Electronic Materials and Devices

5 Semiconductor

QQ Group:

群名称:电子功能材料与器件

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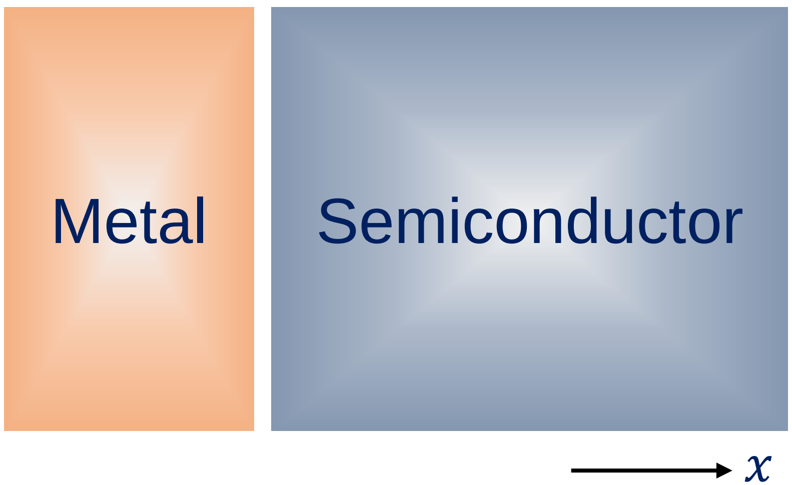
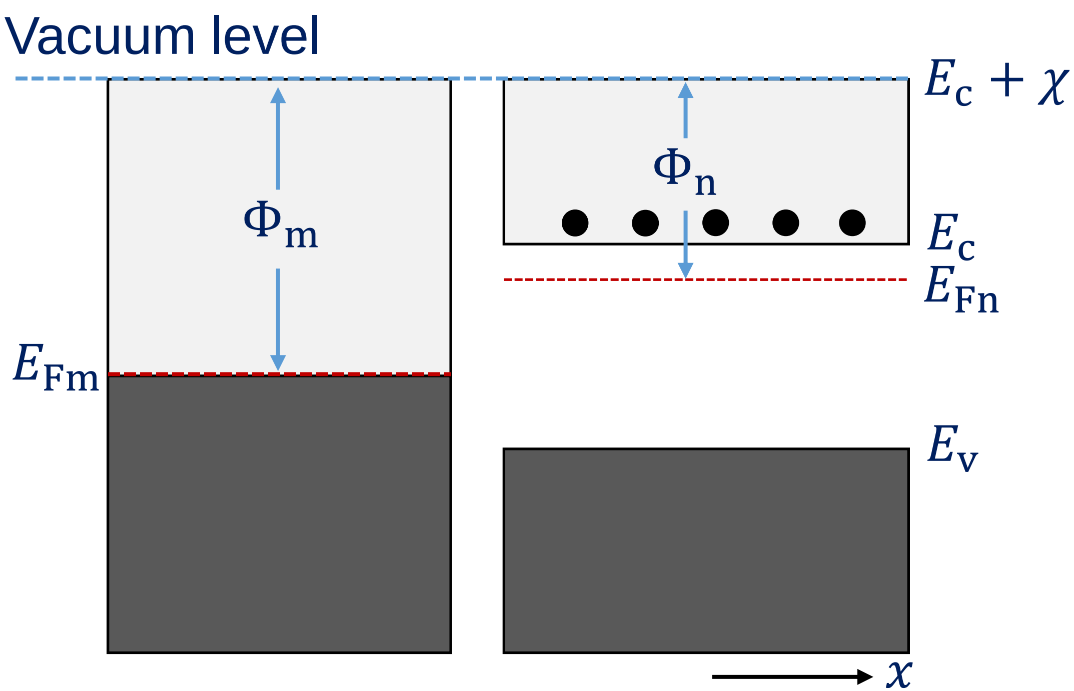
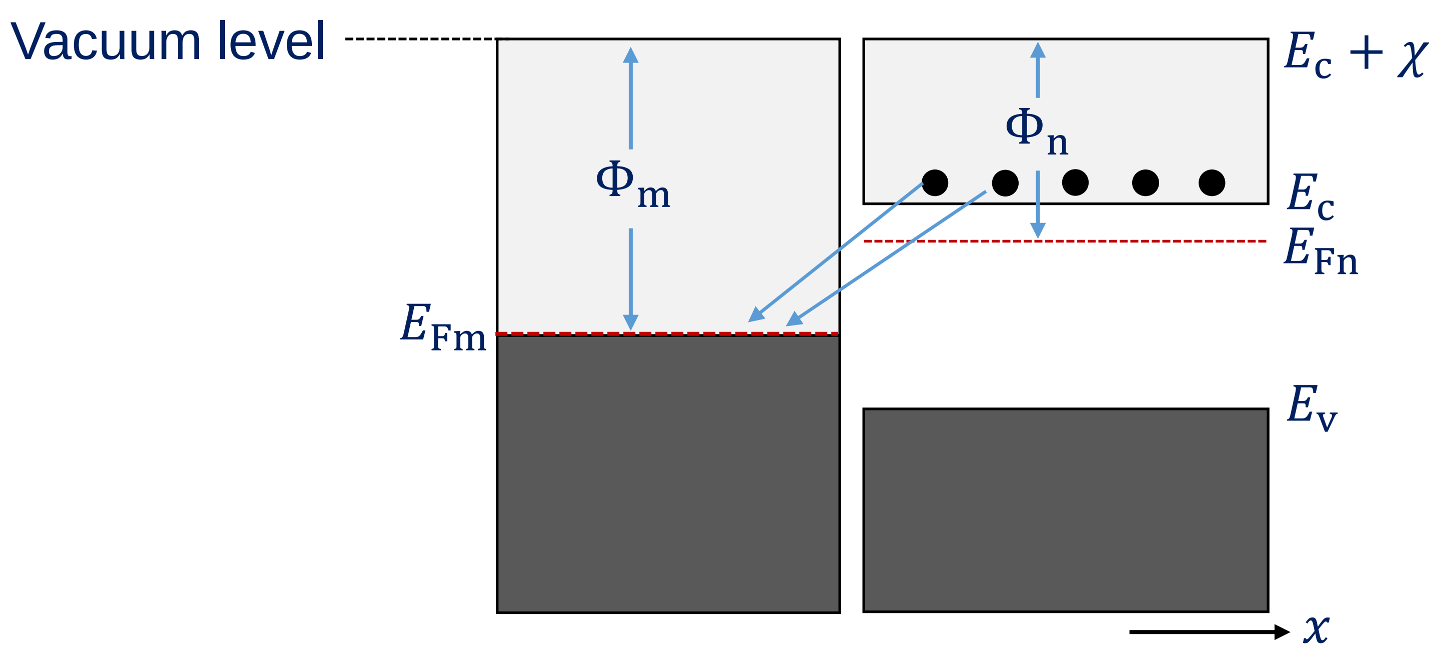
5.1 Schottky junction

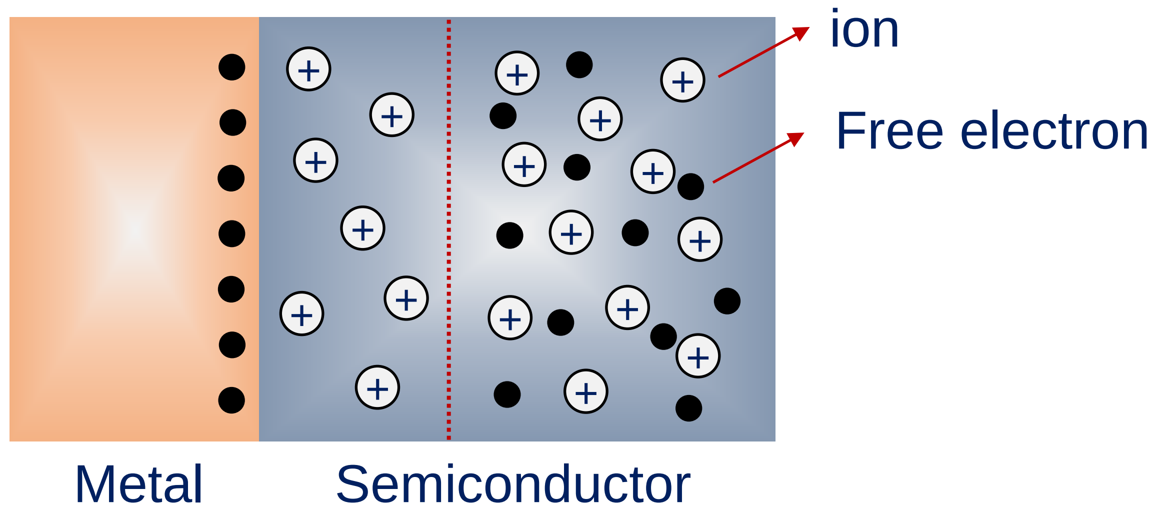
Q: What will happen at the metal-semiconductor interface?



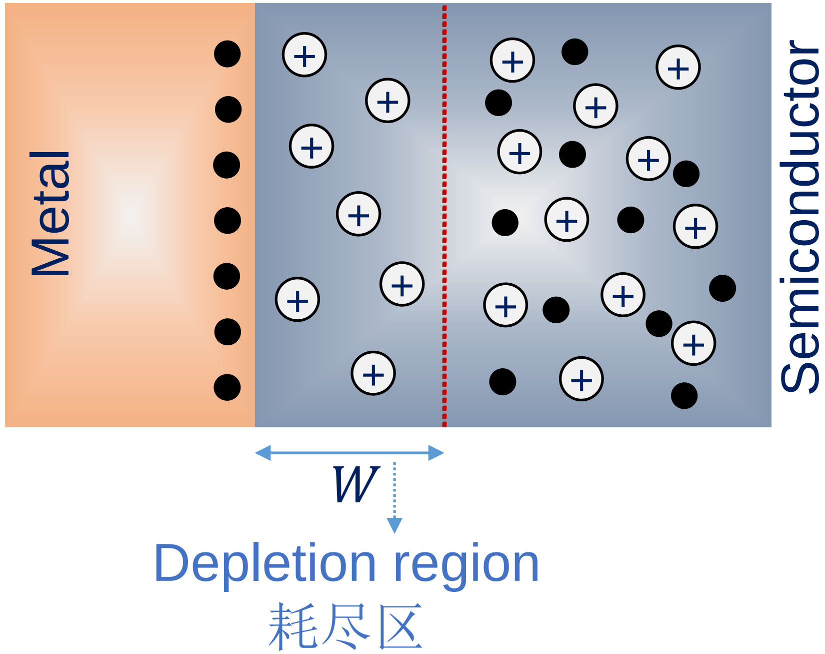




Vacuum level
Φ_{m}
Φ_{n}
$E_{\mathrm{c}} + \chi$
E_{c}
E_{Fn}
E_{Fm}
E_{v}
x

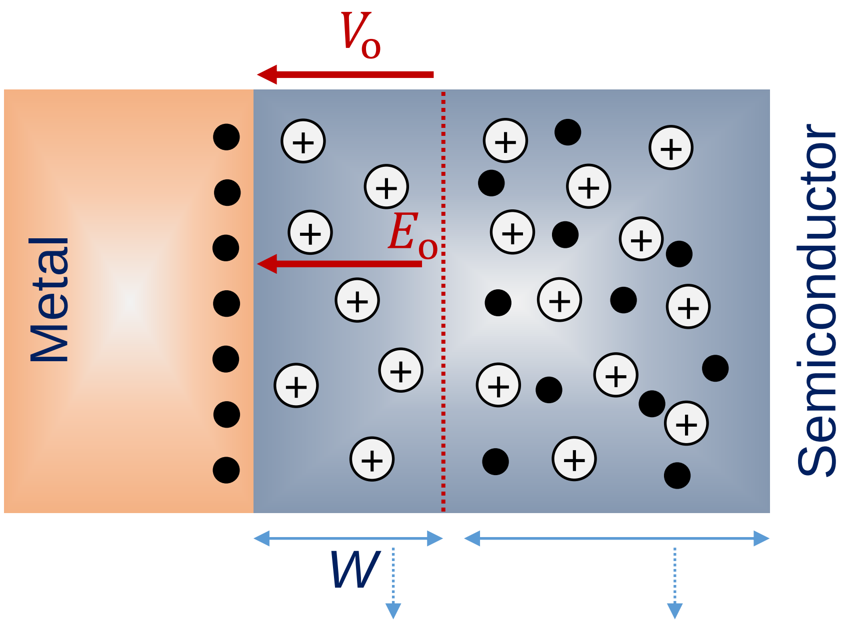


ion
Free electron
Metal
Semiconductor



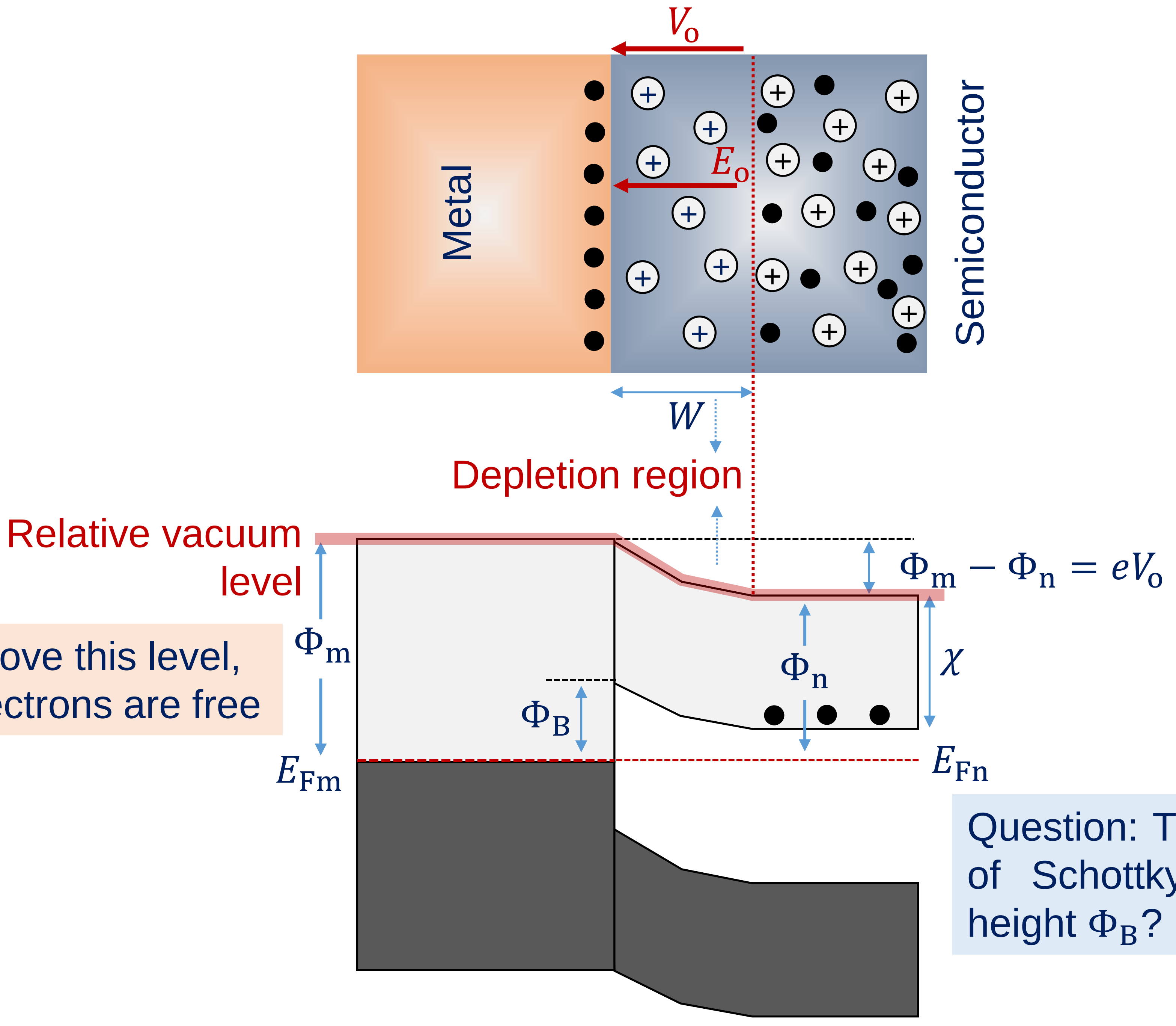
Q: Why depletion region is in semiconductor? (in other words, why there is a width of depletion region?)

Build-in electric field E_o and potential V_o



Depletion region
耗尽区

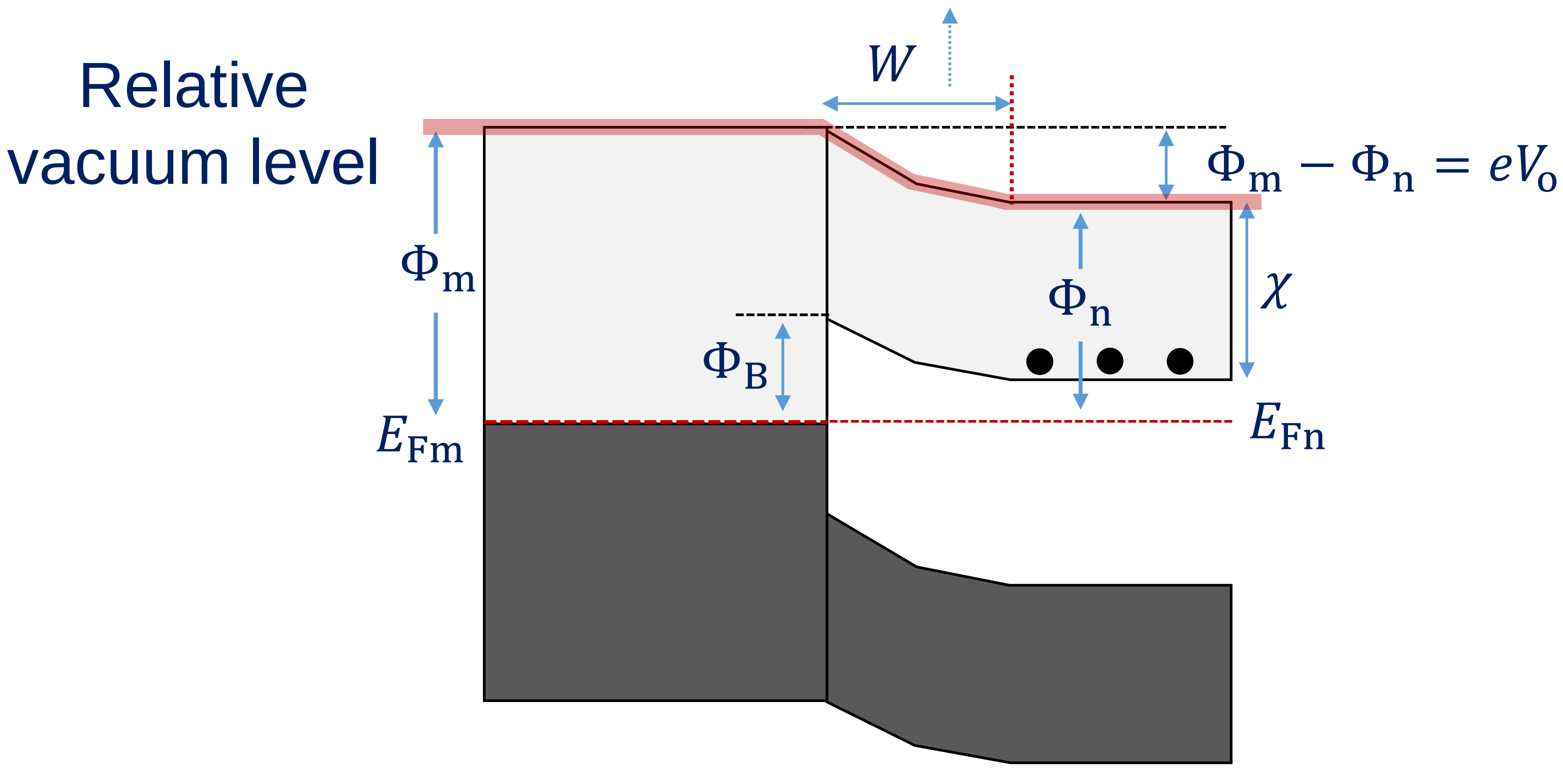
Neutral semiconductor region



Above this level, electrons are free

Question: The value of Schottky barrier height Φ_B?

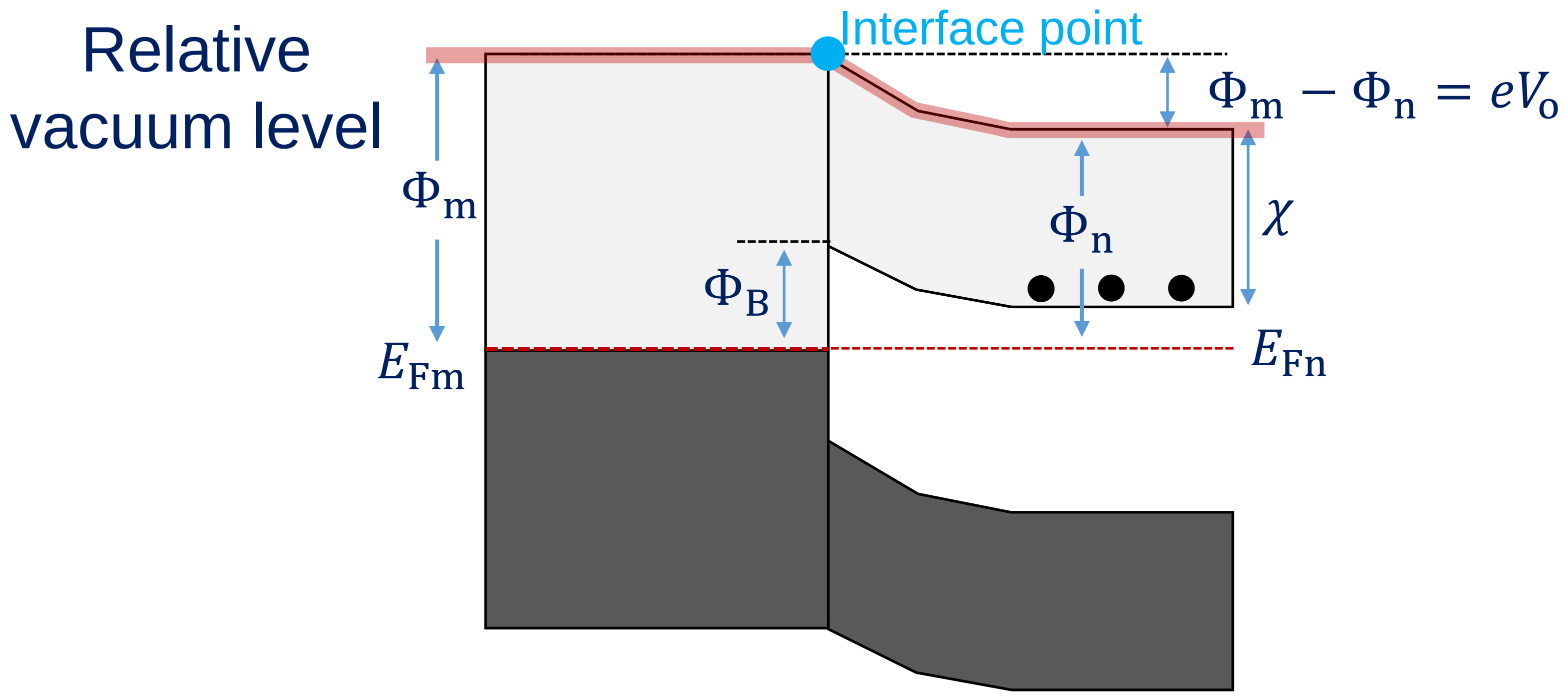
Depletion region 耗尽区

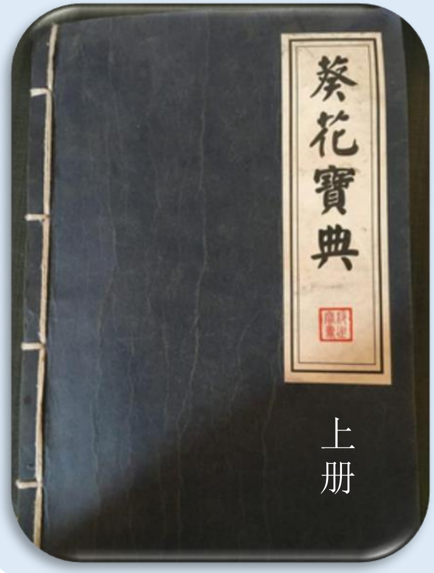


$$\Phi_B = \Phi_m - \chi$$

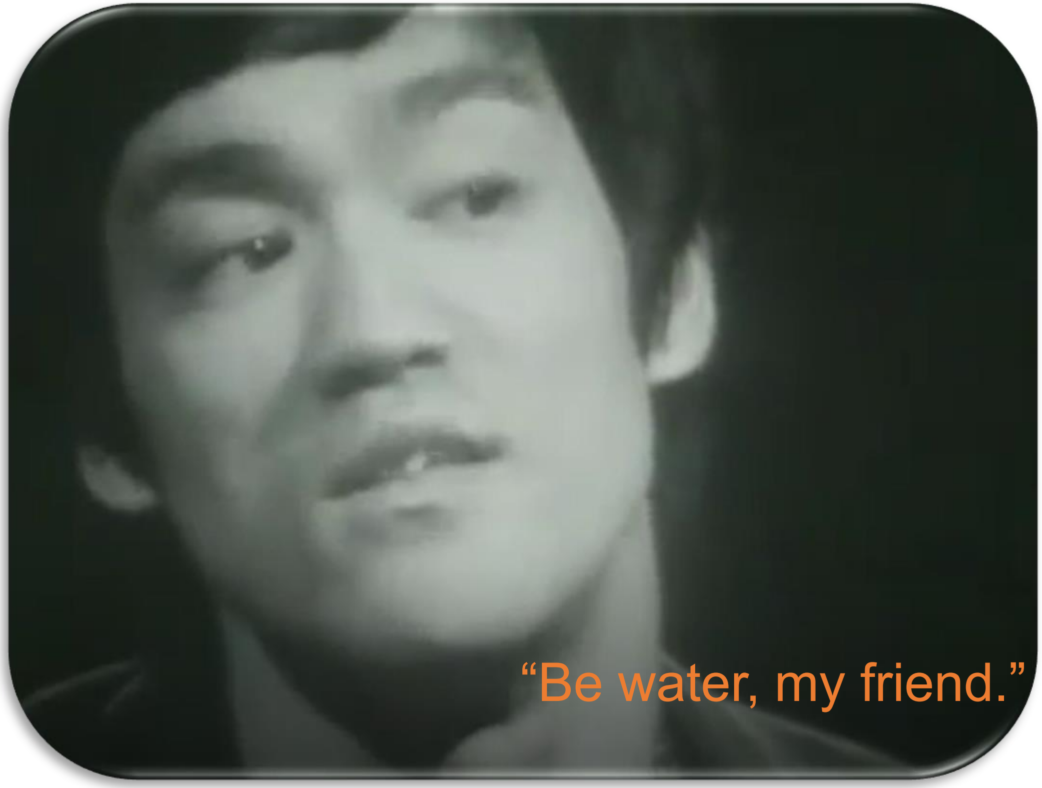
$$= \Phi_n + eV_o - \chi$$

$$= eV_o + (E_c - E_{Fn})$$

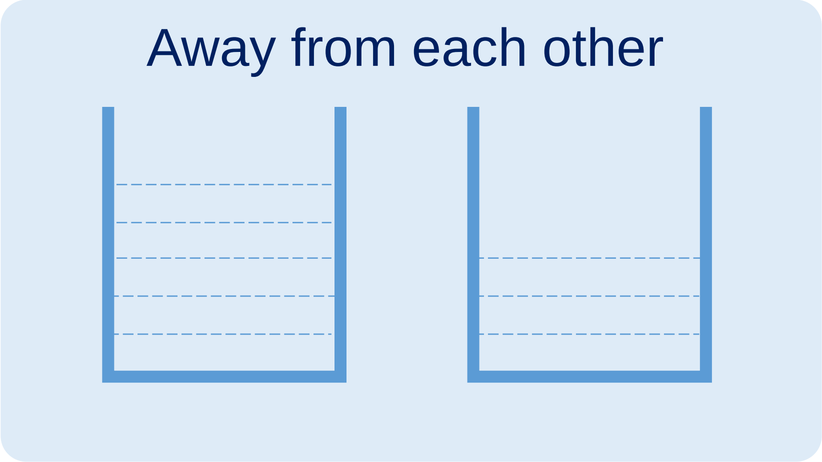


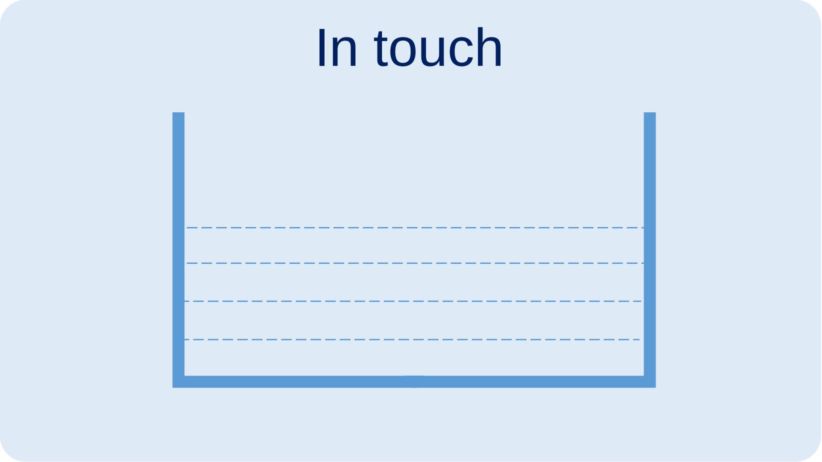


- **If there is no current flow**, the Fermi levels of different materials should be the **same**.
- Lower free carrier density, **larger band bending**.
- The vacuum level at interface point must be **continuous**.
- **Far away from interface**, the relative position of E_F, Φ_n, and χ does not change.

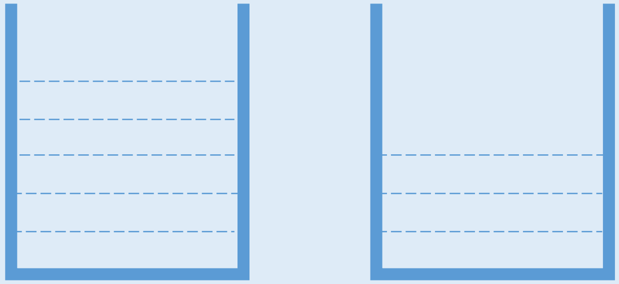


- Treat electrons as water.
- Treat energy band as a cup.
- Treat vacuum level as the upper rim 上缘 of a cup.
- Treat Fermi energy as the water surface.

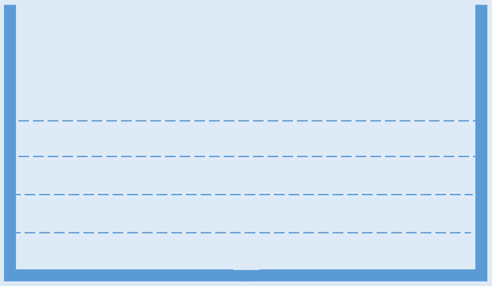




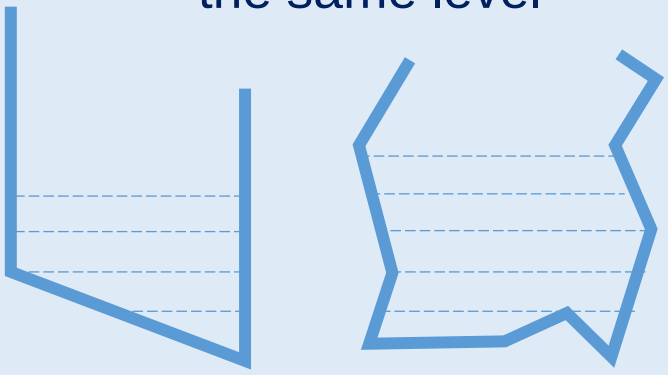
Away from each other



In touch



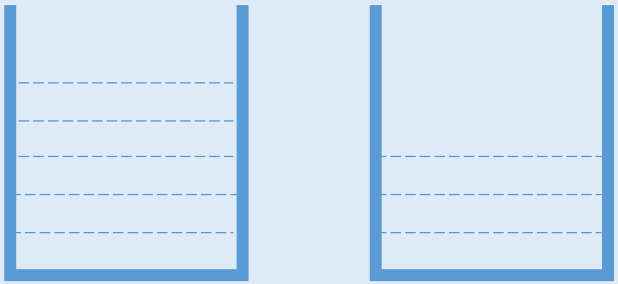
Water surface is always at the same level



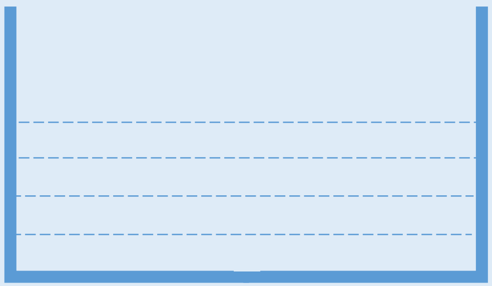
Water surface is tilted only when water flows

Water molecule: charge neutral

Away from each other

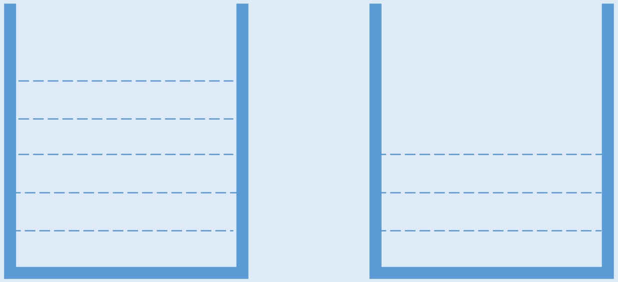


In touch

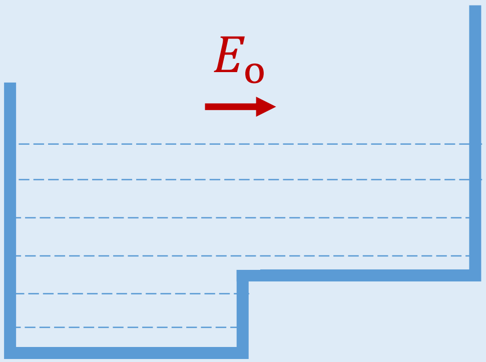


Electron: charged particle

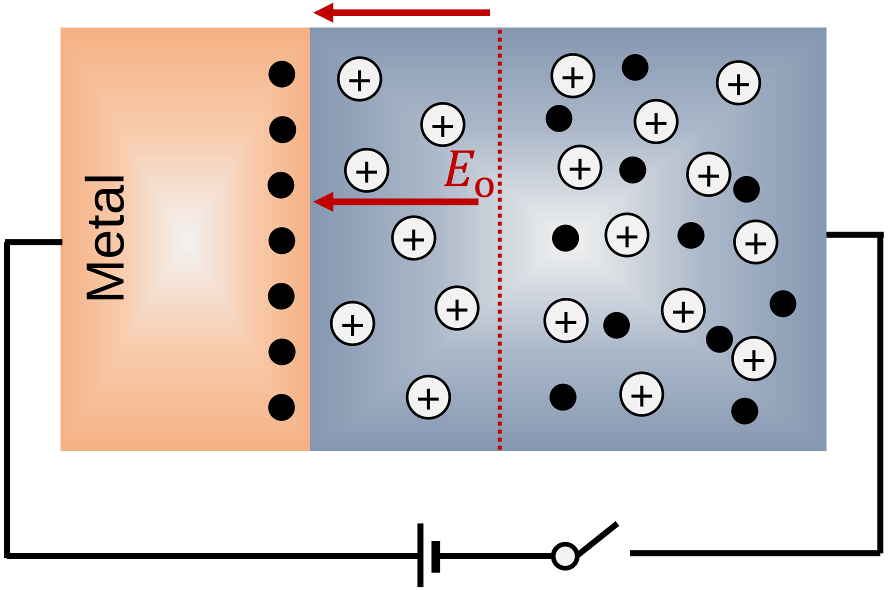
Away from each other

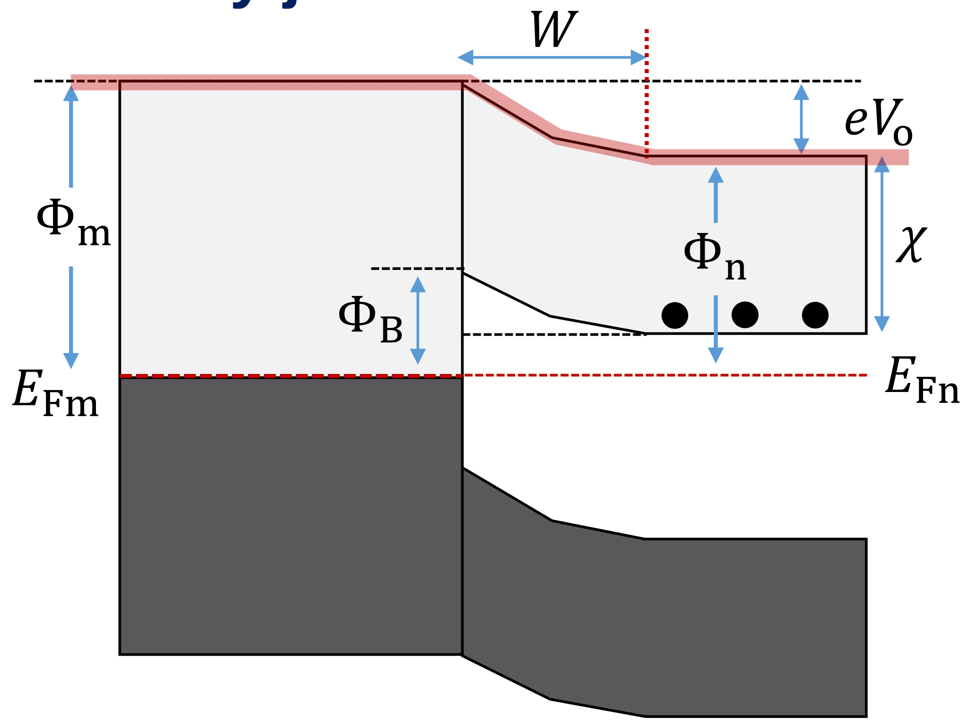


In touch



Current flow in Schottky junction





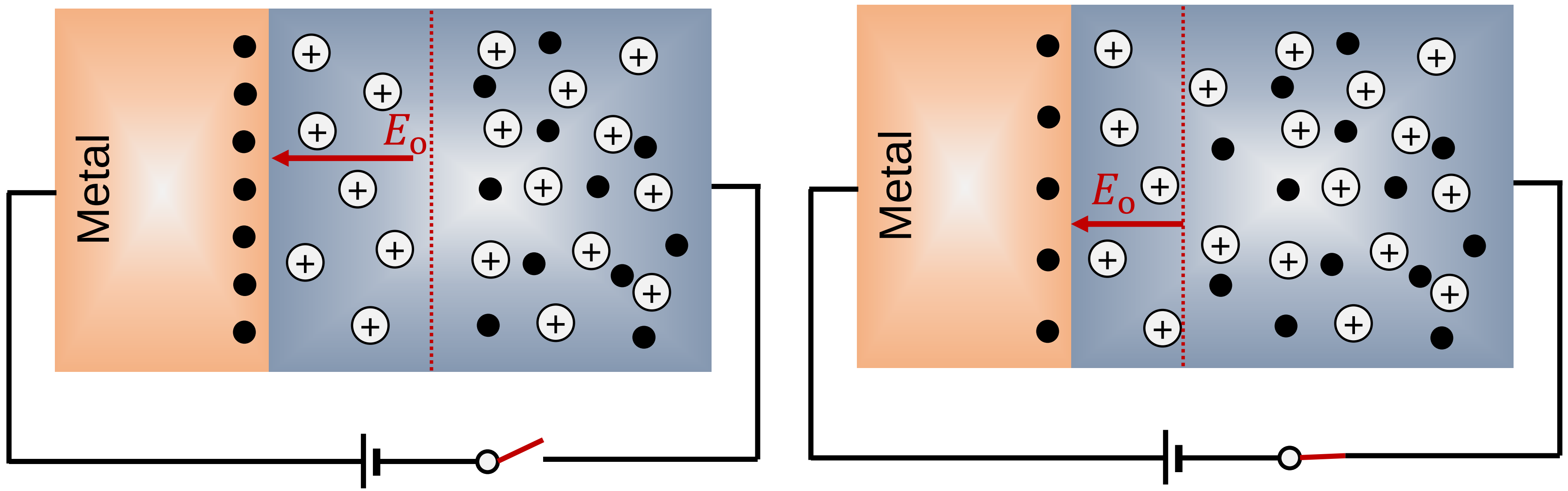
(1) Open circuit

Current from metal to CB of semiconductor: $J_1 = C_1 \exp(-\frac{\Phi_B}{kT})$

Current from CB of semiconductor to metal: $J_2 = C_2 \exp(-\frac{eV_o}{kT})$

For open circuit: $J = J_2 - J_1 = 0$

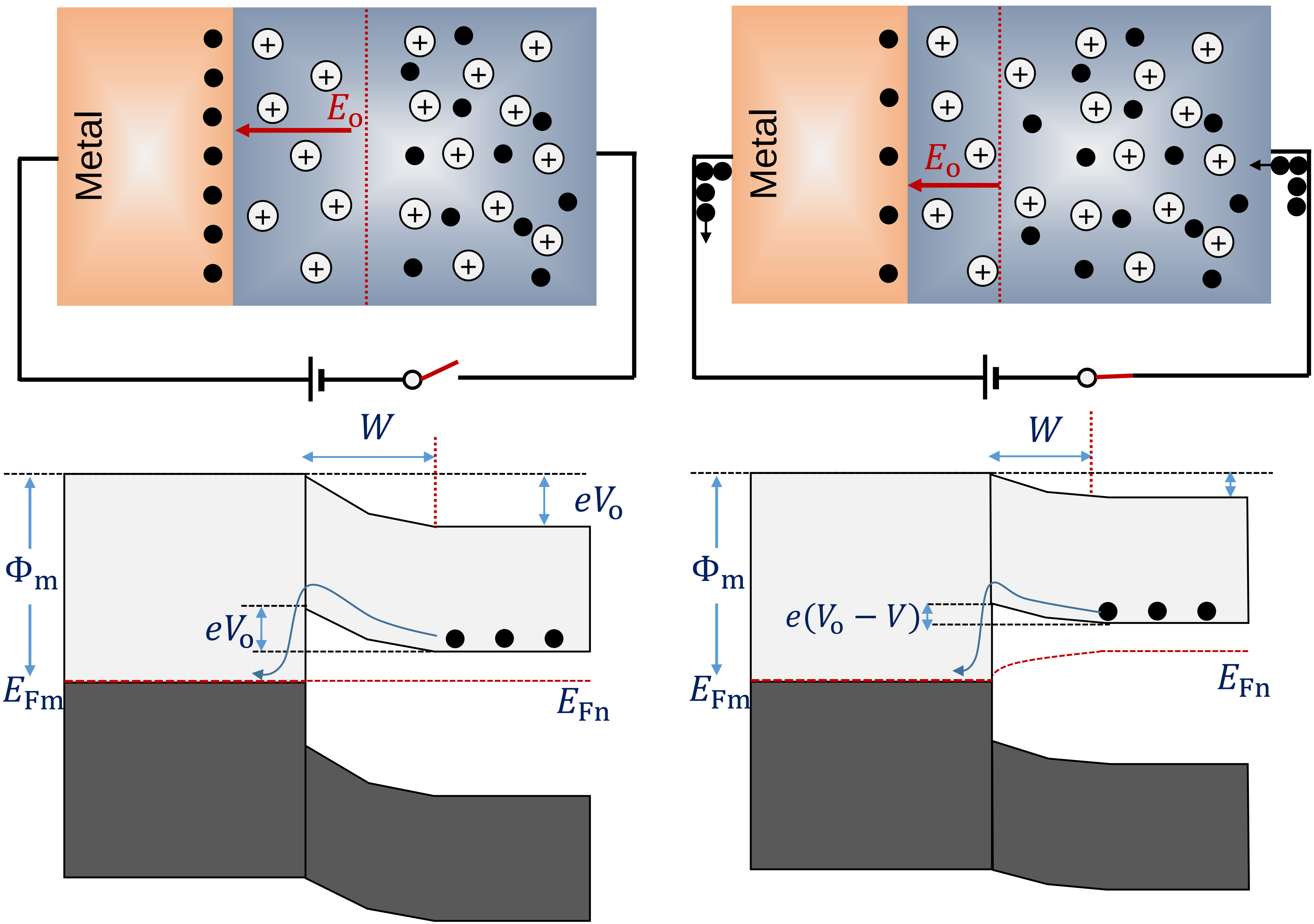
(2) Forward bias



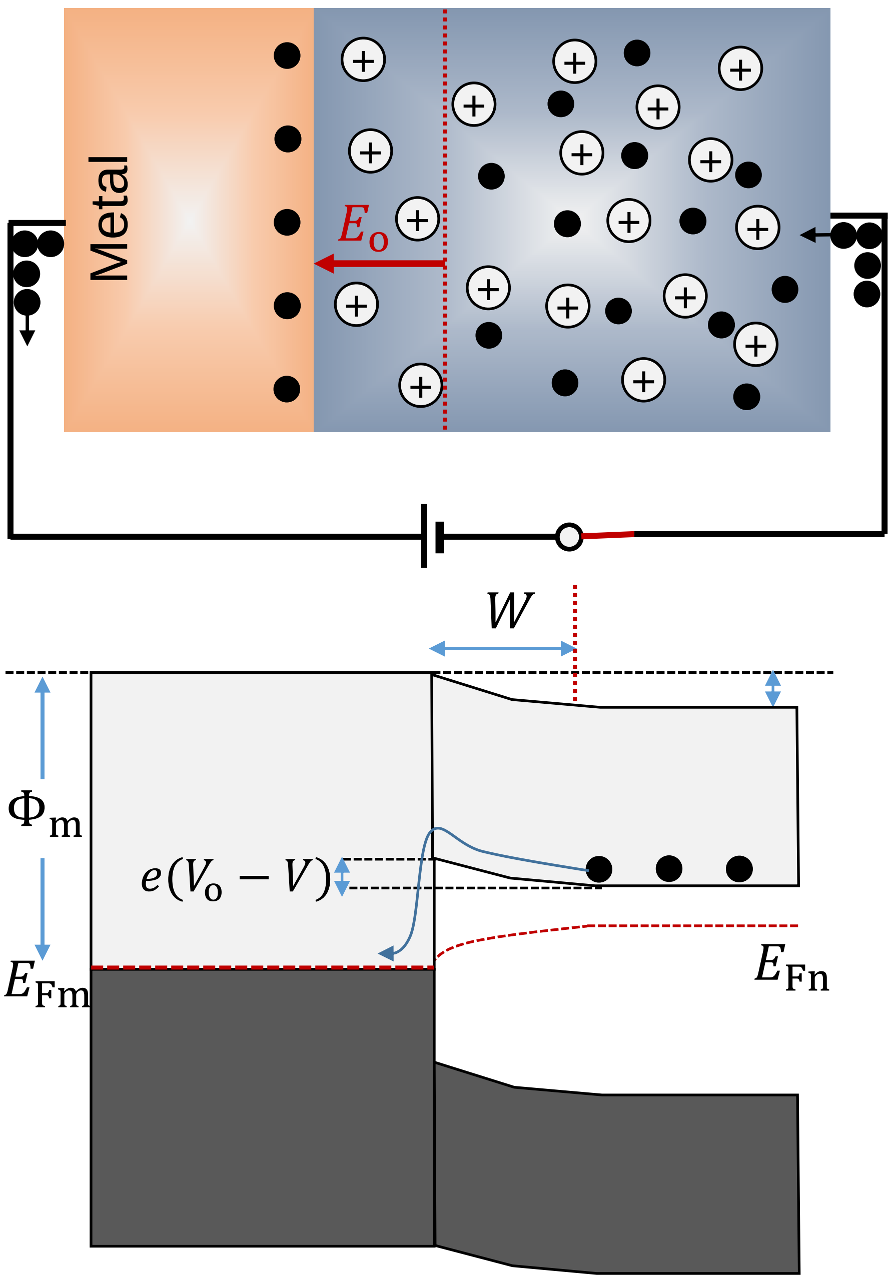
Internal electric field E_o decreases

Depletion region is thinner

Current increases!



Metal
E_o
Metal
E_o
W
eV_o
Φ_m
eV_o
E_{Fm}
E_{Fn}
W
Φ_m
$e(V_o - V)$
E_{Fn}
E_{Fm}



- Current from CB of semiconductor to metal:

$$J_2^{for} = C_2 \exp\left[-\frac{e(V_o - V)}{kT}\right]$$

- Current from metal to CB of semiconductor:

$$J_1 = C_1 \exp\left(-\frac{\Phi_B}{kT}\right) = C_2 \exp\left(-\frac{eV_o}{kT}\right)$$

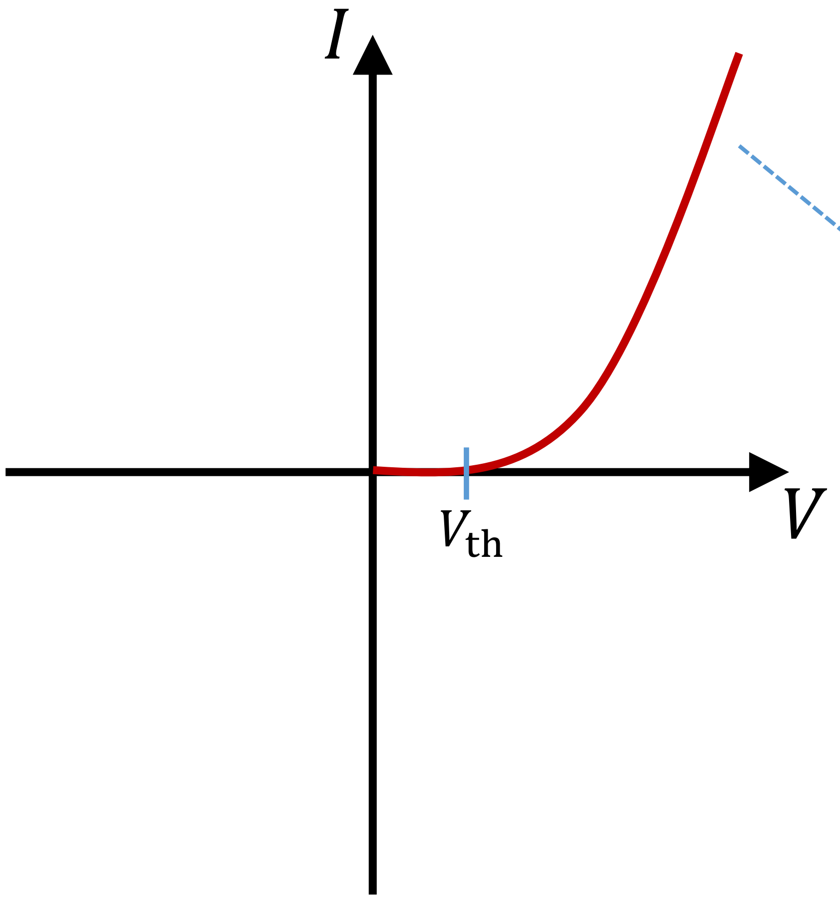
- The net current:

$$J = J_2 - J_1$$

$$= C_2 \exp\left(-\frac{eV_o}{kT}\right)\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

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

Forward bias

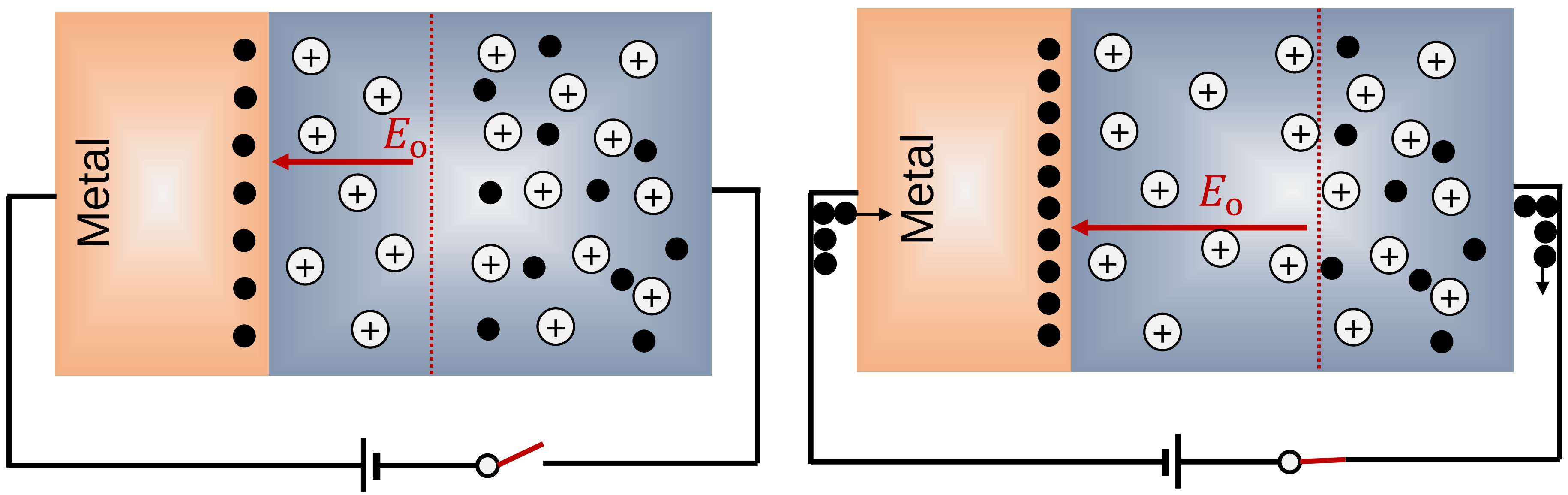


$$J = J_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

When $V \gg kT$:

$$J \approx J_o \exp\left(\frac{eV}{kT}\right)$$

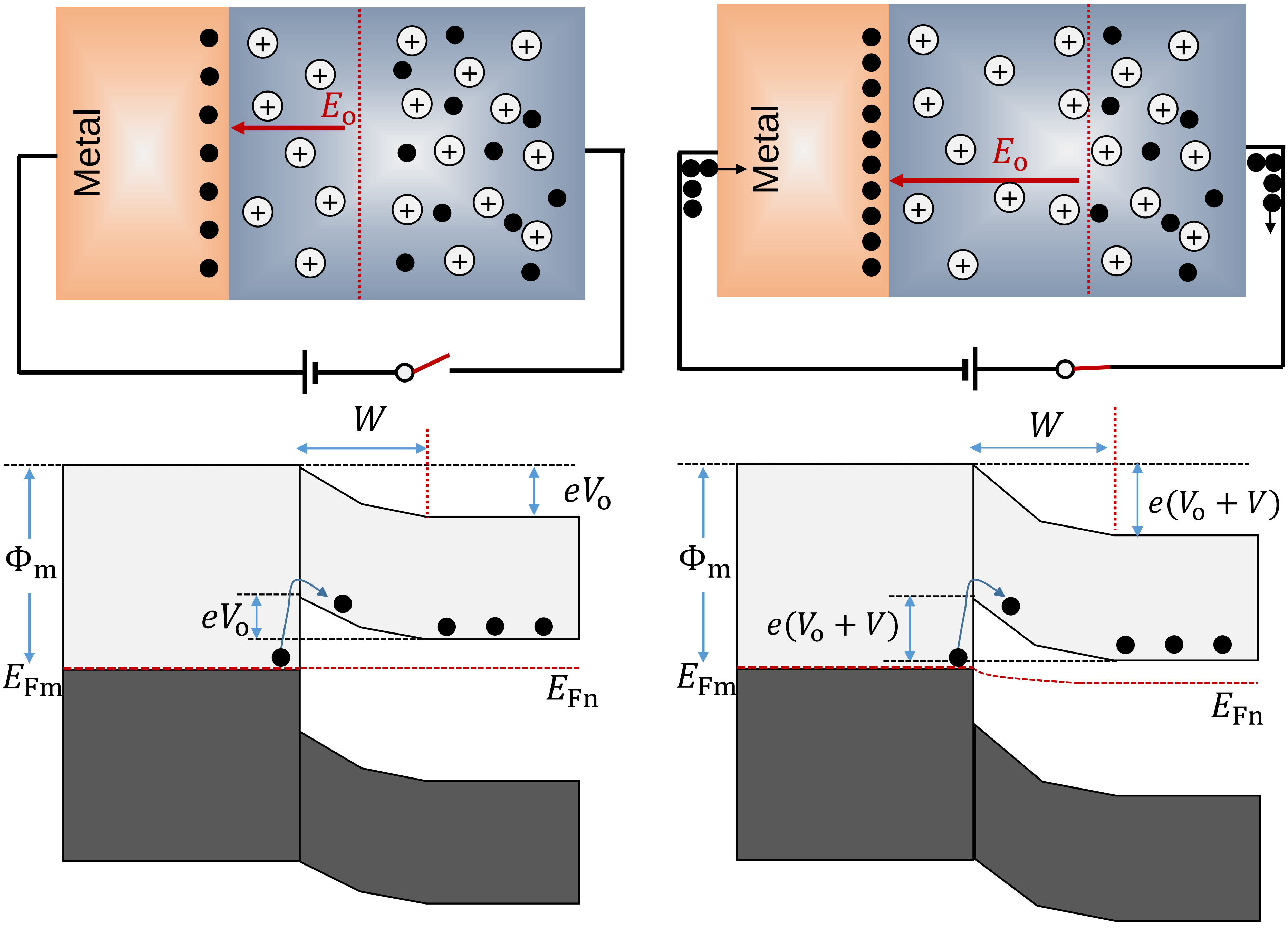
(3) Reverse bias



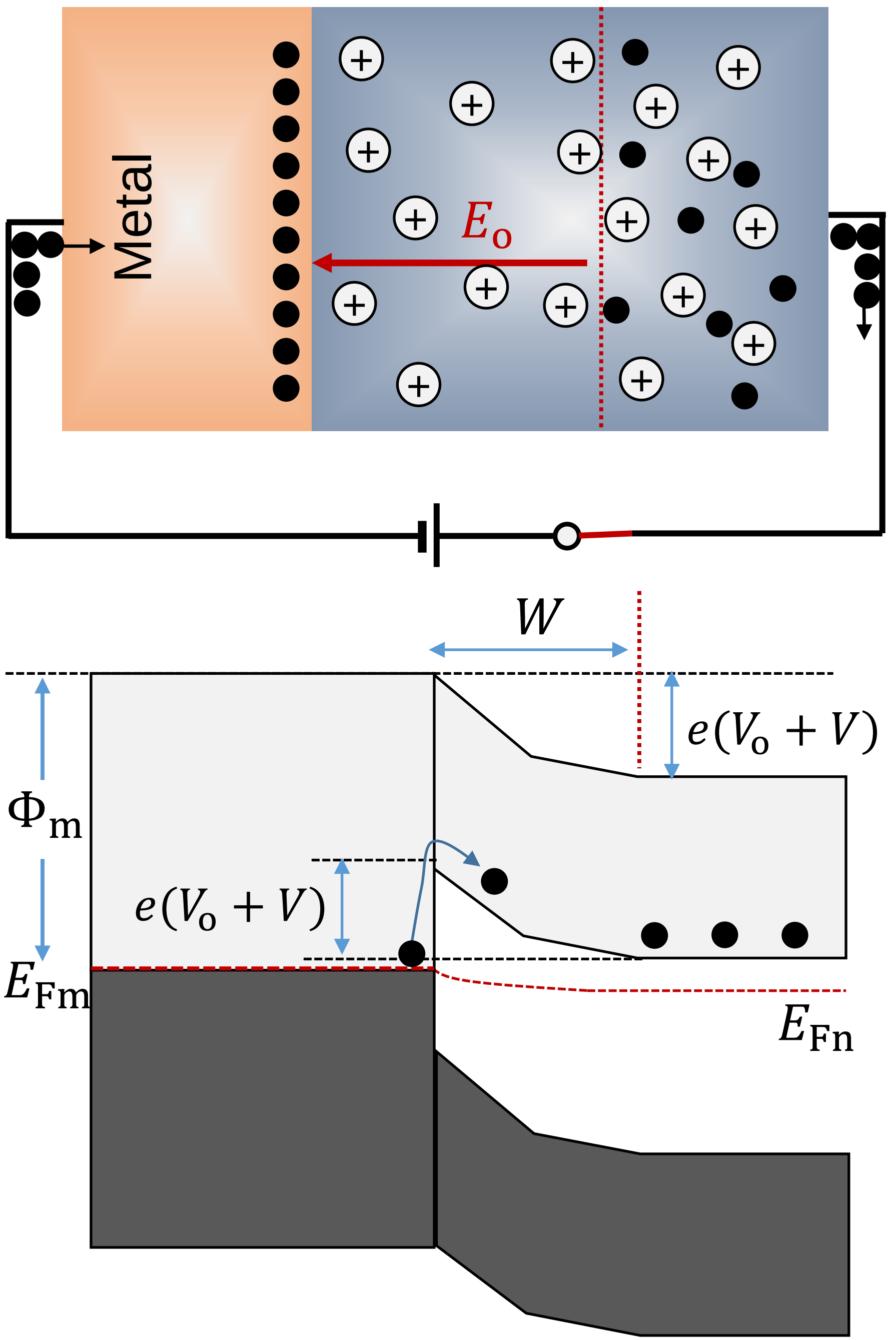
Internal electric field E_o increases

Depletion region is thicker

Current decreases!



Metal
E_o
Metal
E_o
W
eV_o
Φ_m
eV_o
E_{Fm}
E_{Fn}
W
$e(V_o + V)$
Φ_m
$e(V_o + V)$
E_{Fm}
E_{Fn}



- Current from CB of semiconductor to metal:

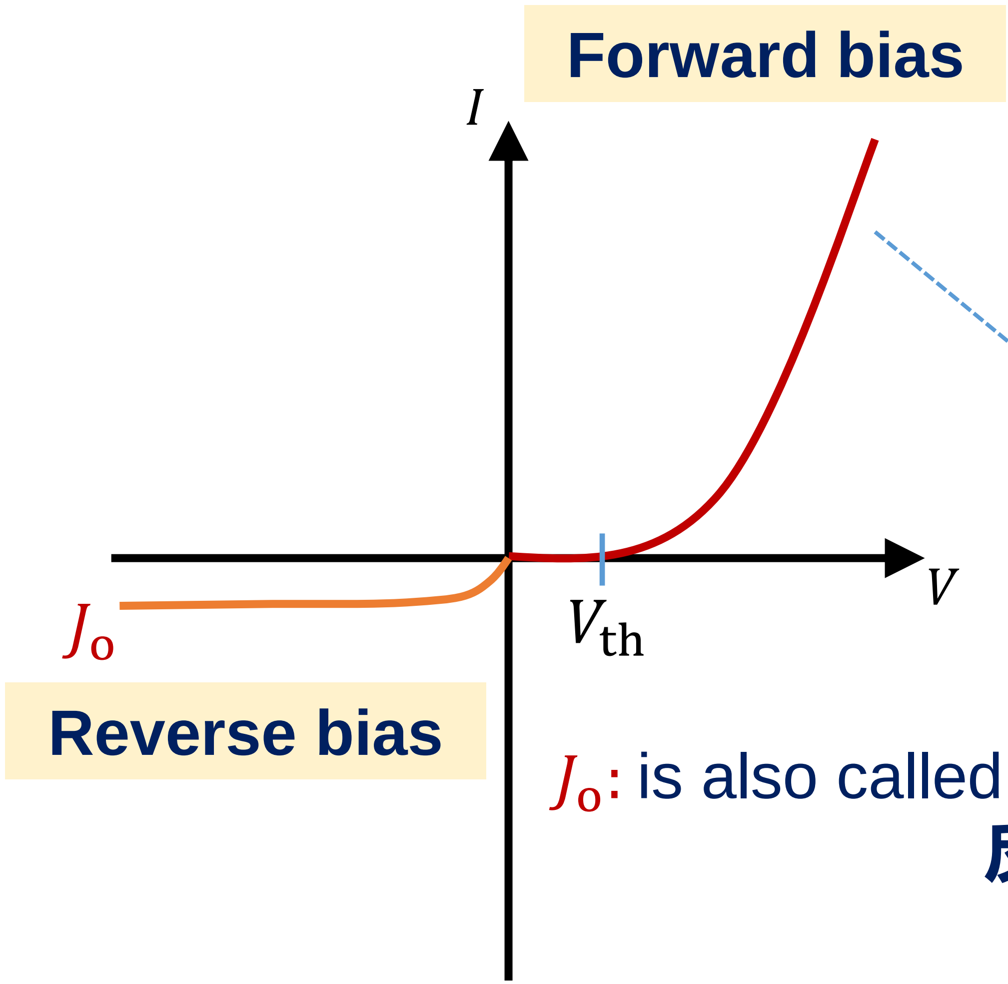
$$J_2^{\text{rev}} = C_2 \exp\left[-\frac{e(V_o + V)}{kT}\right]$$

- Current from metal to CB of semiconductor:

$$J_1 = C_1 \exp\left(-\frac{\Phi_B}{kT}\right) = C_2 \exp(-\frac{eV_o}{kT})$$

- When $J_1 \gg J_2$

The net current: $J \approx J_1 = J_o$



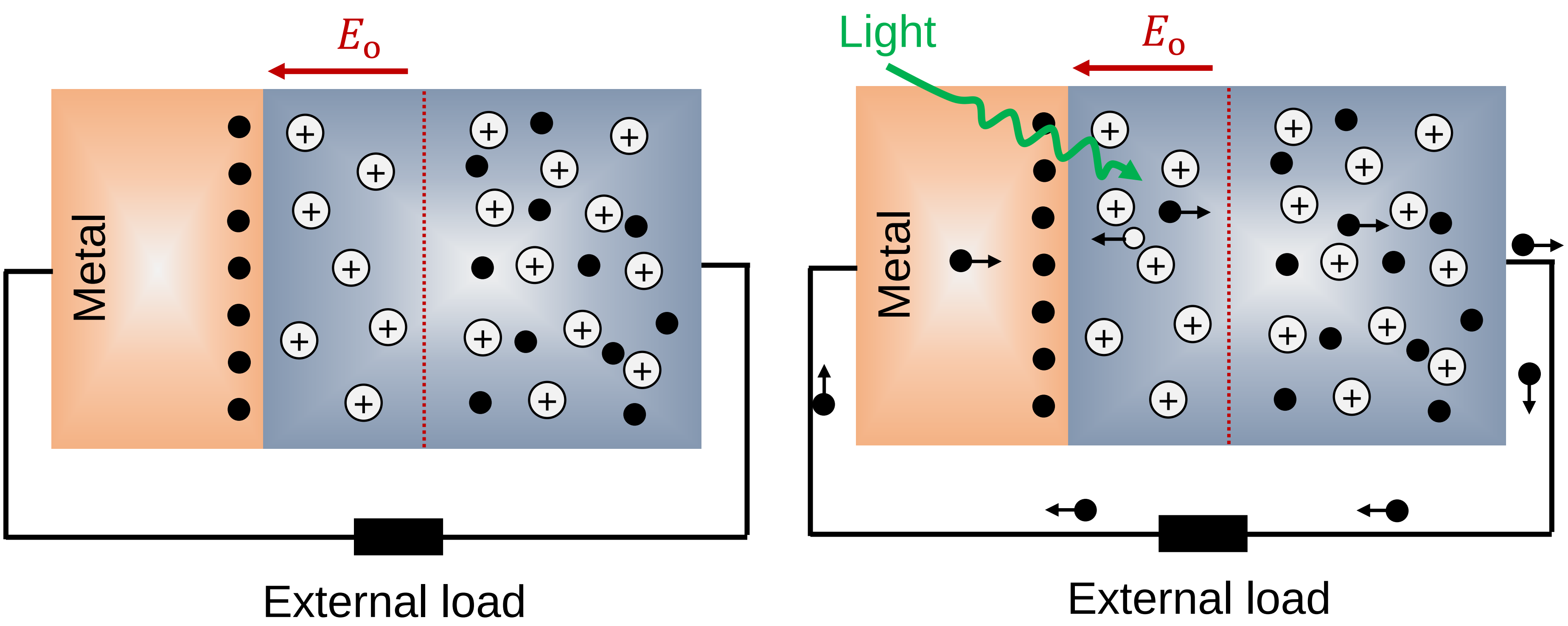
$$J = J_{\mathrm{o}}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

When $V \gg kT$:

$$J \approx J_{\mathrm{o}}\exp\left(\frac{eV}{kT}\right)$$

J_{o}: is also called **reverse saturation current 反向饱和电流**.

5.2 Schottky junction solar cell and photodiode

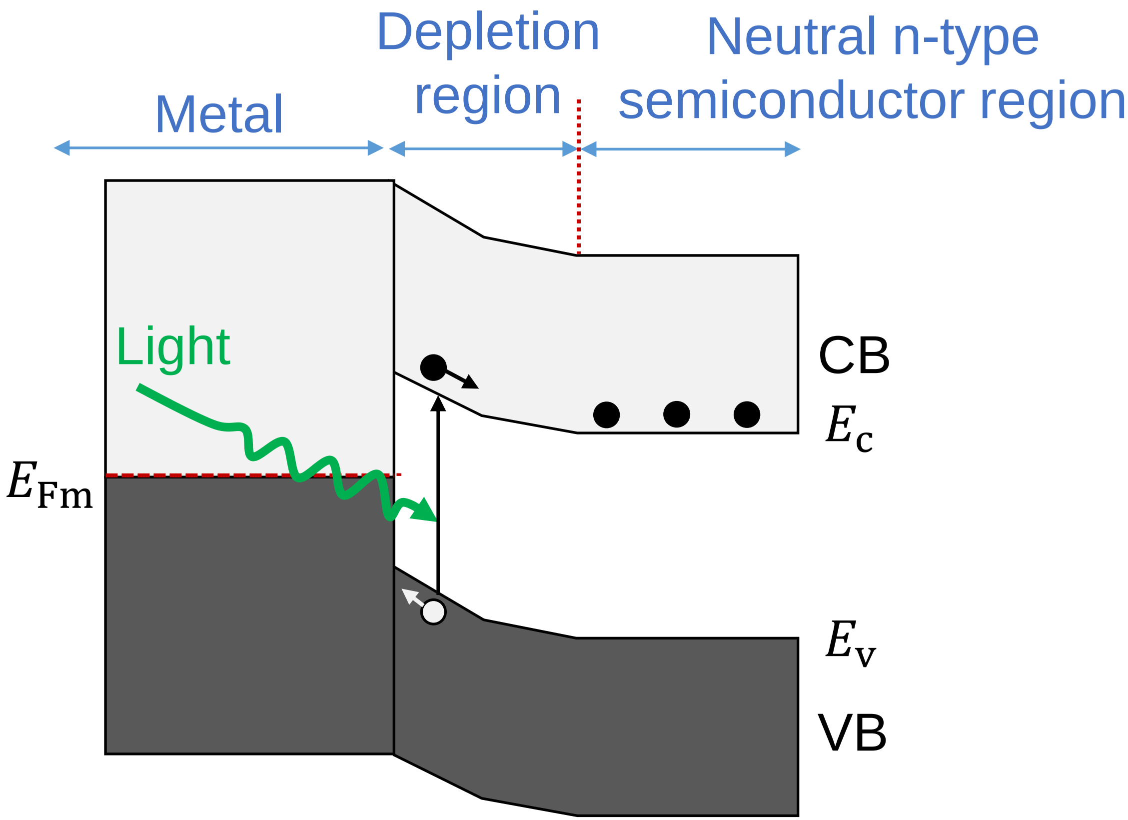


Light ➡ Electron-hole pair excitation

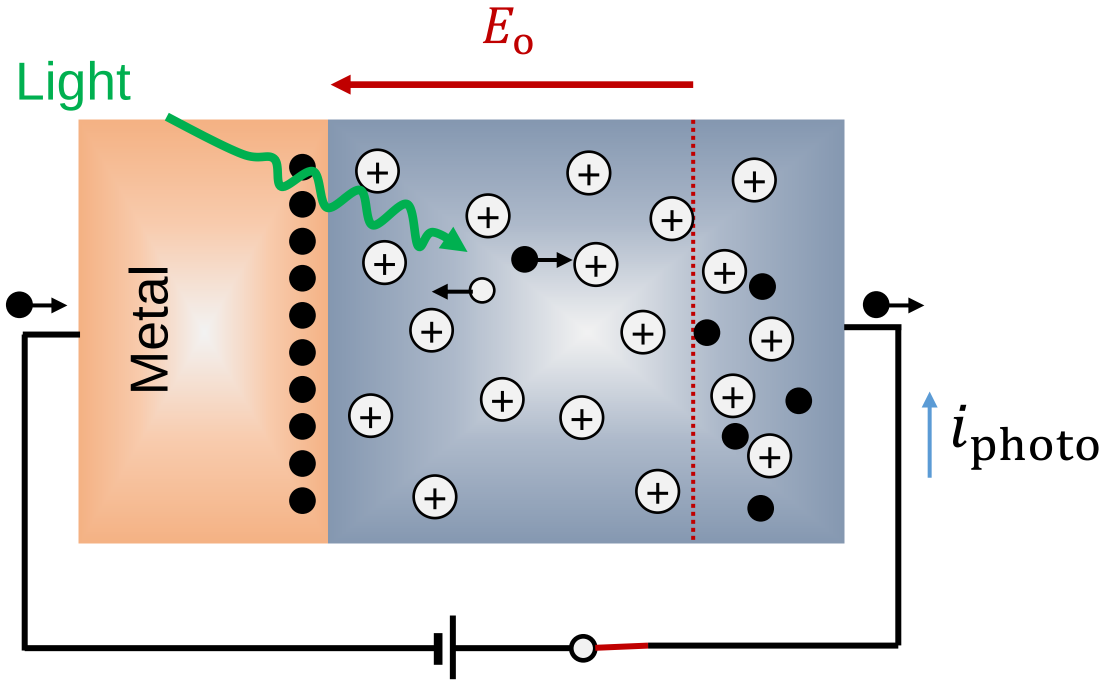
⬇

Electron-hole pair separation by internal electric field

Solar cell

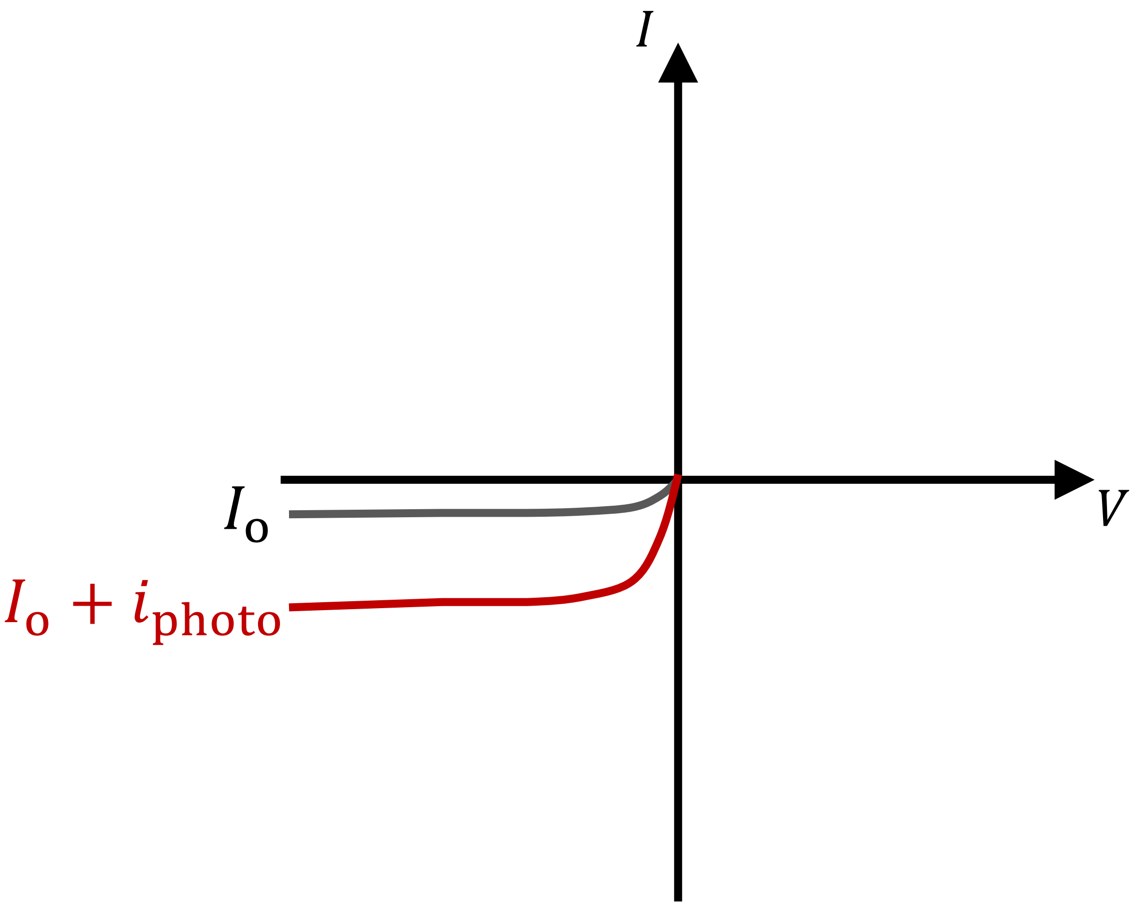

Depletion region
Neutral n-type semiconductor region
Metal
Light
CB
E_c
E_{Fm}
E_v
VB

Schottky junction photodiode



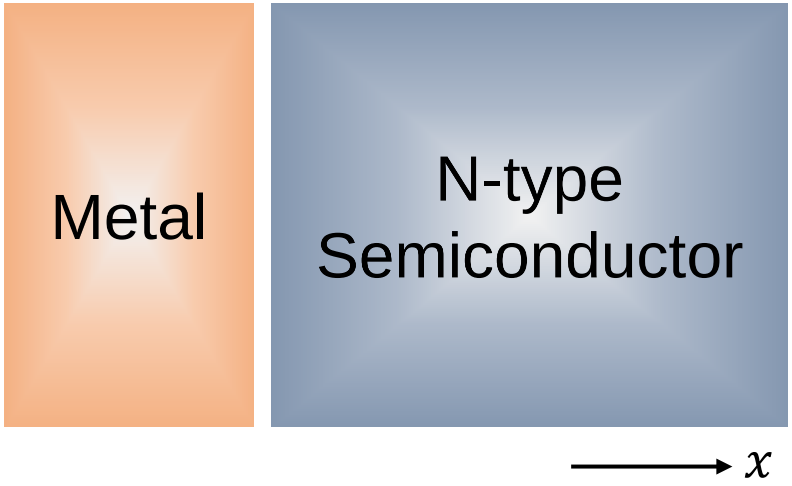
Without light: I_o

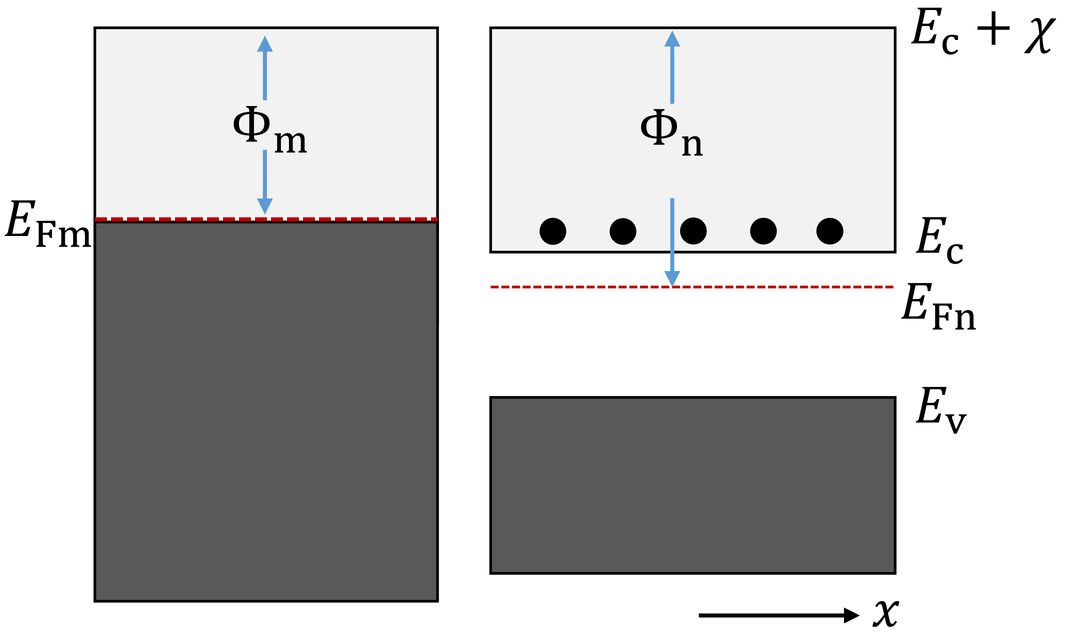
With light: $I_o + i_{photo}$

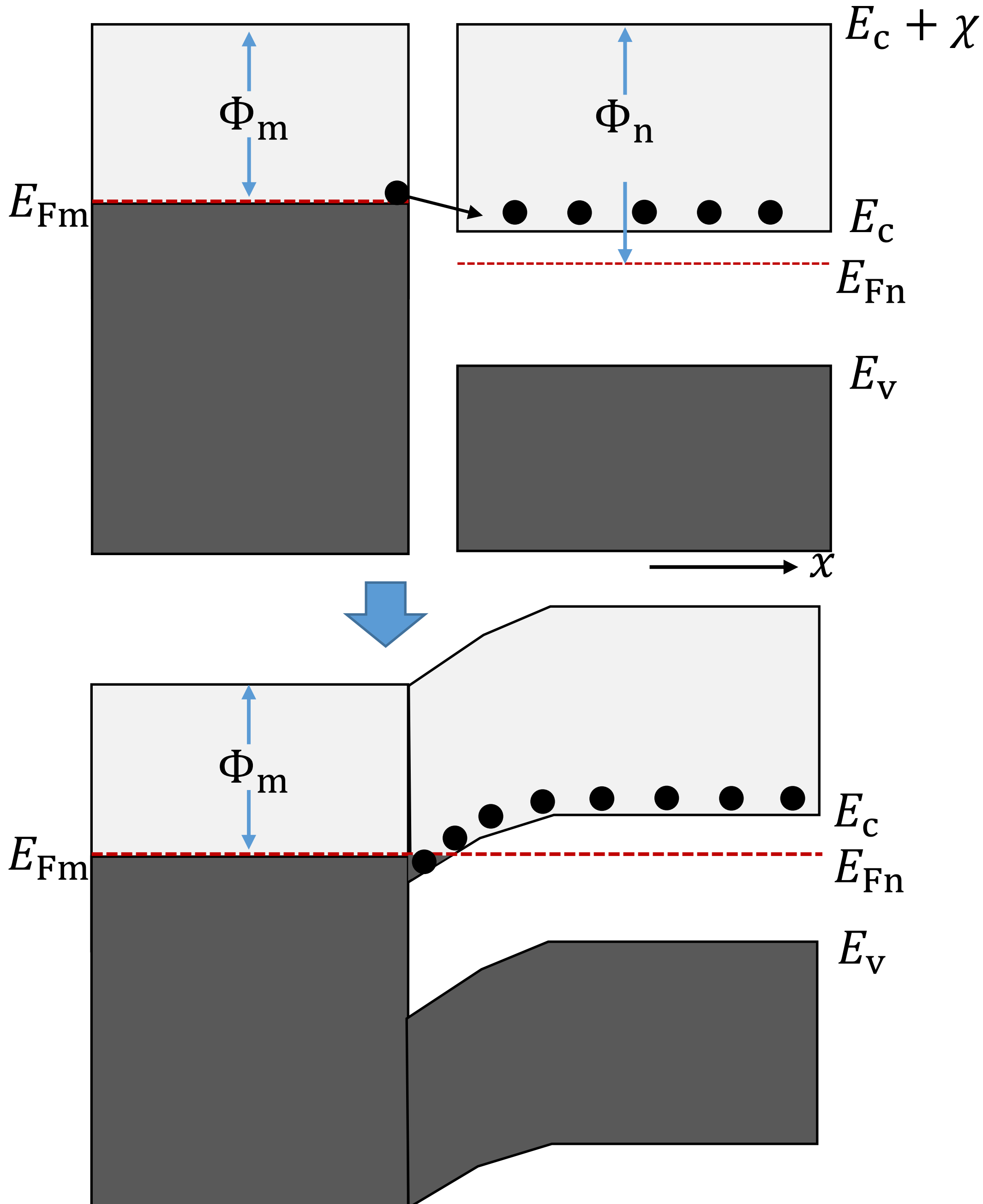

I
V
I_o
$I_o + i_{photo}$

5.3 Ohmic contacts and thermoelectric coolers

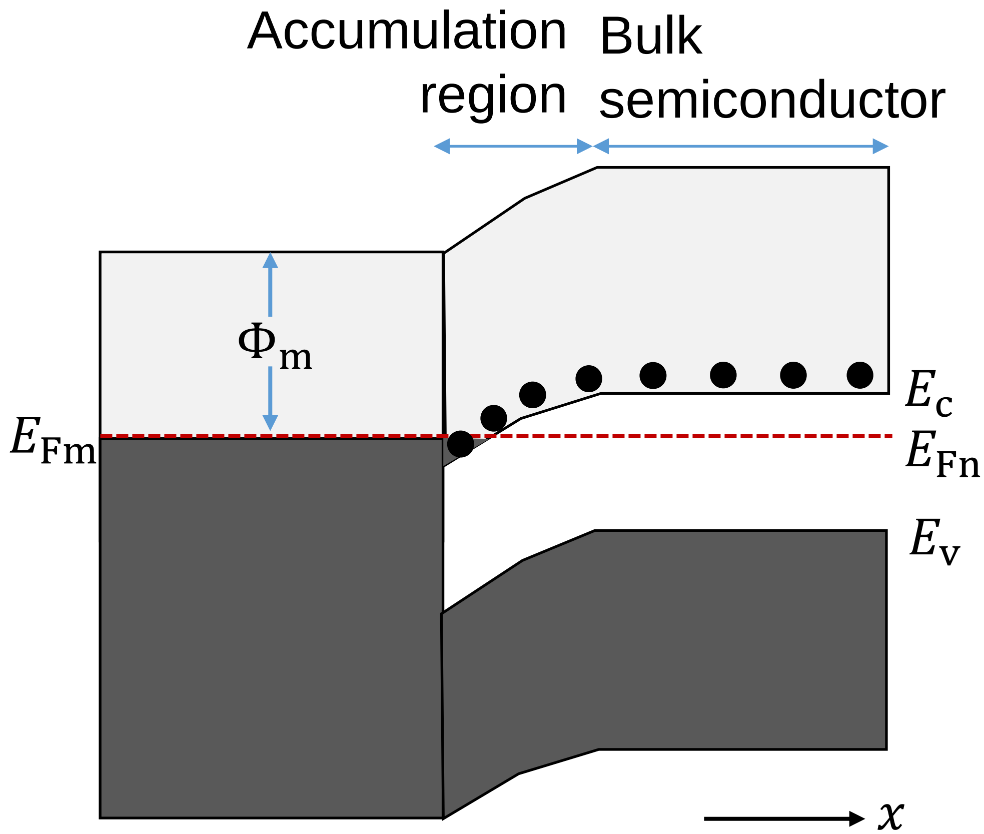
Q: What will happen at the metal-semiconductor interface?







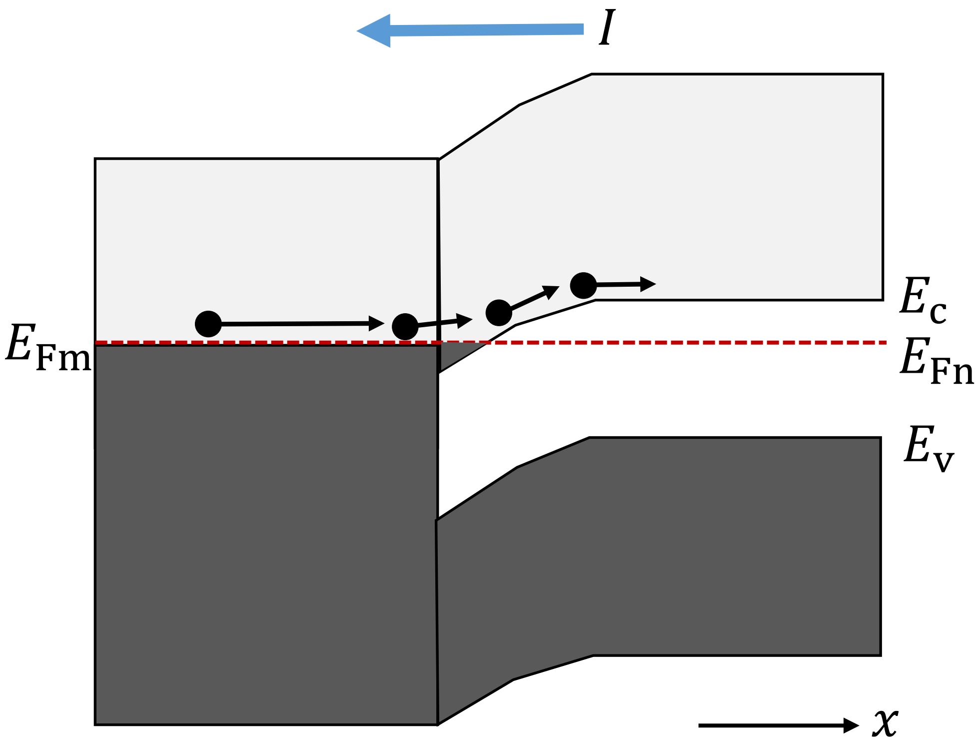
$E_{\mathrm{c}} + \chi$
Φ_{m}
Φ_{n}
E_{Fm}
E_{c}
E_{Fn}
E_{v}
x
Φ_{m}
E_{Fm}
E_{c}
E_{Fn}
E_{v}
x

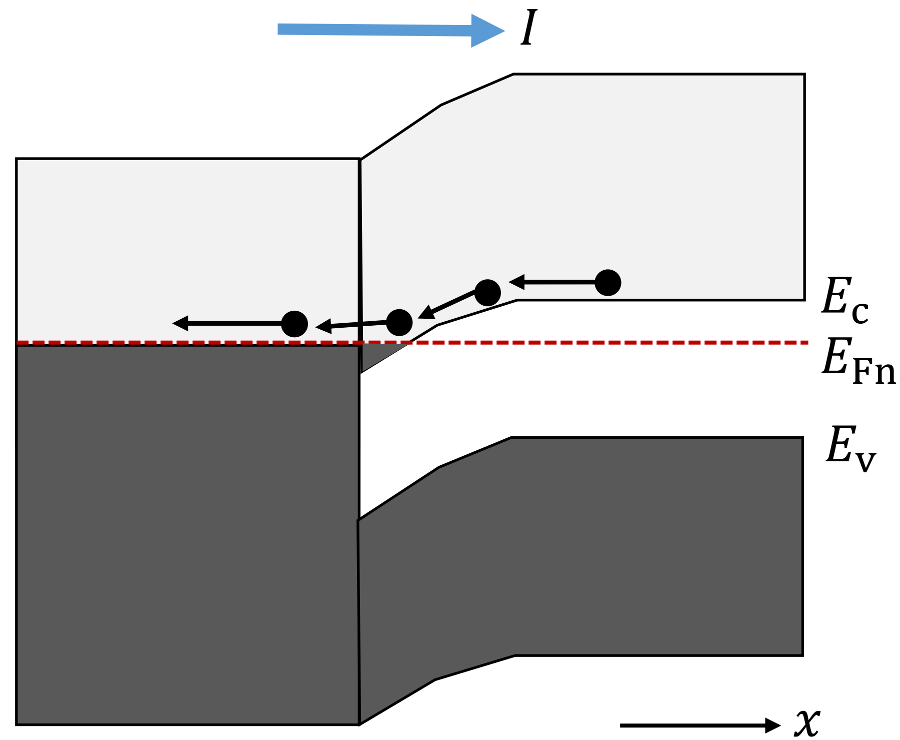


Ohmic contact in accumulation region:

- No Schottky barrier between metal and semiconductor.
- Low resistance at metal-semiconductor interface.
- Total resistance is dominated by the resistance of bulk region.

Peltier effect 珀尔帖效应





Electron energy increase.

Absorb thermal energy from junction area.

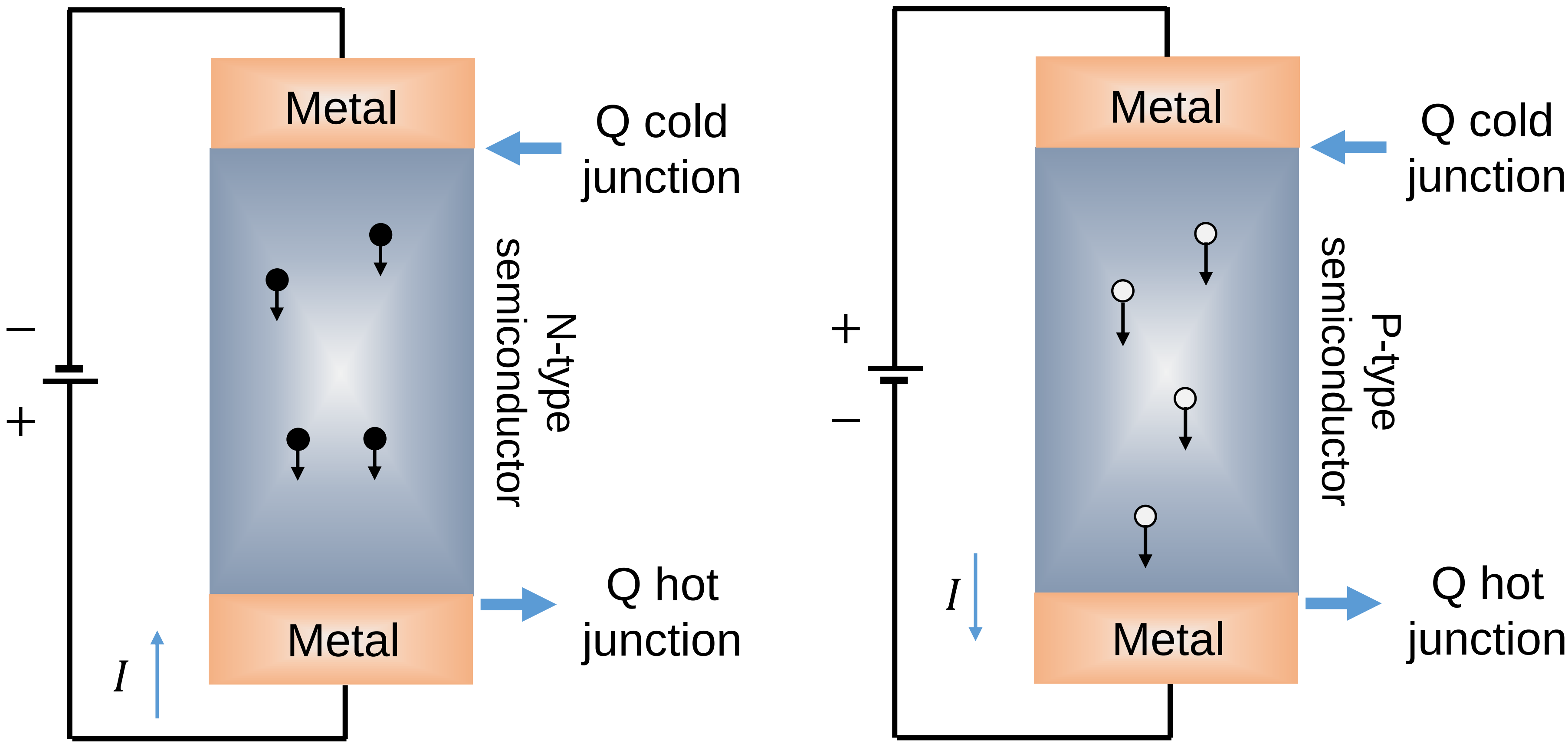
Junction area is cooled.

Electron energy decrease.

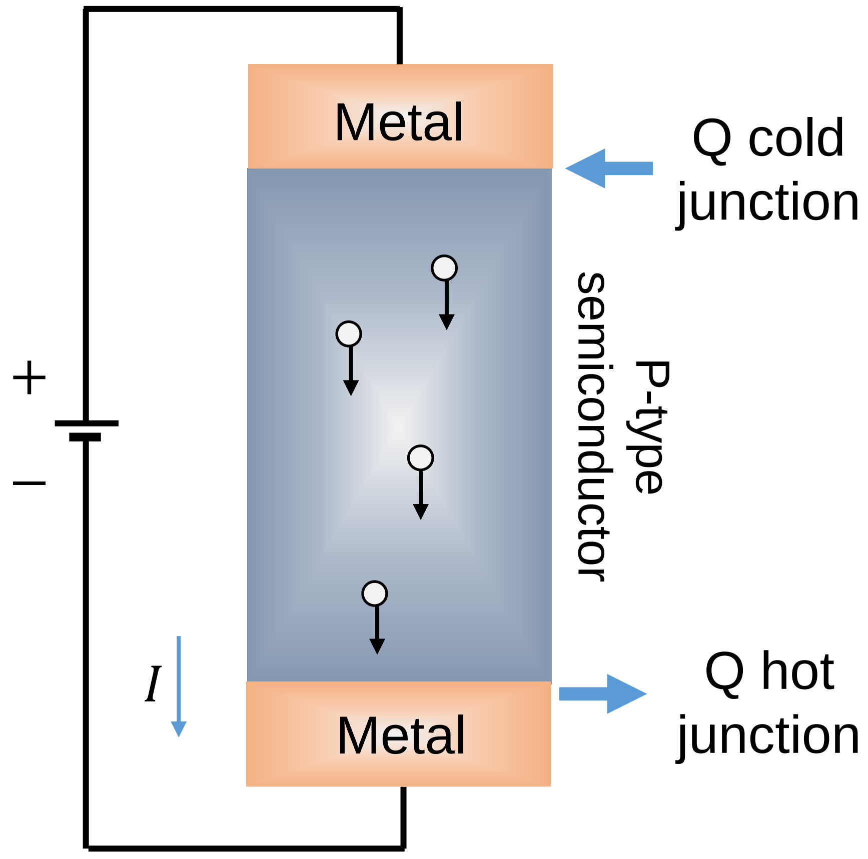
Release thermal energy to junction area.

Junction area is heated.

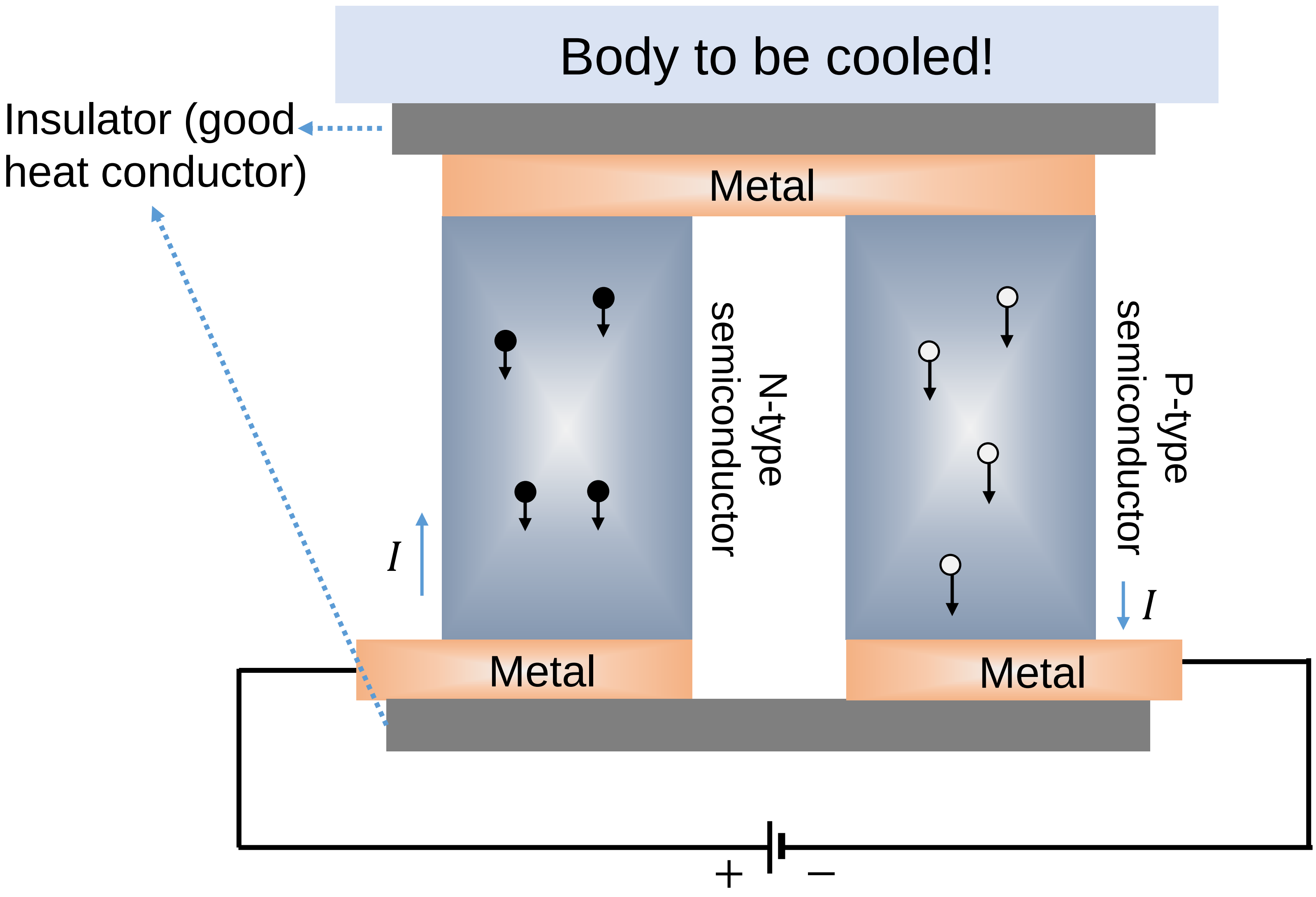
Peltier effect 珀尔帖效应



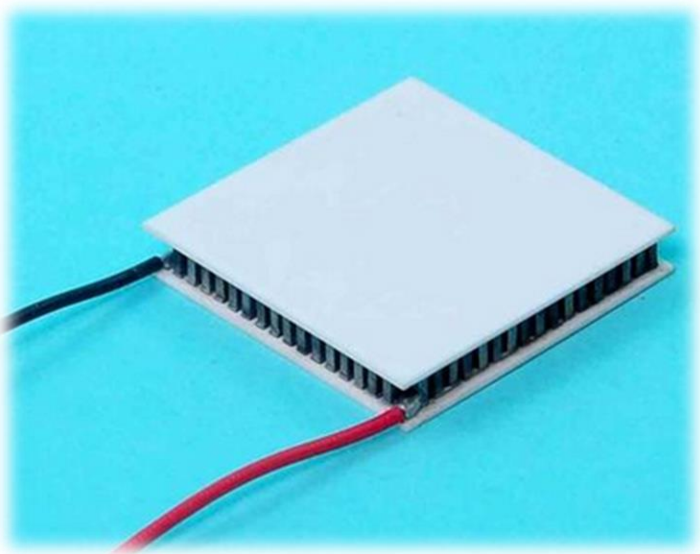
Homework 1-3: For p-type semiconductor, please draw the band diagram and describe the working principles of Peltier effect.

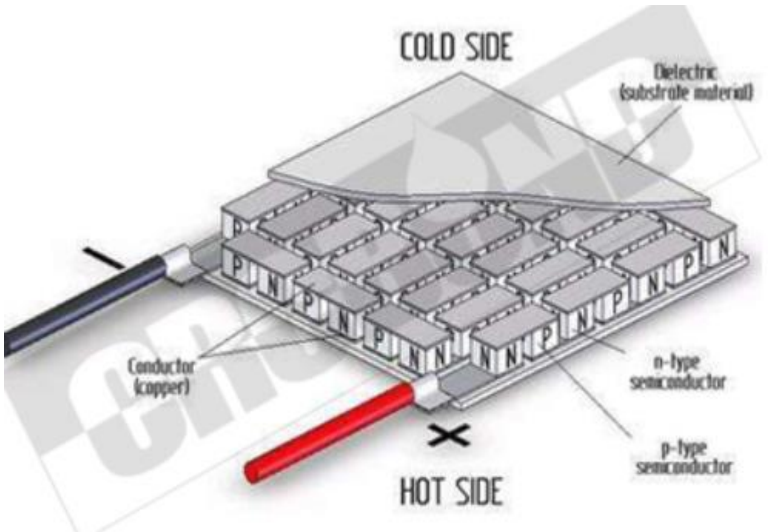


A typical thermoelectric cooler



A typical thermoelectric cooler



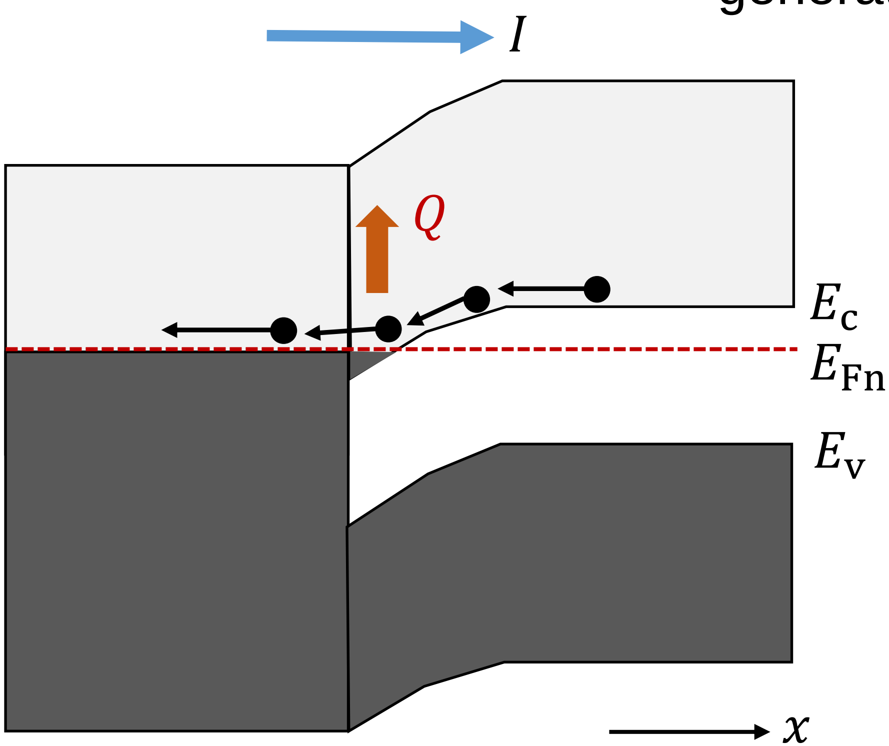


The Peltier coefficient 珀尔帖系数

The rate of heat generation

$$Q = \Pi I$$

Current



Electron average energy in CB of semiconductor:

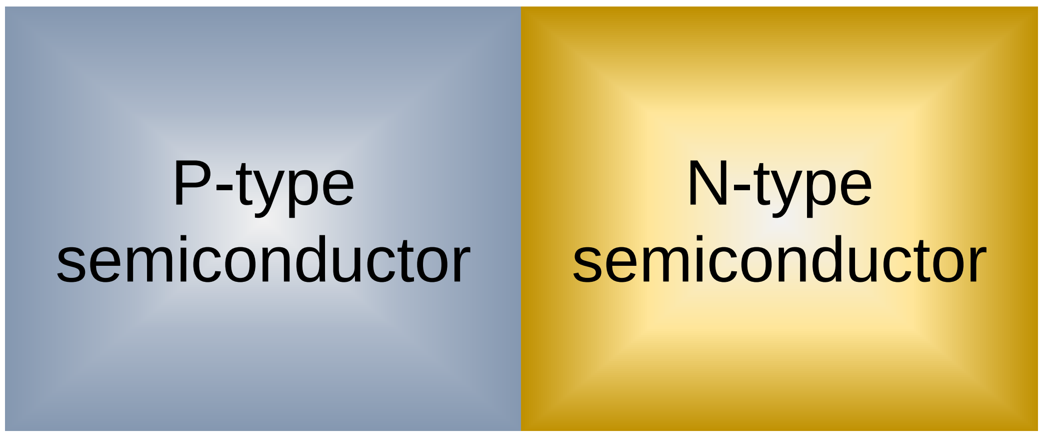
$$E_\mathrm{c} + \frac{3}{2}kT$$

Electron average energy in metal: E_Fn

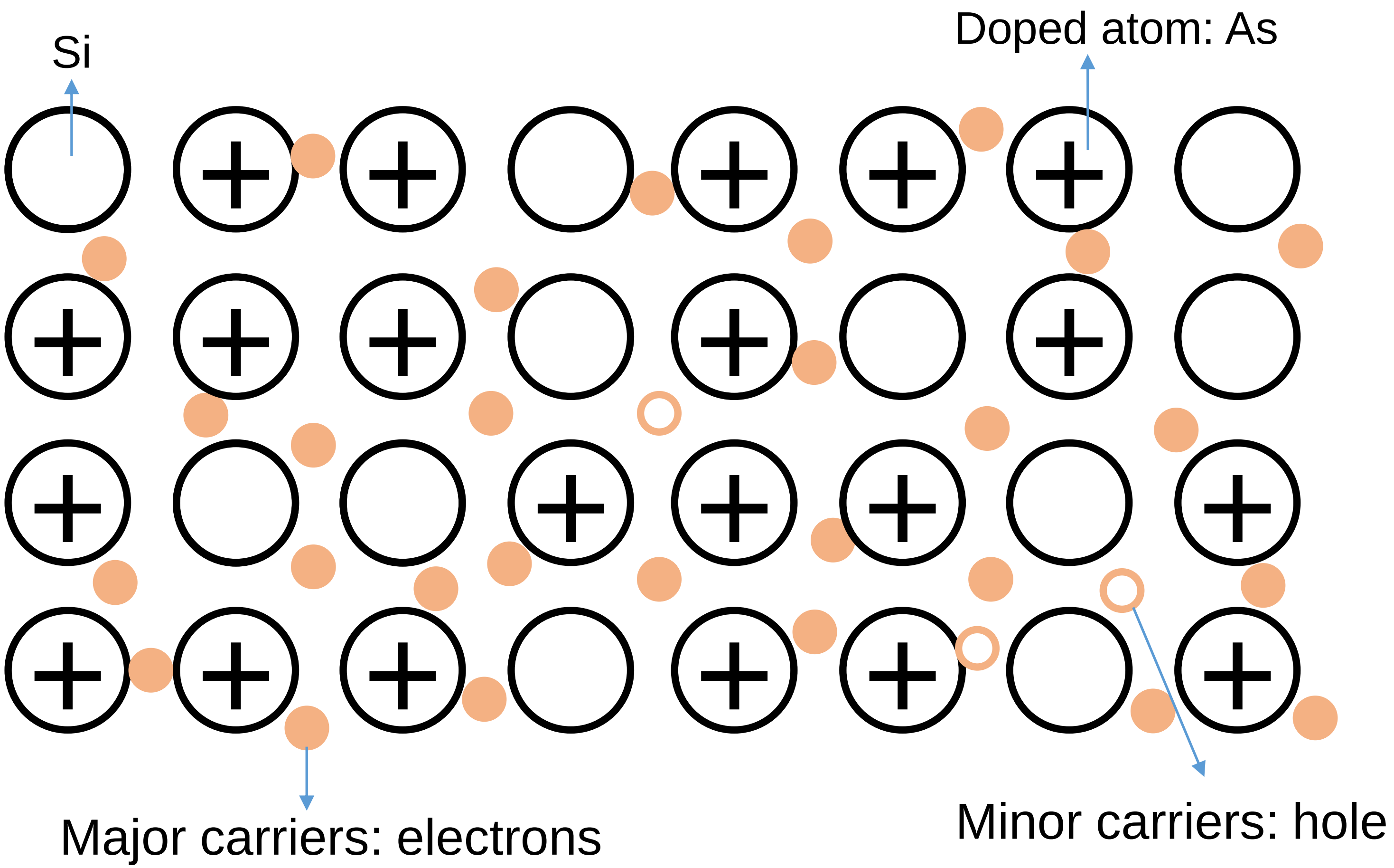
$$\begin{cases} Q = N\left(E_\mathrm{c} + \frac{3}{2}kT - E_\mathrm{Fn}\right)/\Delta t \\ I = Ne/\Delta t \end{cases}$$

$$\Pi = \frac{1}{e}\left(E_\mathrm{c} + \frac{3}{2}kT - E_\mathrm{Fn}\right)$$

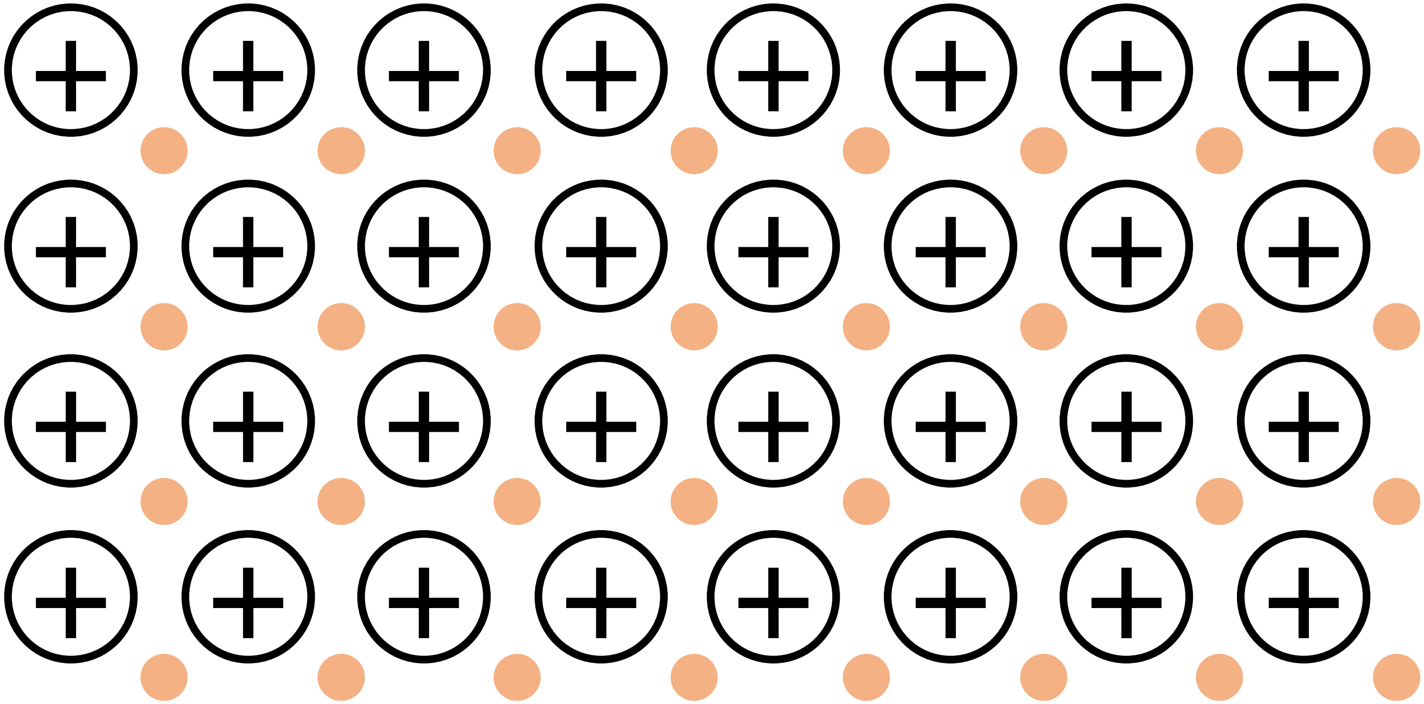
5.4 Ideal PN junction



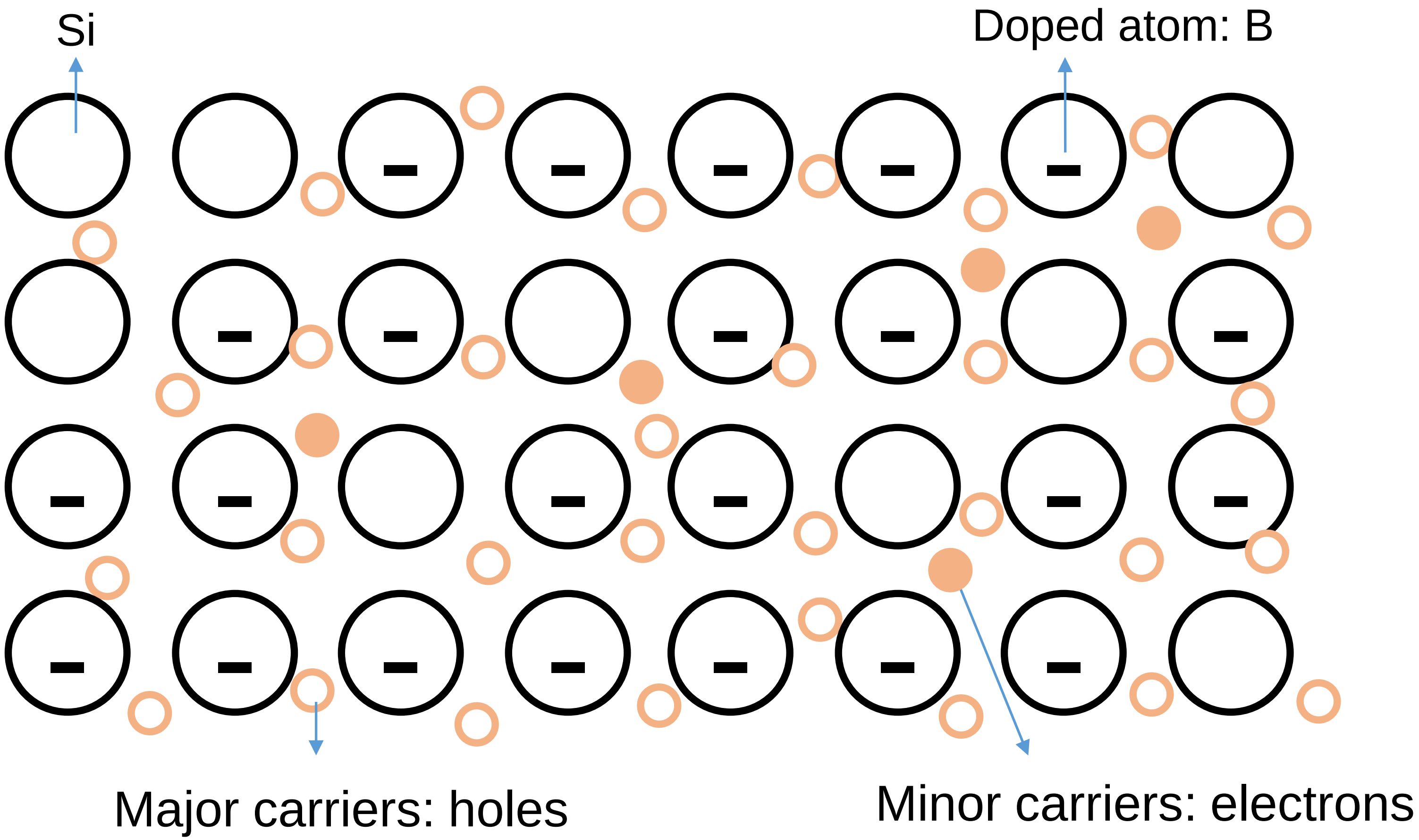
N-type semiconductor



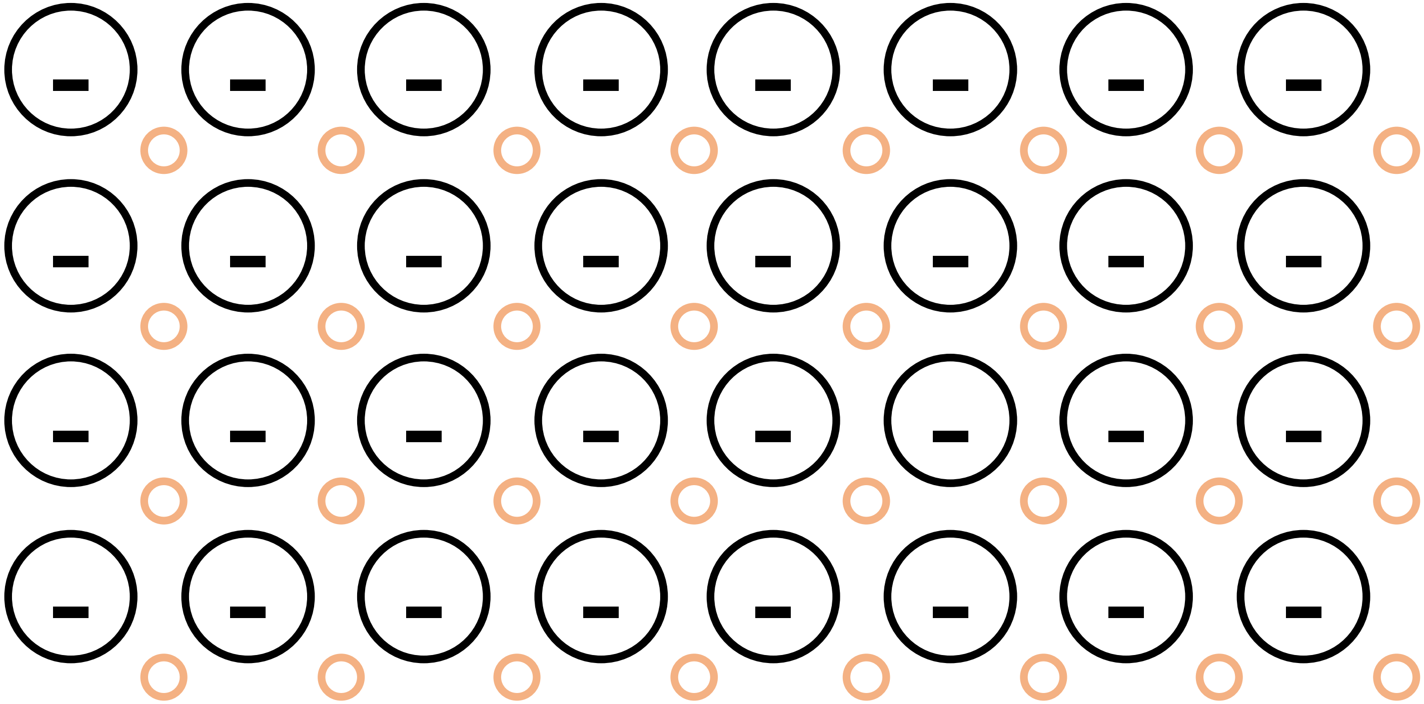
Schematic for N-type semiconductor



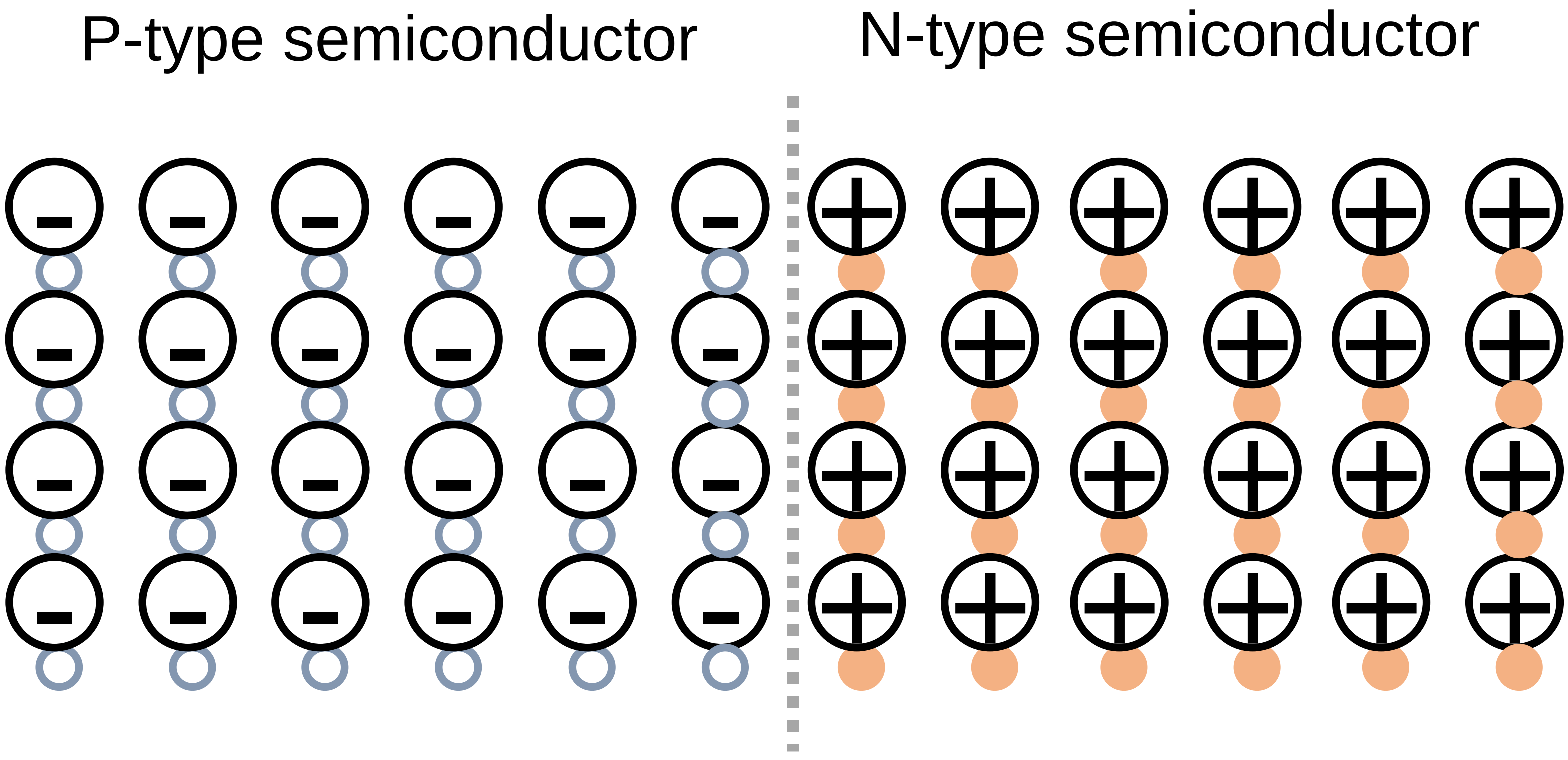
P-type semiconductor



Schematic for P-type semiconductor

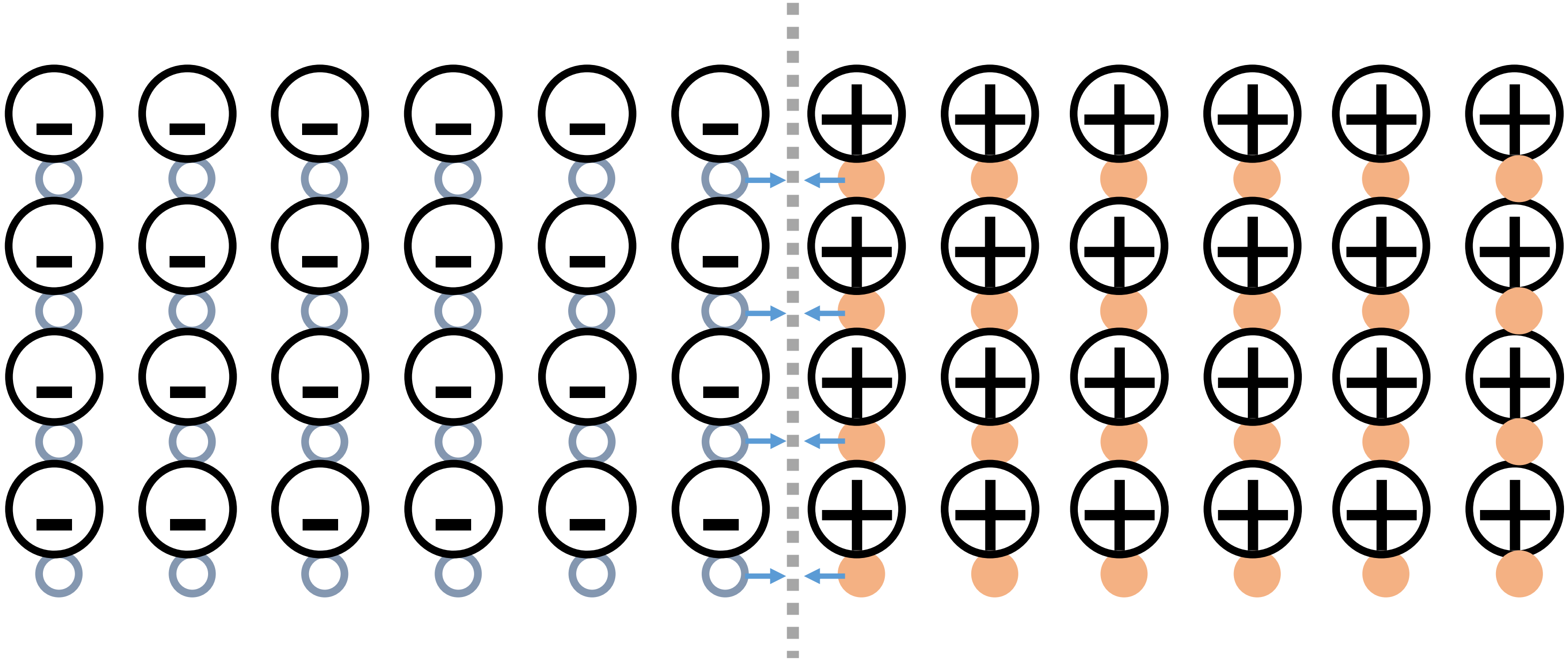


PN junction



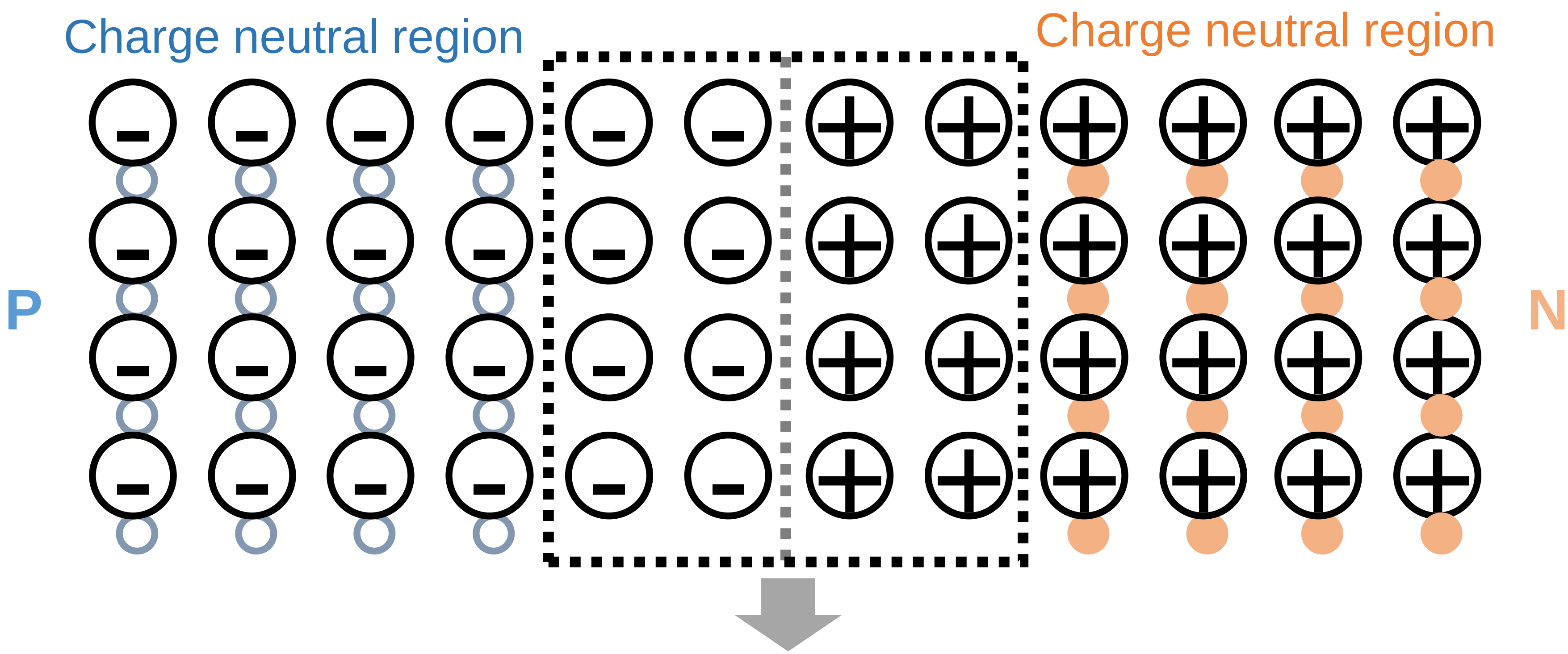
Electrons diffusive from N-type region to P-type region

Holes diffusive from P-type region to N-type region



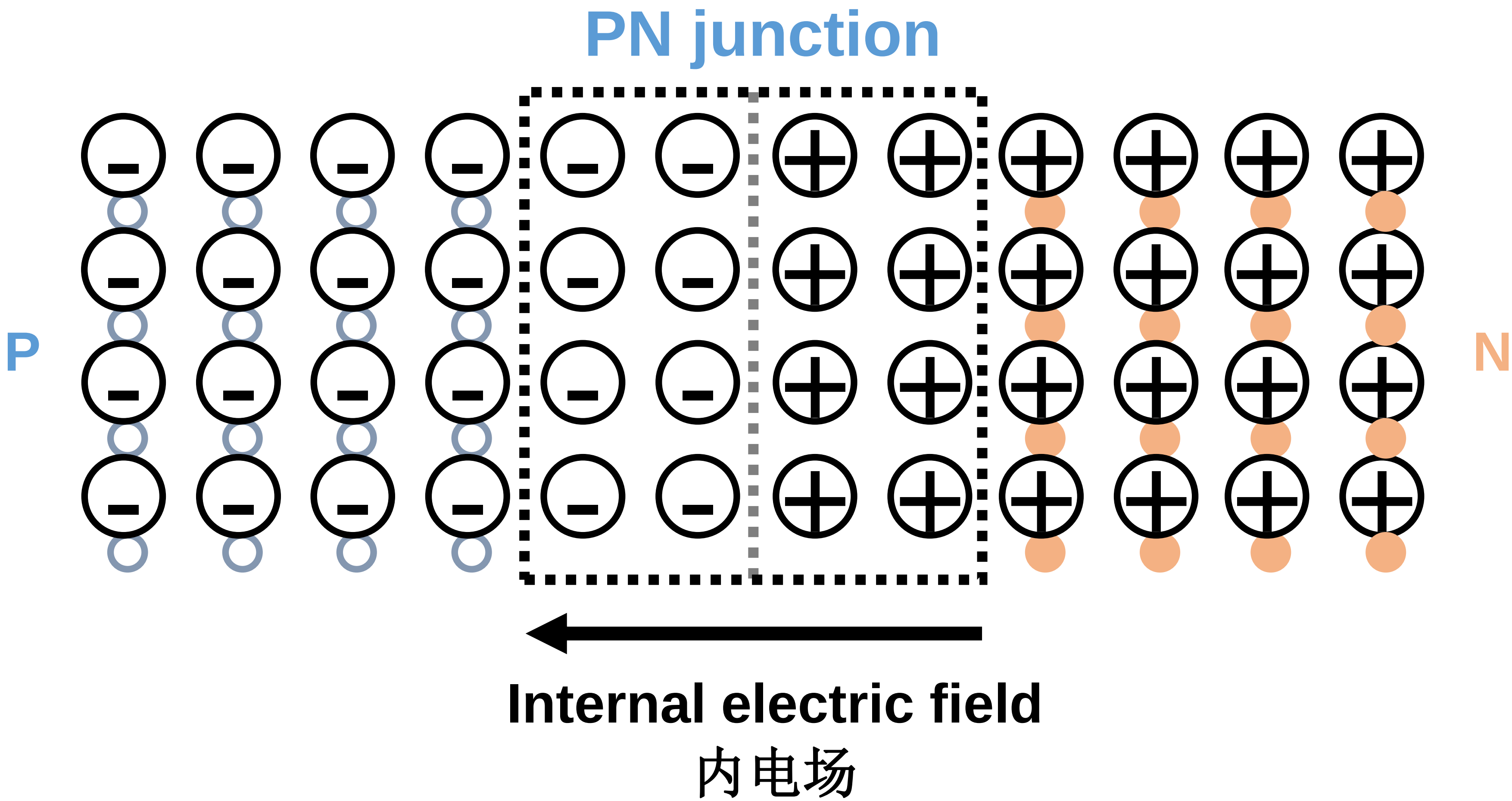
P-type semiconductor N-type semiconductor

Electrons and holes recombine near the P and N region interface. When the system is equilibrium, only positive and negative ions left near the interface.



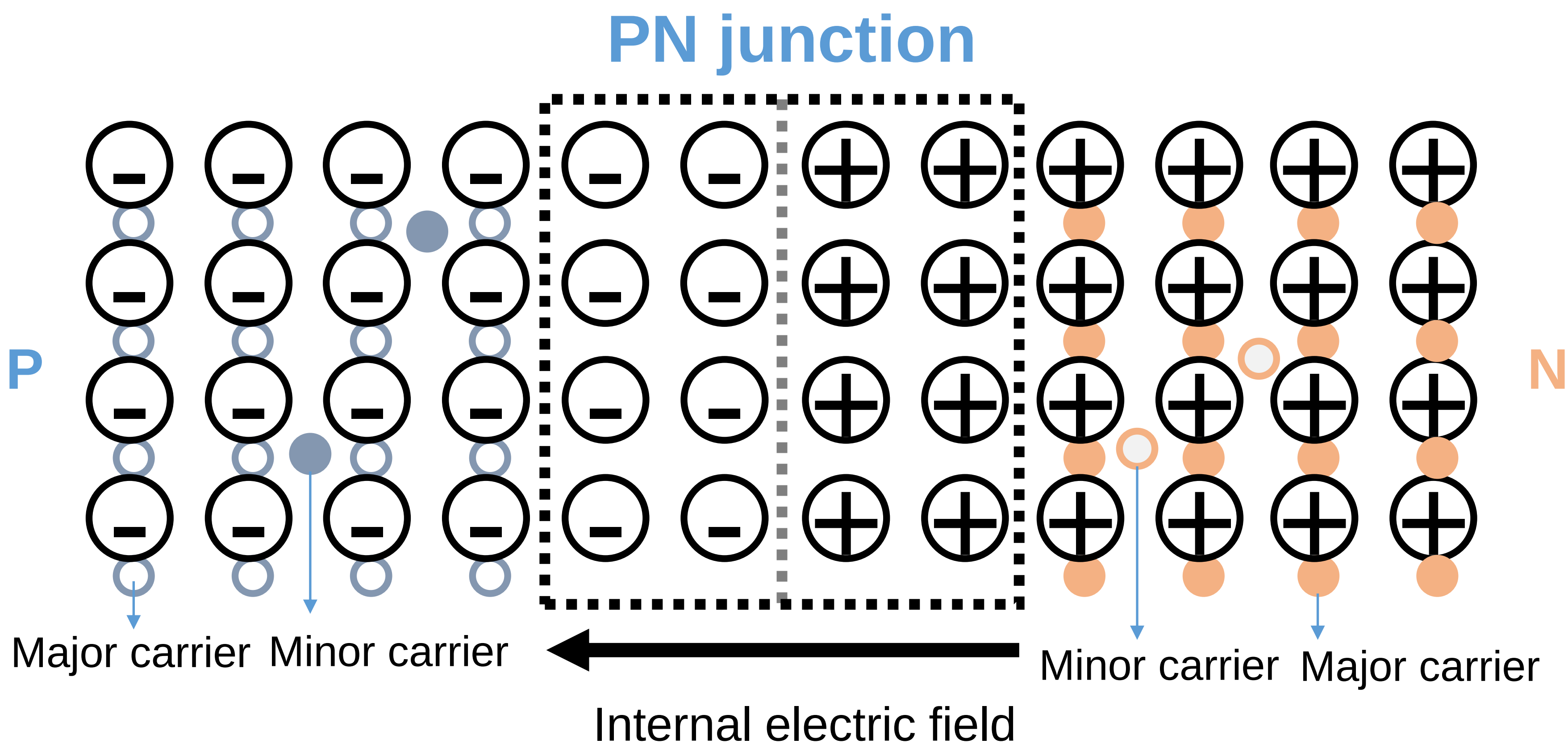
Space charge region/ Depletion region

空间电荷区/耗尽层



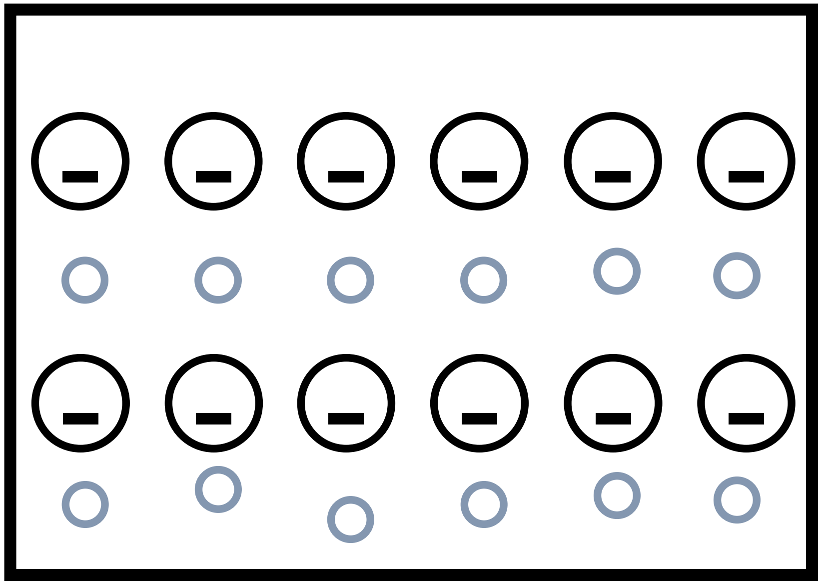
Block the diffusion of major carriers, accelerate the drift of minor carriers.阻碍多数载流子的扩散，加速少数载流子的漂移。

Block the diffusion of major carriers.
Accelerate the drift of minor carriers.



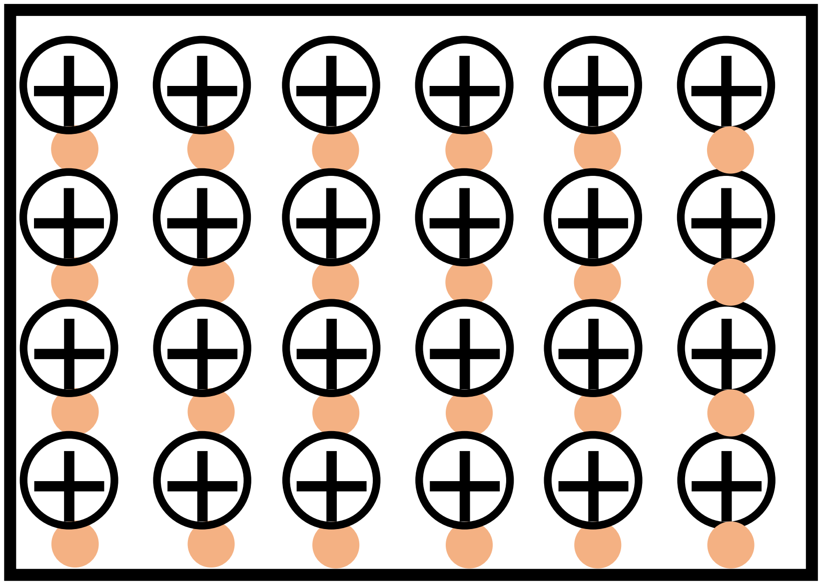
Asymmetric PN junction

Q: if they are in contact, whose space charge region is thicker?



Slightly doped P-type

Ion and free hole concentration is low

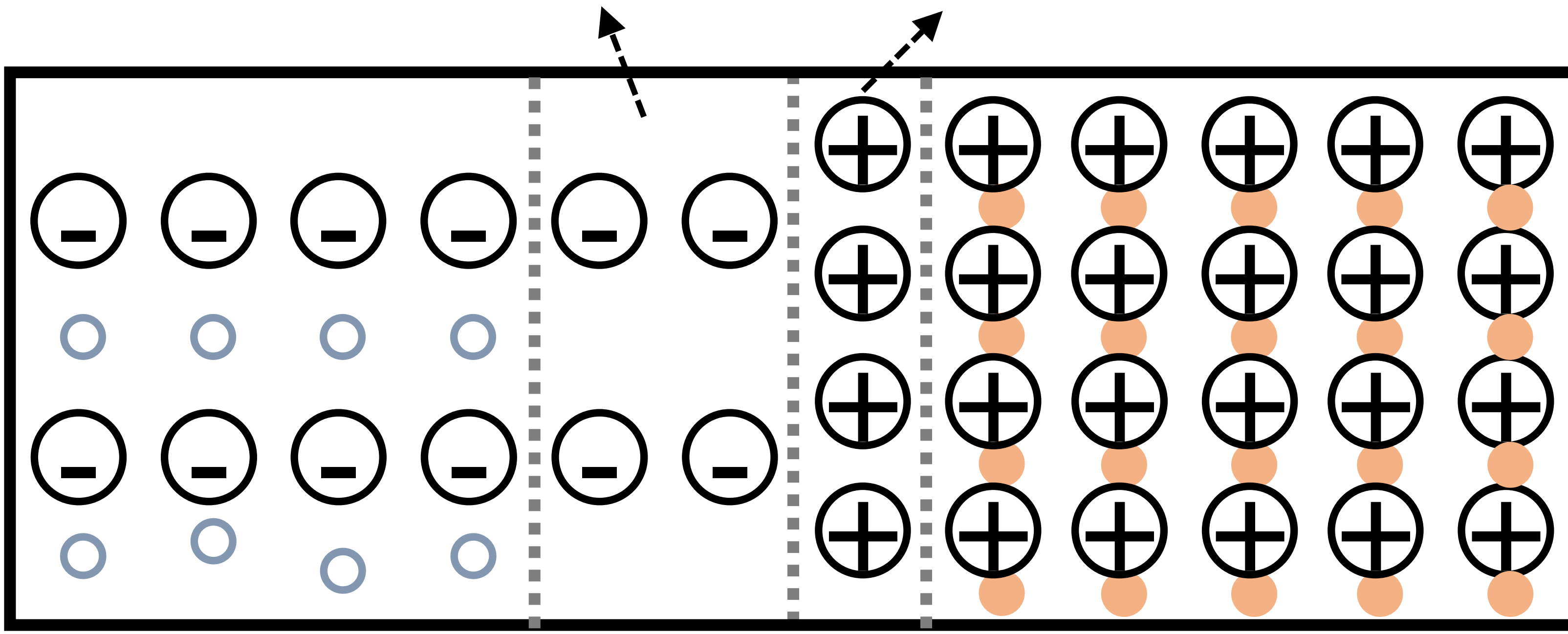


Heavily doped N-type

Ion and free electron concentration is high

Asymmetric PN junction

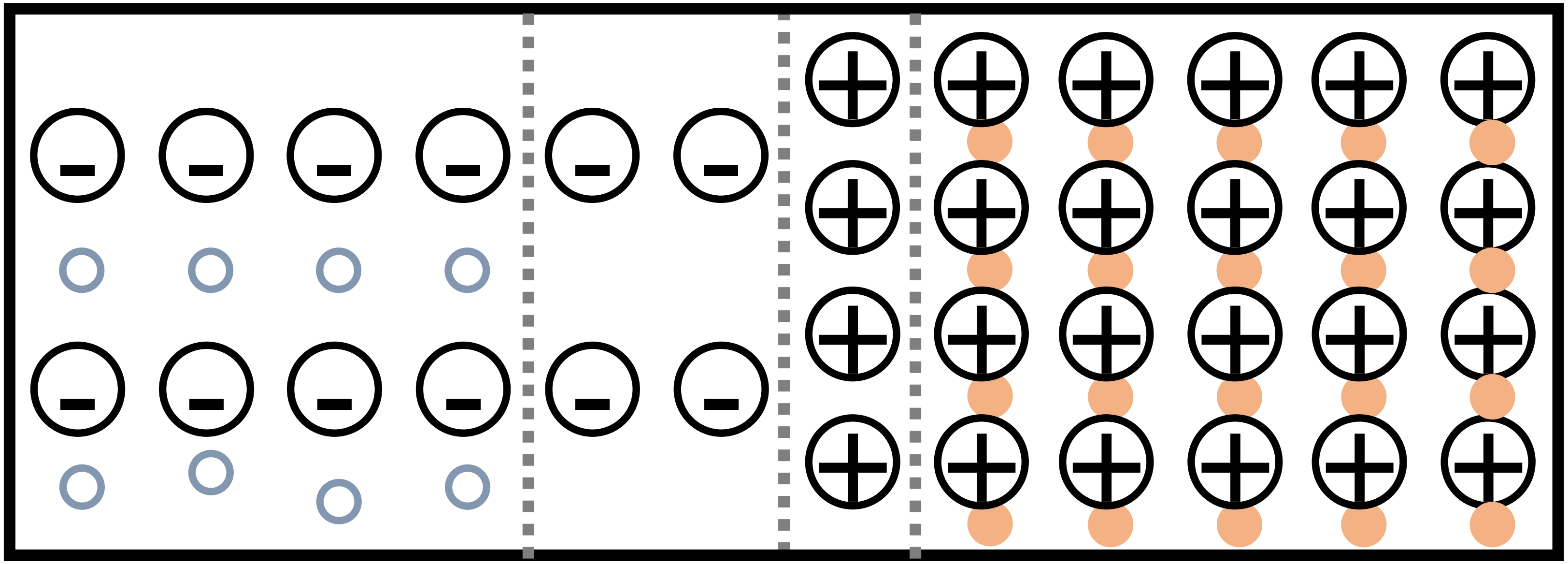
Space charge region is thick Space charge region is thin



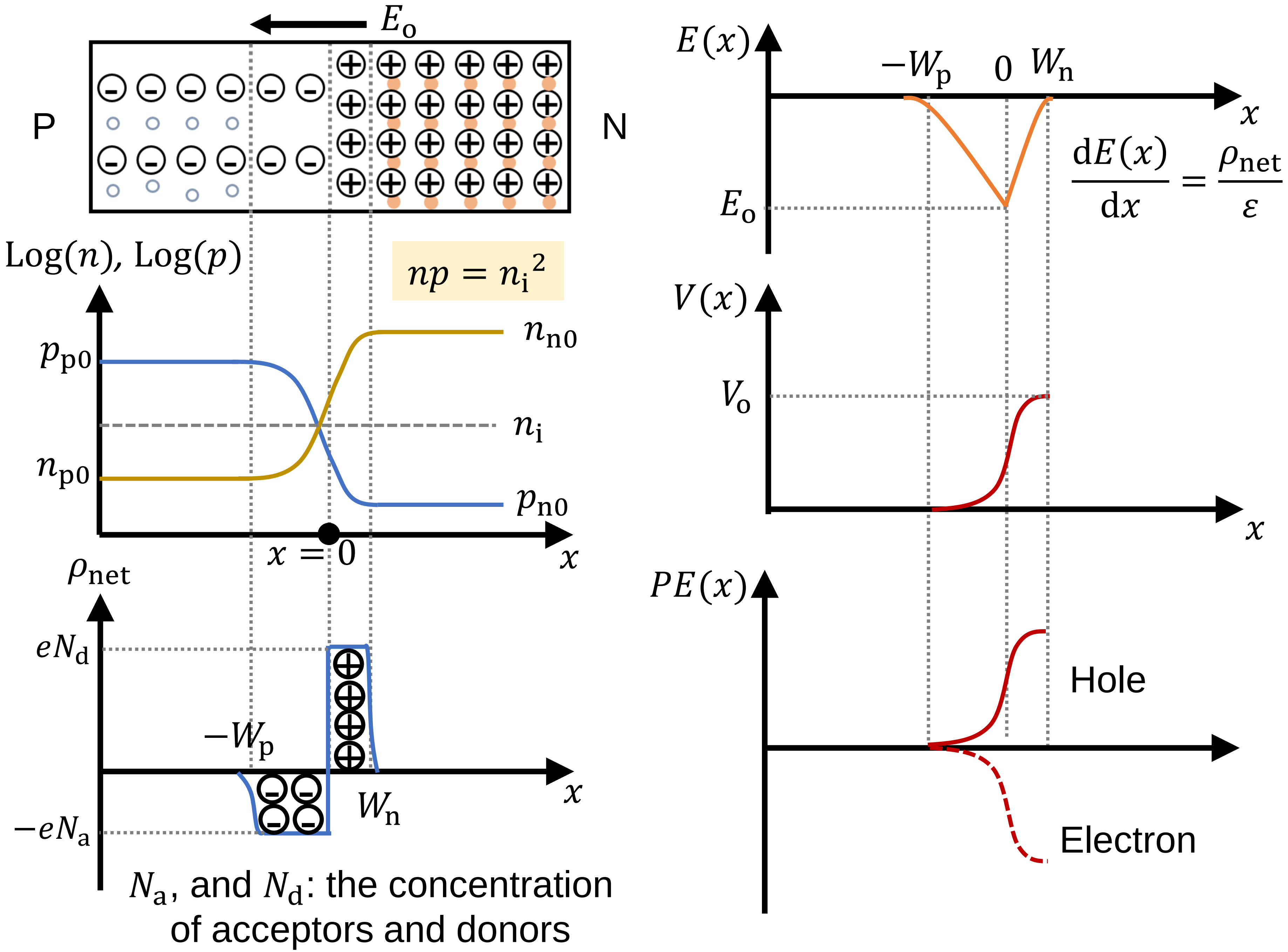
Slightly doped P-type Heavily doped N-type

Ion and free hole concentration is low

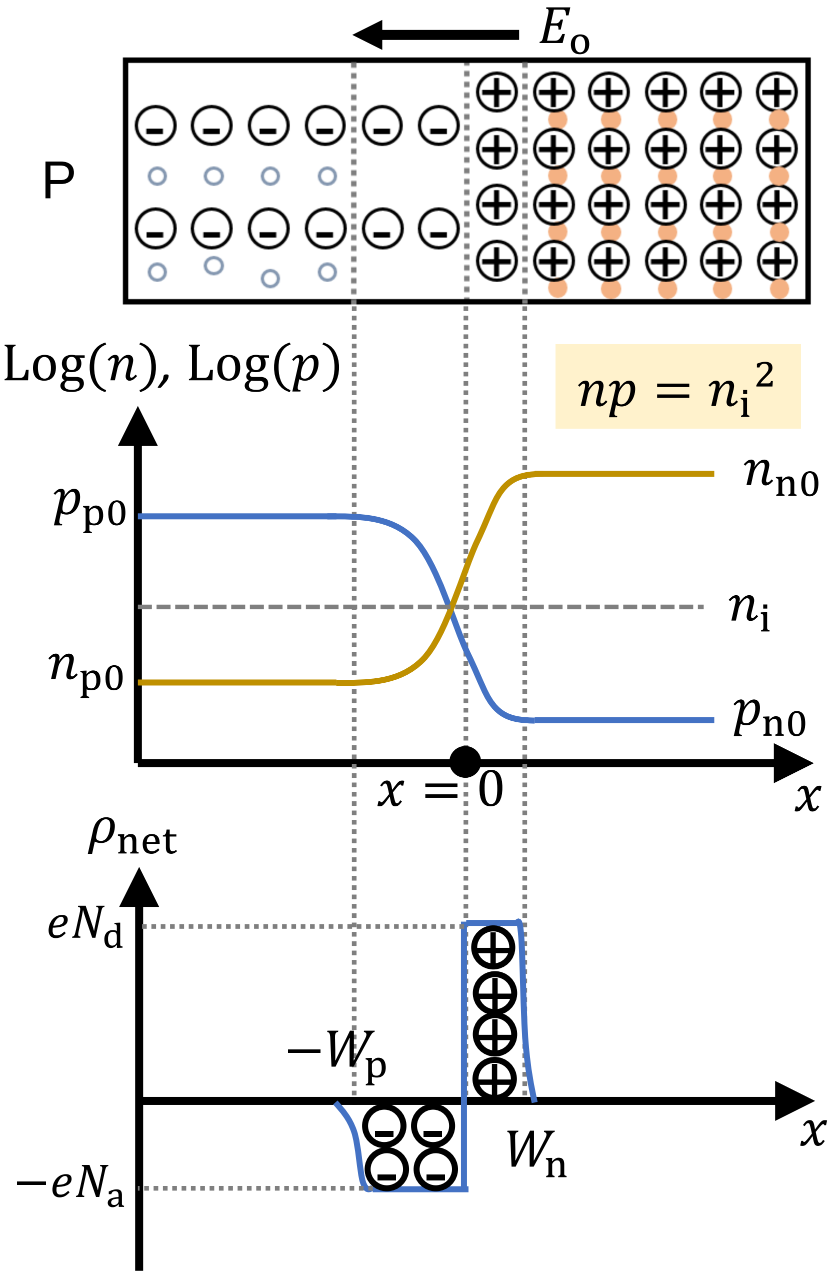
Ion and free electron concentration is high



Q: What's the distribution of electron and hole concentrations (*n* and *p*), net space charge density (ρ_{net}), internal electric field (*E*), potential *(V)*, potential energy (*PE*)?



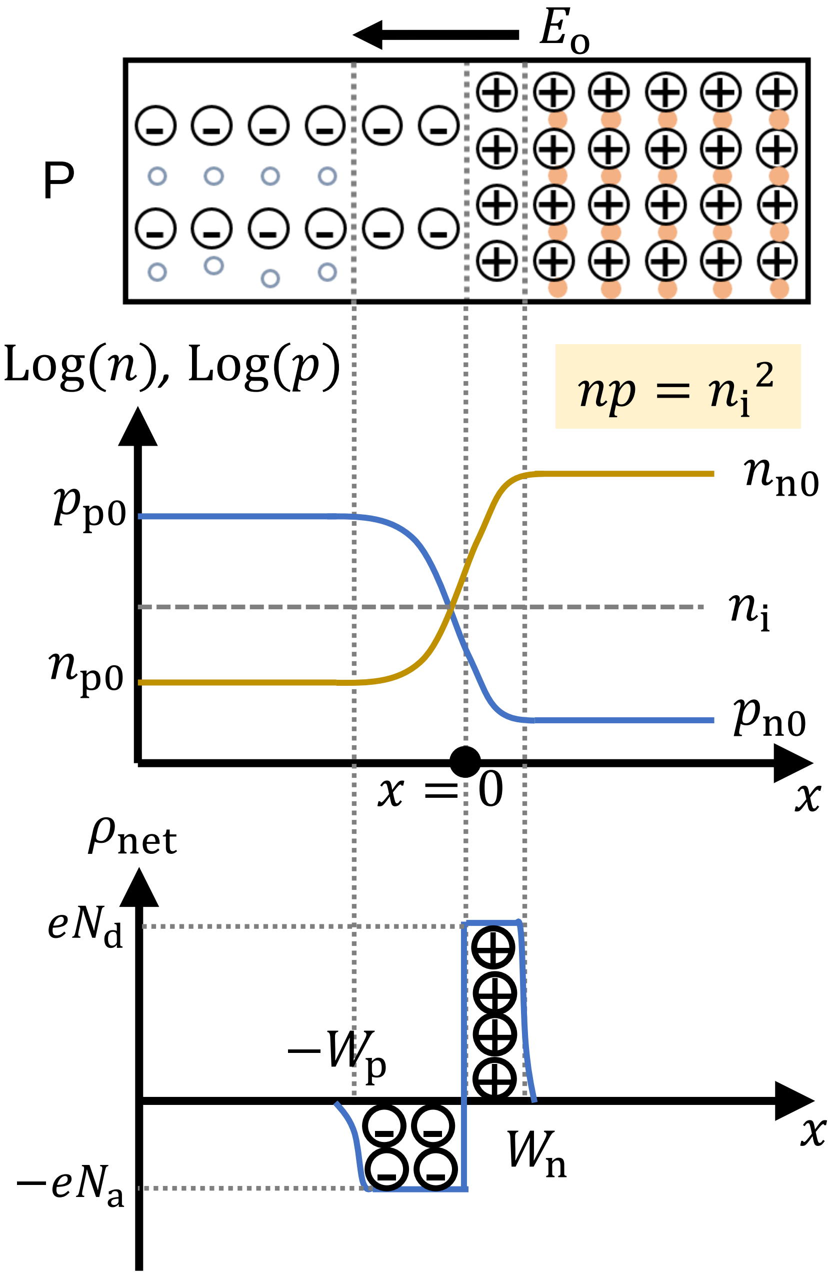
E_o
P
N
$\mathrm{Log}(n)$, $\mathrm{Log}(p)$
$np = n_i{}^2$
p_{p0}
n_{n0}
n_i
n_{p0}
p_{n0}
$x = 0$
x
ρ_{net}
eN_d
$-W_p$
W_n
$-eN_a$
x
$E(x)$
$-W_p$
0
W_n
x
E_o
$\frac{dE(x)}{dx} = \frac{\rho_{net}}{\varepsilon}$
$V(x)$
V_o
x
$PE(x)$
Hole
Electron
N_a, and N_d: the concentration
of acceptors and donors



Question: What's the relation between W_p, W_n, N_a, and N_d?

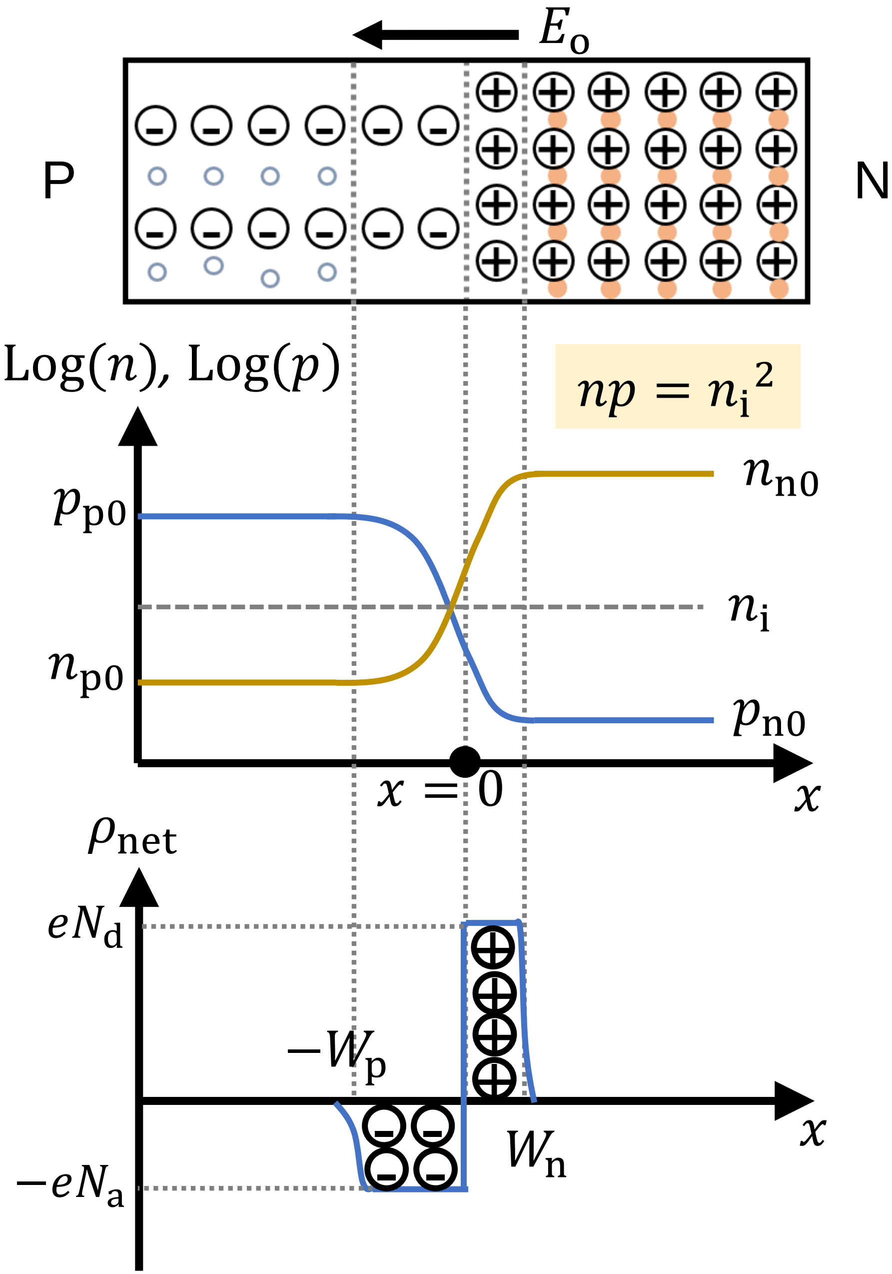
N_a, and N_d: the concentration of acceptors and donors

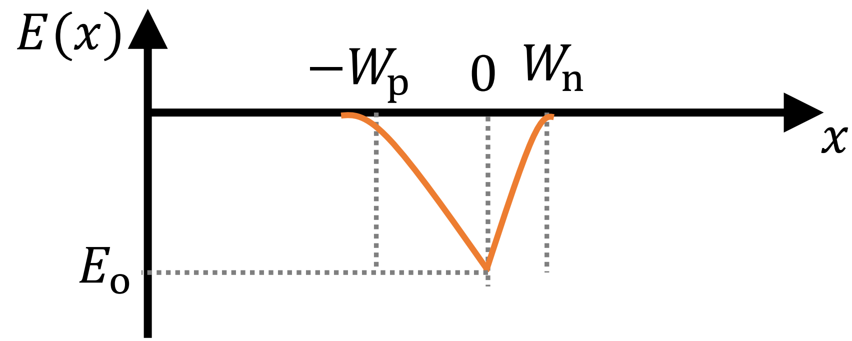
$$N_a W_p = N_d W_n$$



Q: What's the width of depletion region?

$$W_o = W_p + W_n$$



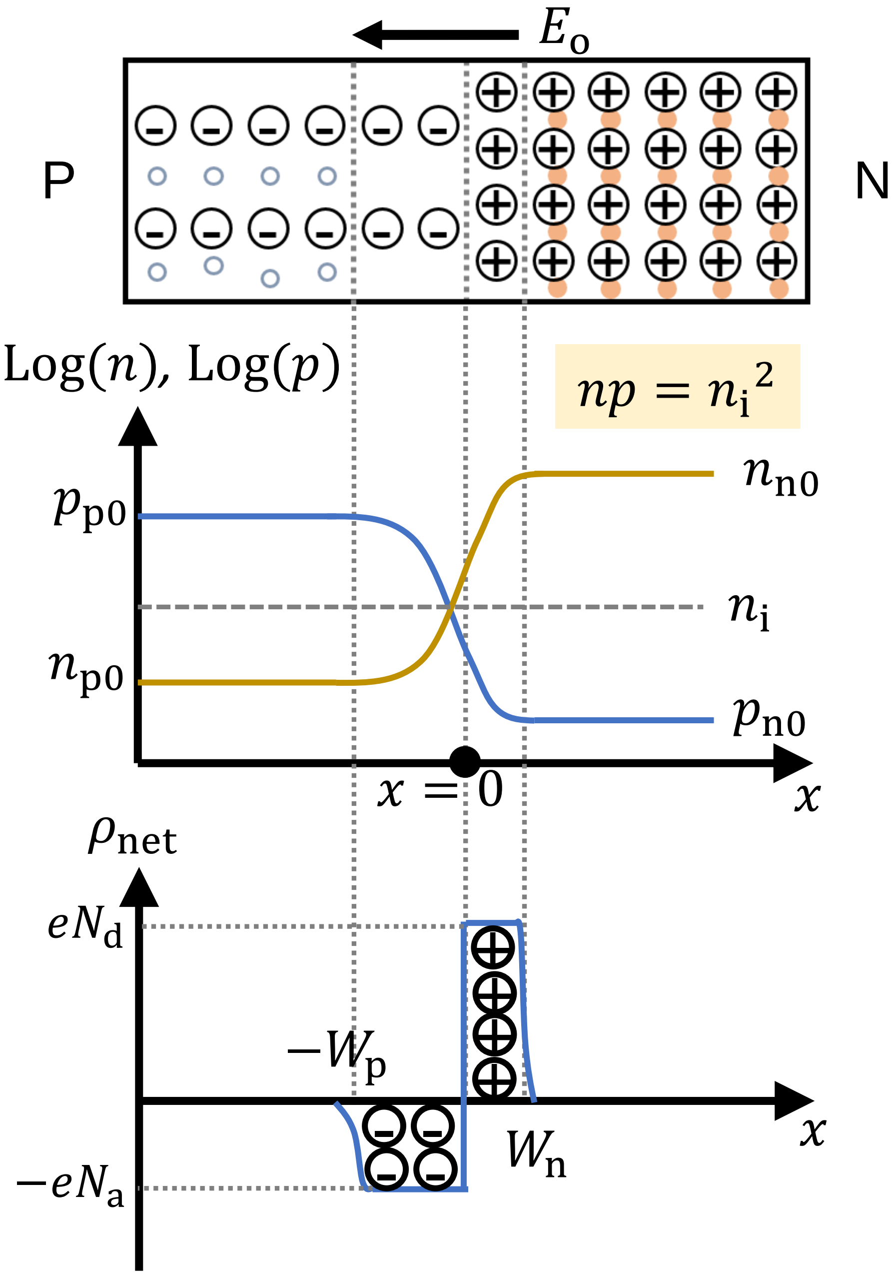


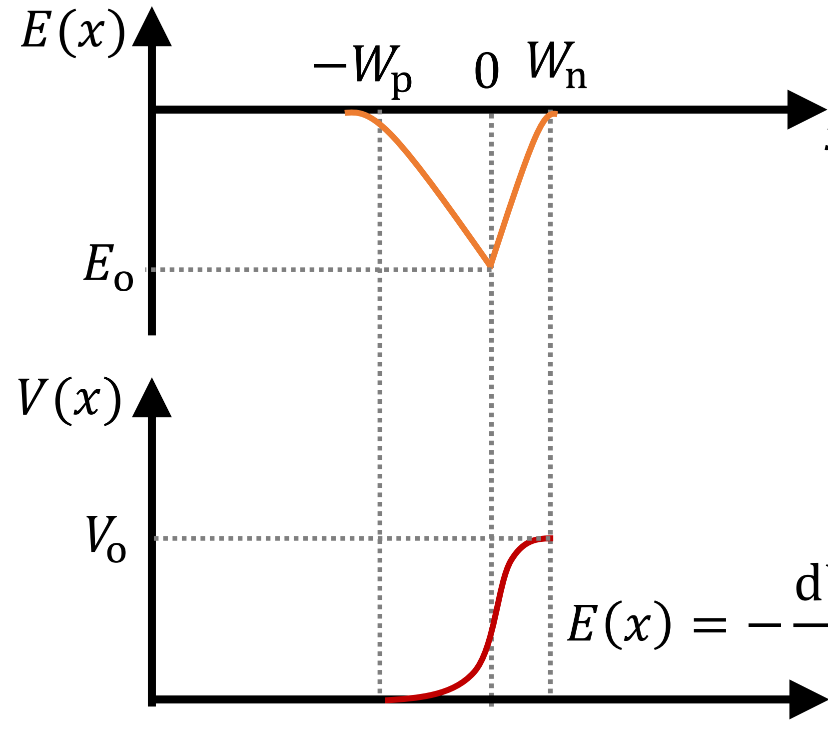
Let's start from $\dfrac{dE(x)}{dx} = \dfrac{\rho_{net}}{\varepsilon}$

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

Assume $\rho_{net}(x)$ is step function

$$E_o = -\frac{eN_aW_p}{\varepsilon} = -\frac{eN_dW_n}{\varepsilon}$$



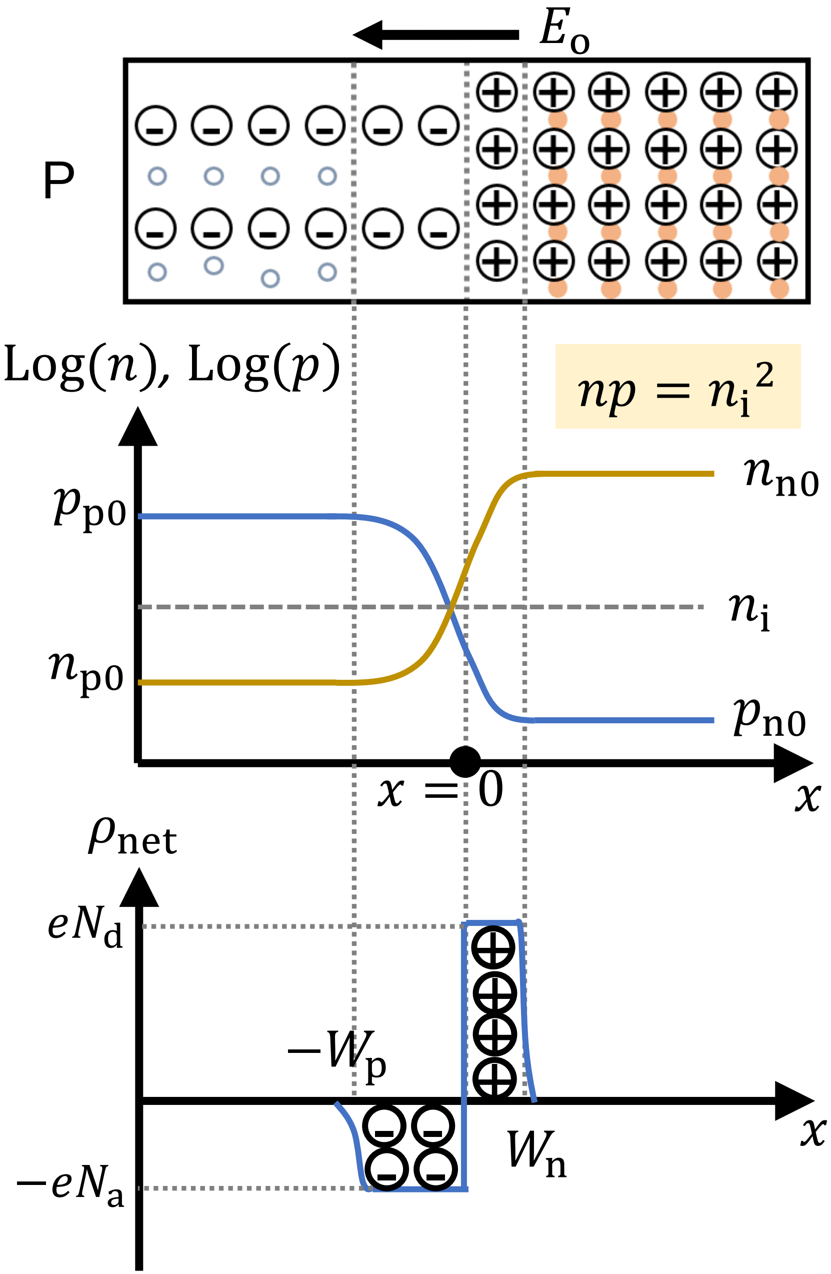


$$E(x) = -\frac{dV(x)}{dx}$$

$$V = -\int_{-W_p}^{0} E\,dx - \int_{0}^{W_n} E\,dx$$

$$V_o = \int_{-W_p}^{0} \frac{eN_a(x + W_p)}{\varepsilon}\,dx + \int_{0}^{W_n} \frac{e(N_d - x)W_n}{\varepsilon}\,dx$$

$$= \frac{eN_aN_dW_o^2}{2\varepsilon(N_a + N_d)}$$



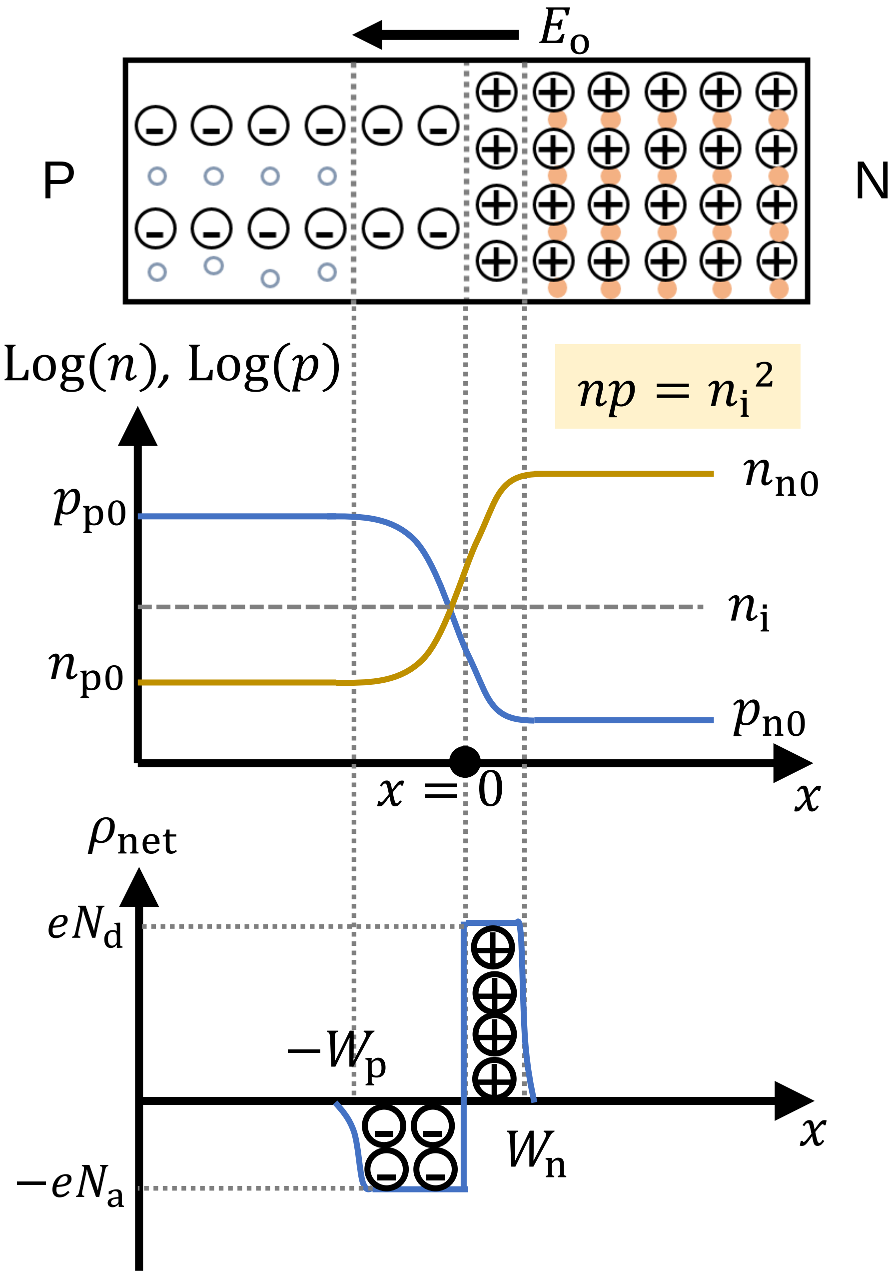
In most situations, *PE>>kT*

FD distribution → Boltzmann distribution

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

$$\begin{cases} \dfrac{n_{p0}}{n_{n0}} = \exp\left[-\dfrac{eV_0}{kT}\right] \\[2ex] \dfrac{p_{n0}}{p_{p0}} = \exp\left[-\dfrac{eV_0}{kT}\right] \end{cases}$$

$$V_0 = \frac{kT}{e}\ln\left[\frac{n_{n0}}{n_{p0}}\right] = \frac{kT}{e}\ln\left[\frac{p_{p0}}{p_{n0}}\right]$$

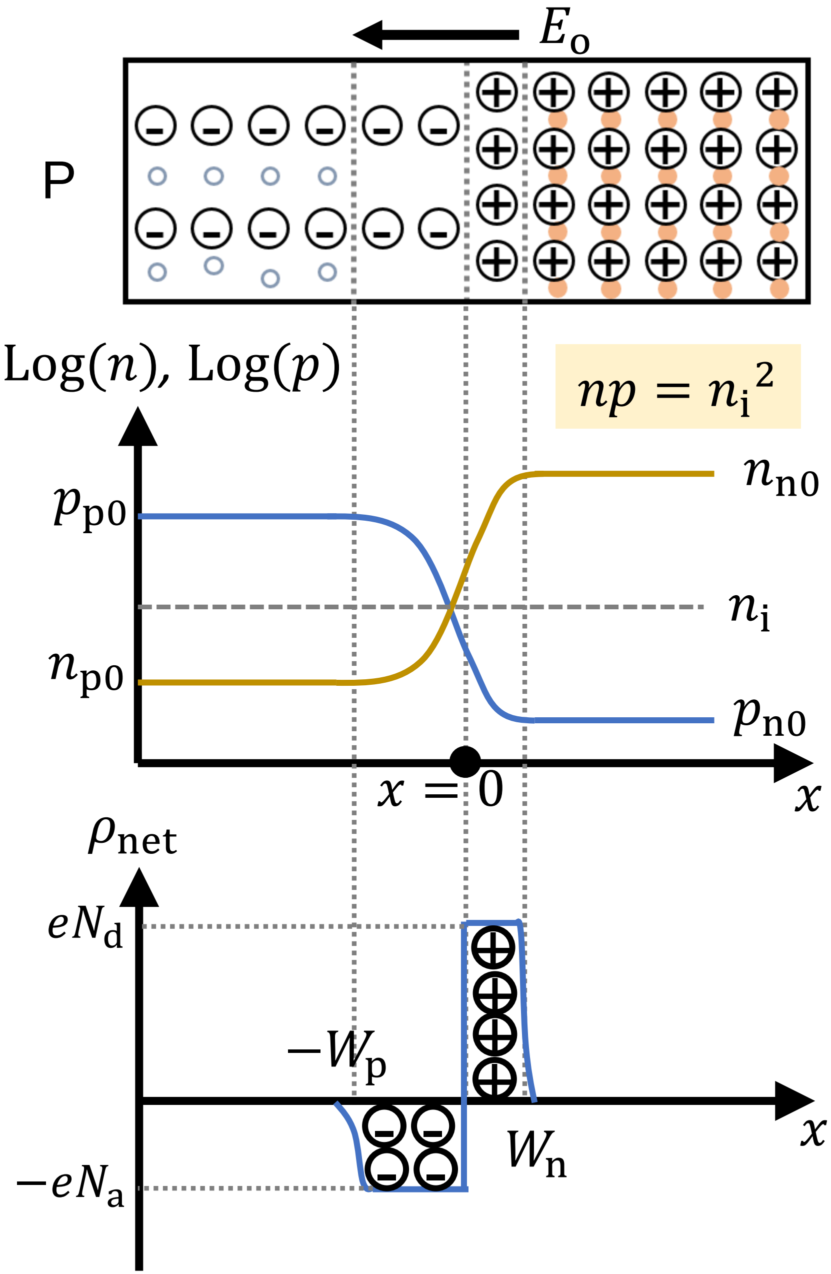


$$V_0 = \frac{kT}{e} \ln\left[\frac{n_{n0}}{n_{p0}}\right] = \frac{kT}{e} \ln\left[\frac{p_{p0}}{p_{n0}}\right]$$

If we assume $p_{p0} = N_a$, $n_{n0} = N_d$:

$$p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{n_i^2}{N_d}$$

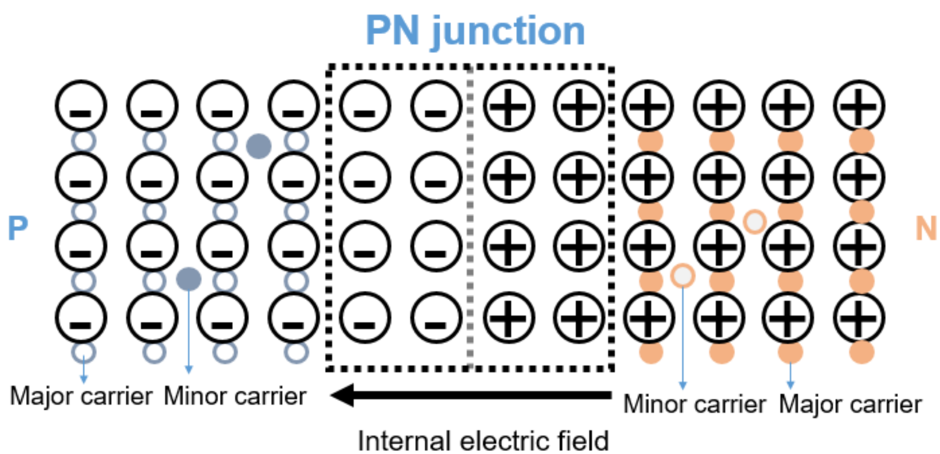
$$V_0 = \frac{kT}{e} \ln\left[\frac{N_a N_d}{n_i^2}\right]$$



$$W_0 = \left[\frac{2\varepsilon(N_a + N_d)V_0}{eN_aN_d}\right]^{1/2}$$

$$V_0 = \frac{kT}{e}\ln\left[\frac{N_aN_d}{n_i^2}\right]$$

Another way to get: $V_0 = \frac{kT}{e}\ln\left[\frac{n_{\mathrm{n0}}}{n_{\mathrm{p0}}}\right] = \frac{kT}{e}\ln\left[\frac{p_{\mathrm{p0}}}{p_{\mathrm{n0}}}\right]$



$$V = 0 \qquad V = V_0$$

$$p = p_{\mathrm{p0}} \qquad p = p_{\mathrm{n0}}$$

Considering holes alone:

$$J_{\mathrm{h}} = ep\mu_{\mathrm{h}}E_{\mathrm{x}} - eD_{\mathrm{h}}\frac{\mathrm{d}p}{\mathrm{d}x} = 0$$

$$-ep\mu_{\mathrm{h}}\frac{\mathrm{d}V}{\mathrm{d}x} - eD_{\mathrm{h}}\frac{\mathrm{d}p}{\mathrm{d}x} = 0$$

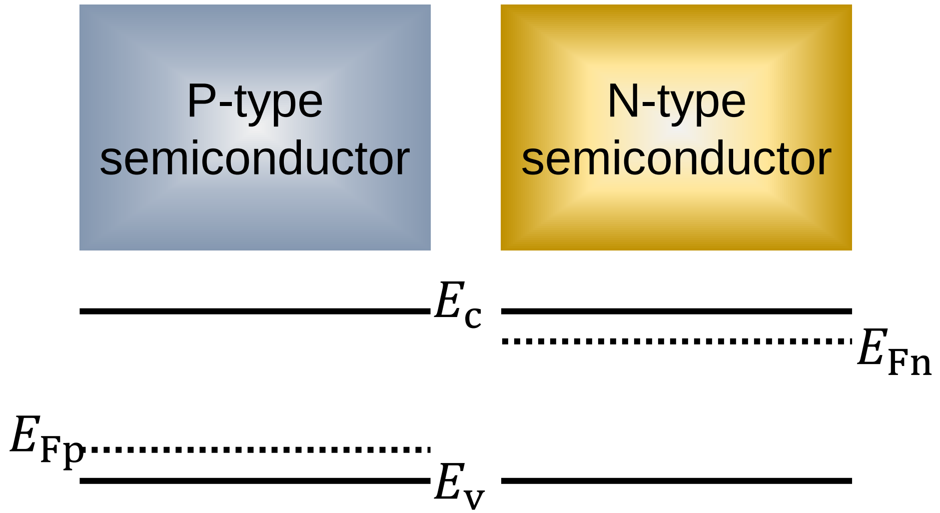
$$\Downarrow$$

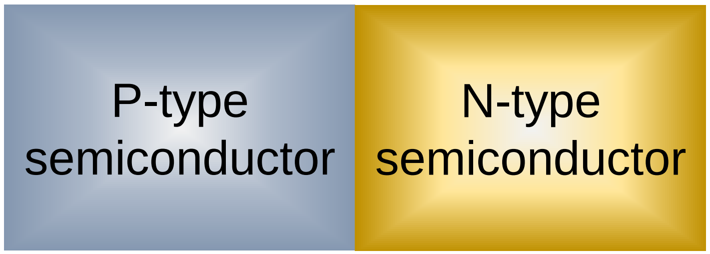
$$-ep\mathrm{d}V - kT\mathrm{d}p = 0$$

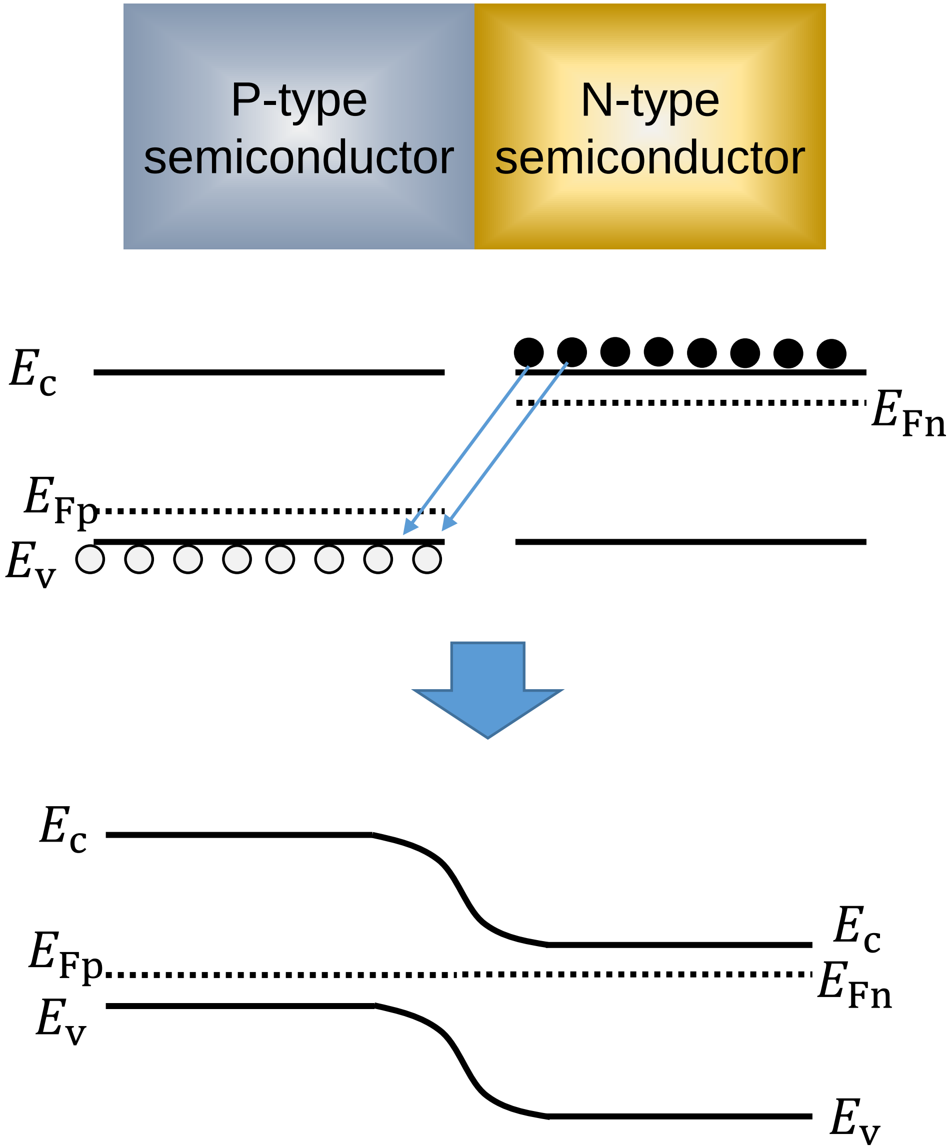
$$\Downarrow$$

$$V_0 = \frac{kT}{e}\ln\left[\frac{p_{\mathrm{p0}}}{p_{\mathrm{n0}}}\right]$$

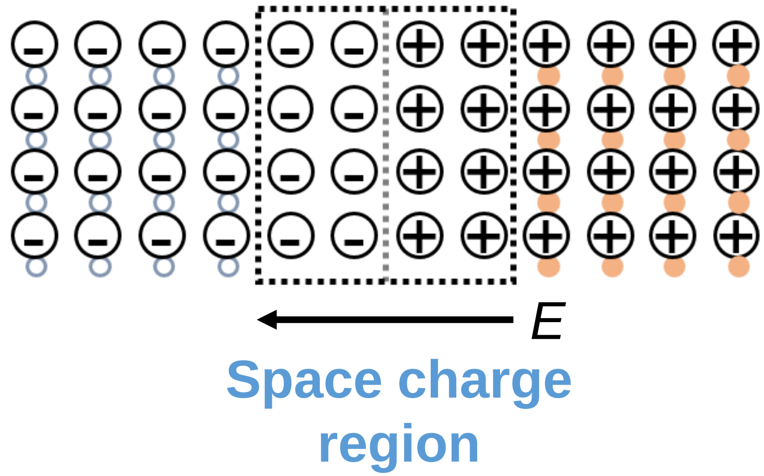
Band diagram of PN junction



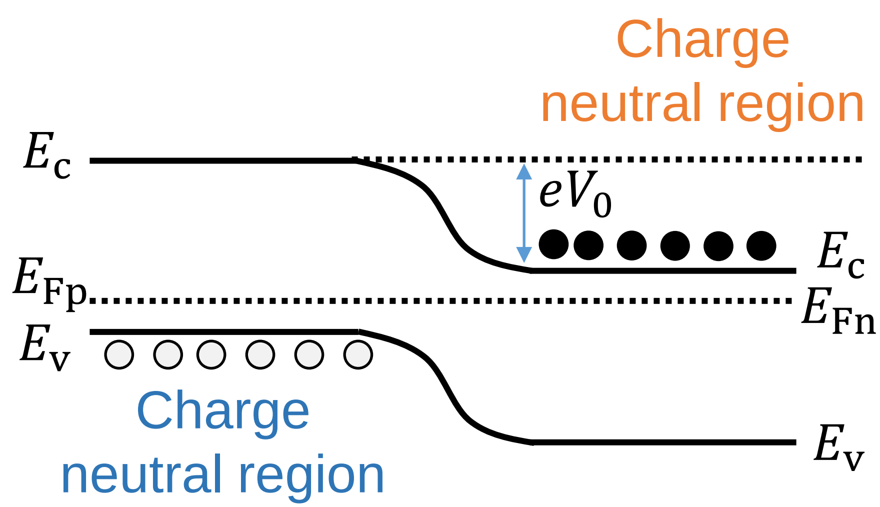




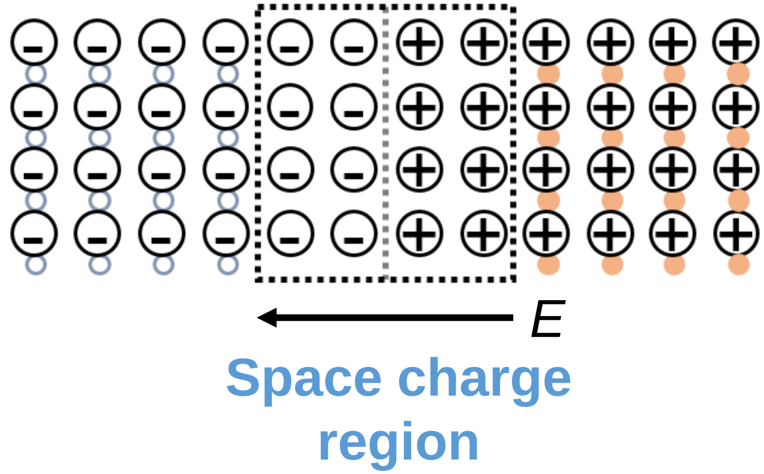
P-type semiconductor
N-type semiconductor
E_c
E_{Fn}
E_{Fp}
E_v
E_c
E_c
E_{Fp}
E_{Fn}
E_v
E_v

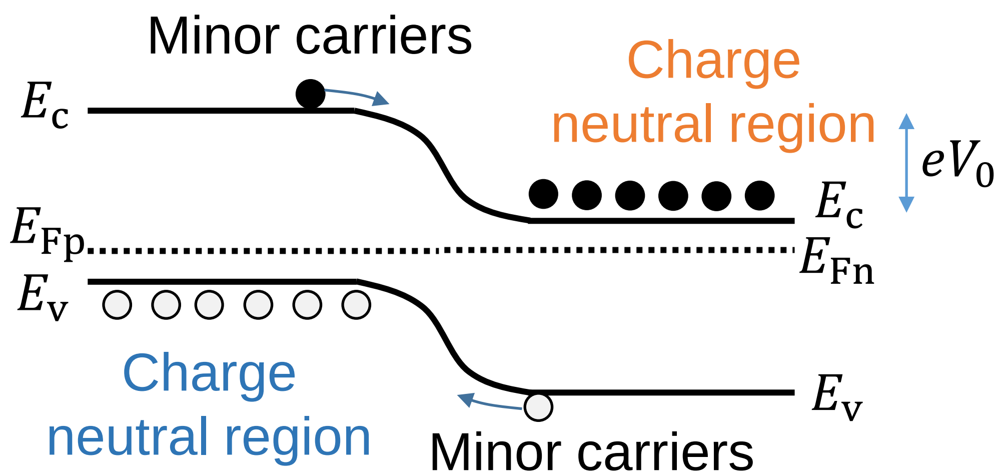


E
Space charge region



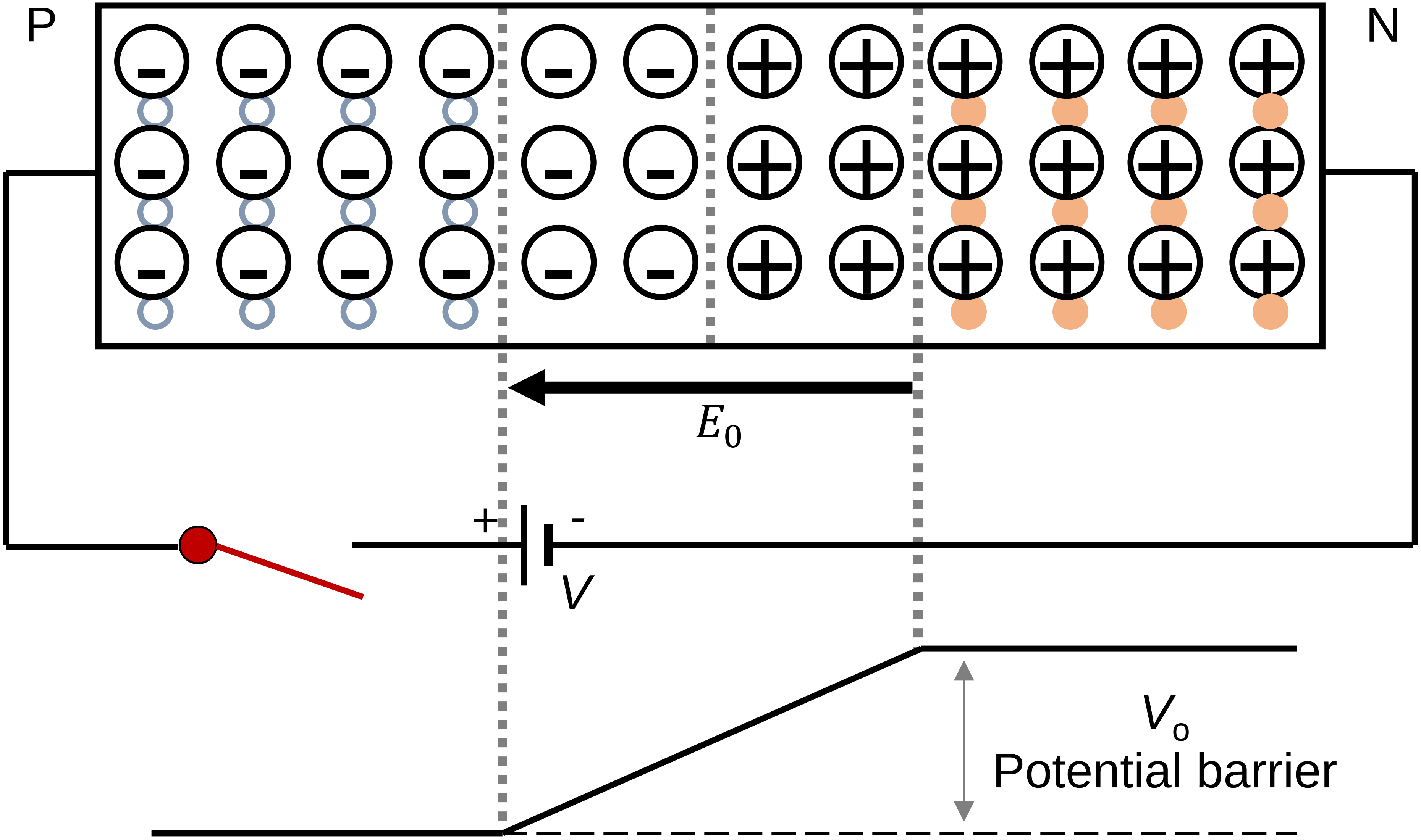
Charge neutral region
E_c
eV_0
E_c
E_{Fp}
E_{Fn}
E_v
Charge neutral region
E_v



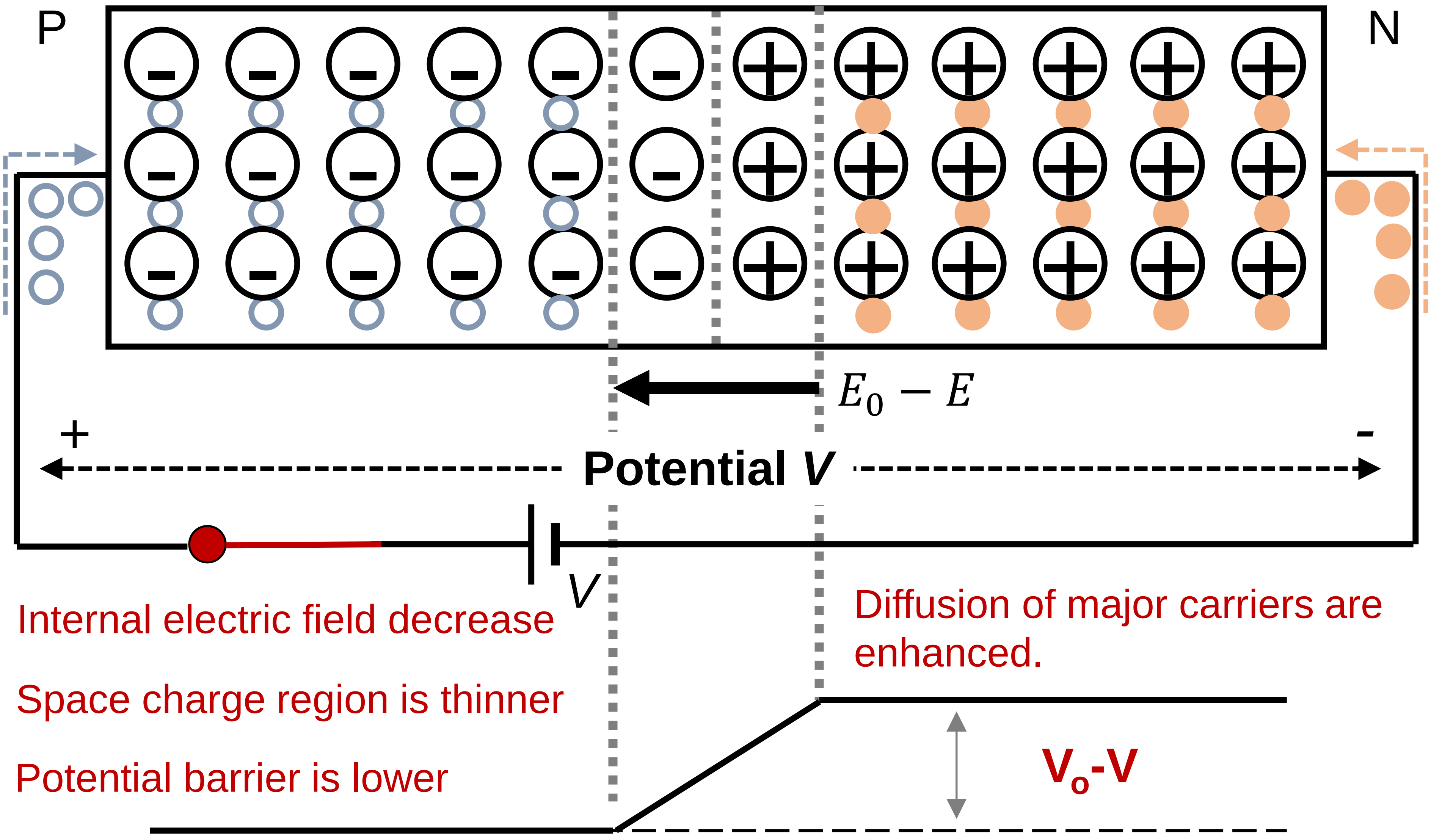


Block the diffusion of major carriers.
Accelerate the drift of minor carriers.

5.5 The electrical properties of PN junction



Forward bias 正向偏置电压



Internal electric field decrease

Space charge region is thinner

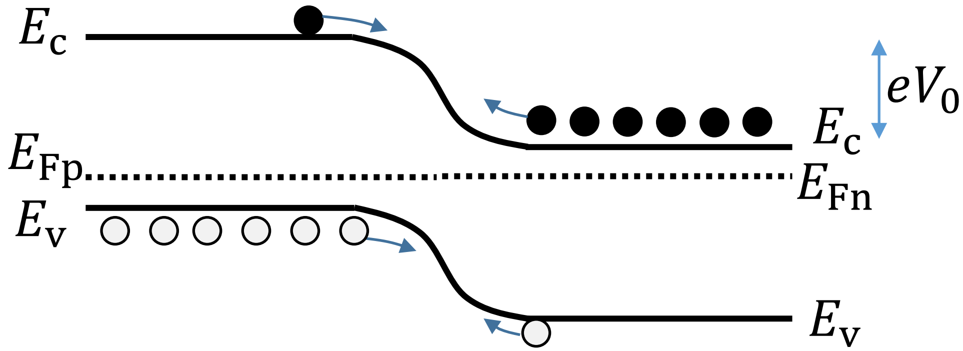
Potential barrier is lower

Diffusion of major carriers are enhanced.

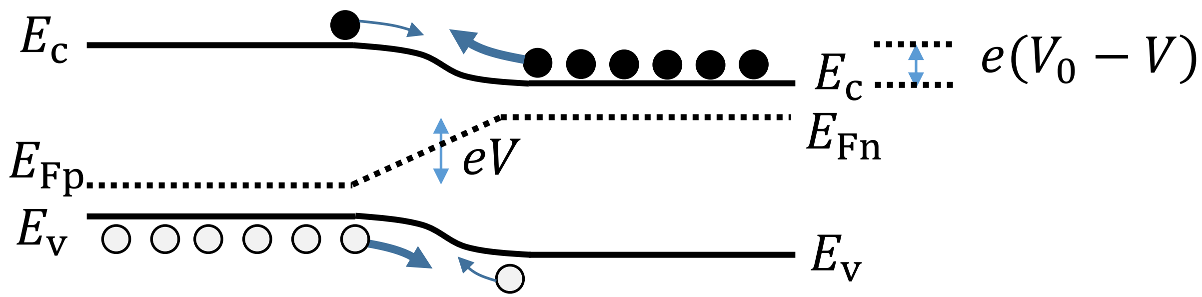
PN-junction is on with low resistance

Band diagram at forward bias

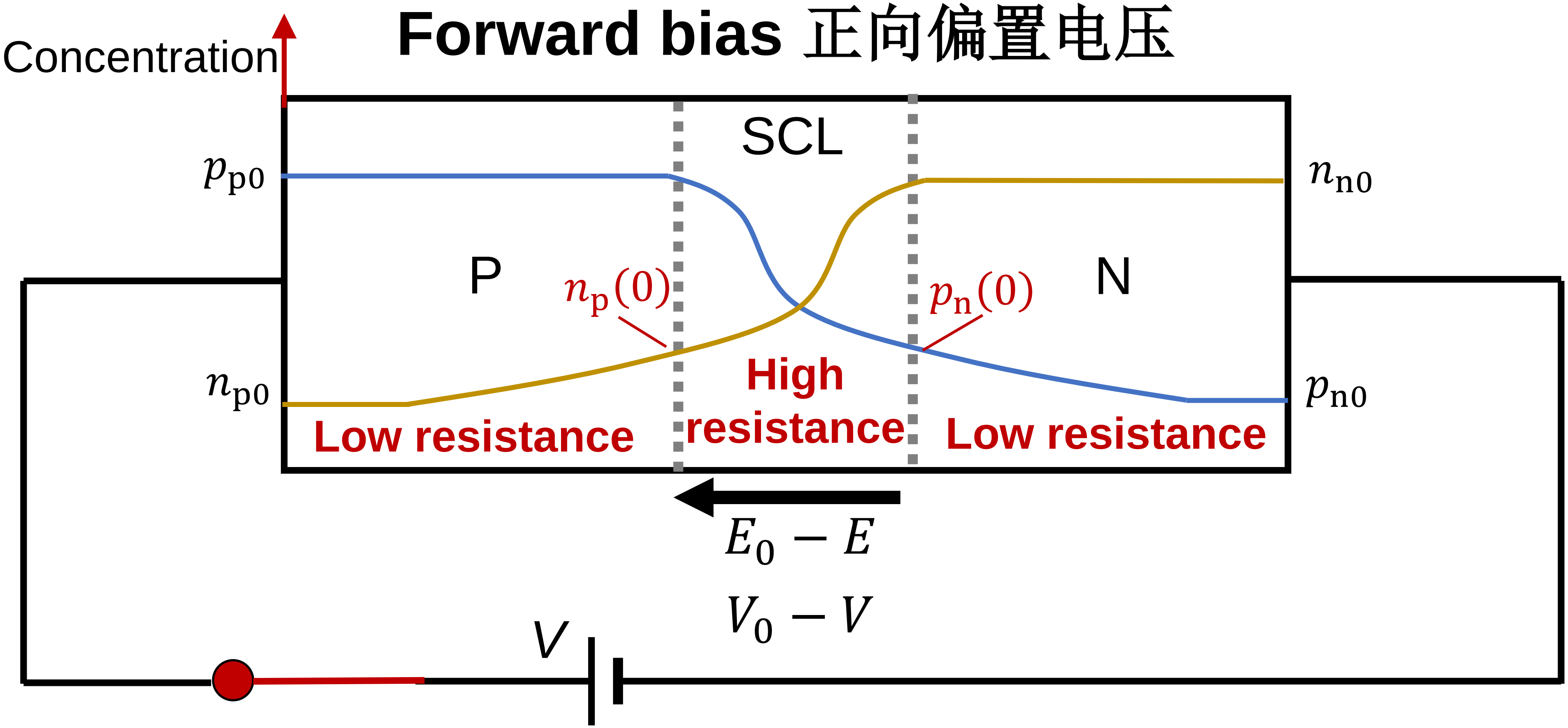
No bias



A forward bias: V



Forward bias 正向偏置电压

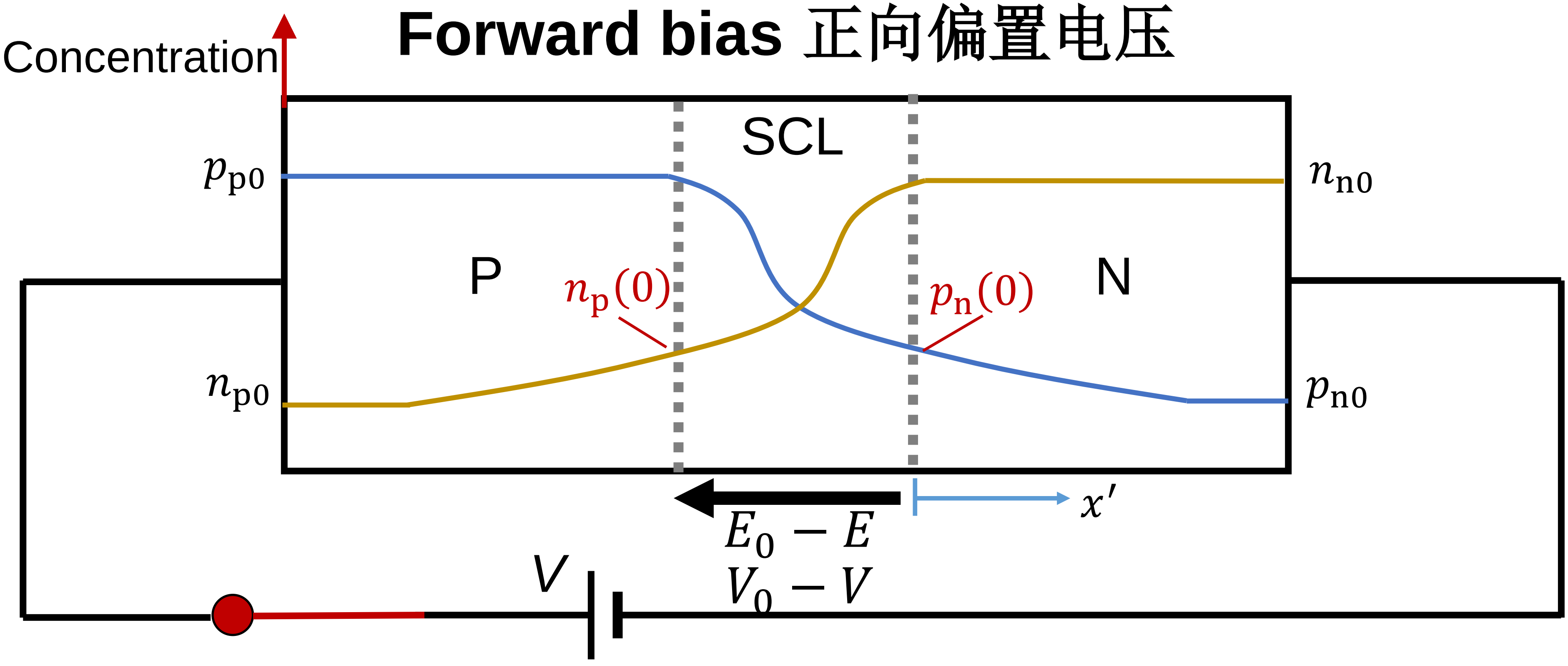


Space charge layer (SCL): high resistance

Almost all voltage are dropped on SCL.

Current is due to **diffusion of minor** carriers and **drift of major** carriers.

Forward bias 正向偏置电压

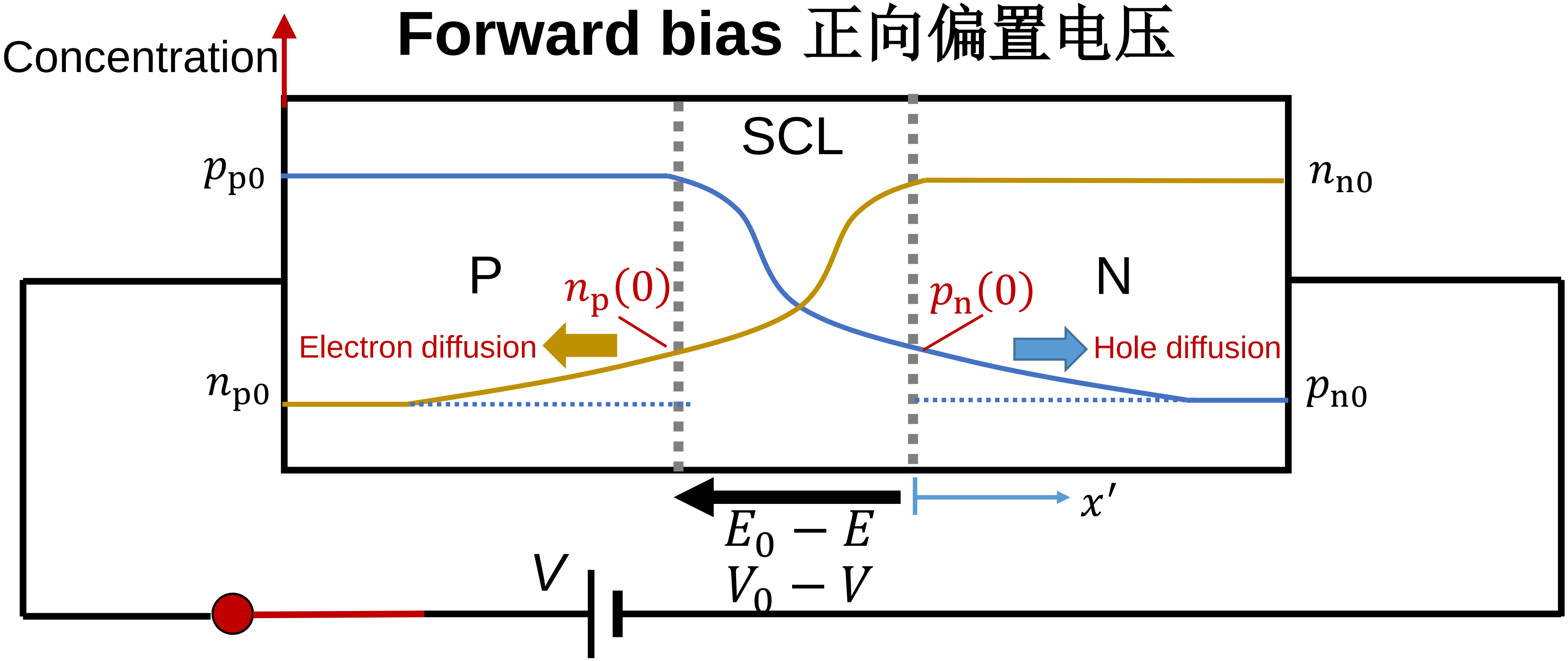


$$p_n(0) = p_{p0}\exp\left[-\frac{e(V_0 - V)}{kT}\right] = p_{n0}\exp\left[\frac{eV}{kT}\right]$$

$$n_p(0) = n_{n0}\exp\left[-\frac{e(V_0 - V)}{kT}\right] = n_{p0}\exp\left[\frac{eV}{kT}\right]$$

This is called the law of the junction.

Forward bias 正向偏置电压



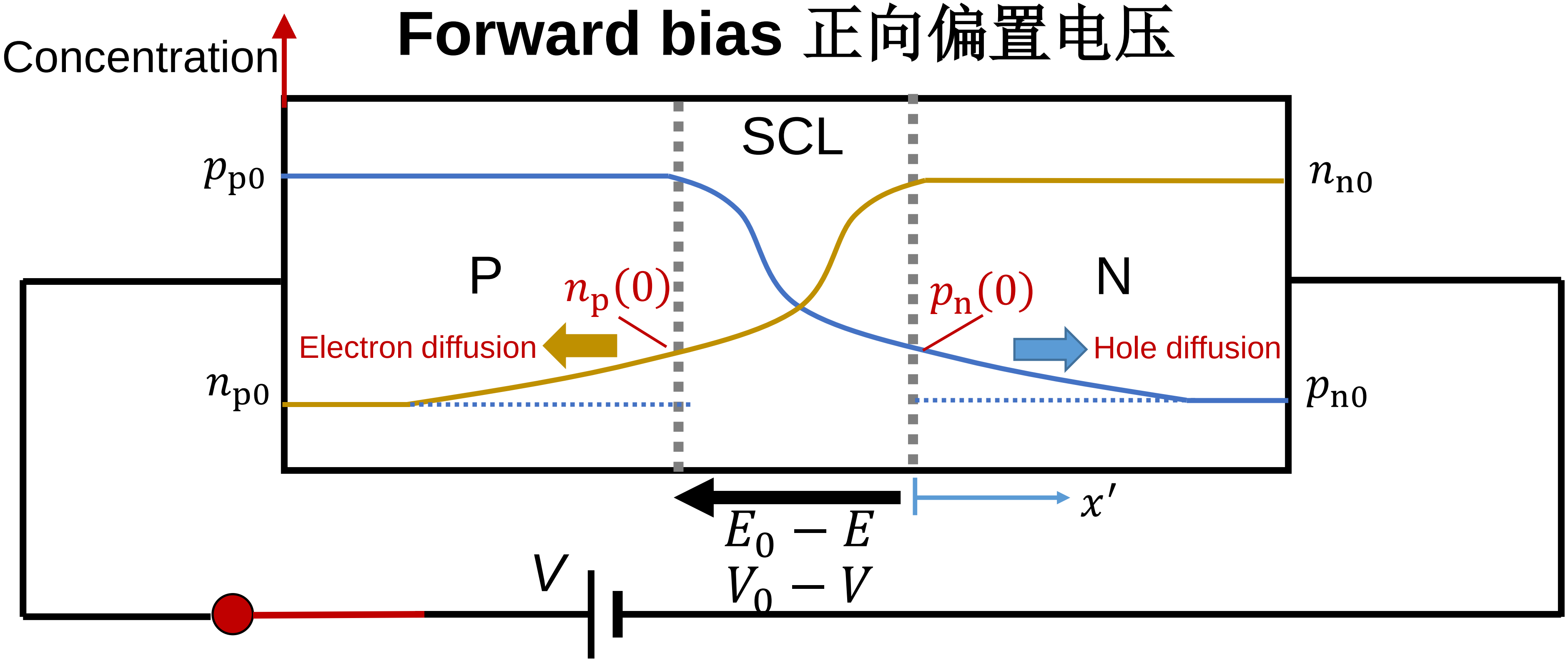
At $x' = 0$, Excess hole: $\Delta p_n(0) = p_n(0) - p_{n0}$

At x', Excess hole: $\Delta p_n(x') = p_n(x') - p_{n0}$

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

Hole diffusion length: $L_h = \sqrt{D_h \tau_h}$

Forward bias 正向偏置电压

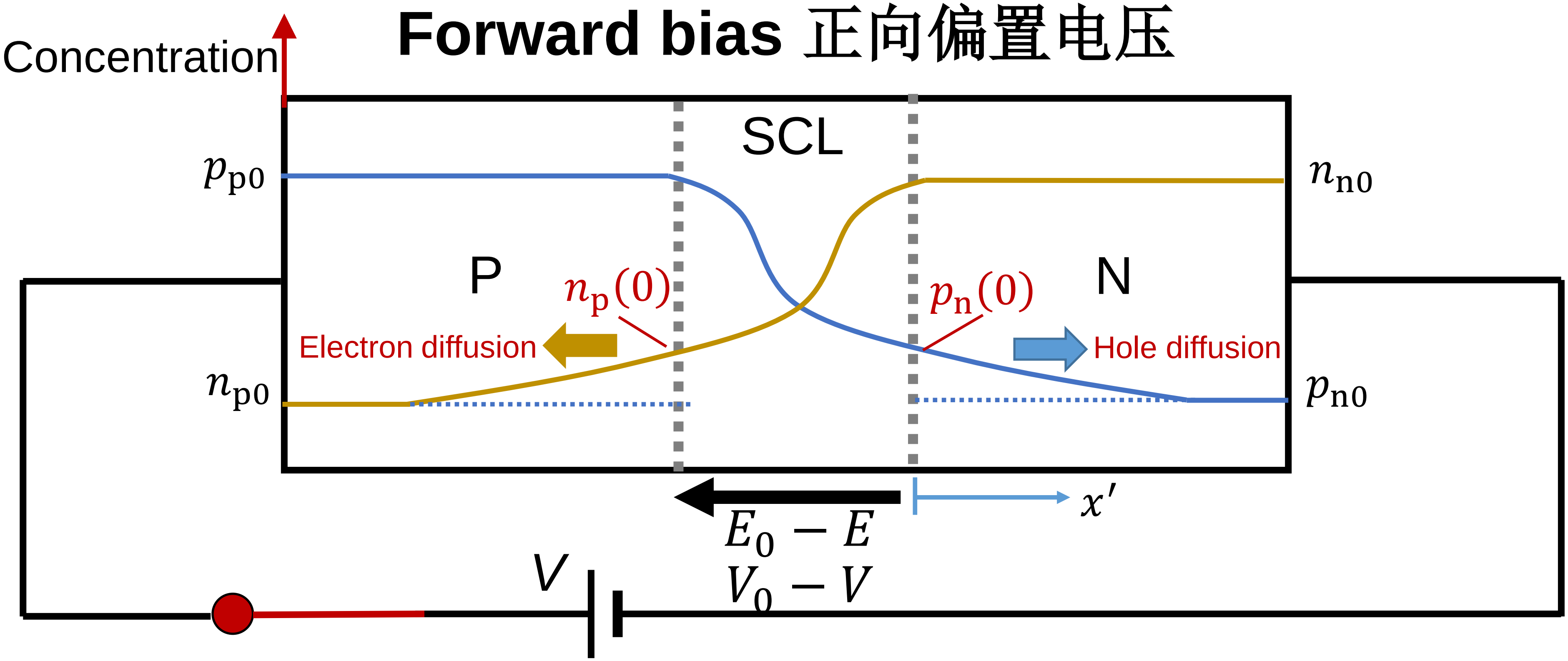


$$J_{\mathrm{D,hole}} = -eD_{\mathrm{h}}\frac{\mathrm{d}p_{\mathrm{n}}(x')}{\mathrm{d}x'} = -eD_{\mathrm{h}}\frac{\mathrm{d}\Delta p_{\mathrm{n}}(x')}{\mathrm{d}x'}$$

$$= \frac{eD_{\mathrm{h}}}{L_{\mathrm{h}}}\Delta p_{\mathrm{n}}(0)\exp\left(-\frac{x'}{L_{\mathrm{h}}}\right)$$

$$= \frac{eD_{\mathrm{h}}p_{\mathrm{n0}}}{L_{\mathrm{h}}}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]\exp\left(-\frac{x'}{L_{\mathrm{h}}}\right) = \frac{eD_{\mathrm{h}}n_{\mathrm{i}}^2}{L_{\mathrm{h}}N_{\mathrm{d}}}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]\exp\left(-\frac{x'}{L_{\mathrm{h}}}\right)$$

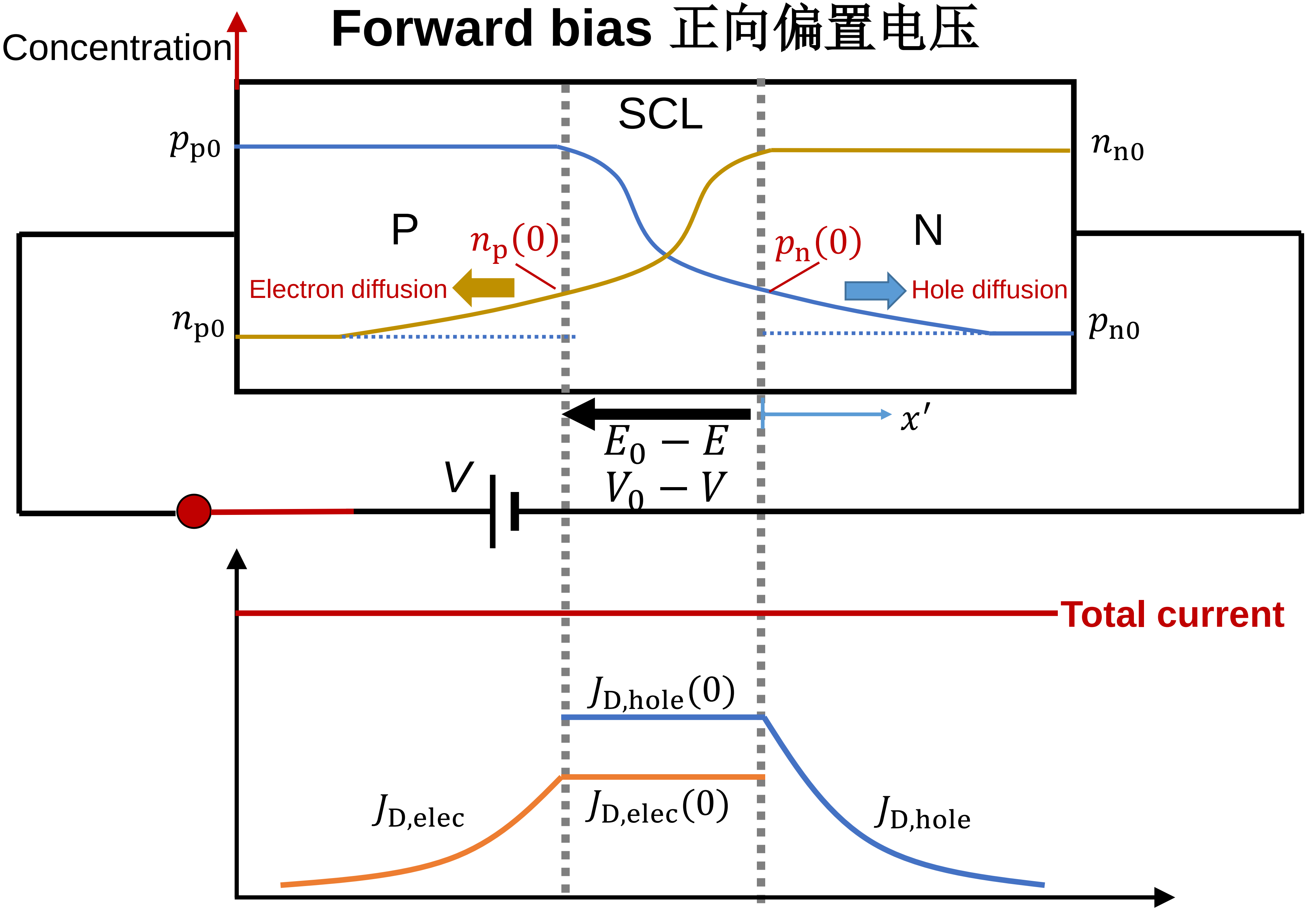
Forward bias 正向偏置电压



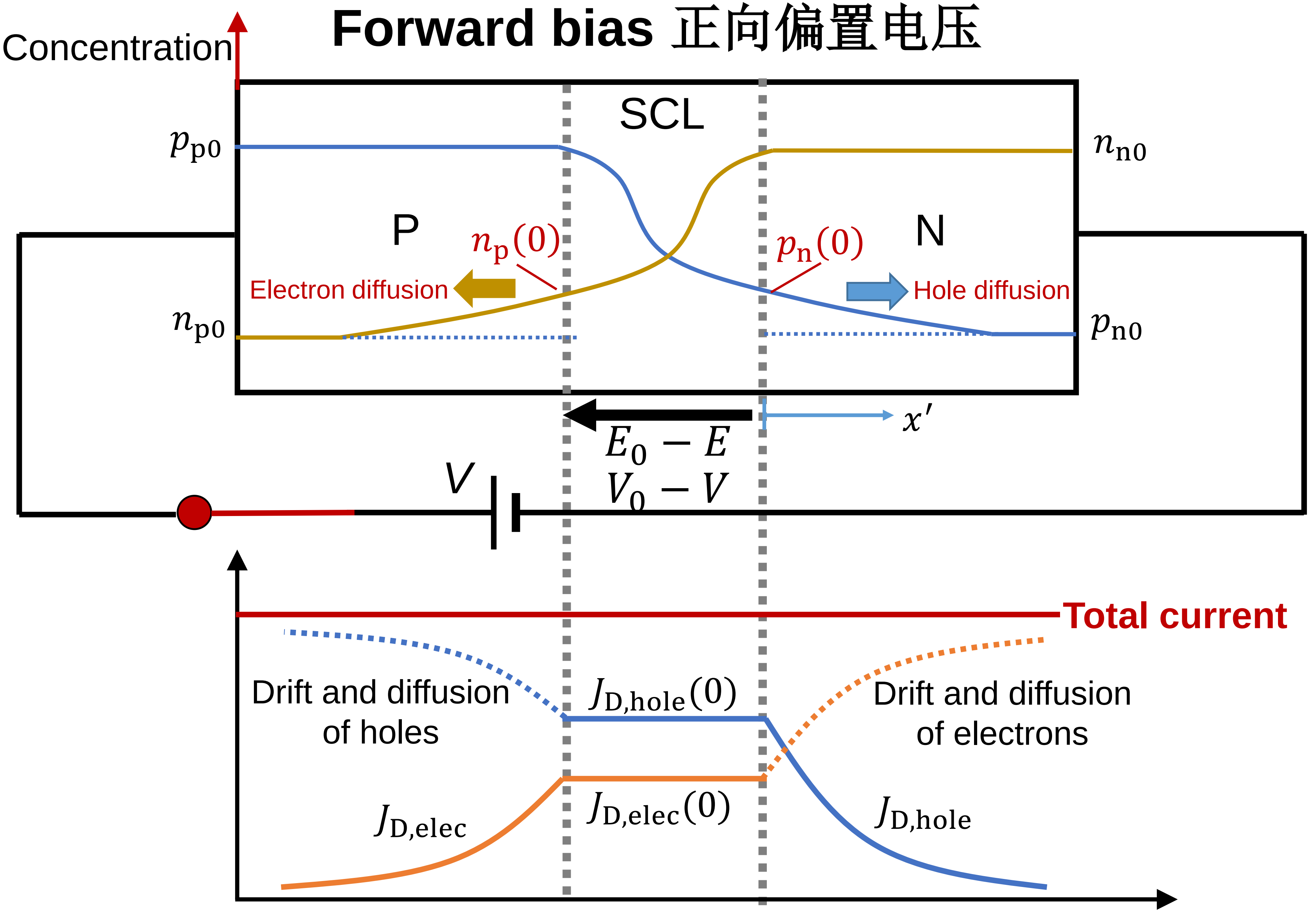
At SCL-N interface: $J_{D,hole}(0) = \dfrac{eD_h n_i^2}{L_h N_d}\left[\exp\left(\dfrac{eV}{kT}\right) - 1\right]$

At SCL-P interface: $J_{D,elec}(0) = \dfrac{eD_e n_i^2}{L_e N_a}\left[\exp\left(\dfrac{eV}{kT}\right) - 1\right]$

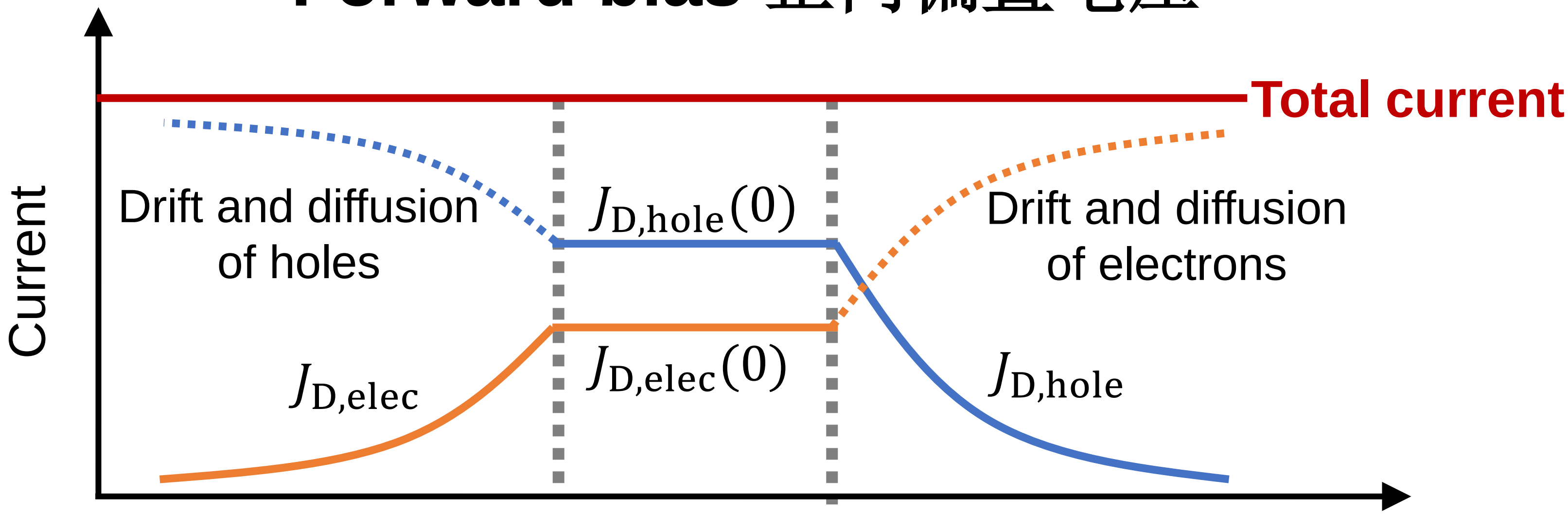
Forward bias 正向偏置电压



Forward bias 正向偏置电压



Forward bias 正向偏置电压



$$J_{\mathrm{D,elec}}(0) = \frac{eD_{\mathrm{e}}n_{\mathrm{i}}^2}{L_{\mathrm{e}}N_{\mathrm{a}}}\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \qquad J_{\mathrm{D,hole}}(0) = \frac{eD_{\mathrm{h}}n_{\mathrm{i}}^2}{L_{\mathrm{h}}N_{\mathrm{d}}}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

Total current: $J = J_{\mathrm{D,hole}}(0) + J_{\mathrm{D,elec}}(0)$

$$= \left(\frac{eD_{\mathrm{h}}}{L_{\mathrm{h}}N_{\mathrm{d}}} + \frac{eD_{\mathrm{e}}}{L_{\mathrm{e}}N_{\mathrm{a}}}\right)n_{\mathrm{i}}^2\left[\exp\left(\frac{eV}{kT}\right) - 1\right] = J_{\mathrm{so}}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

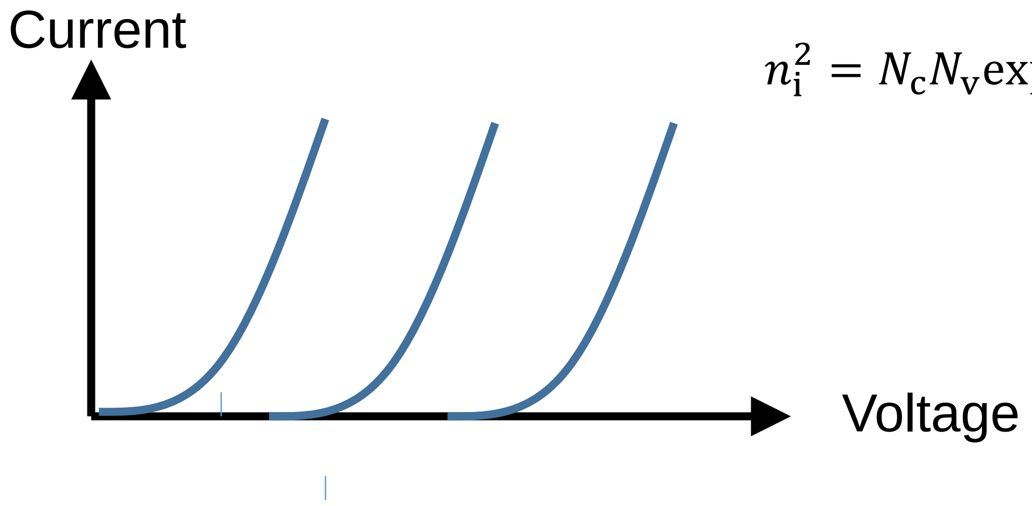
J_{so}: Reverse saturation current density

Forward bias 正向偏置电压

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

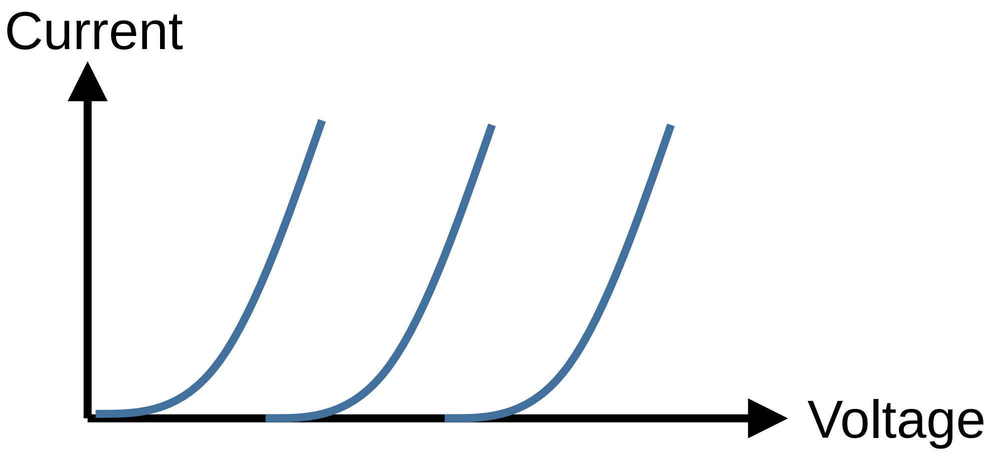
Reverse saturation current density: $J_{so} = \left(\frac{eD_{\mathrm{h}}}{L_{\mathrm{h}}N_{\mathrm{d}}} + \frac{eD_{\mathrm{e}}}{L_{\mathrm{e}}N_{\mathrm{a}}}\right)n_{\mathrm{i}}^2$

Q: The IV curves for GaAs (E_g=1.42 eV), Si (1.12 eV) and Ge (0.66 eV) PN junctions?



$$n_{\mathrm{i}}^2 = N_{\mathrm{c}}N_{\mathrm{v}}\exp\left(-\frac{E_{\mathrm{g}}}{kT}\right)$$

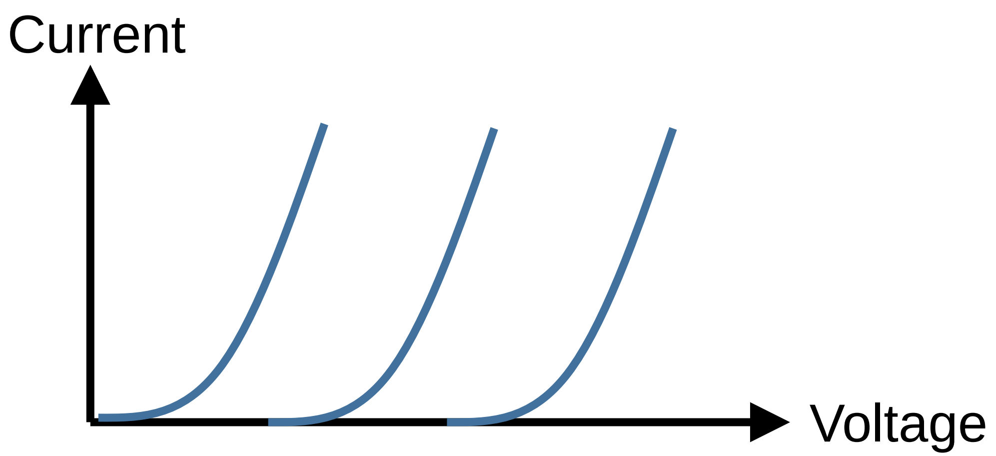
Q: The IV curves for GaAs (E_g = 1.12 eV), Si (1.12 eV) and Ge (0.66 eV) semiconductors?



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

$$J = J_{so}\left[\exp\left(\frac{eV}{kT}\right) - 1\right] = \left(\frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a}\right) N_c N_v \exp\left(-\frac{E_g}{kT}\right)\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

$$\approx \left(\frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a}\right) N_c N_v \exp\left(\frac{eV - E_g}{kT}\right)$$



$$J=\left(\frac{eD_{\mathrm{h}}}{L_{\mathrm{h}}N_{\mathrm{d}}}+\frac{eD_{\mathrm{e}}}{L_{\mathrm{e}}N_{\mathrm{a}}}\right)N_{\mathrm{c}}N_{\mathrm{v}}\exp\left(\frac{eV-E_{\mathrm{g}}}{kT}\right)$$

Diode	**Working voltage *U* (~0.1 mA)**
GaAs	~0.9 V
Si	~0.6 V
Ge	~0.2 V