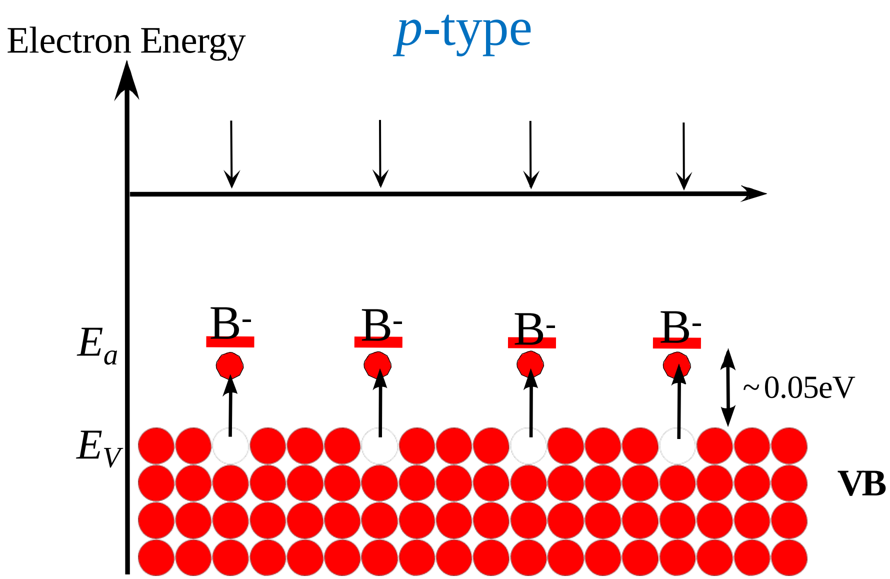
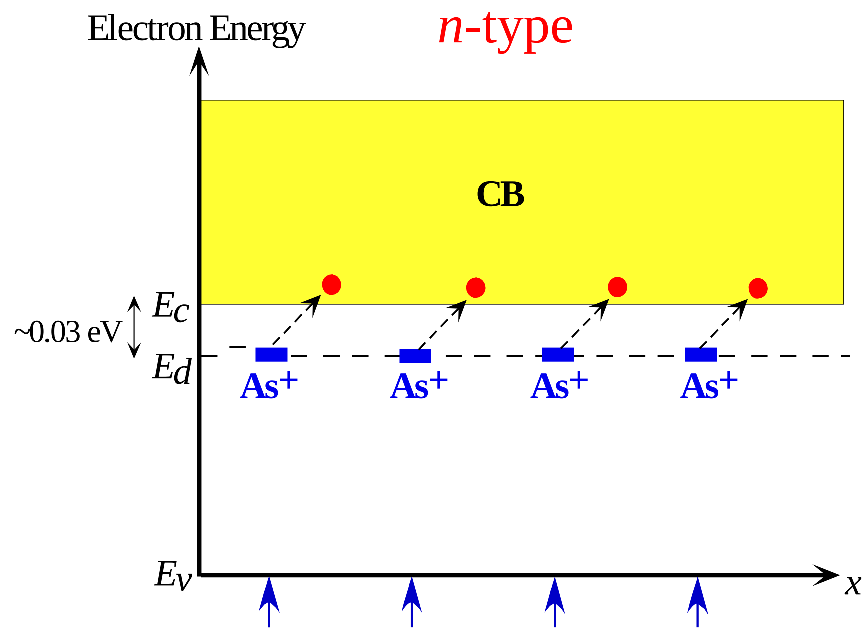
Devices always involve interfaces:

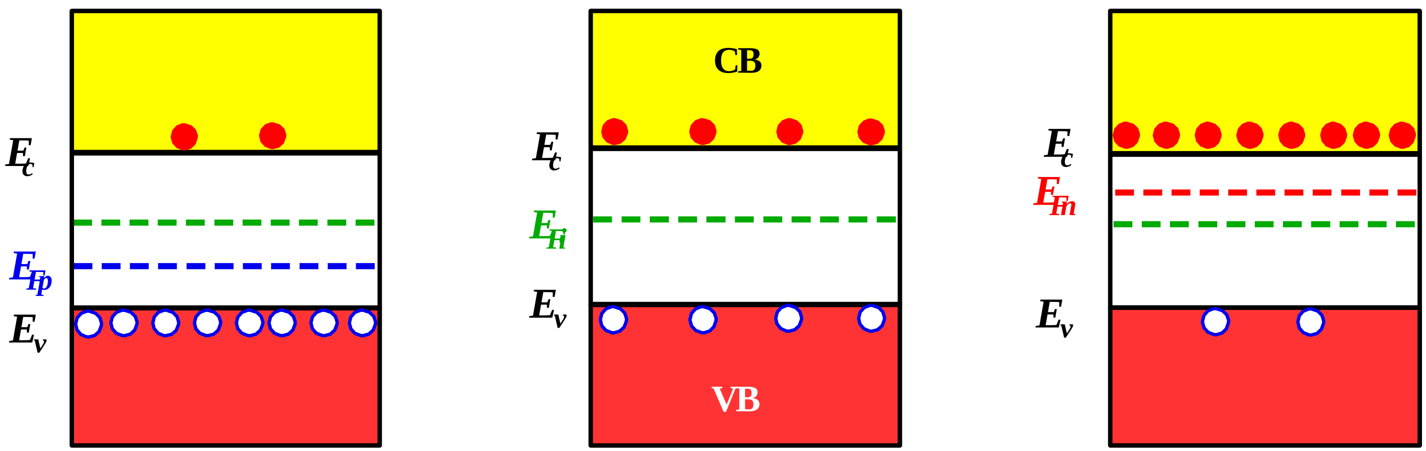
1. *metal-semiconductor interface*
   - *Schottky Junction*
   - *Ohmic Contact*
   - *Tutorial 1*

2. *semiconductor-semiconductor interface*
   - ***pn Junction***
   - *Tutorial 2, MOSFET*

What happens When *n* Meets *p*?

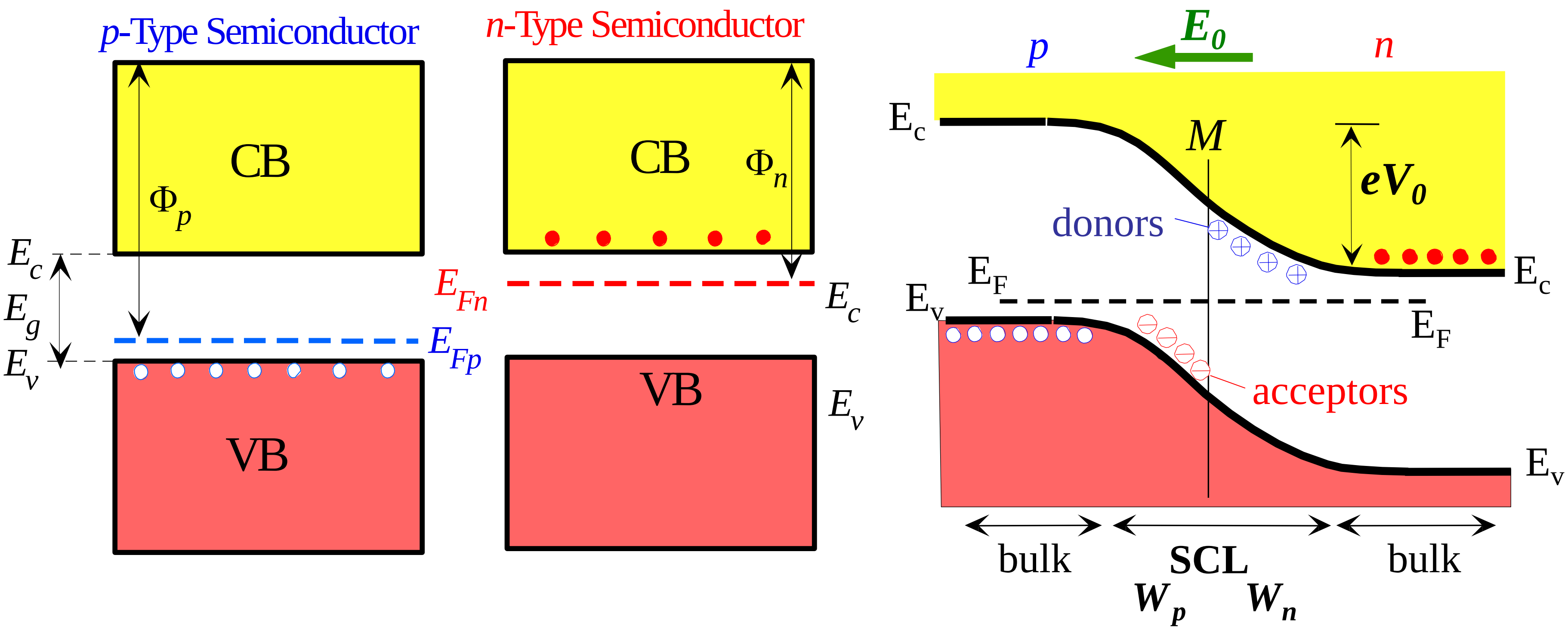






Electrons move from *p*-side to *p*-side and recombine with holes.
Eventually, Fermi levels will line up at equilibrium.

Band Diagram of pn Junction: No Bias (Open Circuit)

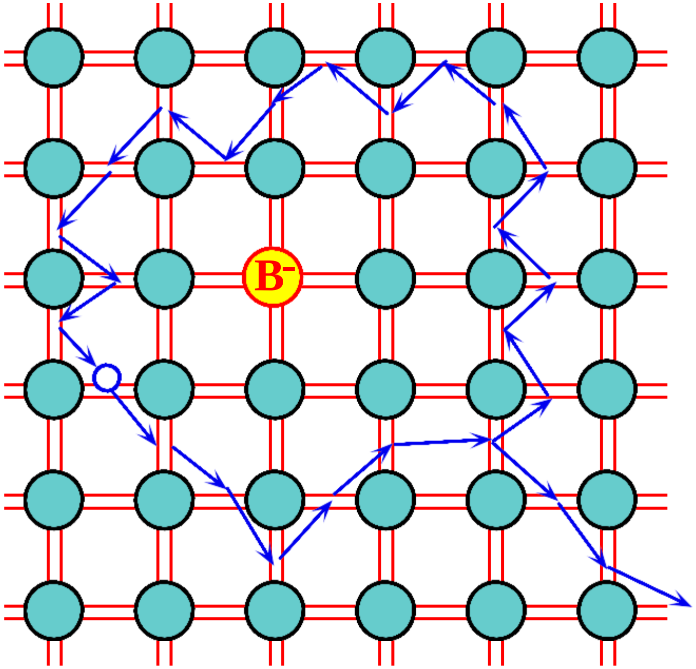


Space charge layer width $W = W_p + W_n$

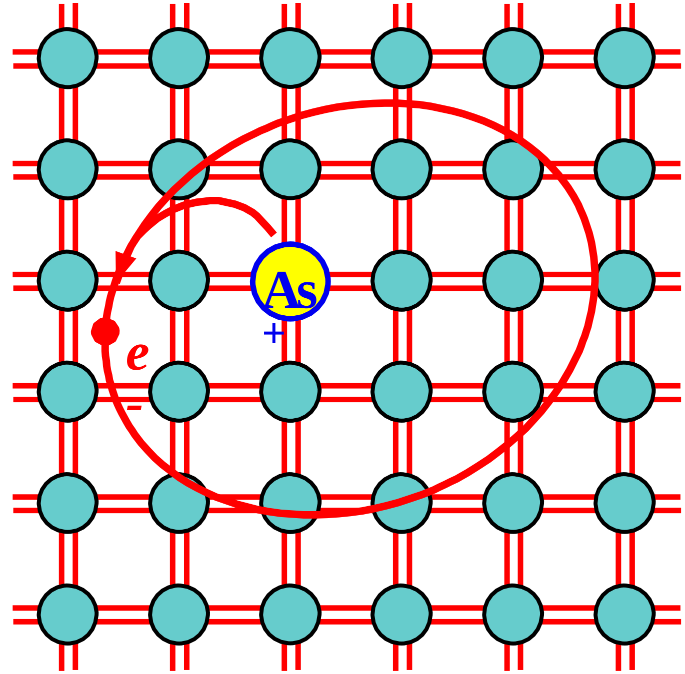
The region around the M contains the **space charge layer (SCL)**. On the *n*-side of M, SCL has the exposed positively charged donors whereas on the *p*-side it has the exposed negatively charged accepters.

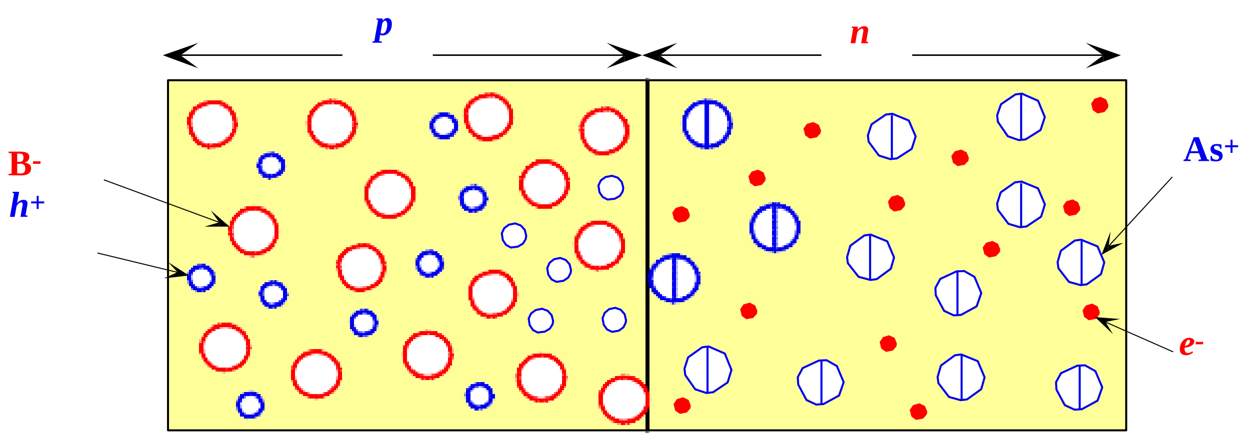
SCL: space charge layer（空间电荷层）/ depletion region/depletion layer (耗尽层)
M: metallurgical junction (冶金结), Bulk (块体)

p-Type Semiconductor

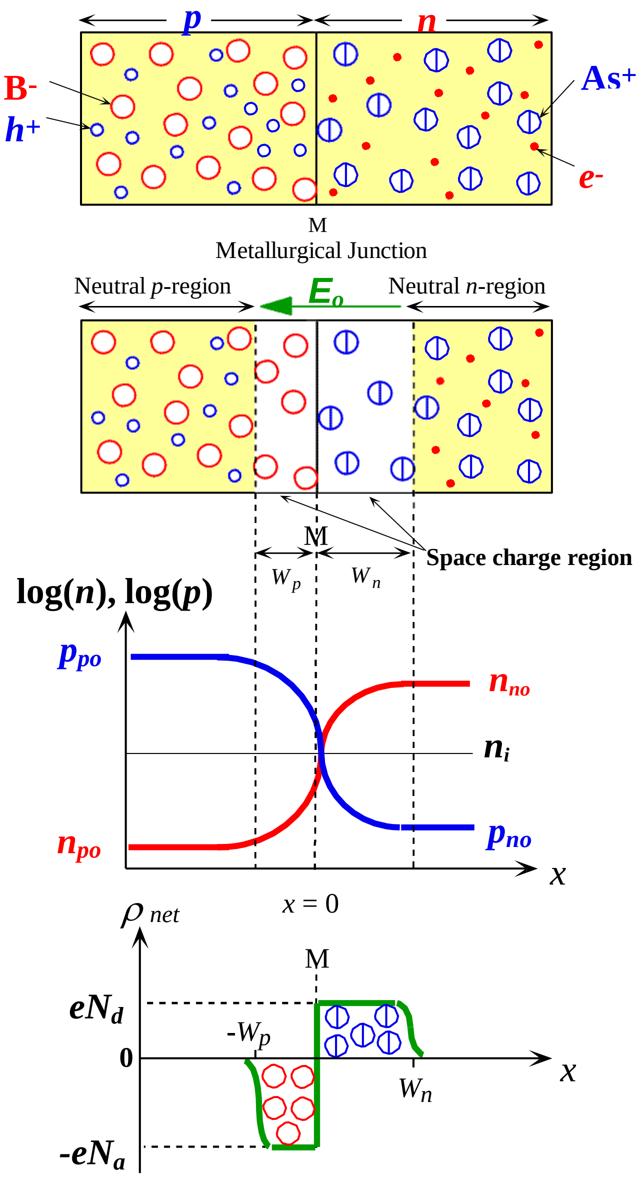


n-Type Semiconductor





pn Junction: Space Charge Layer



Each electron moves over the interface will combine with one hole.

The total number of negative charge on *p* side equals to that of positive charge on *n* side to remain charge neutrality

p_{p0}: majority carrier concentration on *p* side

n_{p0}: minority carrier concentration on *p* side

p_{n0}: minority carrier concentration on *n* side

n_{n0}: majority carrier concentration on *n* side

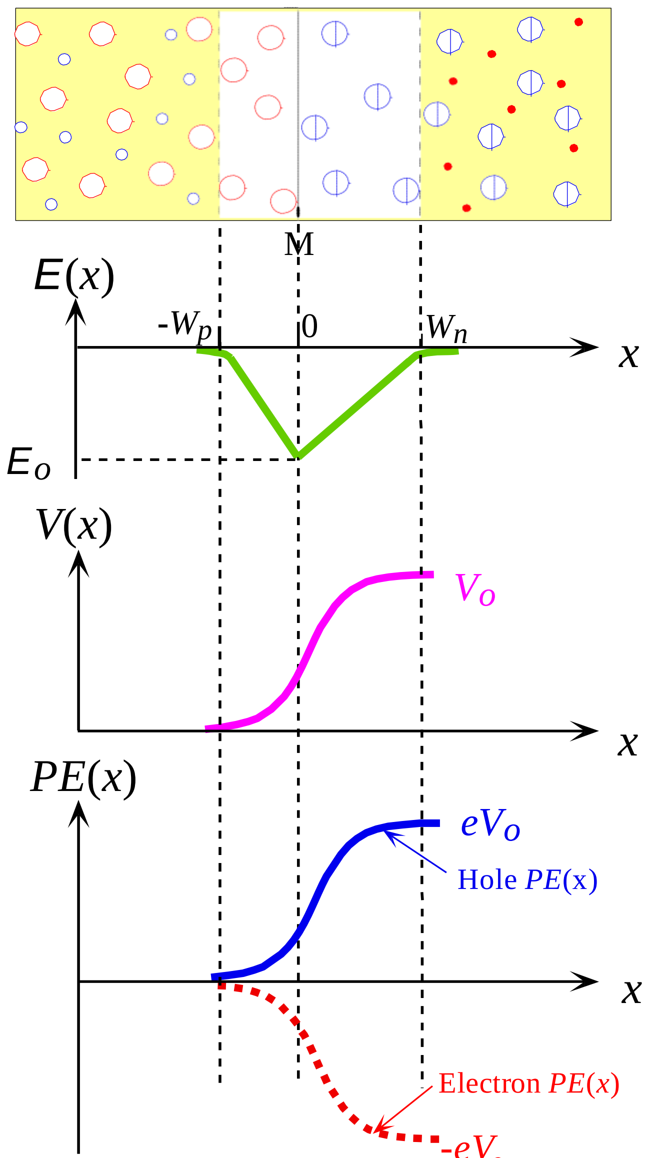
$$N_a W_p = N_d W_n$$

ρ_{net}: net space charge density

N: doping concentration

W: space charge layer width

pn Junction: Space Charge Layer



Gauss's law in point form:

ε_o and ε_r: absolute and relative permittivity （介电常数） of the semiconductor material

$$\frac{dE}{dx} = \frac{\rho_{net}(x)}{\varepsilon_r \varepsilon_o} \Rightarrow E(x) = \frac{\rho_{net}}{\varepsilon_r \varepsilon_o} x + C_1$$

$$E_0 = -\frac{eN_d W_n}{\varepsilon_r \varepsilon_o} = -\frac{eN_a W_p}{\varepsilon_r \varepsilon_o}$$

The negative field means −x direction

$$E(x) = -\frac{dV}{dx} \Rightarrow V(x) = -\int_{-W_p}^{x} E(x)dx$$

By putting x = W_n $\Rightarrow$

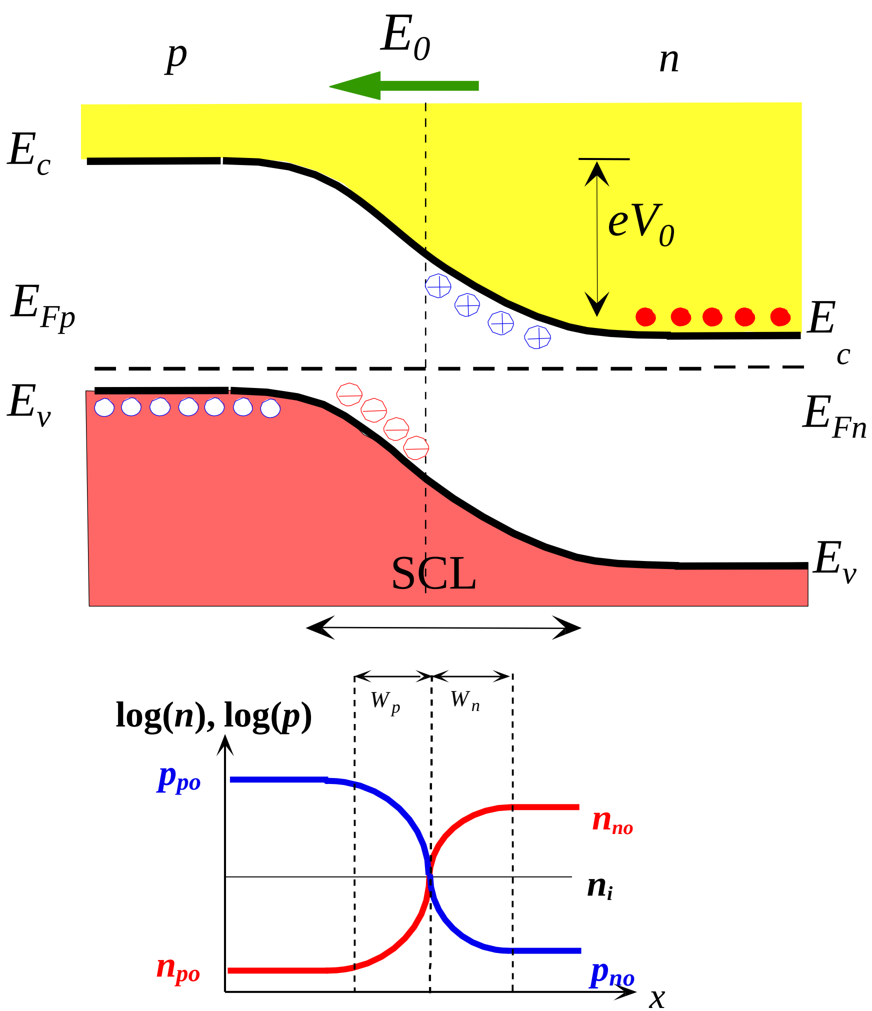
$$\mathbf{V}_0 = \frac{1}{2} E_0 W_0 = \frac{eN_a N_d \mathbf{W}_0^{\,2}}{2\varepsilon_r \varepsilon_0 (N_a + N_d)}$$

V_0: the built-in potential（内置电位）
$W_0 = W_p + W_n$: the total width of the space charge layer under a zero applied voltage

pn Junction: Built-in Potential

Probability of electrons occupying energy E is determined by **Fermi-Dirac statistics**, which is reduced to **Boltzmann statistics** when $E-E_F \gg k_BT$, it demands the concentrations n_1 and n_2 of potential energies E_1 and E_2 are related by:

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



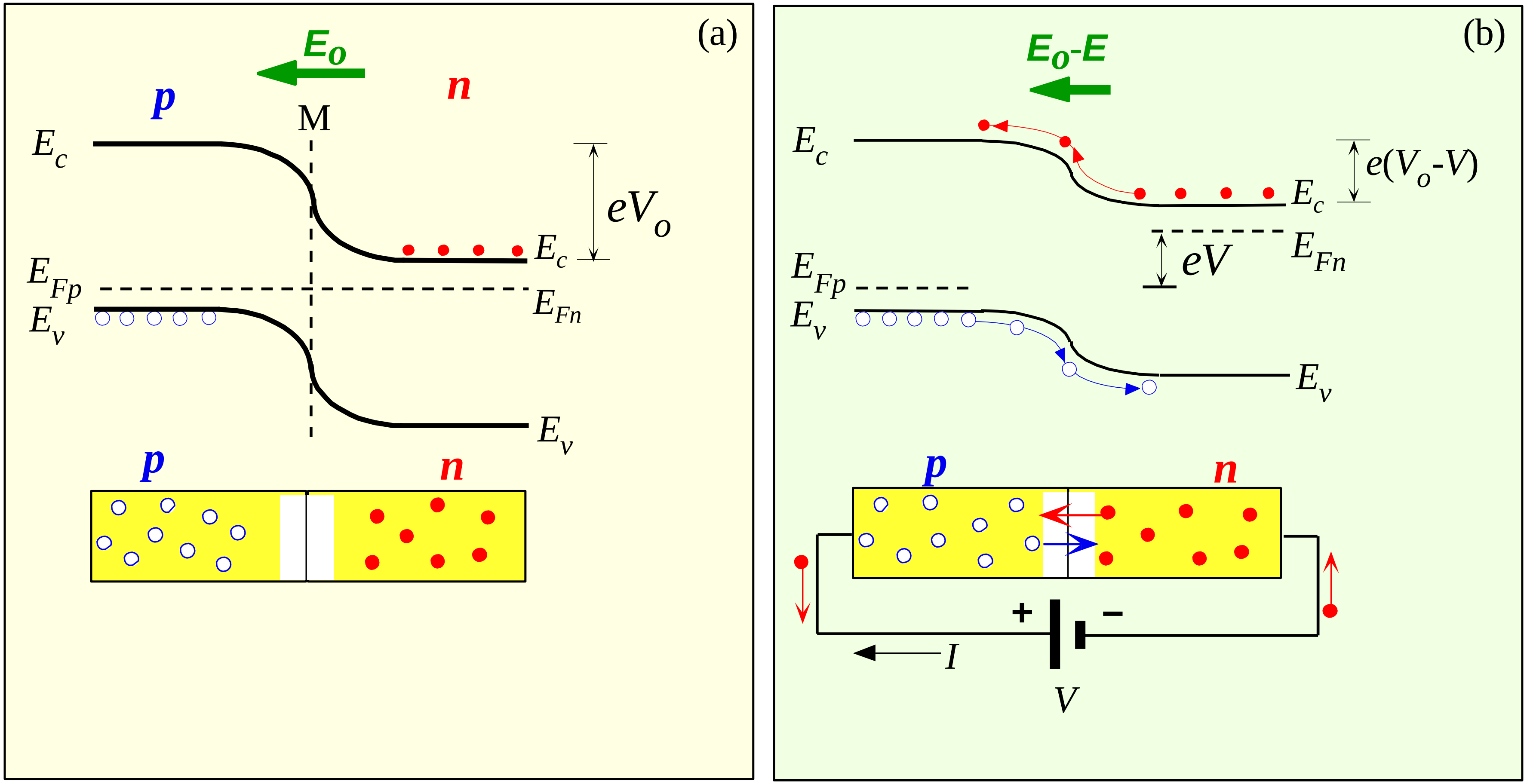
$$\frac{n_{po}}{n_{no}} = \exp\left(-\frac{eV_o}{k_BT}\right) \qquad \frac{p_{no}}{p_{po}} = \exp\left(-\frac{eV_o}{k_BT}\right)$$

$$p_{po} = N_a \qquad p_{no} = \frac{n_i^2}{n_{no}} = \frac{n_i^2}{N_d}$$

$$\boxed{V_o = \frac{k_BT}{e}\ln\left(\frac{N_aN_d}{n_i^2}\right) \qquad W_o = \sqrt{\frac{2\varepsilon_o\varepsilon_r(N_a+N_d)V_o}{eN_aN_d}}}$$

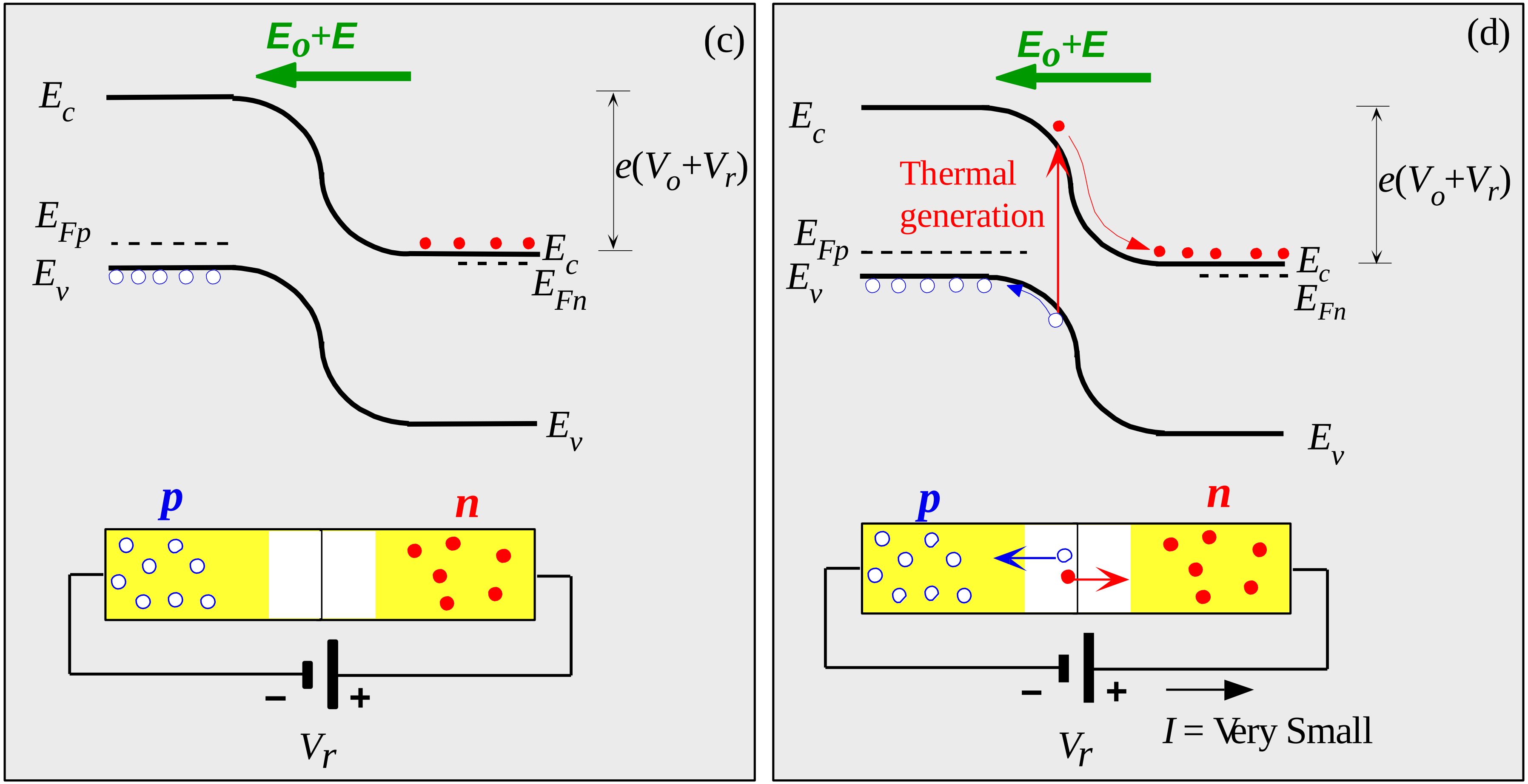
$$N_aW_p = N_dW_n$$

pn Junction: forward bias



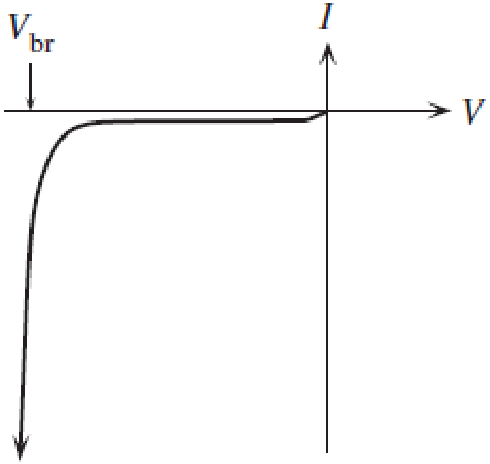
Energy band diagrams for a pn junction under (a) open circuit and (b) forward bias

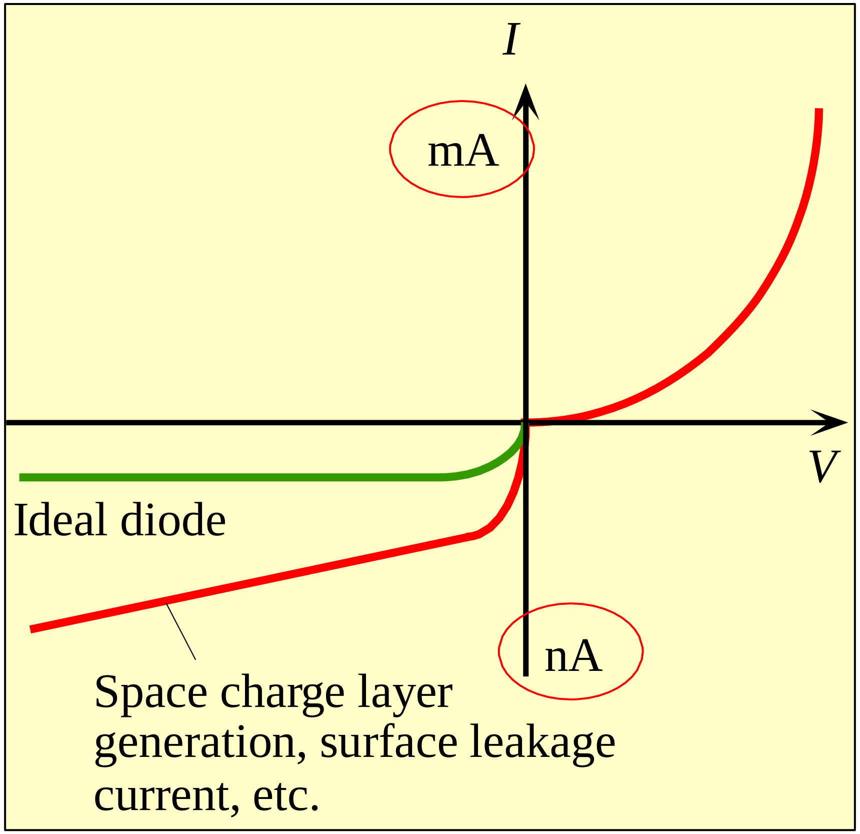
pn Junction: reverse bias



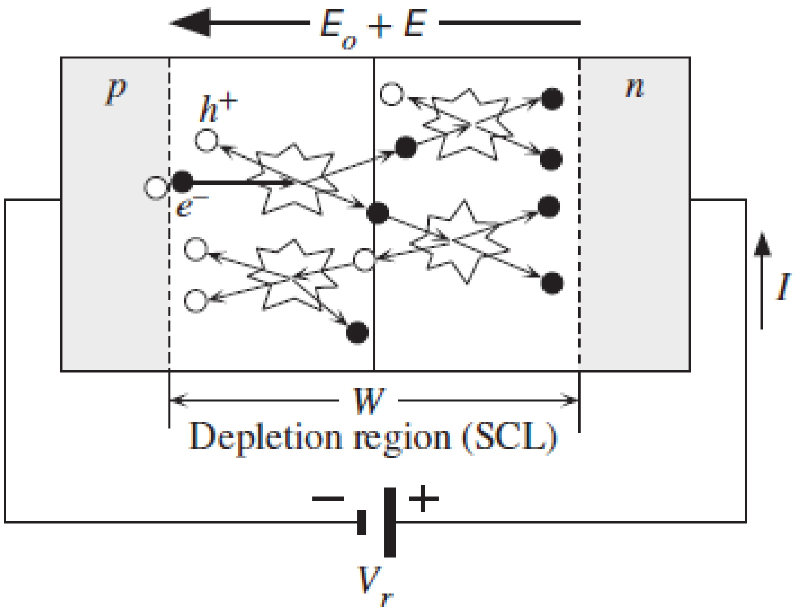
Energy band diagrams for a *pn* junction under (c) reverse bias condition. (d) Thermal generation of electron hole pairs in the depletion region results in a small reverse current.

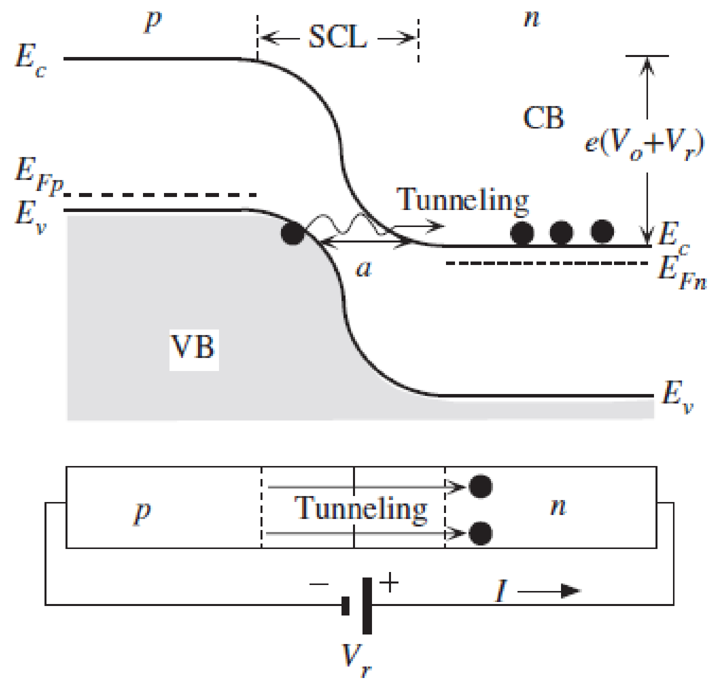
I-V Response of a *pn* Junction





Reverse breakdown

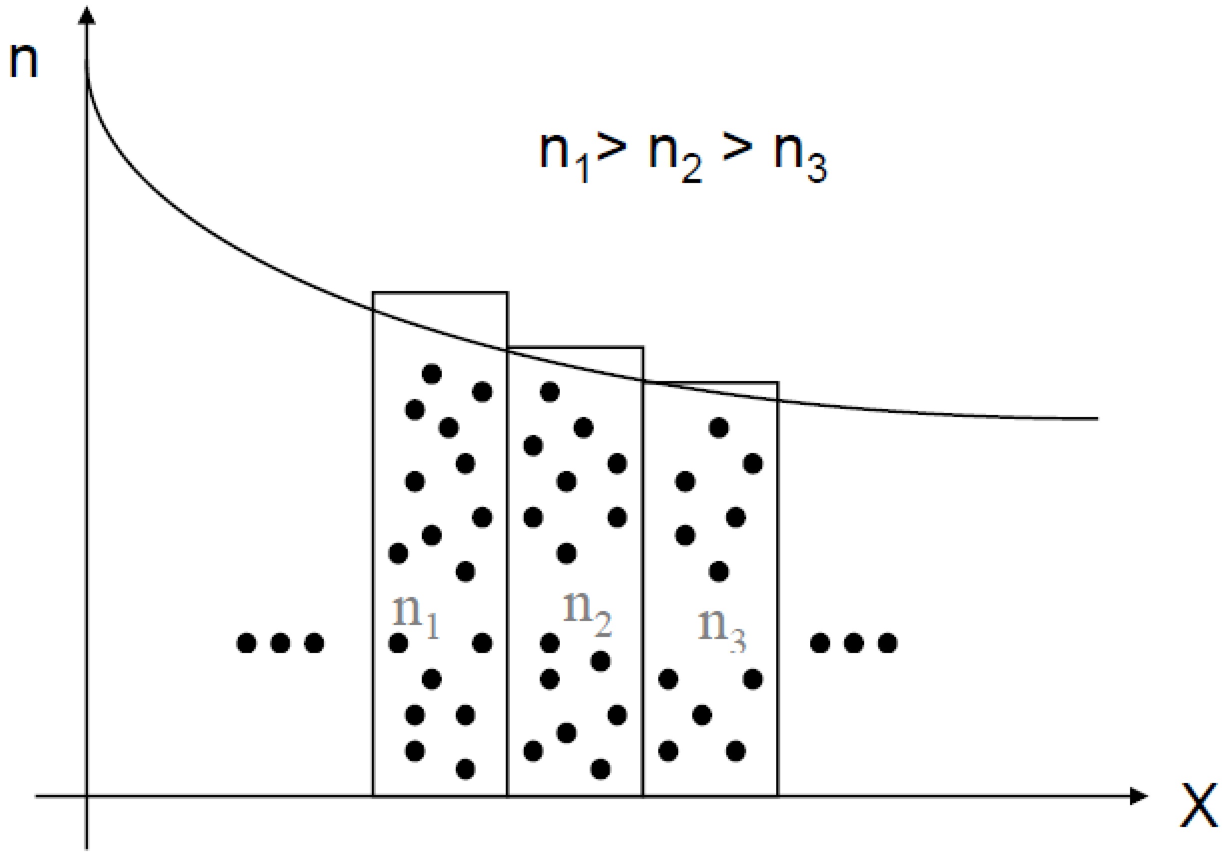




Avalanche breakdown by impact ionization

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

Diffusion （扩散运动）



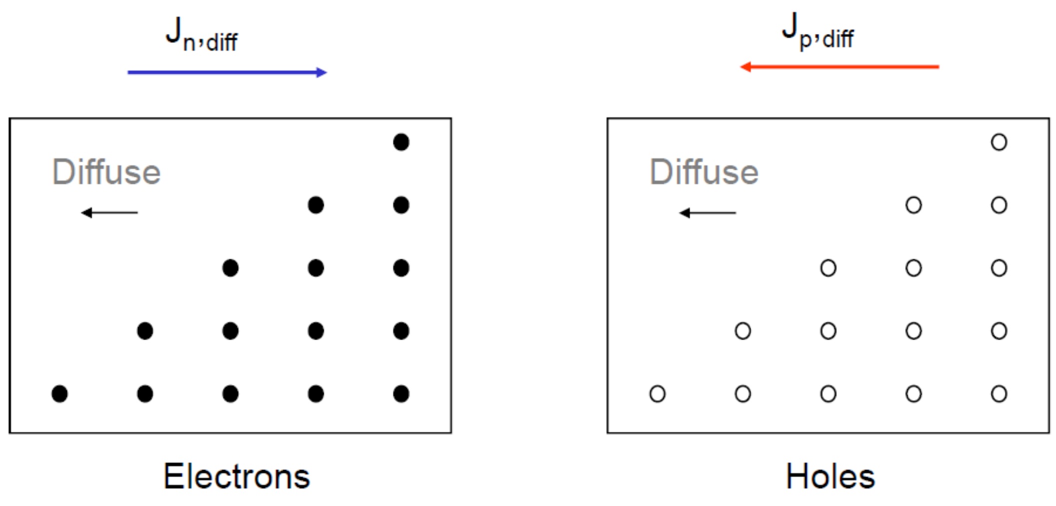
Particles diffusing from higher to lower concentration region.

Diffusion

- Diffusion occurs because of a difference in concentration, i.e. the presence of a concentration gradient.

$$\frac{dn}{dx} \neq 0 \quad \text{or} \quad \frac{dp}{dx} \neq 0$$

- The higher the concentration gradient, the higher is the rate at which particles diffuse in the direction from higher to lower concentration.
- Charge carrier diffusion, leads to current flow.



Diffusion of electrons and holes

Diffusion

Electron diffusion current density

$$J_{D,e} \propto -\frac{dn}{dx}$$
$$= eDe\frac{dn}{dx}$$

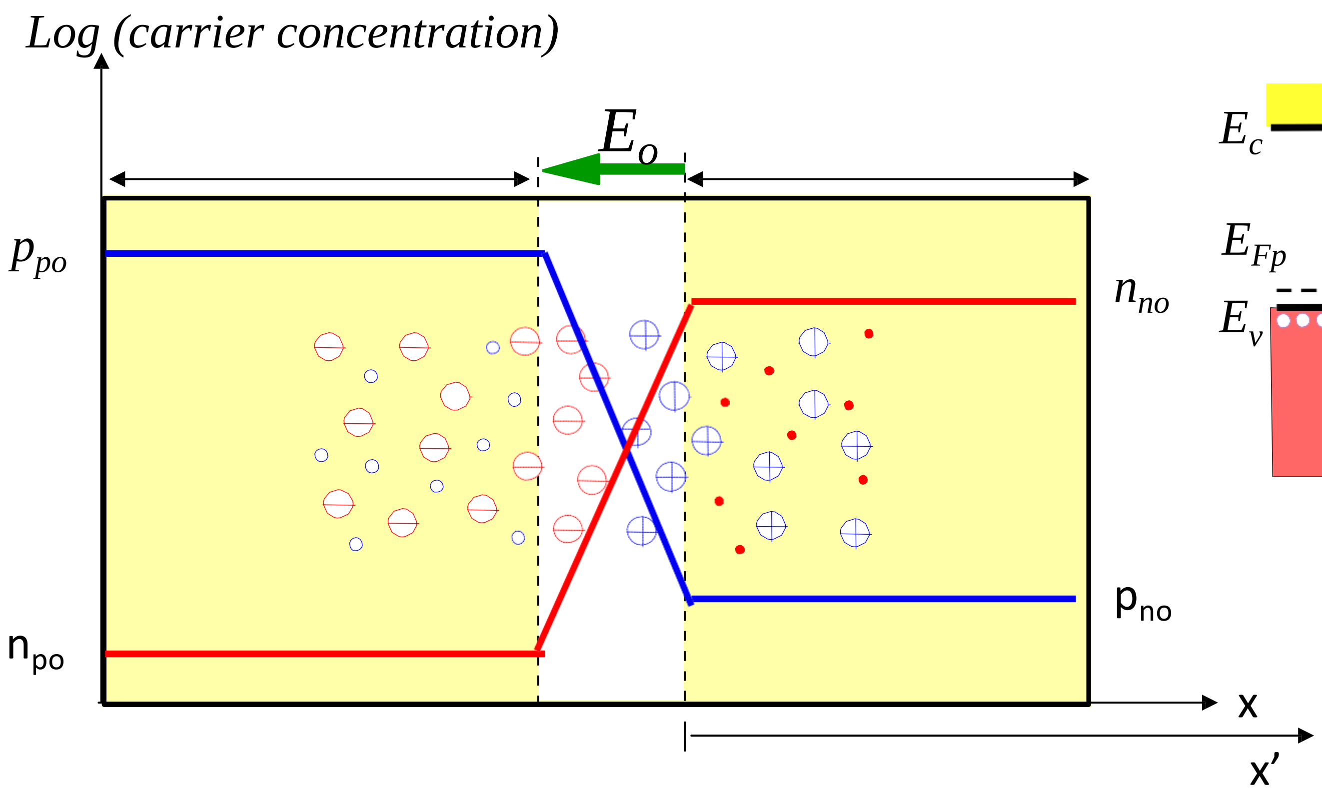
Hole diffusion current density

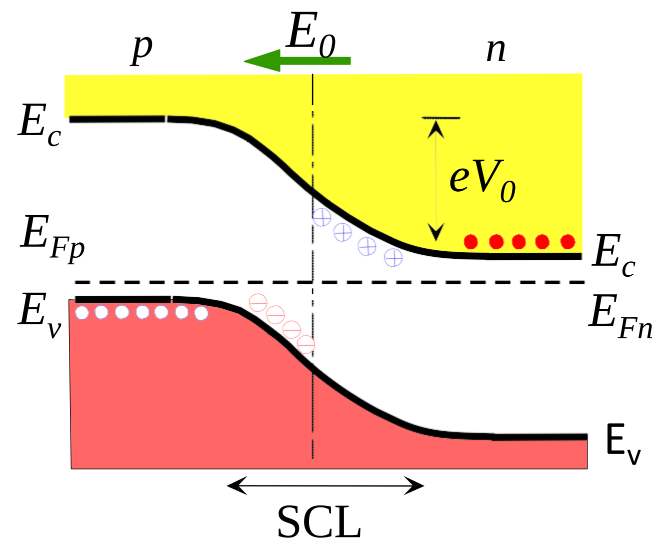
$$J_{D,h} \propto -\frac{dp}{dx}$$
$$= -eDh\frac{dp}{dx}$$

Diffusion coefficient（扩散系数）, $\mathbf{D_e}$ or $\mathbf{D_h}$, is a measure of the ease of carrier ***diffusion*** motion in a medium. Mobility, $\boldsymbol{\mu_e}$ or $\boldsymbol{\mu_h}$, is a measure of the ease of carrier ***drift*** motion in a medium. The two quantities are related by the **Einstein Relation.**

$$\boxed{\frac{D_e}{\mu_e} = \frac{kT}{e} \quad \text{and} \quad \frac{D_h}{\mu_h} = \frac{kT}{e}}$$

Carrier Concentration Profiles Across a *pn* Junction: **No Bias**





$$J_e = en\mu_e E_x + eD_e \frac{dn}{dx} \qquad J_h = ep\mu_h E_x - eD_h \frac{dp}{dx}$$

When there is no electric field applied to a *pn* junction, there is no current. The diffusion current and drift current balance each other within the space charge layer.

完成 **Assignment 6.3 (1)**

提交时间：**5月12日**（周一）中午前

提交方式：电子版（写明姓名、学号），通过本班课代表统一提交