Fundamentals of Solid State Physics

Semiconductors
- Carrier Behaviors

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Carrier Behaviors in Semiconductors

- Equilibrium Carriers (热平衡态载流子)
- Non-equilibrium Carriers (非平衡态载流子)

- Majority & Minority Carriers 多数 / 少数 载流子

- Current Flow
  - diffusion current
  - drift current

- Generation 产生
- Recombination 复合

Equilibrium carriers (热平衡态载流子)

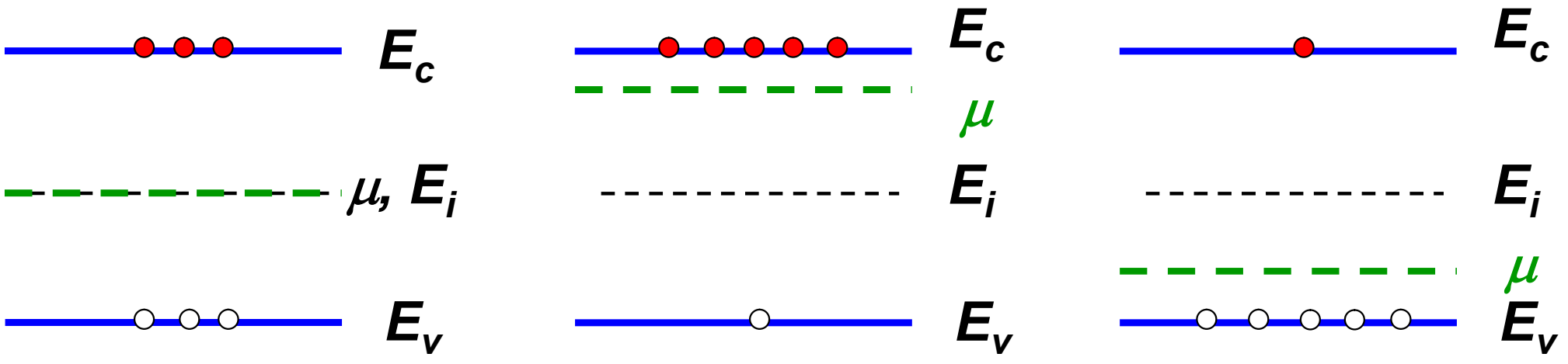
only thermal activation

$$n_c = N_c(T)e^{-(E_c-\mu)/k_BT}$$

$$p_v = P_v(T)e^{-(\mu-E_v)/k_BT}$$

$$n_c p_v = N_v(T)P_v(T)e^{-E_g/k_BT} = n_i^2$$

mass action law



Non-equilibrium carriers (非平衡态载流子)

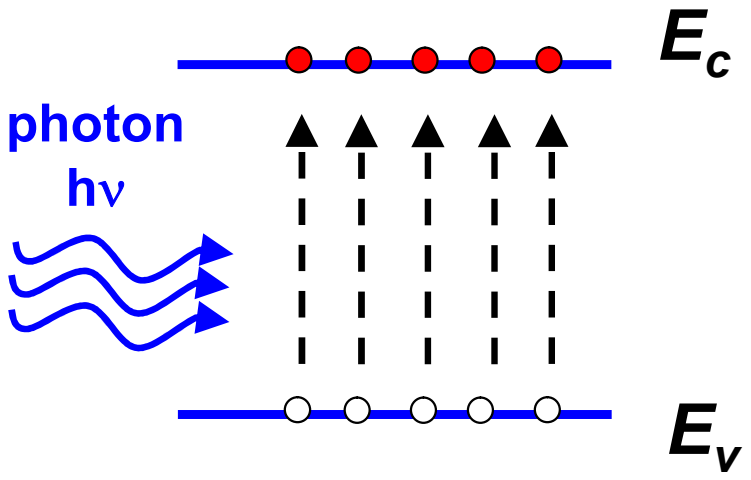
activation by other energy sources
e.g., photon absorption, current injection, ...

extra more carriers n_c and p_v

$$p_v \neq P_v(T)e^{-(\mu-E_v)/k_BT}$$

$$n_c \neq N_c(T)e^{-(E_c-\mu)/k_BT}$$

$$n_c p_v \neq N_v(T)P_v(T)e^{-E_g/k_BT} = n_i^2$$



mass action law is not valid

Non-equilibrium carriers (非平衡态载流子)

activation by other energy sources
e.g., photon absorption, current injection, ...

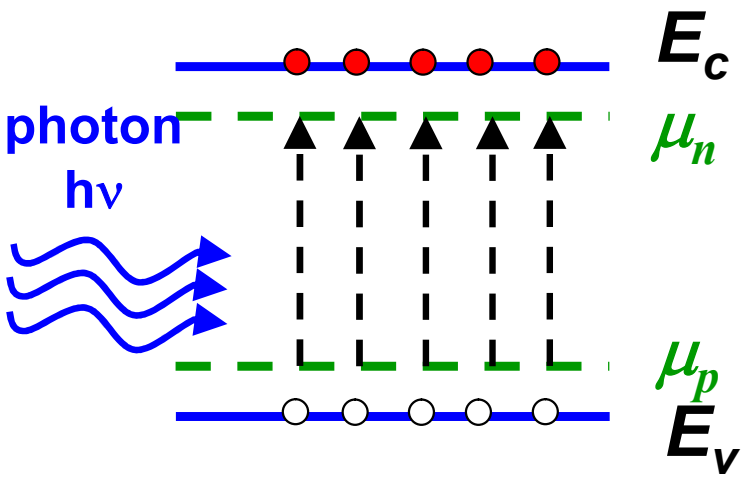
extra more carriers n_c and p_v

rewrite:

$$p_v = P_v(T)e^{-(\mu_p - E_v)/k_BT}$$

$$n_c = N_c(T)e^{-(E_c - \mu_n)/k_BT}$$

$$\mu_n \neq \mu_p$$



quasi-Fermi levels (准费米能级)

Non-equilibrium carriers (非平衡态载流子)

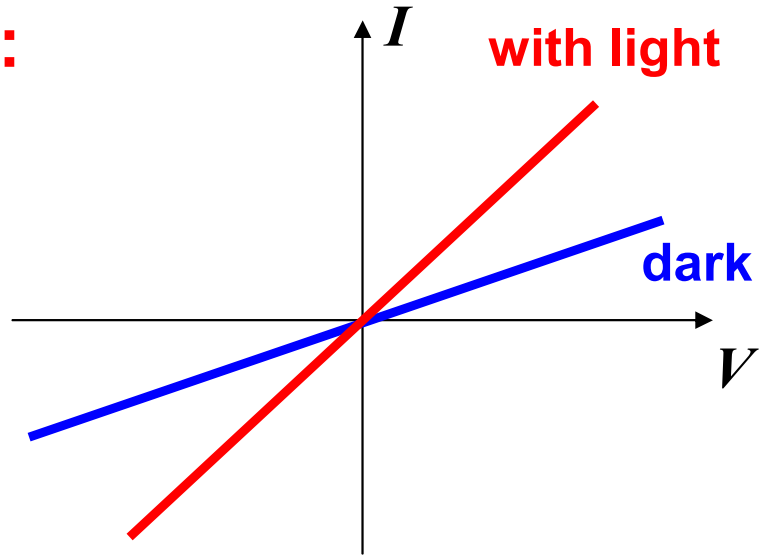
activation by other energy sources
e.g., photon absorption, current injection, ...

extra more carriers n_c and p_v

light absorption increases the conductivity of a semiconductor:

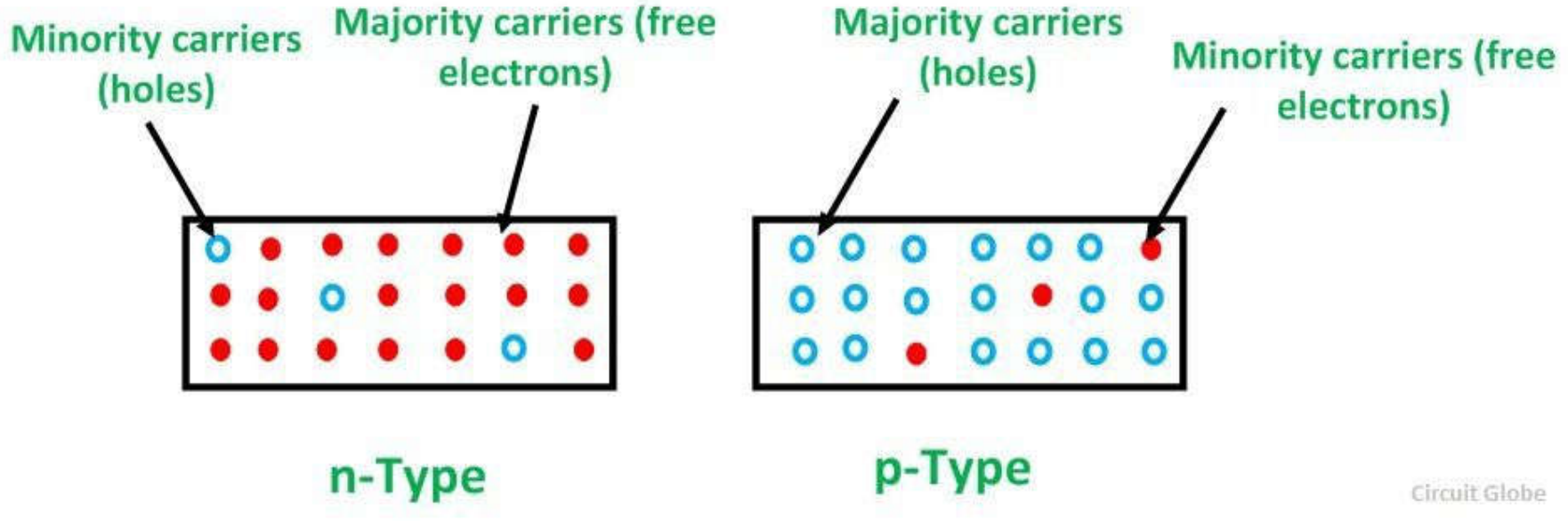
---- photoconductor

$$\sigma = n_c e\mu_e + p_v e\mu_h$$



Majority & Minority Carriers

- **Majority carriers (多数载流子)**
- **Minority carriers (少数载流子)**
  - **minority carriers are very important, because their amount can be easily changed by current injection, optical absorption, etc.**



Current Flow

- **Diffusion current 扩散电流**
  - **caused by concentration gradient**

- **Drift current 迁移电流**
  - **caused by electric field**

Current Flow

- **Diffusion current 扩散电流**
  - **caused by concentration gradient**

ink in water

1D $$j = -qD\frac{\partial n}{\partial x}$$

3D $$\mathbf{j} = -q\mathbf{D}\nabla\mathbf{n}$$

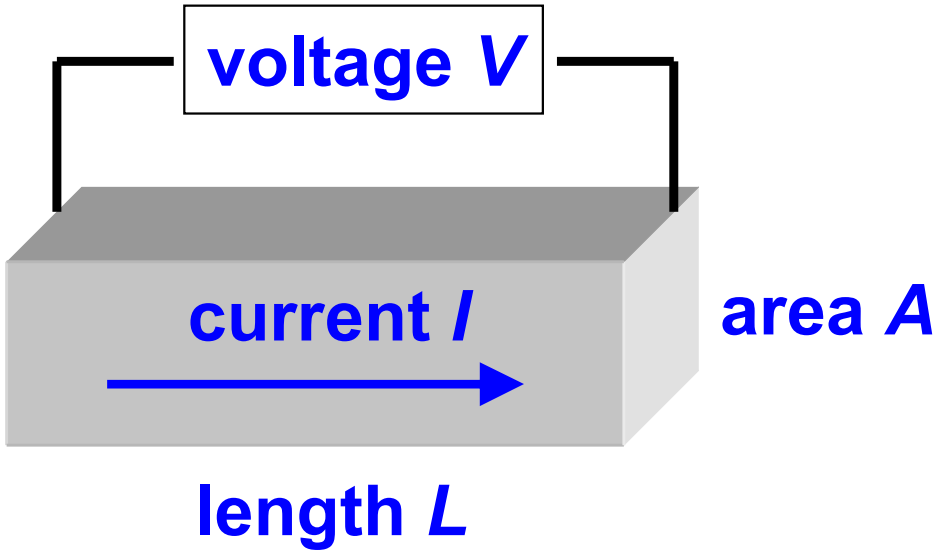
diffusivity 扩散系数

$$D = \mu\frac{kT}{q}$$

n **- carrier concentration (#/m^3)**
D **- diffusivity (m^2/s) 扩散率**
μ **- mobility (m^2/V/s)**

Current Flow

- **Drift current 迁移电流**
  - **caused by electric field**



Ohm's Law

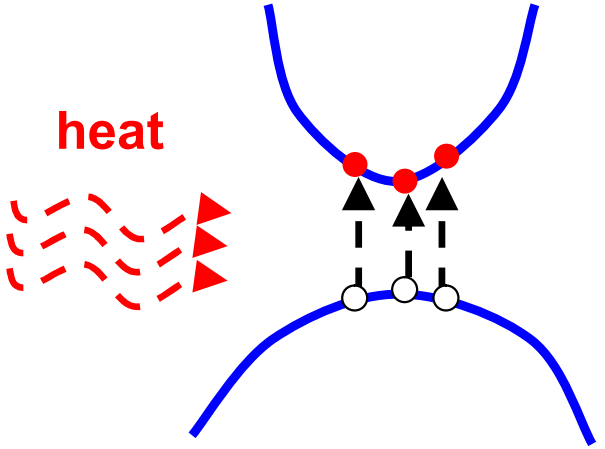
$$j = \sigma E = nq\mu E = nqv$$

n **- carrier concentration (#/m^3)**
D **- diffusivity (m^2/s) 扩散率**
μ **- mobility (m^2/V/s)**

Carrier Generation

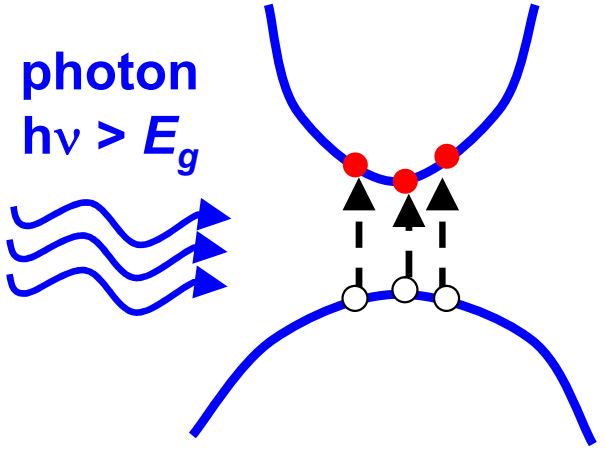
- **Excited by thermal energy**

$$n_c p_v = N_v(T) P_v(T) e^{-E_g/k_B T} = n_i^2$$



- **Excited by photons**
  - **photodetector**
  - **solar cells**
  - **...**

$$h\nu = \mathbf{e} + \mathbf{h}$$

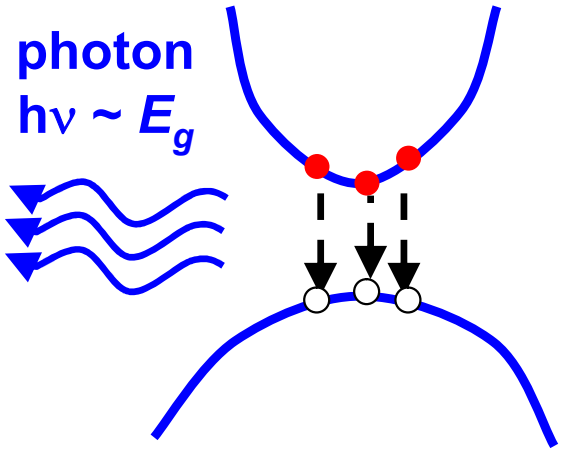


- **Other sources**
- **...**

Carrier Recombination 复合

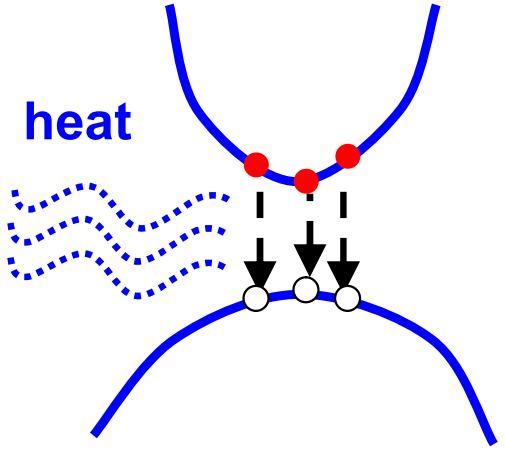
- **Radiative 辐射**
  - LED
  - laser
  - ...

$$e + h = photon$$



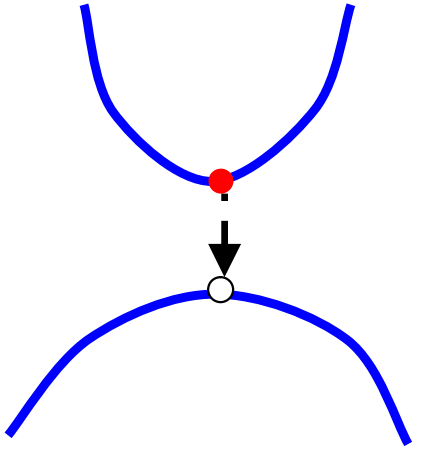
- **Non-radiative recombination**
  - defects, impurities, surfaces
  - lattice (phonons)
  - Auger process
  - ...

$$e + h = phonons$$



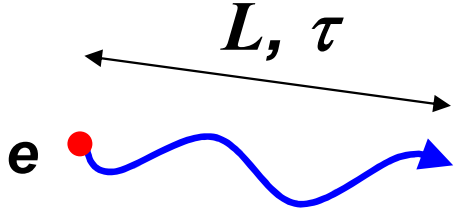
Carrier Recombination 复合

- 载流子寿命 Carrier lifetime τ_n and τ_p
  - the averaged time before the non-equilibrium carriers recombine
- 扩散率 Diffusivity D_n and D_p



- 扩散长度 Diffusion length L_n and L_p
  - the averaged distance carriers move before recombination

$$L = \sqrt{D\tau}$$

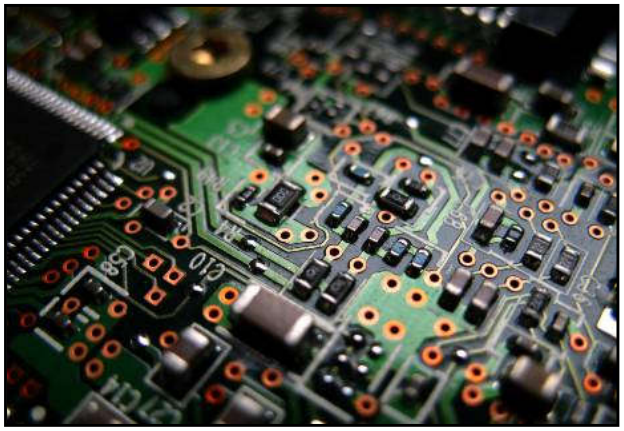


  - At non-equilibrium, minority carrier diffusion and lifetime are important for device performance

D - diffusivity (m^2/s) 扩散率

Semiconductors - Applications

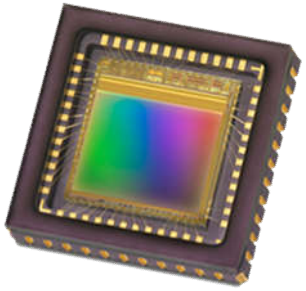
different carrier behaviors offer different applications



integrated circuits

LEDs

lasers



detectors

solar cells

Thank you for your attention