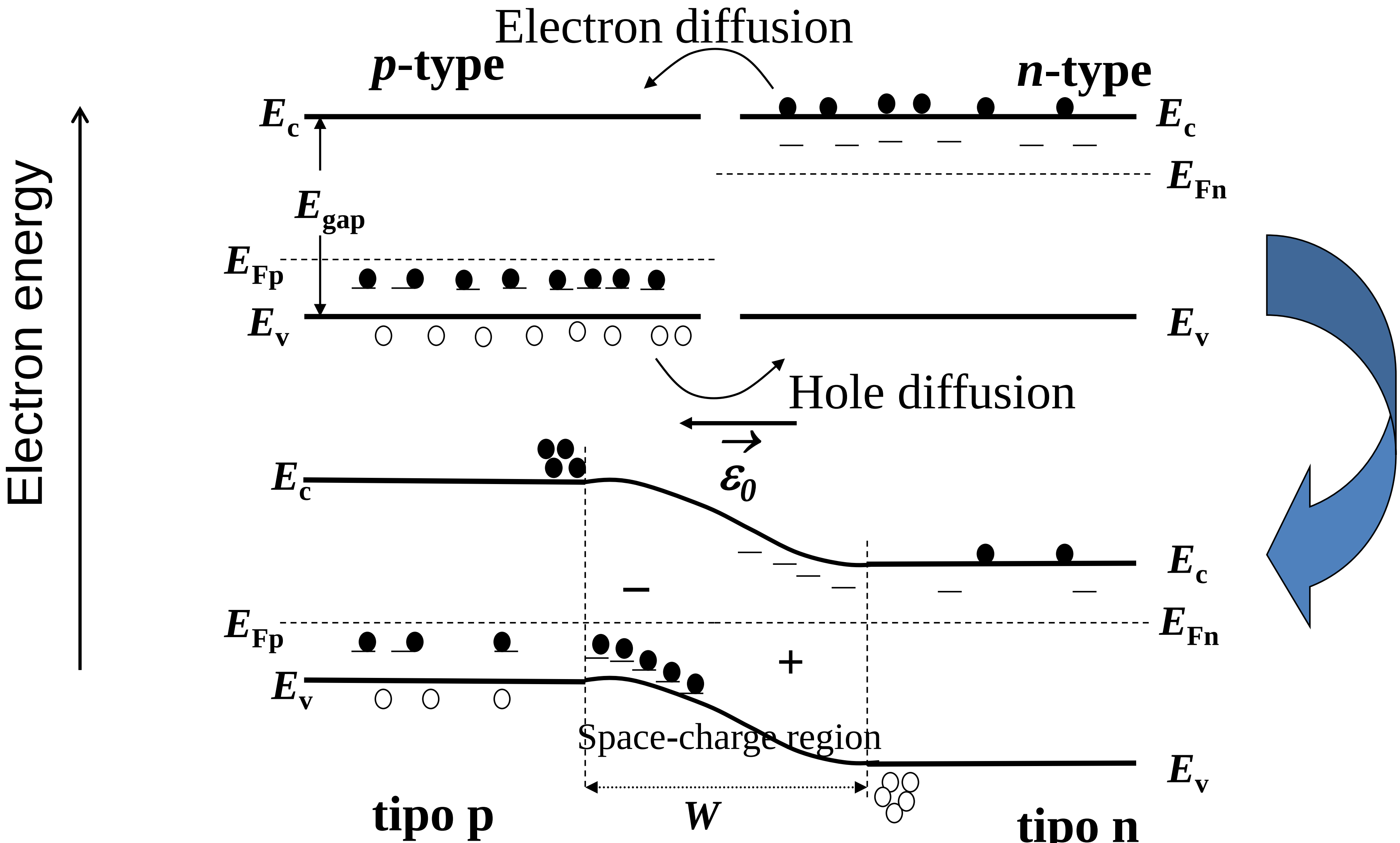
A photodetector made of 2D materials

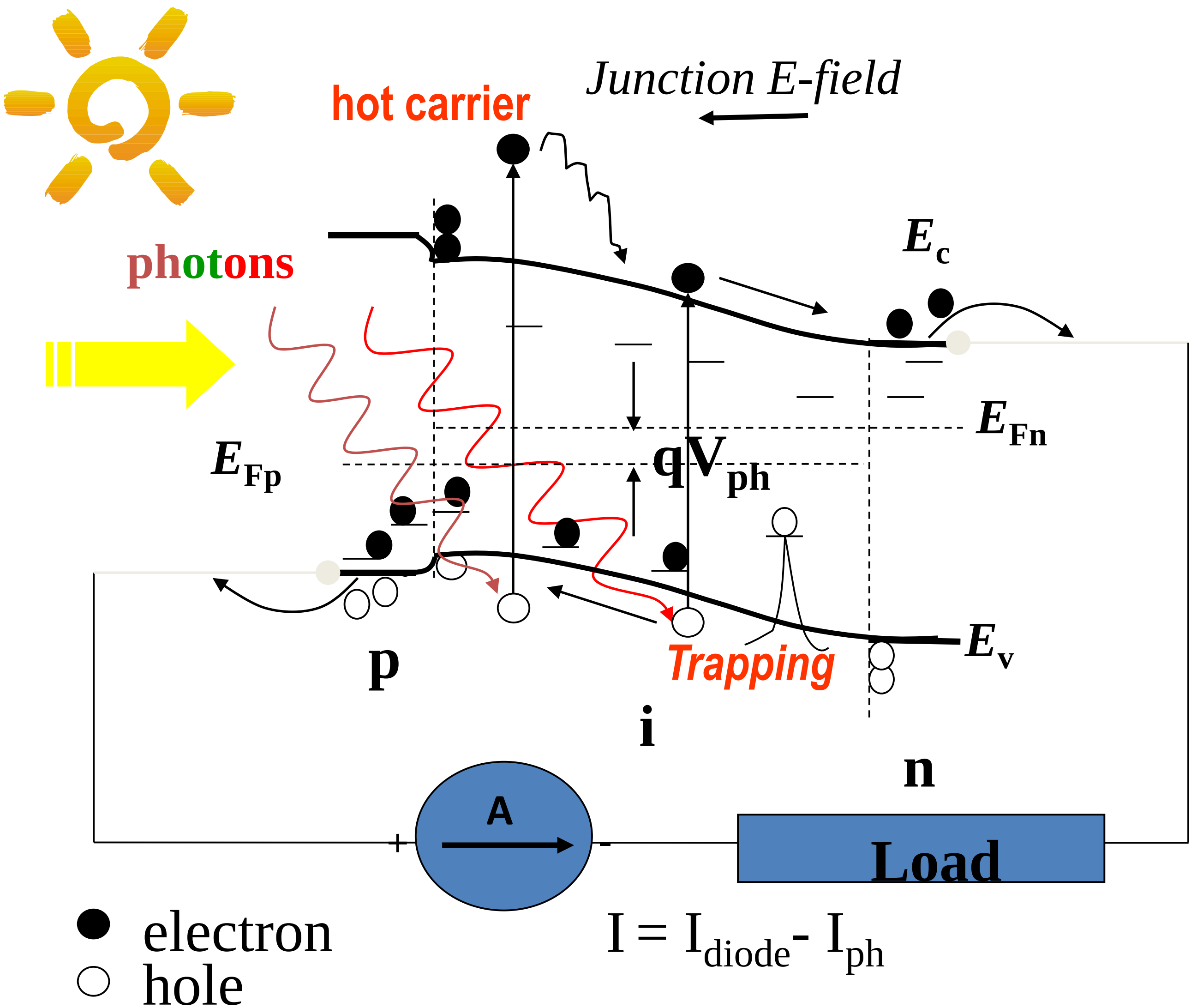
Woo Jong Yu et al., from University of California



The *p-n* (homo) junction in equilibrium

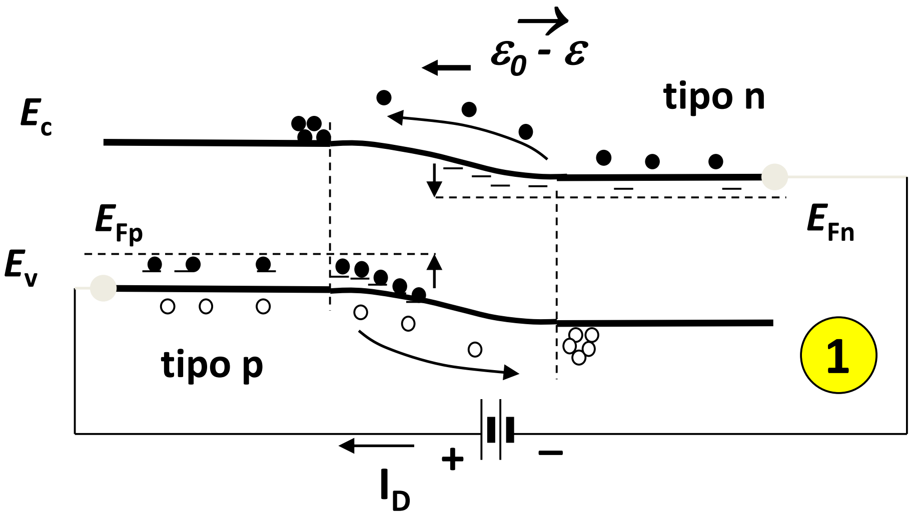


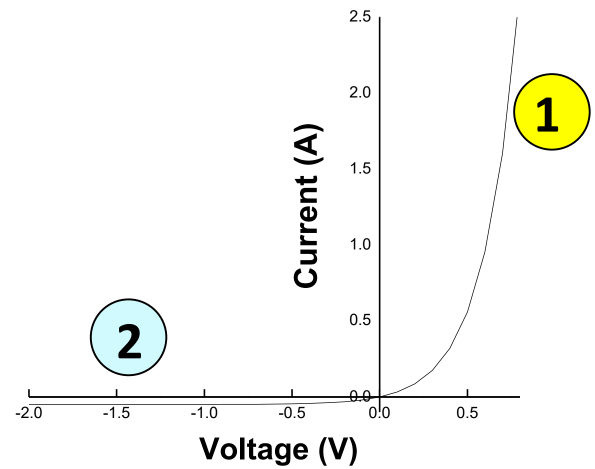
The *p-n* junction under illumination

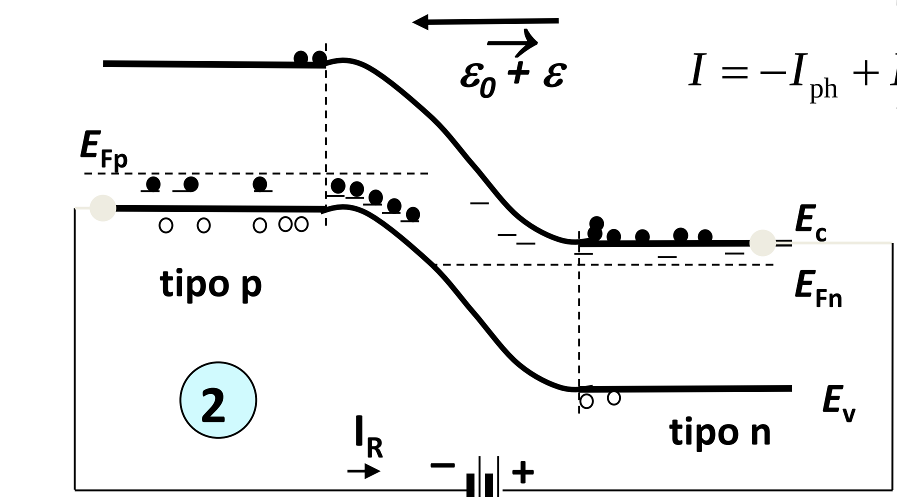


$I = I_{diode} - I_{ph}$

I-V characteristic of p-n junction (dark & light)

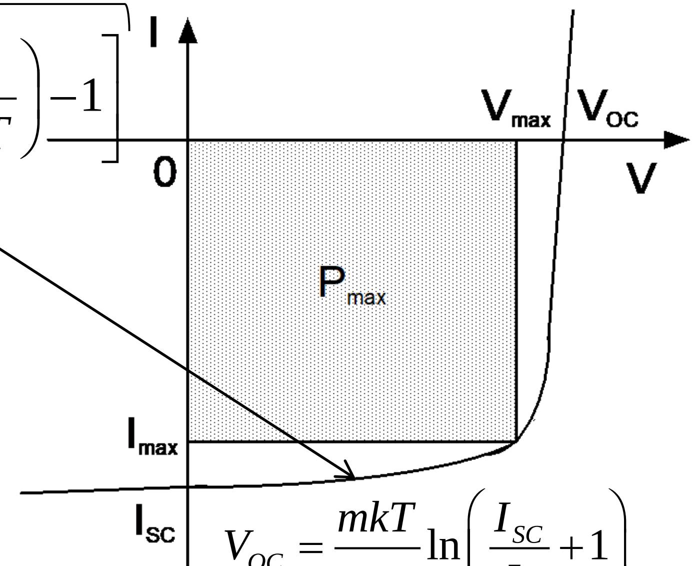




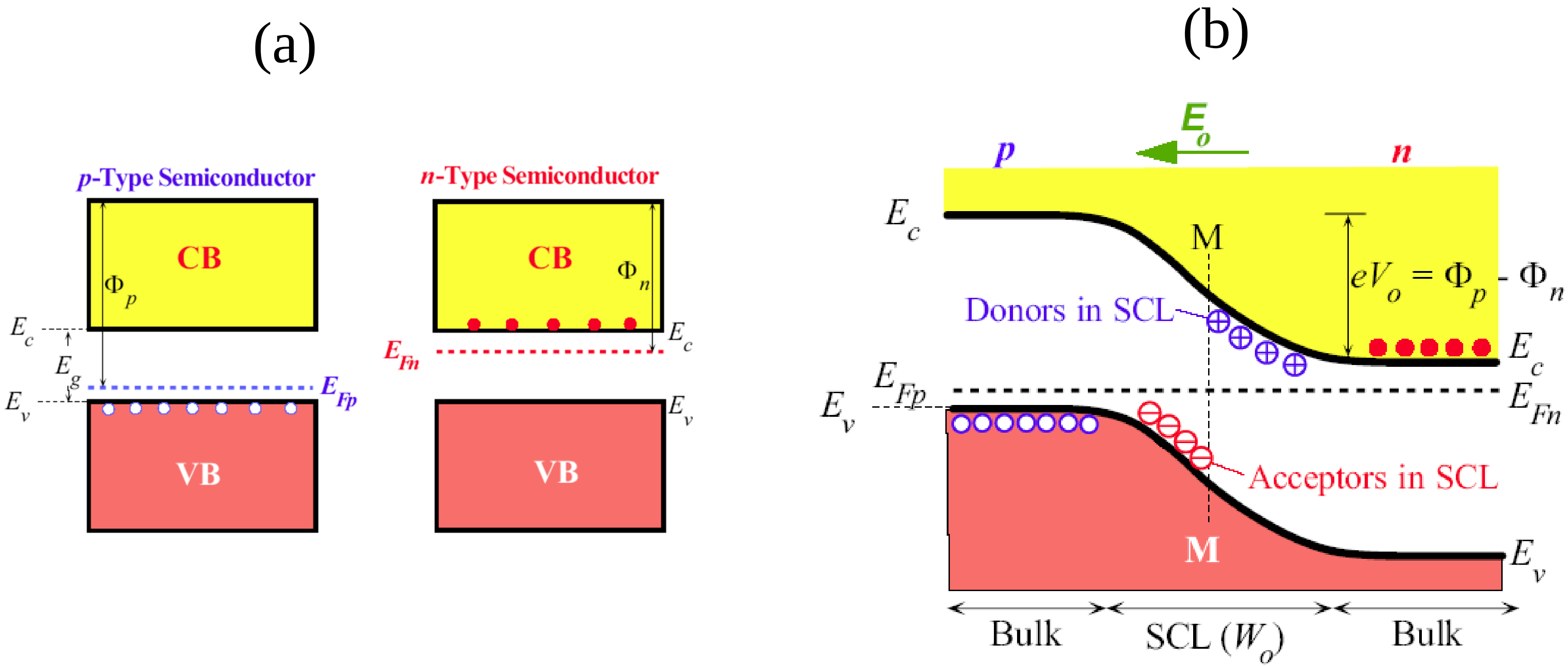


$$I = -I_{ph} + \underbrace{I_o\left[\exp\left(\frac{eV}{mkT}\right) - 1\right]}_{1}$$

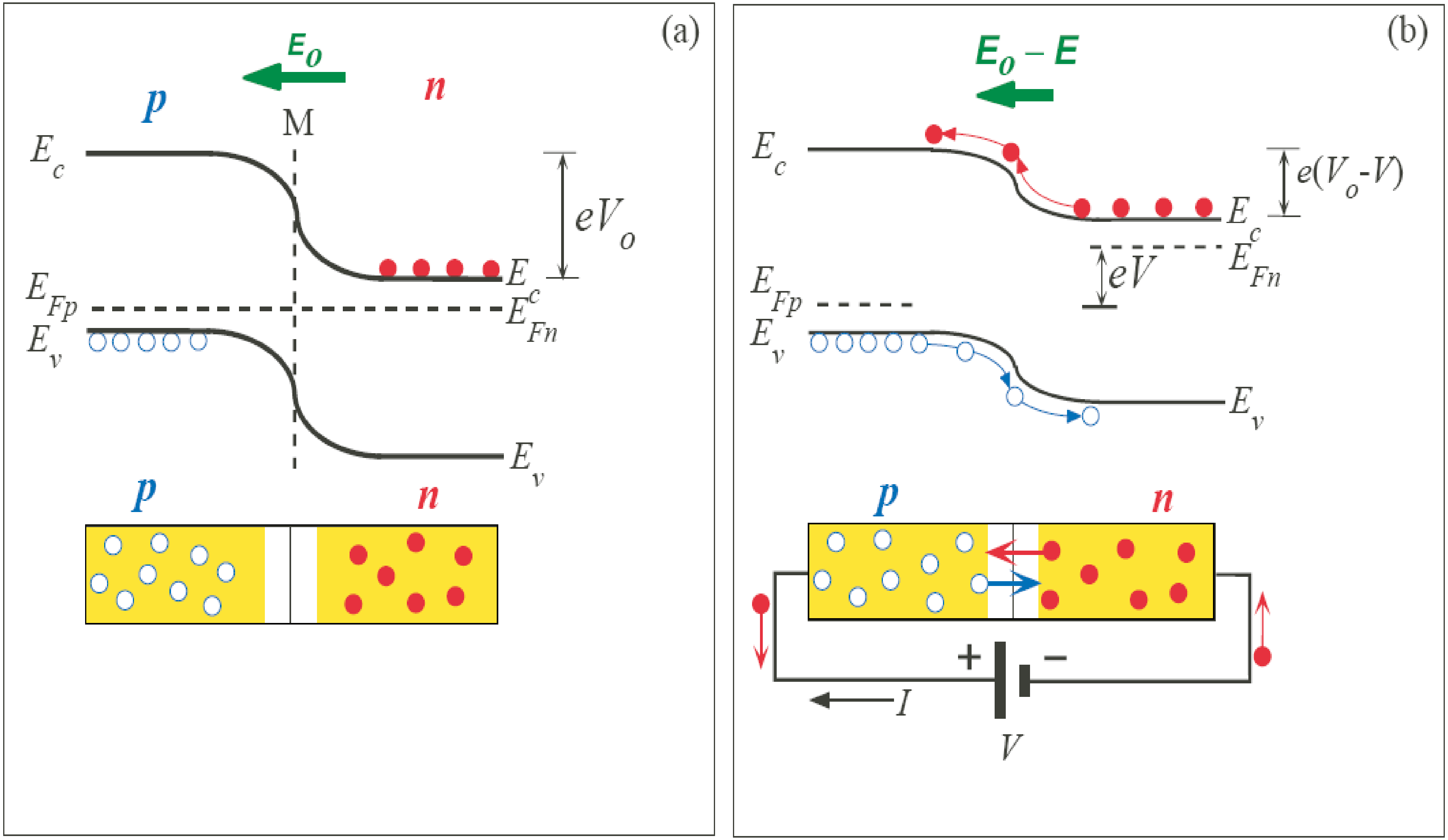
2



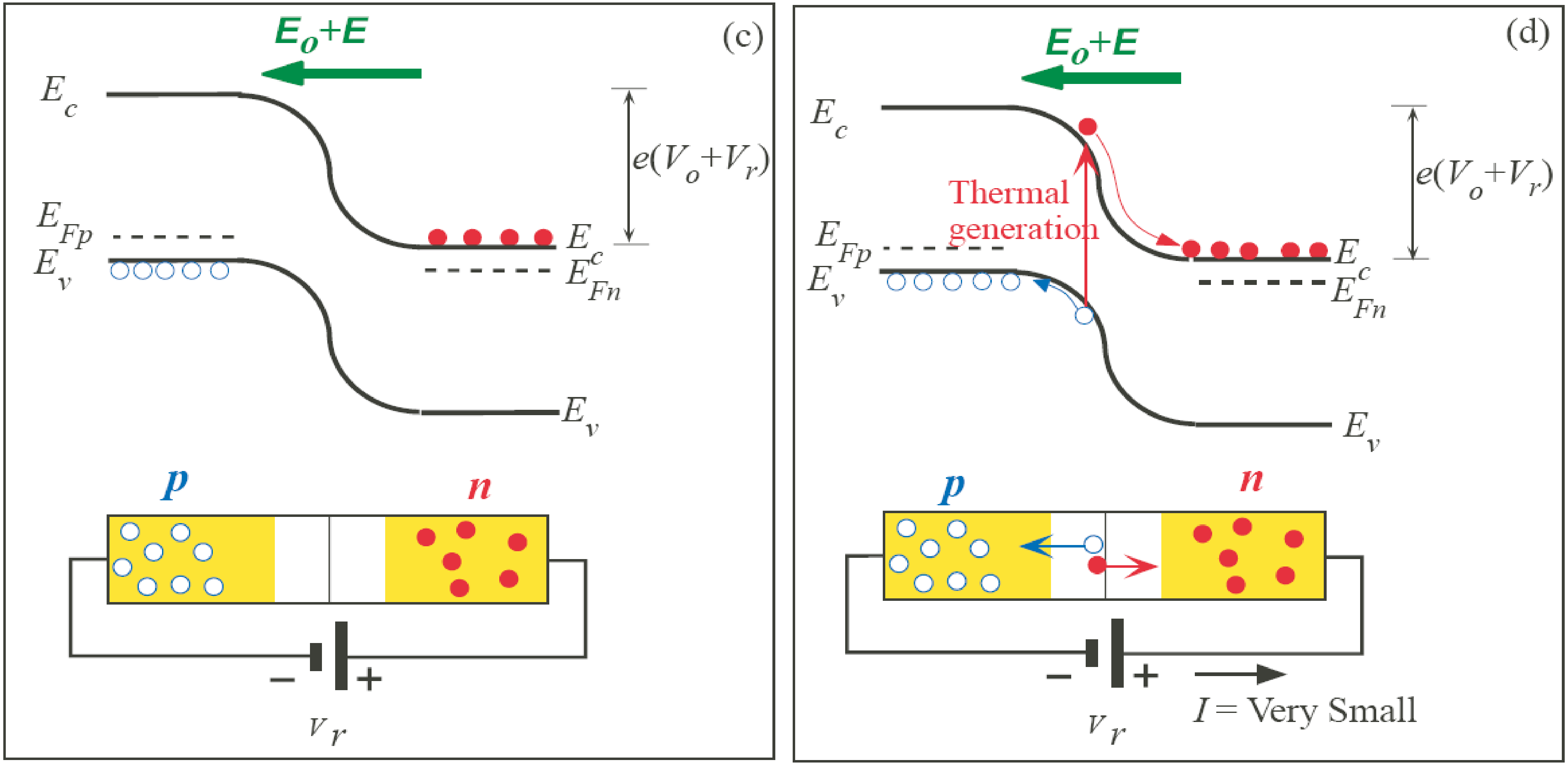
$$V_{OC} = \frac{mkT}{e}\ln\left(\frac{I_{SC}}{I_0} + 1\right)$$



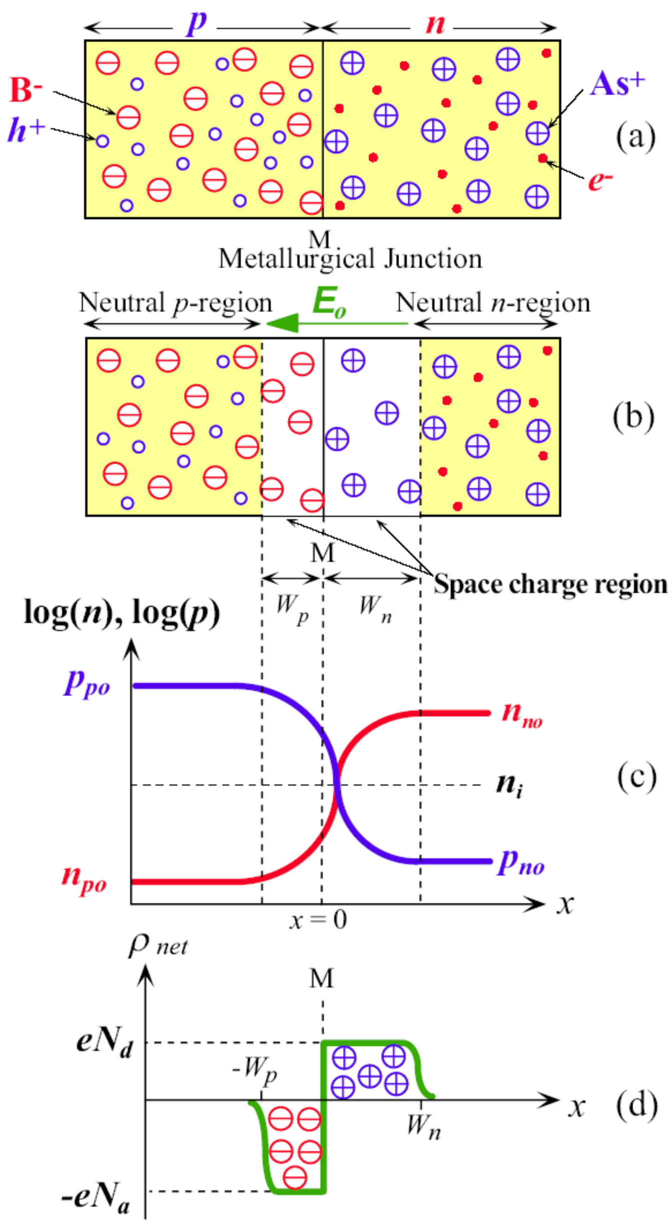
(a) Two isolated *p* and *n*-type semiconductors (same material).
(b) A pn junction band diagram when the two semiconductors are in contact. The Fermi level must be uniform in equilibrium. The metallurgical junction is at M. The region around M contains the space charge layer (SCL). On the *n*-side of M, SCL has the exposed positively charged donors whereas on the p-side it has the exposed negatively charged acceptors.



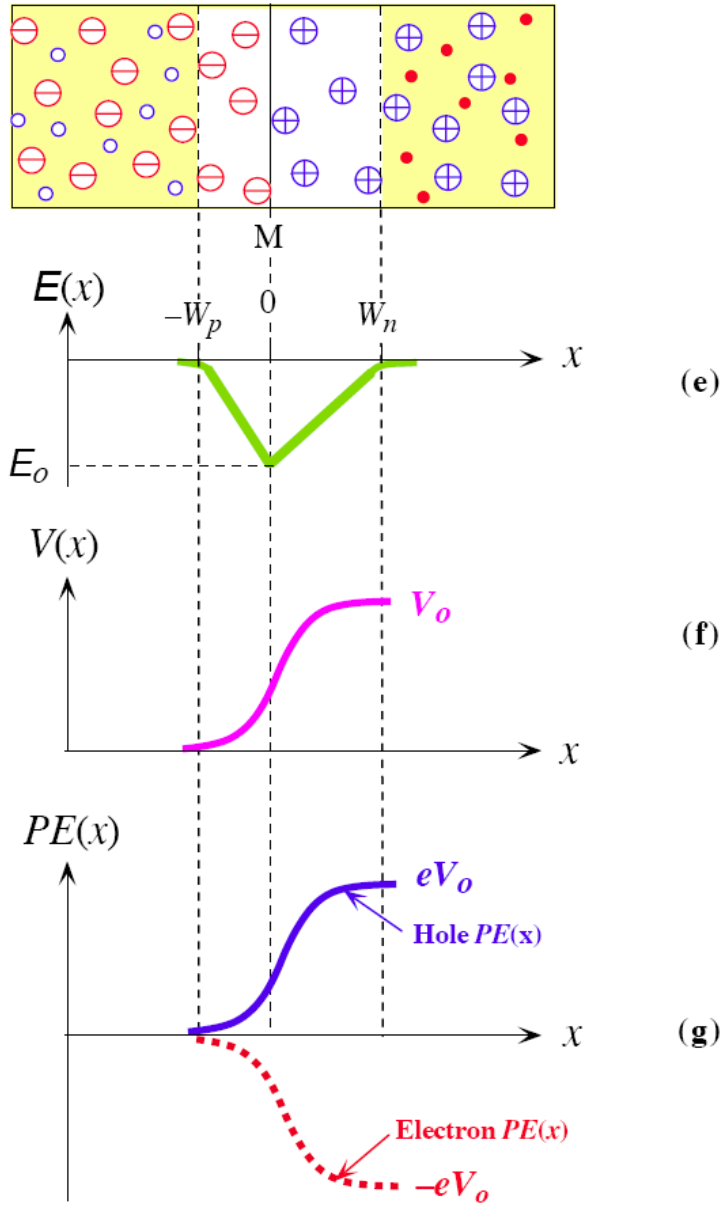
Energy band diagrams for a pn junction under
(a) open circuit and (b) forward bias



Energy band diagrams for a pn junction under (c) reverse bias conditions; and (d) thermal generation of electron hole pairs in the depletion region results in a small reverse current.



Properties of the pn junction



M
E(x)
$-W_p$
0
W_n
x
E_o
(e)
V(x)
V_o
x
(f)
PE(x)
eV_o
Hole PE(x)
x
(g)
Electron PE(x)
$-eV_o$

Ideal *pn* Junction

Acceptor concentration

Donor concentration

Depletion Widths

$$N_a W_p = N_d W_n$$

Field (*E*) and net space charge density

Net space charge density

$$\frac{d\mathcal{E}}{dx} = \frac{\rho_{\mathrm{net}}(x)}{\varepsilon}$$

Permittivity of the medium

Field in depletion region

$$\mathcal{E}(x) = \frac{1}{\varepsilon}\int_{-W_p}^{x} \rho_{\mathrm{net}}(x)dx$$

Electric Field

Ideal *pn* Junction

Built-in field

$$\mathcal{E}_o = -\frac{eN_d W_n}{\varepsilon}$$

where $\varepsilon = \varepsilon_o\, \varepsilon_r$

Built-in voltage

$$V_o = -\frac{1}{2} E_0 W_0 = \frac{eN_a N_d W_0^2}{2\varepsilon\left(N_a + N_d\right)}$$

Depletion region width

$$W_o = \left[\frac{2\varepsilon\left(N_a + N_d\right)V_o}{eN_a N_d}\right]^{1/2}$$

where $W_o = W_n + W_p$ is the total width of the depletion region under a zero applied voltage

Boltzmann statistics for electrons and holes

$$\frac{n_2}{n_1} = \exp\left(-\frac{(E_2 - E_1)}{kT}\right)$$

Minority carrier concentrations in equilibrium

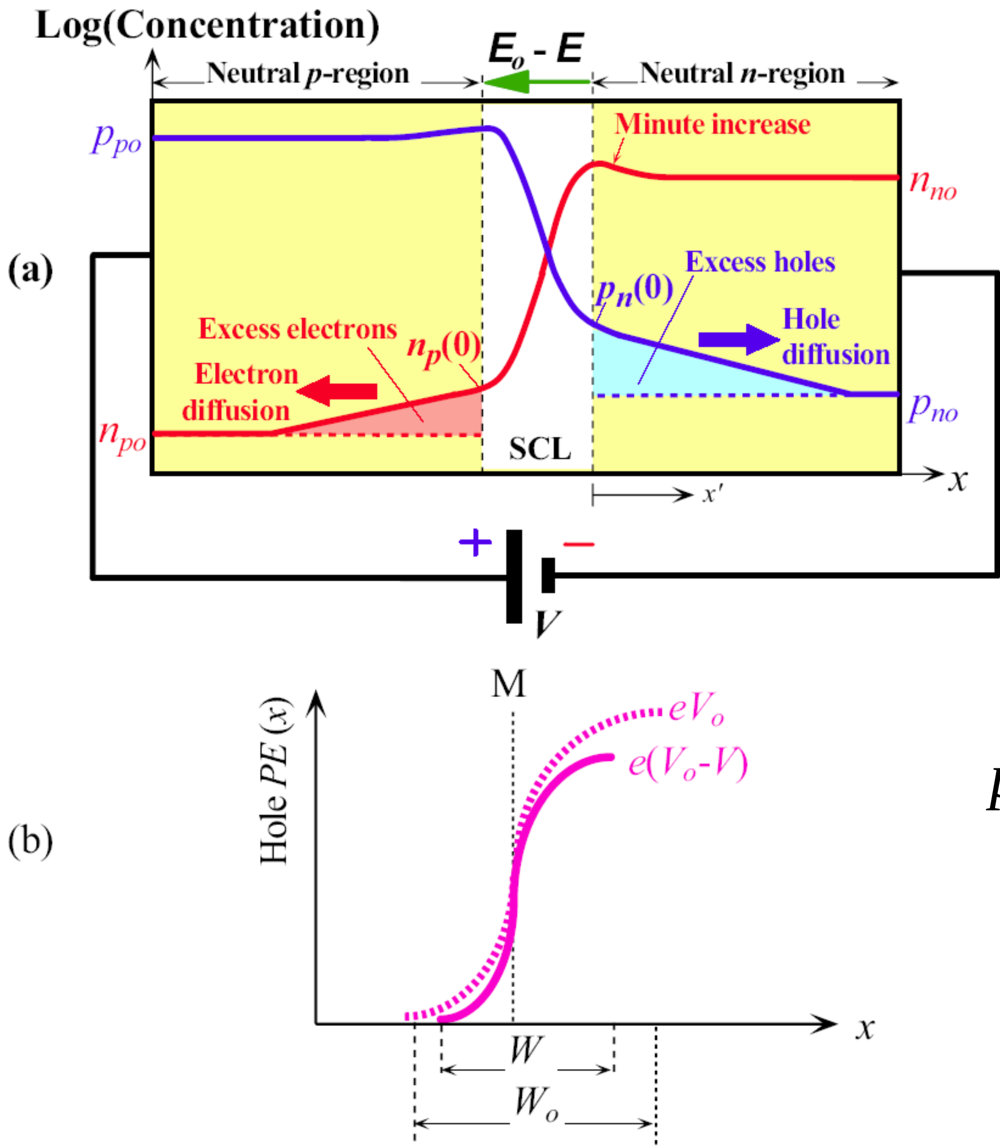
$$p_{no}(0) = p_{po}\exp\left(-\frac{eV_0}{kT}\right) \Rightarrow V_0 = \frac{kT}{e}\ln\left(\frac{p_{po}}{p_{no}}\right)$$

$$n_{po}(0) = n_{no}\exp\left(-\frac{eV_0}{kT}\right) \Rightarrow V_0 = \frac{kT}{e}\ln\left(\frac{n_{no}}{n_{po}}\right)$$

Law of mass action

$$p_{no} = \frac{n_i^2}{n_{no}} = \frac{n_i^2}{N_D}$$

$$\boxed{V_o = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right)}$$



$$p_n(0) = p_{po} \exp\left[-\frac{e(V_0 - V)}{kT}\right]$$

Forward biased *pn* junction and the injection of minority carriers.

(a) Carrier concentration profiles across the device under forward bias.

(b) The hole potential energy with and without an applied bias. *W* is the width of the SCL with forward bias.

Forward Bias: Diffusion Current

Law of the Junction: Minority Carrier Concentrations and Voltage

$$p_n(0) = p_{no}\exp\left(\frac{eV}{kT}\right)$$

$$n_p(0) = n_{po}\exp\left(\frac{eV}{kT}\right)$$

$p_n(0)$ is the hole concentration just outside the depletion region on the *n*-side

$n_p(0)$ is the electron concentration just outside the depletion region on the *p*-side

Definition of Particle Flux

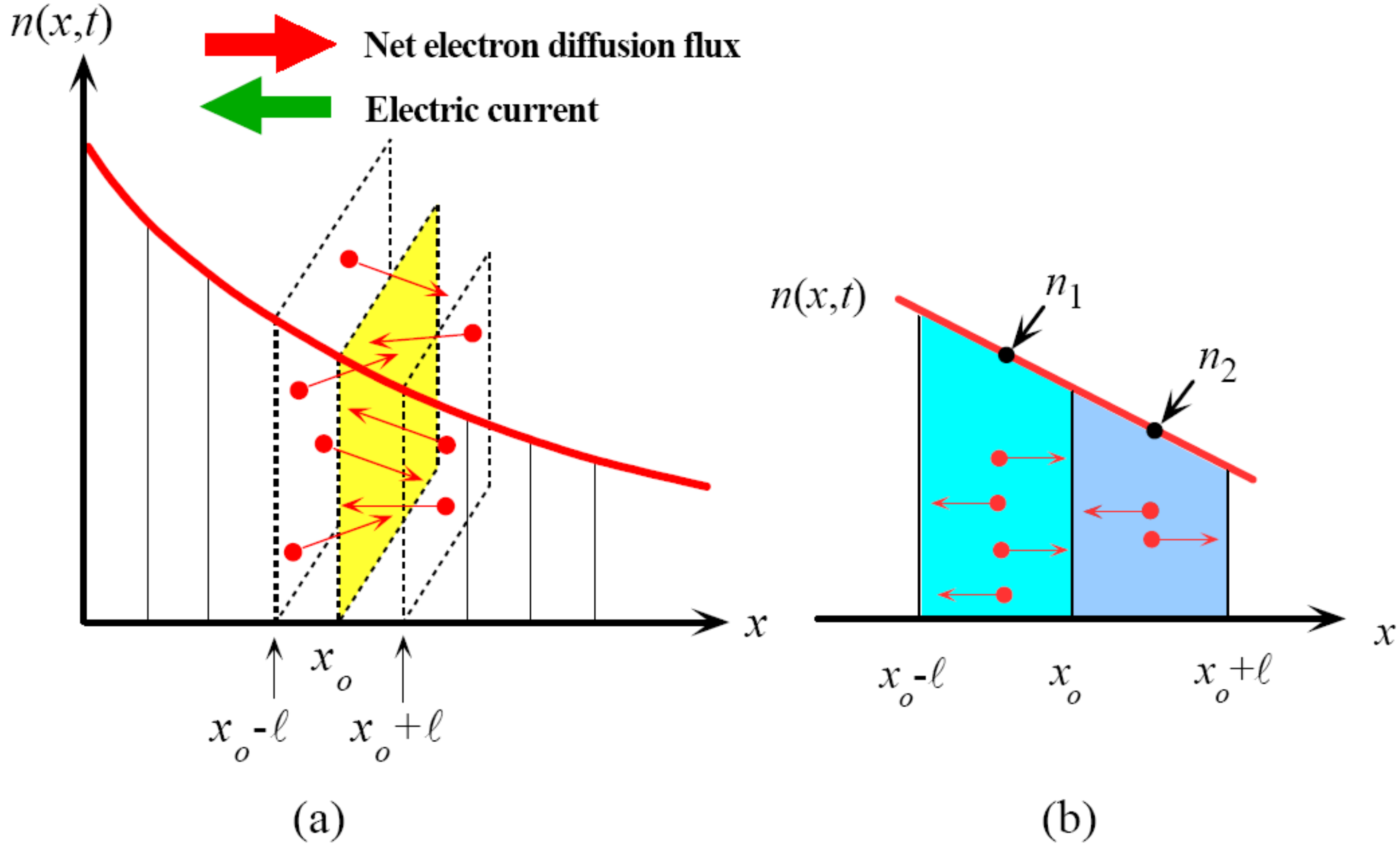
$$\Gamma = \frac{\Delta N}{A \Delta t}$$

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



$$\Gamma_e = \frac{\frac{1}{2}n_1 A\lambda - \frac{1}{2}n_2 A\lambda}{A\tau} = -\frac{\lambda}{2\tau}(n_2 - n_1) \qquad (n_2 - n_1) \approx \frac{dn}{dx}\lambda$$

(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-λ) than coming from the right (x_0+λ)

Fick's First Law

$$\Gamma_e = -\frac{\lambda^2}{2\tau}\left(\frac{dn}{dx}\right) \qquad \Gamma_e = -D_e\frac{dn}{dx}$$

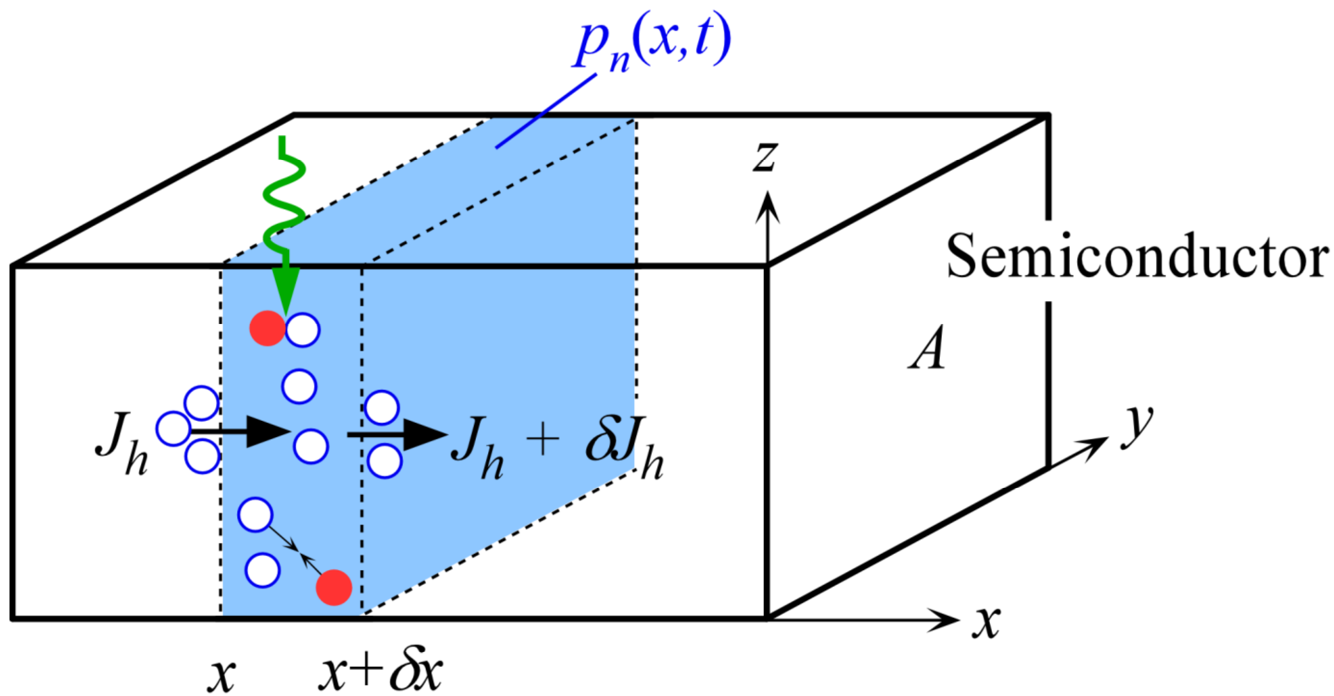
Γ_e = electron flux, D_e = diffusion coefficient of electrons, dn/dx = electron concentration gradient

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

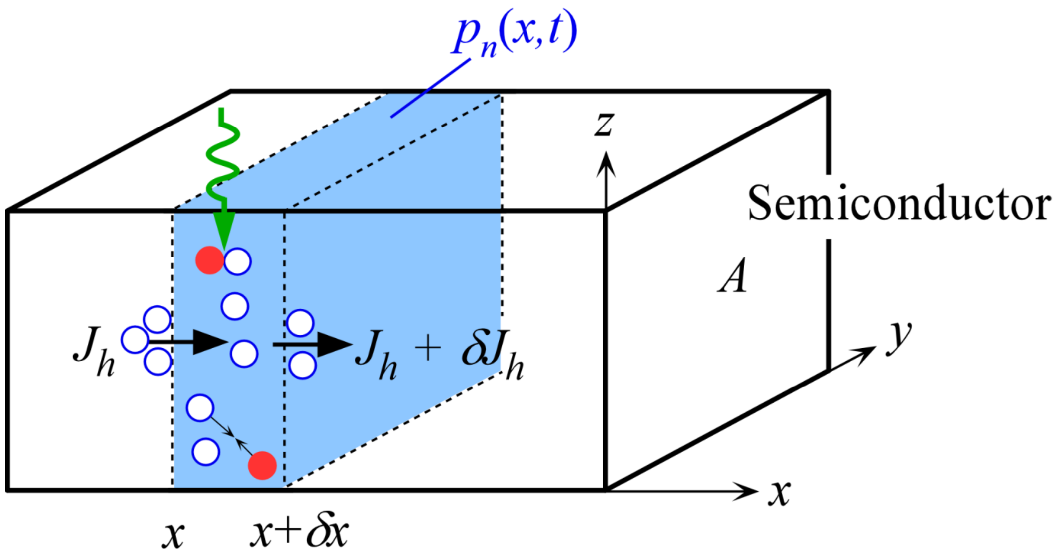
Continuity Equation



Consider an elemental volume $A\delta$x in which the instantaneous hole concentration is $p(x, t)$. The electric current flow and hole drift are in the same direction.

Fig 5.34

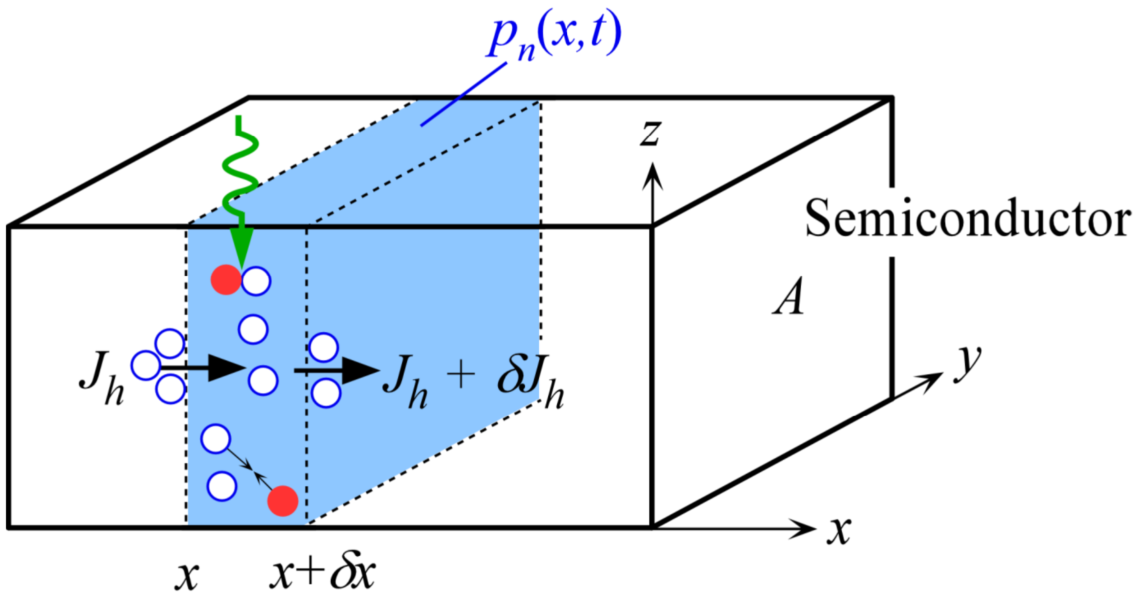
Continuity Equation



$$\frac{1}{A\delta x}\left(\frac{-A\,\delta J_h}{e}\right)$$ =

Rate of increase in hole concentration due to the change in J_h.

Continuity Equation



The *net* rate of increase in the hole concentration p_n in $A\delta x$

= Rate of increase due to decrease in J_h

+ Rate of photogeneration

− Rate of recombination

Continuity Equation for Holes

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

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

OR

$$\frac{\partial \Delta p_n}{\partial t} = -\frac{1}{e}\left(\frac{\partial J_h}{\partial x}\right) - \frac{\Delta p_n}{\tau_h} + G_{\mathrm{ph}}$$

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

Steady-State Continuity Equation for Holes

No t dependence $\therefore$ $\partial/\partial t = 0$

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

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

$$L_h = \sqrt{(D_h \tau_h)}$$

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

$$J_e = en\mu_e \mathcal{E}_x + eD_e \frac{dn}{dx}$$

J_e = electron current due to drift and diffusion, n = electron concentration, μ_e = electron drift mobility, $\mathcal{E}_x$ = 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

$$J_h = ep\mu_h \mathcal{E}_x - eD_h \frac{dp}{dx}$$

J_h = hole current due to drift and diffusion, p = hole concentration, μ_h = hole drift mobility, $\mathcal{E}_x$ = 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

Forward Bias: Diffusion Current

Excess minority carrier concentration profile

$$\frac{\partial^2 \Delta p_n}{\partial x^2} = \frac{\Delta p_n}{L_h^2} \Longrightarrow \Delta p_n(x') = \Delta p_n(0)\exp\left(-\frac{x'}{L_h}\right)$$

where L_h is the hole diffusion length, defined by $L_h = \sqrt{D_h \tau_h}$ in which τ_h is the mean hole recombination lifetime (minority carrier lifetime in the *n*-region.

$L_h \sim 1 – 100$ µm , $\tau_h \sim 1$ ns – 10 µs

Excess minority carrier concentration

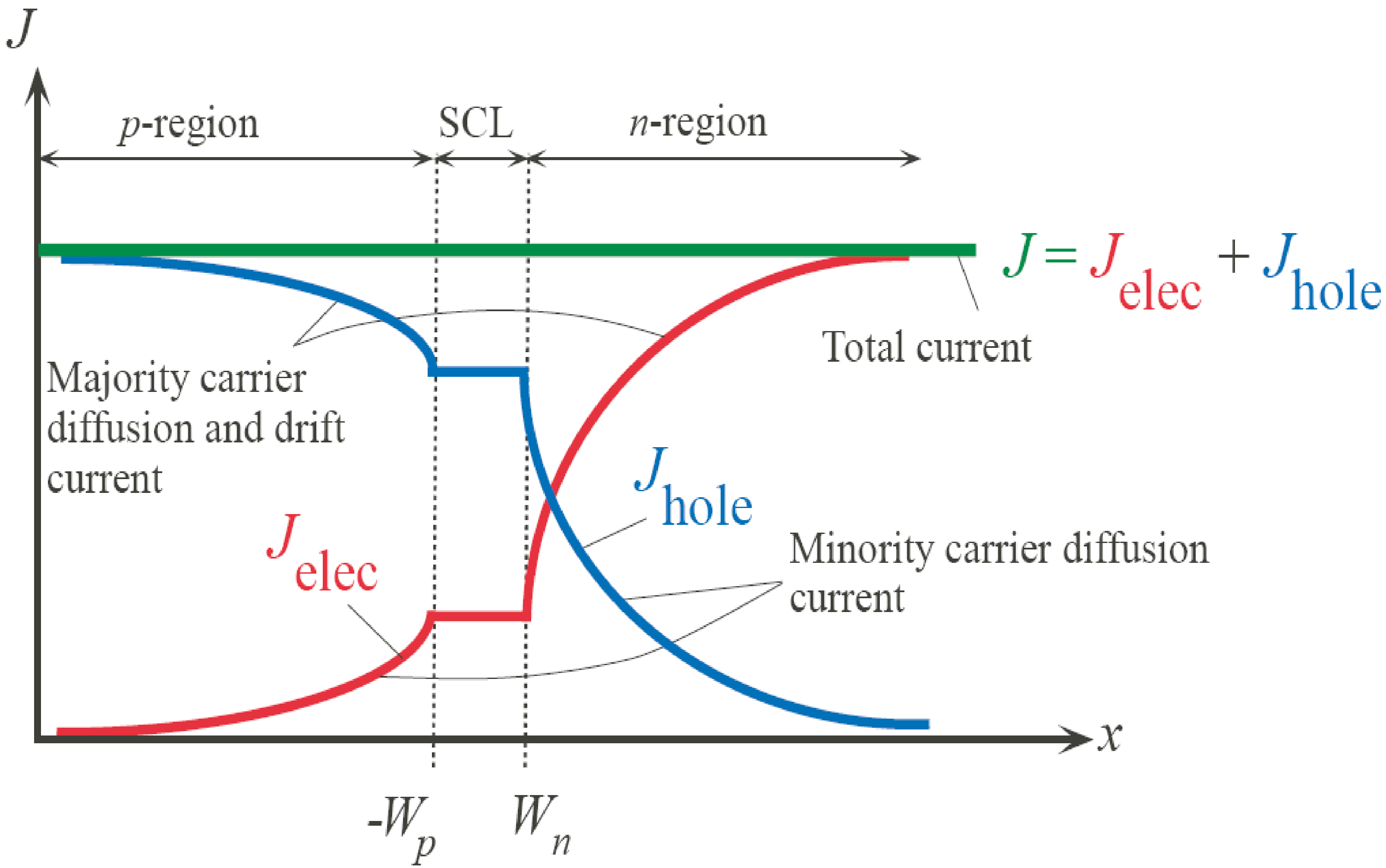
$$\Delta p_n(x') = p_n(x') - p_{no}$$

Forward Bias: Diffusion Current Density

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

$$J_{D,hole} = -eD_h\frac{dp_n(x')}{dx'} = -eD_h\frac{d\Delta p_n(x')}{dx'}$$

$$J_{D,hole} = \left(\frac{eD_h}{L_h}\right)\Delta p_n(0)\exp\left(-\frac{x'}{L_h}\right)$$



The total current anywhere in the device is constant. Just outside the depletion region it is due to the diffusion of minority carriers.

Minority carrier diffusion current at *x'* = 0

$$J_{D,hole} = \left(\frac{eD_h}{L_h}\right)\Delta p_n(0)$$

$$\Delta p_n(0) = p_n(0) - p_{no} = p_{no}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

$$p_{no} = \frac{n_i^2}{n_{no}} = \frac{n_i^2}{N_D}$$

Forward Bias: Diffusion Current

Hole diffusion current in *n*-side in the neutral region

$$J_{D,\mathrm{hole}} = \left(\frac{eD_h n_i^2}{L_h N_d}\right)\left[\exp\left(\frac{eV}{kT}-1\right)\right]$$

There is a similar expression for the electron diffusion current density $J_{D,\mathrm{elec}}$ in the *p*-region.

Forward Bias: Diffusion Current

Ideal diode (Shockley) equation

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

Reverse saturation current

$$J_{so} = \left[\left(\frac{eD_h}{L_h N_d}\right) + \left(\frac{eD_e}{L_e N_a}\right)\right] n_i^2$$

Forward Bias: Diffusion Current

Intrinsic concentration

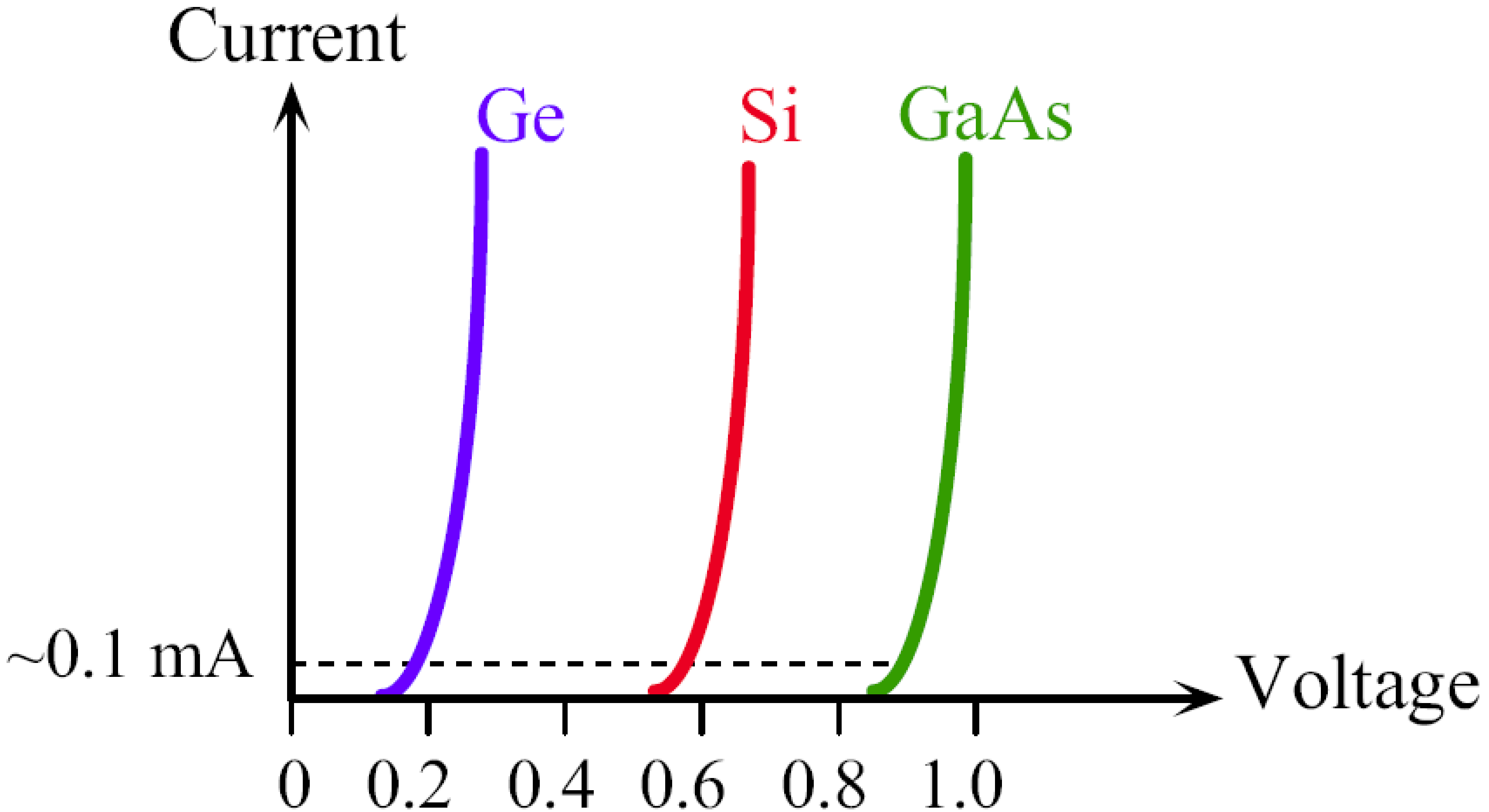
$$n_i^2 = (N_c N_v)\exp\left(-\frac{eV_g}{kT}\right)$$

where $V_g = E_g / e$ is the bandgap energy expressed in volts

$V_g =$ 0.67 V for Ge, 1.1 V for Si, and 1.42 V for GaAs

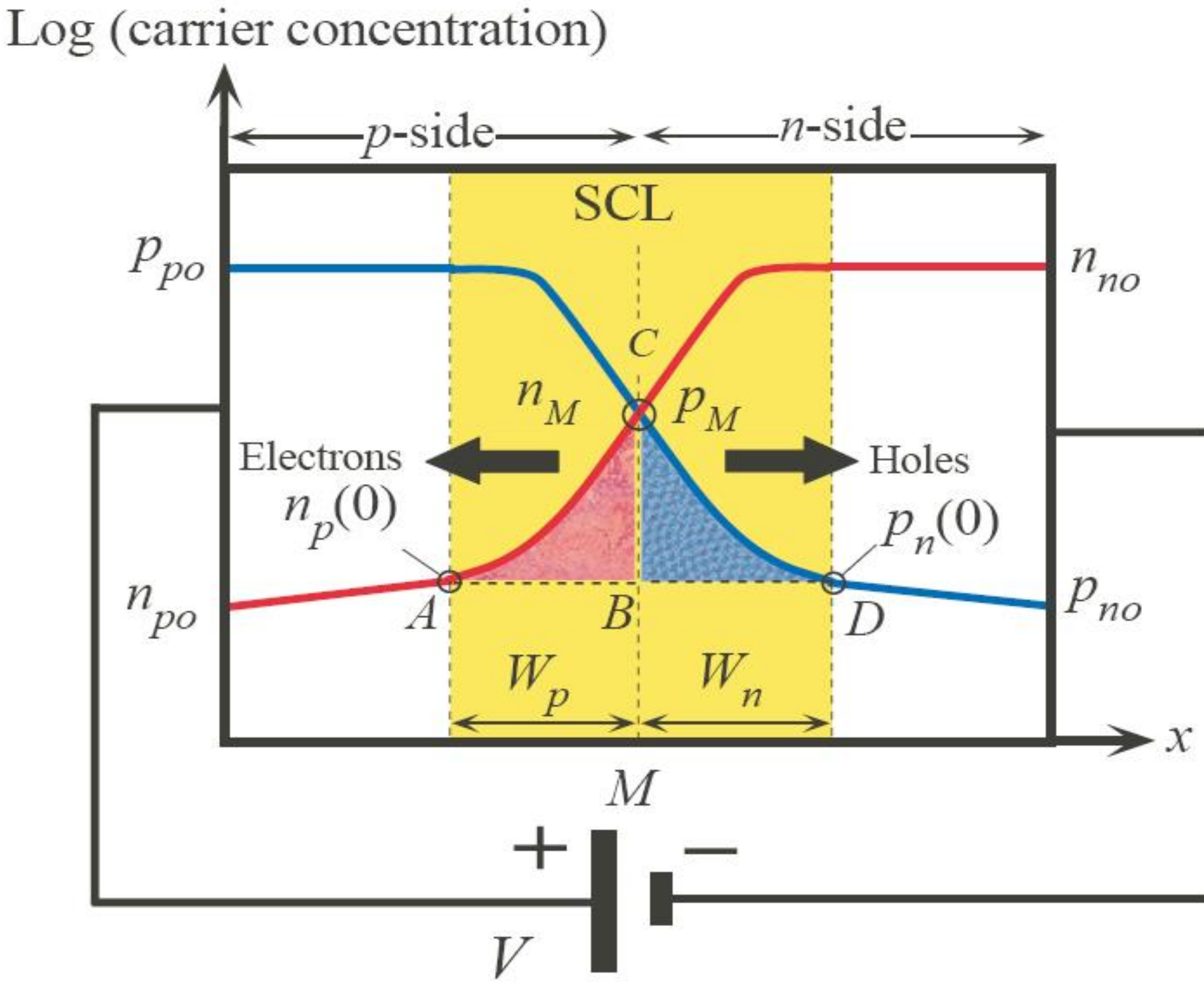
$$J = J_{so}\exp\left(\frac{eV}{kT}\right) = C\exp\left(\frac{e(V - V_g)}{kT}\right) \qquad V > kT/e$$

We can plot I vs. V for Ge, Si and Ge



Schematic sketch of the I-V characteristics of Ge, Si, and GaAs pn junctions.

Forward Bias: Recombination and Total Current



Forward biased pn junction and the injection of carriers and their recombination in the SCL

Fig 6.6

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

Forward bias: Recombination Current

$$J_{\text{recom}} = \frac{eABC}{\tau_e} + \frac{eBCD}{\tau_h}$$

$$ABC \approx \frac{1}{2} W_p n_M \qquad BCD \approx \frac{1}{2} W_n p_M$$

$$\frac{p_M}{p_{po}} = \exp\left(-\frac{e(V_0 - V)}{2kT} \right)$$

$$p_M = p_{po} \exp\left(-\frac{eV_0}{2kT} \right) \exp\left(\frac{eV}{2kT} \right) = n_i \exp\left(\frac{eV}{2kT} \right)$$

Forward Bias: Recombination and Total Current

Recombination Current

$$J_{\mathrm{recom}} = J_{ro}[\exp(eV/2kT) - 1] \quad \text{where } J_{ro} = \frac{en_i}{2}\left(\frac{W_p}{\tau_e} + \frac{W_n}{\tau_h}\right)$$

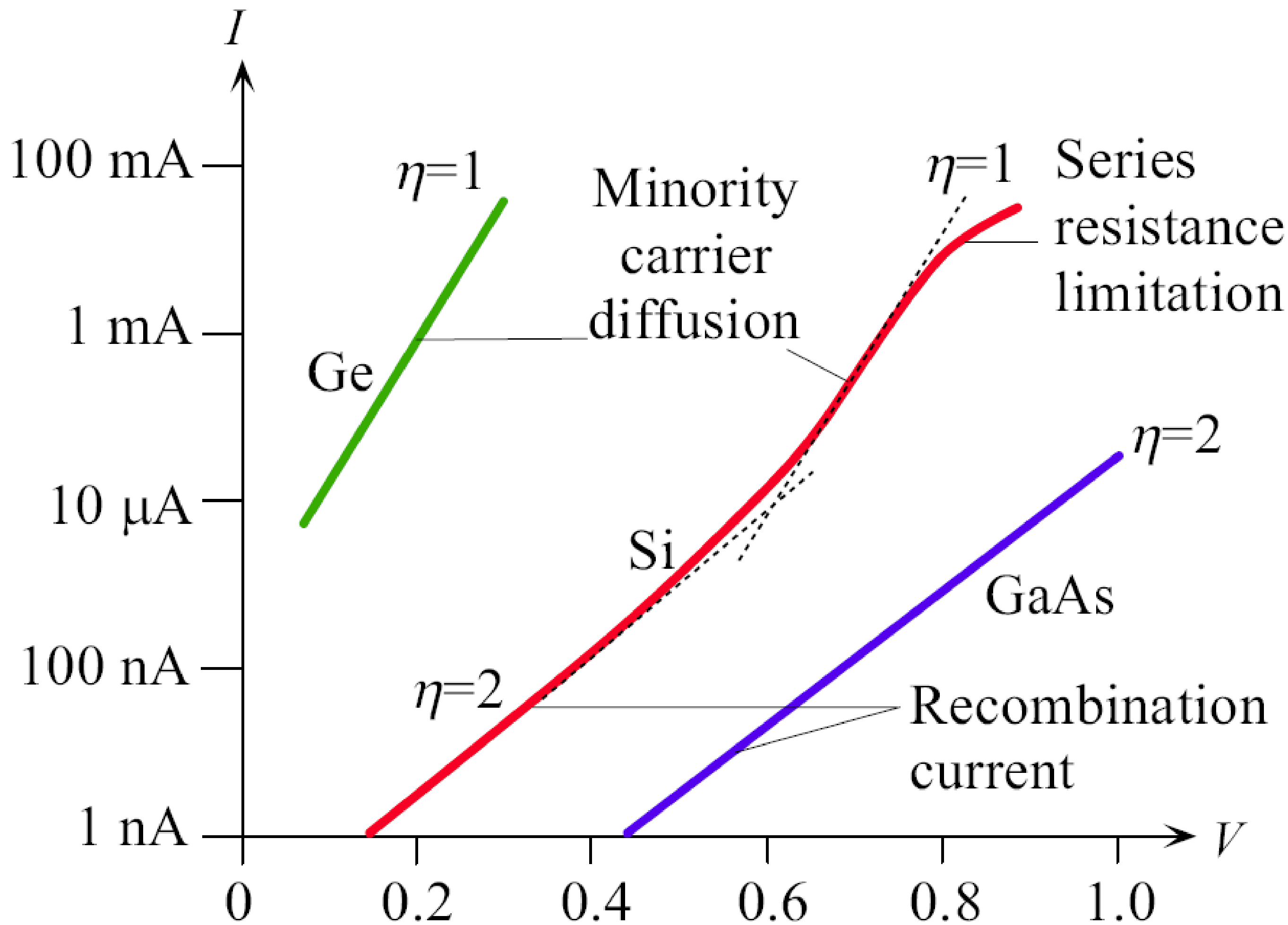
Total diode current = diffusion + recombination

$$J = J_{so}\exp\left(\frac{eV}{kT}\right) + J_{ro}\exp\left(\frac{eV}{2kT}\right) \qquad V > \frac{kT}{e}$$

The diode equation

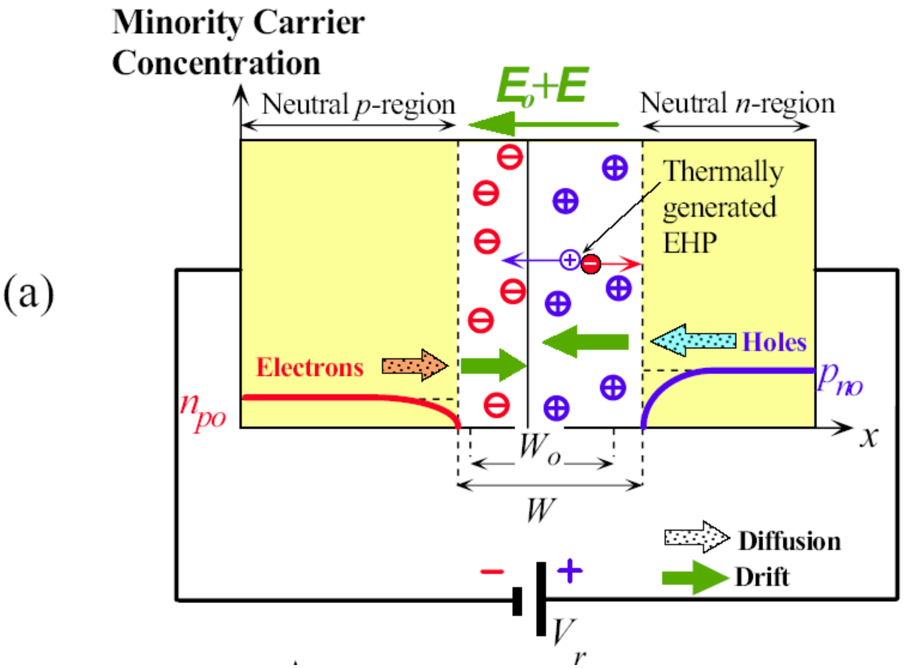
$$J = J_o\exp\left(\frac{eV}{\eta kT}\right) \qquad V > \frac{kT}{e}$$

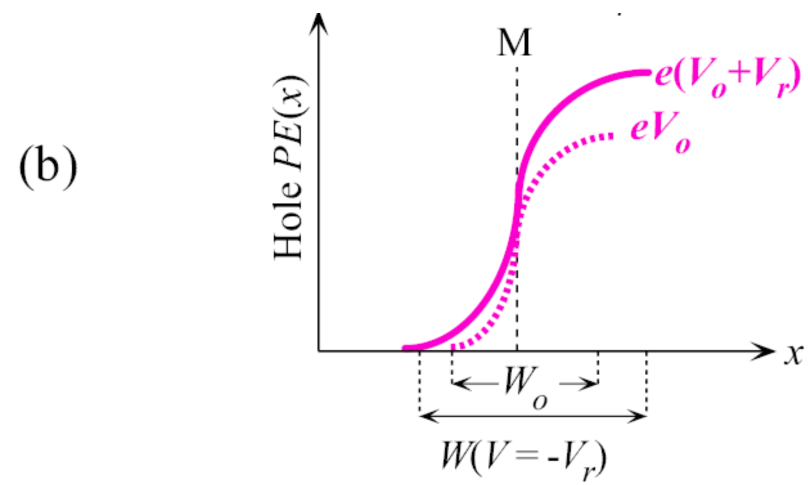
Where J_o is a new constant and η is an ideality factor



Schematic sketch of typical I-V characteristics of Ge, Si and GaAs pn junctions as log(I) vs. V. The slope indicates $e/(\square kT)$

Fig 6.7





Reverse biased pn junction. (a) Minority carrier profiles and the origin of the reverse current. (b) Hole PE across the junction under reverse bias

Fig 6.8

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

Reverse Bias

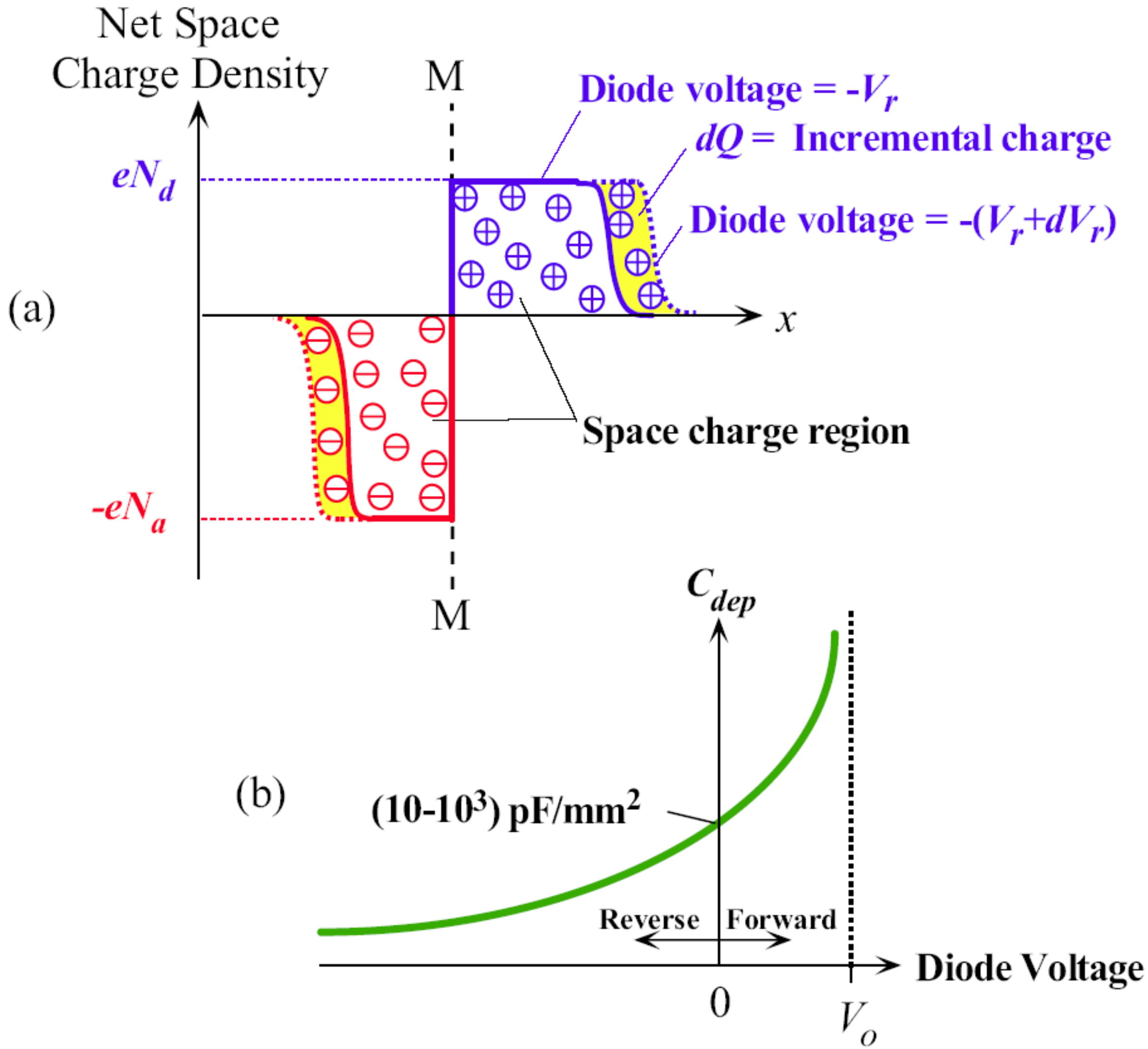
Total Reverse Current

Thermal generation in depletion region

$$J_{\mathrm{rev}} = \underbrace{\left(\frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a} \right) n_i^2}_{\text{Diffusion current in neutral regions}} + \overbrace{\frac{eWn_i}{\tau_g}}^{\text{Thermal generation in depletion region}}$$

Mean thermal generation time

Diffusion current in neutral regions
the Shockley reverse current



The depletion region behaves like a capacitor.

(a) The charge in the depletion region depends on the applied voltage just as in a capacitor

(b) The incremental capacitances of the depletion region increases with forward bias and decreases with reverse bias. Its value is typically in the range of picofarads per mm^2

Fig 6.12

Depletion layer capacitance of the pn junction

Depletion region width

$$W = \left[\frac{2\varepsilon (N_a + N_d)(V_o - V)}{eN_a N_d} \right]^{1/2}$$

where, for forward bias, V is positive, which reduces V_o, and, for reverse bias, V is negative , so V_o is increased.

Definition of depletion layer capacitance C_{dep}

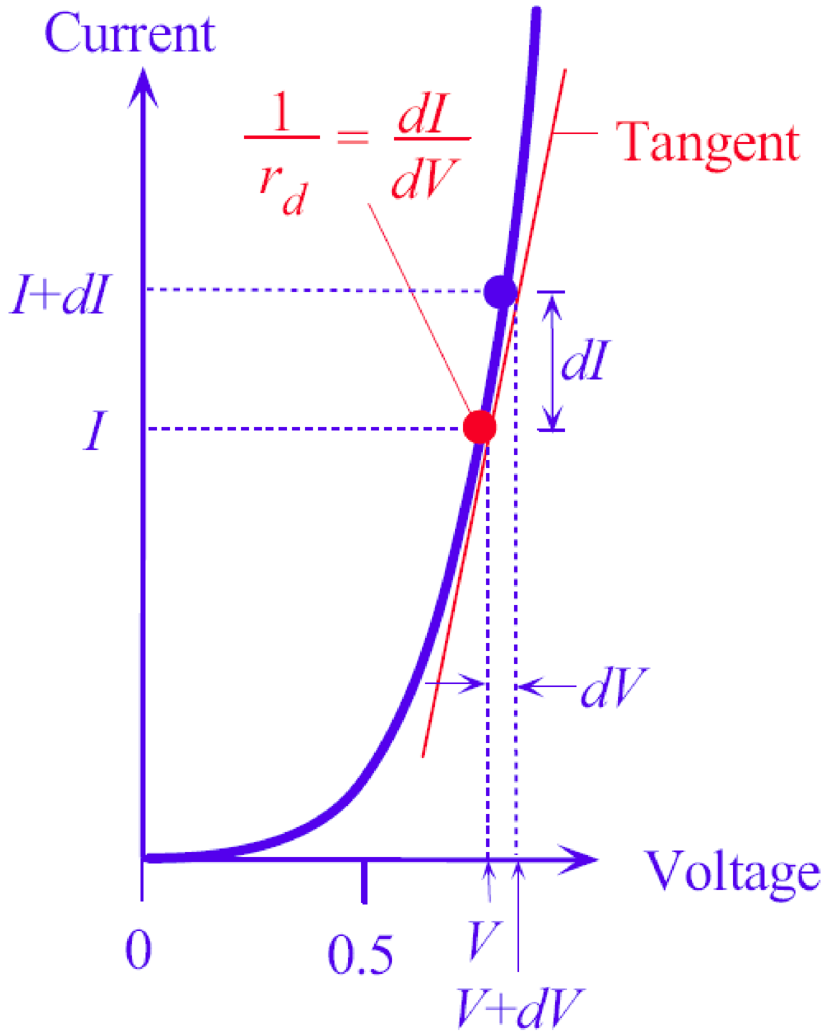
$$C_{\mathrm{dep}} = \left| \frac{dQ}{dV} \right|$$

where the amount of charge on any one side of the depletion layer is $|Q| = eN_d W_n A = eN_a W_p A$ and $W = W_n + W_p$

Depletion Capacitance

$$C_{\mathrm{dep}} = \frac{\varepsilon A}{W} = \frac{A}{\left(V_o - V\right)^{1/2}}\left[\frac{e\varepsilon\left(N_a N_d\right)}{2\left(N_a + N_d\right)}\right]^{1/2}$$

Varactor diodes (varicaps) are based on this effect, providing tuning circuits with voltage-dependent capacitors



The dynamic resistance of the diode is defined as *dV/dI* which is the inverse of the tangent at *I*.

Fig 6.14

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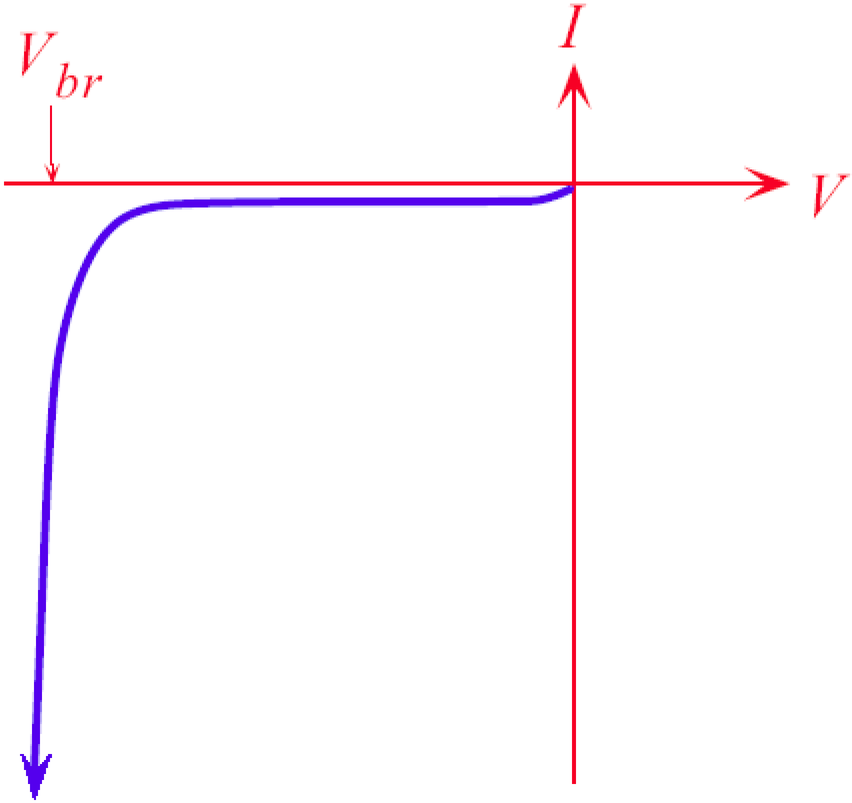
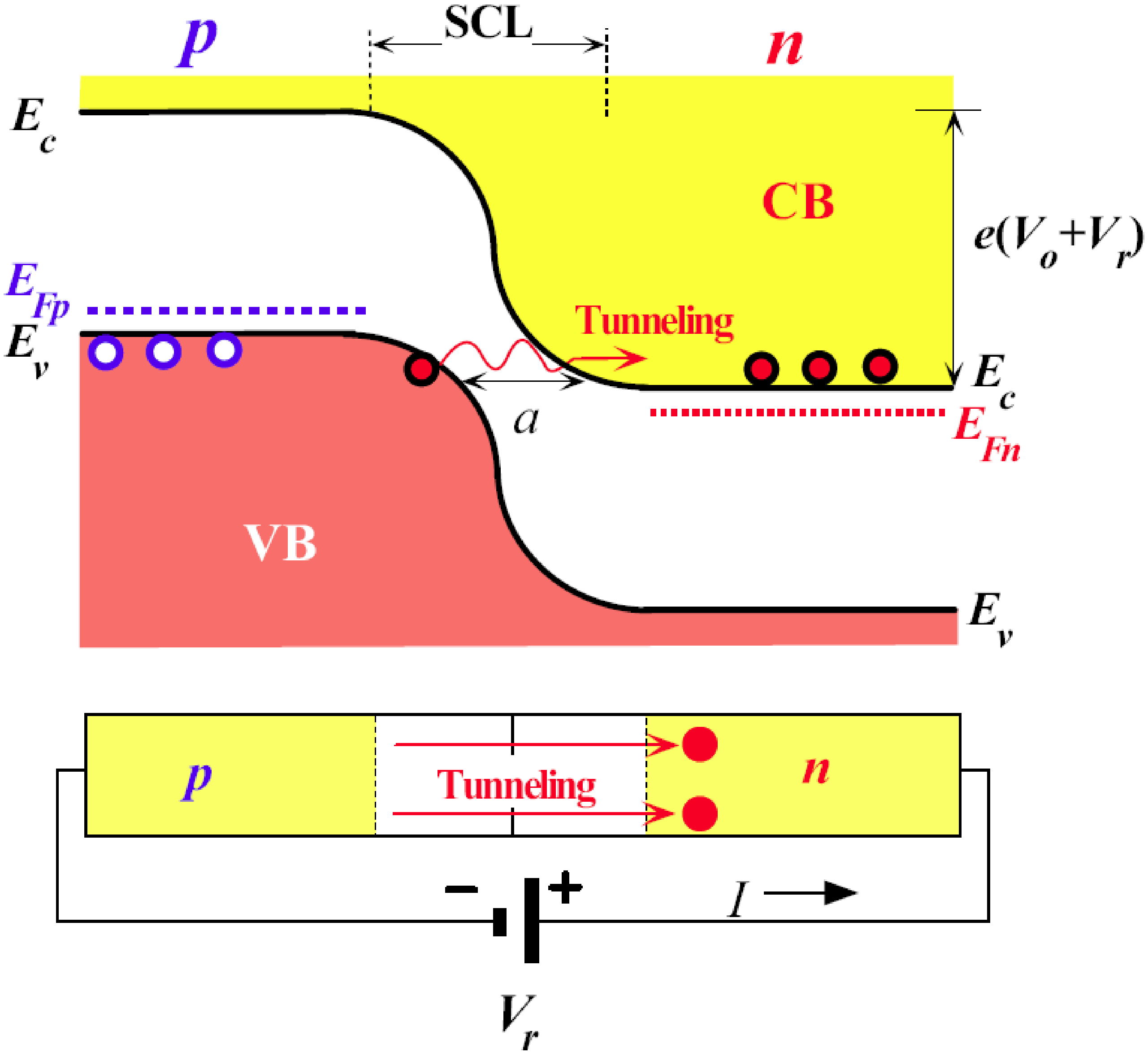


$$M = \frac{1}{1-\left(\frac{V_r}{V_{br}}\right)^n} \quad , \quad n \approx 3-5$$

Reverse *I-V* characteristics of a *pn* junction.

Fig 6.15



Zener breakdown involves electrons tunneling from the VB of p side to the CB of *n*-side when the reverse bias reduces E_c to line up with E_v.

Fig 6.18

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

Intrinsic carrier mobility

semiconductor	E_g (eV)	u_e ($cm^2V^{-1}s^{-1}$)	u_h ($cm^2V^{-1}s^{-1}$)
c-Si	1.10	1350	450
Ge	0.66	3900	1900
GaAs	1.42	8500	400
CIGS	1.04	1000 (crystal)	~150-300
a-Si:H	1.85	1	0.003
nc-Si:H	1.10	20-100	0.05
OPV	1.6-2.0	0.001	0.001
graphene	0	1500-40 000 200 000 (suspended)	1500-40 000 200 000 (suspended)

Thin films

Minority carrier diffusion length: $L = \sqrt{D\tau}$

Einstein relation: $D = \frac{kT}{e}\mu$