Outline

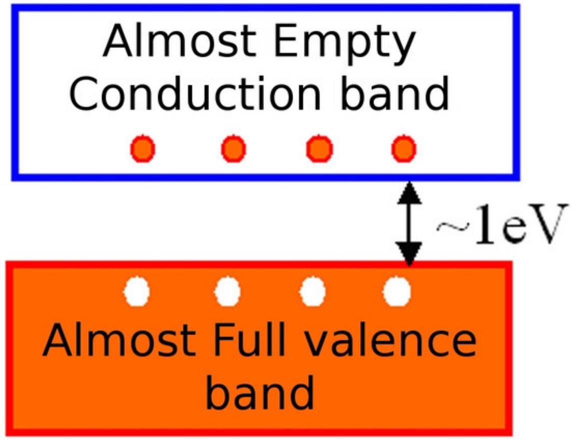
- **Chapter 5.1** Free-Electron Theory of Metals (金属自由电子论)
- **Chapter 5.2** Electron Theory of Semiconductors (半导体电子论)

Objectives

- To understand the **basic properties of semiconductors**.
- To learn the **classification of semiconductors**.

Semiconductors (半导体)

- From the standpoint of **band theory**, a semiconductor is **a special insulator with a small band gap** such that the electrons at the top of the valence band can be thermally excited to the bottom of the conduction band.



Semiconductor

Conduction band (导带):
The lowest unoccupied energy band.

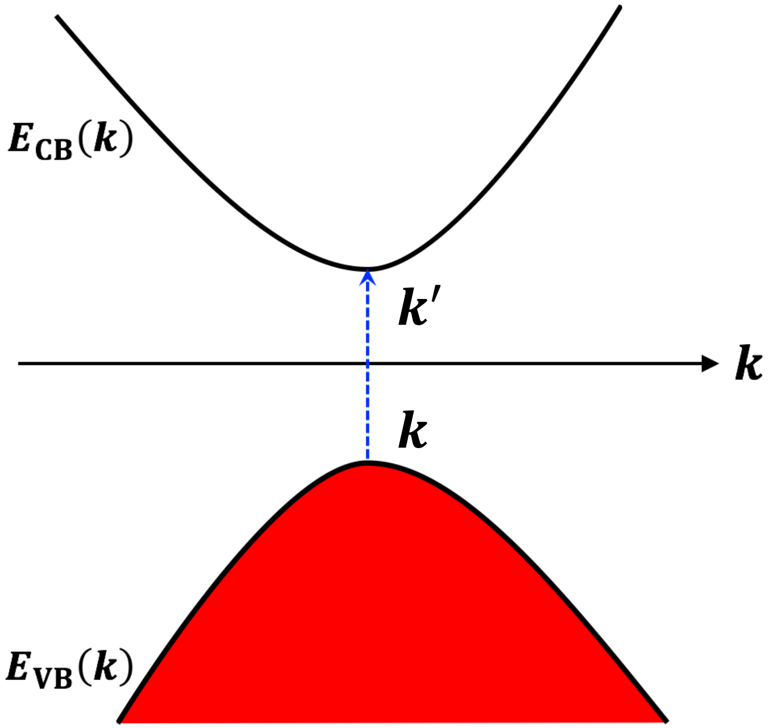
Valence band (价带):
The highest occupied energy band.

➢ Band Gap (带隙)

❖ Direct band gaps (直接带隙)

The wave vector $\boldsymbol{k}$ of the electronic state at the top of valence band is **the same** as the wave vector $\boldsymbol{k}'$ at the bottom of the conduction band.

$$\boxed{\boldsymbol{k} = \boldsymbol{k}'}$$



Direct bandgap semiconductors (直接带隙半导体):

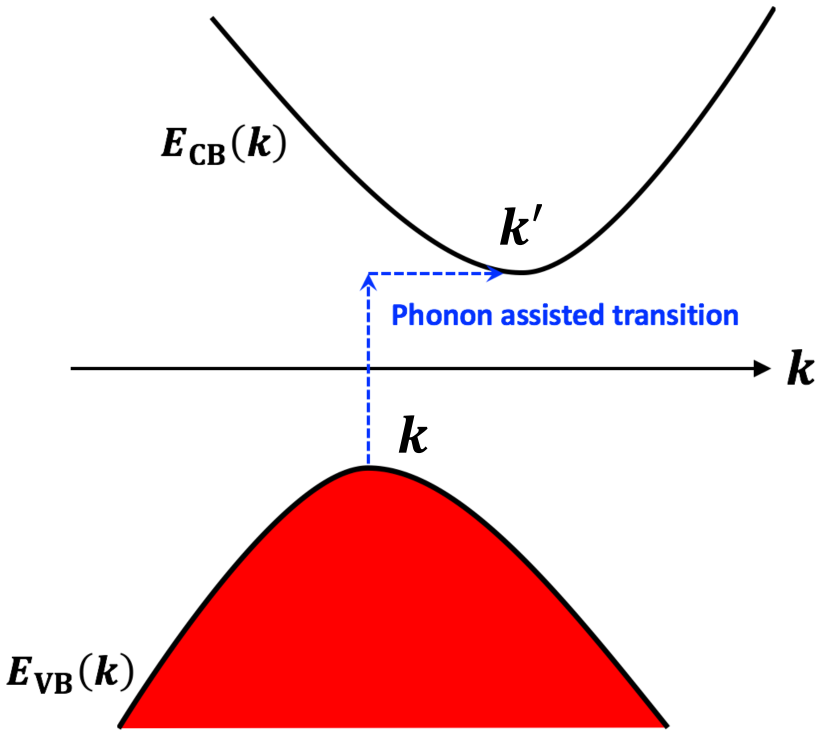
Direct bandgap Semiconductors	**GaAs**	**InAs**	**PbS**
E_g (eV)@0K	**1.52**	**0.43**	**0.29**

➢ Band Gap (带隙)

❖ Indirect band gaps (间接带隙)

The wave vector $\boldsymbol{k}$ of the electronic state at the top of valence band is **different from** the wave vector $\boldsymbol{k}'$ at the bottom of the conduction band.

$$\boxed{\boldsymbol{k} \neq \boldsymbol{k}'}$$

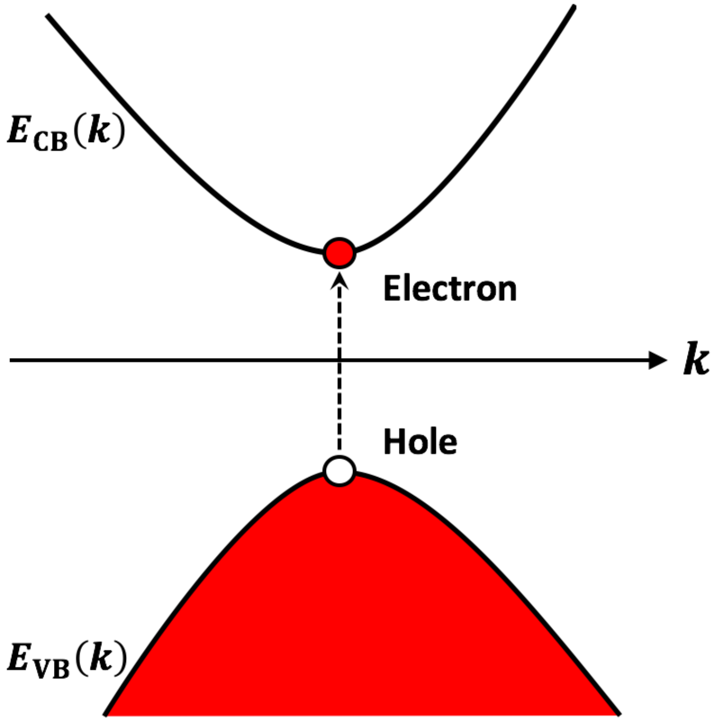


Indirect bandgap semiconductors (间接带隙半导体):

Indirect bandgap Semiconductors	**Diamond**	**Si**	**Ge**
E_g (eV)@0K	**5.4**	**1.17**	**0.74**

➢ Charge Carriers (载流子)

❖ Electrons and Holes (电子与空穴)



The charge carriers in conduction band are **electrons (电子).**

The charge carriers in valence band are **holes (空穴).**

➢ Charge Carriers (载流子)

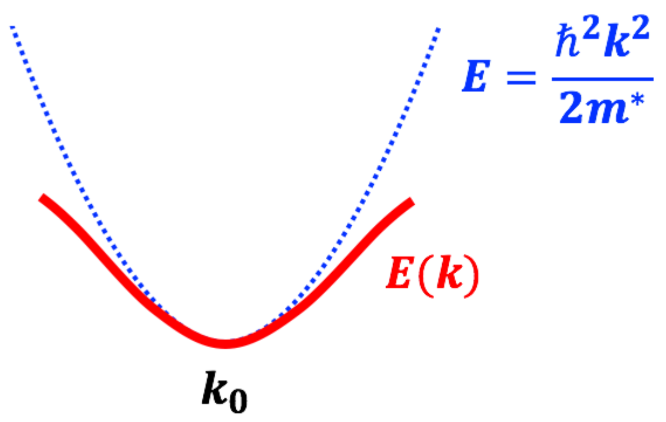
❖ Effective mass of charge carriers (载流子有效质量)

- **Effective mass m^* at the band edges (带边有效质量)** represents an important parameter for semiconductors.

$$\boxed{\frac{1}{m_\alpha^*} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k_\alpha^2}}$$

The energy dispersion at the band edges can be approximately expressed as:

$$E(k) \approx E(k_0) + \frac{\hbar^2 (k_x - k_{0x})^2}{2m_x^*} + \frac{\hbar^2 \left(k_y - k_{0y}\right)^2}{2m_y^*} + \frac{\hbar^2 (k_z - k_{0z})^2}{2m_z^*}$$



➢ Charge Carriers (载流子)

❖ Effective mass of charge carriers (载流子有效质量)

- Effective masses $\boldsymbol{m}^*$ have significant impacts on both the **electrical conductivity (电导率)** and **mobility (迁移率)** of charge carriers in semiconductors:

Conductivity: $\boxed{\boldsymbol{\sigma} = \dfrac{\boldsymbol{ne^2\tau}}{\boldsymbol{m^*}}}$

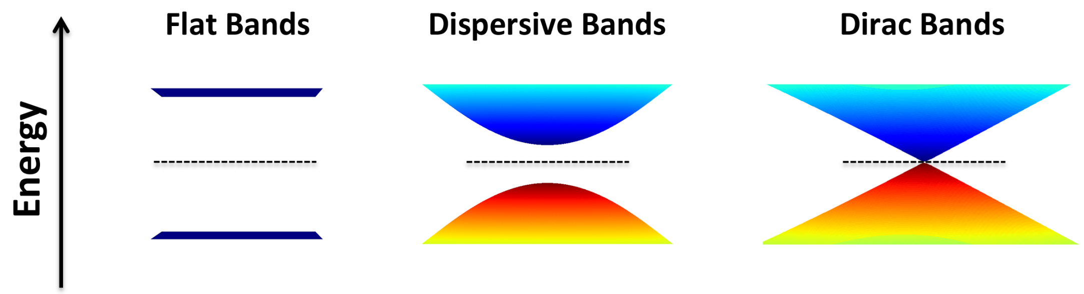
Mobility: $\boxed{\boldsymbol{\mu} = \dfrac{\boldsymbol{e\tau}}{\boldsymbol{m^*}}}$ $\boldsymbol{\sigma = ne\mu}$

➢ Charge Carriers (载流子)

❖ Effective mass of charge carriers (载流子有效质量)

The charge-carrier effective masses of real semiconductors ($\boldsymbol{m_0}$ denotes electron rest mass):

$\boldsymbol{m^*/m_0}$	Si	Ge	GaAs	InSb	ZnO
m_e^* (electron)	**1.09**	**0.55**	**0.067**	**0.013**	**0.29**
m_h^* (hole)	**1.15**	**0.37**	**0.45**	**0.6**	**1.21**



$|\boldsymbol{m^*}| = \infty$ $\quad$ $0 < |\boldsymbol{m^*}| < \infty$ $\quad$ $|\boldsymbol{m^*}| = 0$

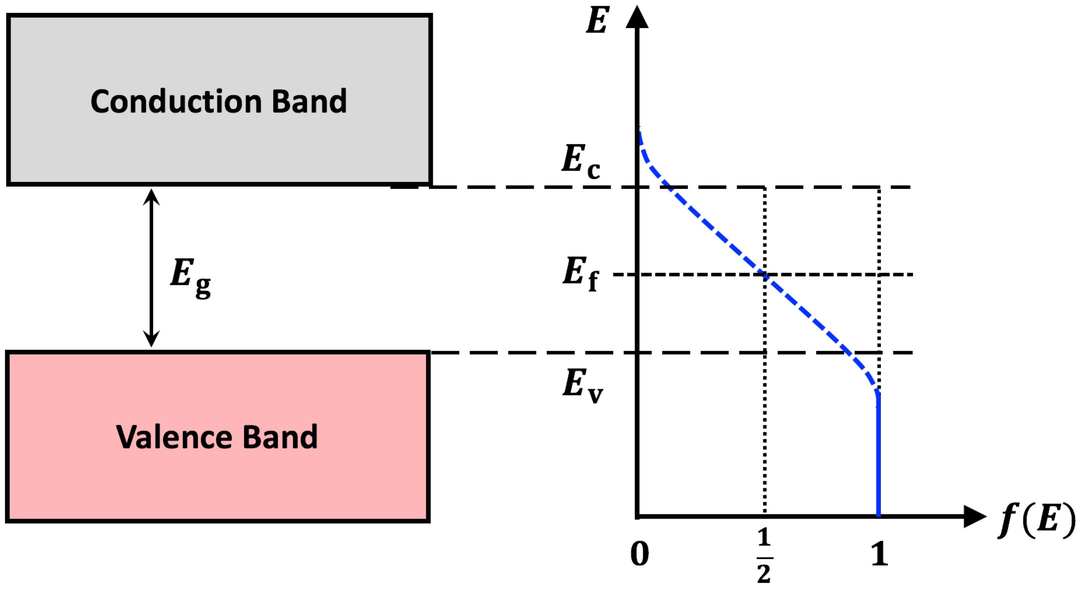
➢ Charge Carriers (载流子)

❖ Statistics of charge carriers (载流子统计分布)

- The Fermi level E_f of semiconductors is **in band gap**:

Fermi distribution of charge carriers:

$$f(E) = \frac{1}{e^{(E-E_f)/k_B T} + 1}$$



➢ Charge Carriers (载流子)

❖ Statistics of charge carriers (载流子统计分布)

- In band gap of semiconductors, the position of Fermi level is usually far from band edges:

$$E_{\mathrm{c}} - E_{\mathrm{f}} \gg k_{\mathrm{B}}T \qquad\qquad E_{\mathrm{f}} - E_{\mathrm{v}} \gg k_{\mathrm{B}}T$$

As a result, charger carriers at band edges approximately obey **Boltzmann distribution**:

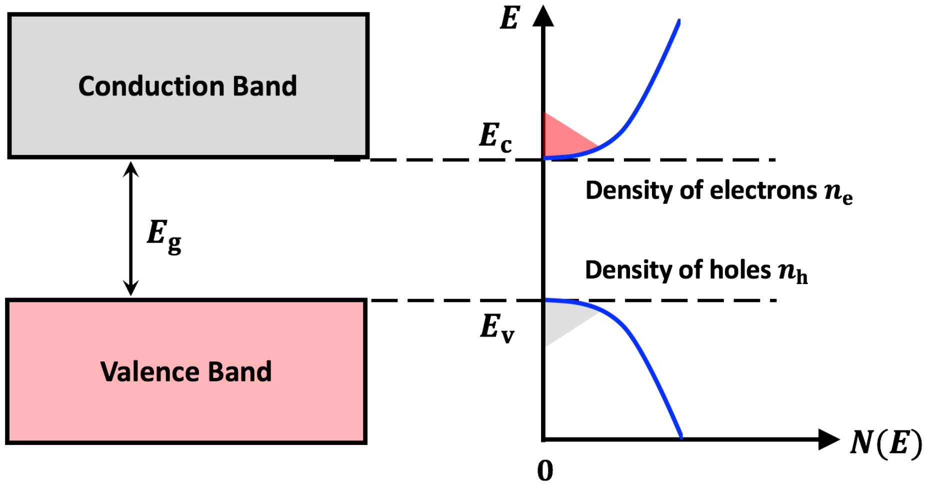
$$f(E) = \frac{1}{e^{(E-E_{\mathrm{f}})/k_{\mathrm{B}}T} + 1} \longrightarrow \boxed{f(E) \approx e^{-(E-E_{\mathrm{f}})/k_{\mathrm{B}}T}}$$

➢ Charge Carriers (载流子)

❖ Density of charge carriers (载流子密度)

- At thermal equilibrium, the density of electrons $\boldsymbol{n}_{\mathbf{e}}$ and holes $\boldsymbol{n}_{\mathbf{h}}$ satisfies:

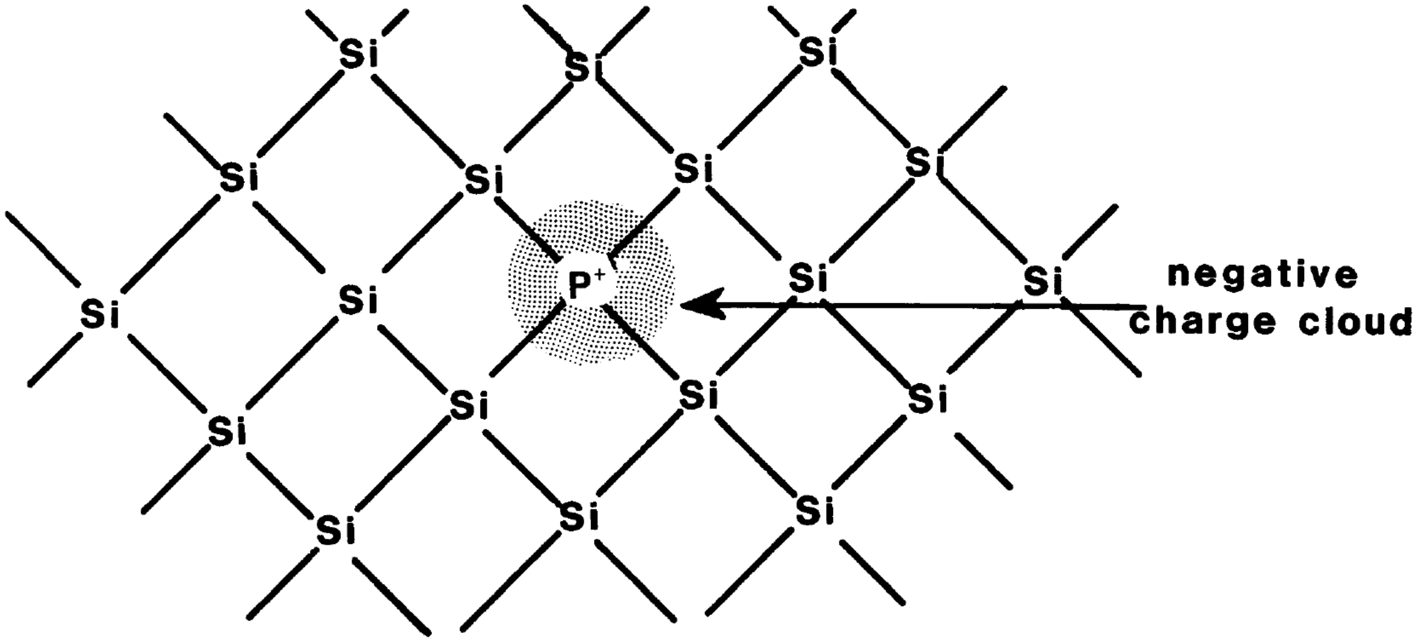
$$\boxed{n_{\mathrm{e}} n_{\mathrm{h}} = N_{\mathrm{c}} N_{\mathrm{v}} \mathrm{e}^{-E_{\mathrm{g}}/k_{\mathrm{B}}T}}$$



It suggests that **the more electrons in the conduction band, the less holes in the valence band**, and vice versa.

➢ Dopants (掺杂物)

❖ A dopant is an **impurity element** intentionally inserted into a solid/crystal in order to modify the electrical, optical, and magnetic properties of the material.



An impurity atom of **P** is introduced to replace a **Si** atom in a silicon crystal.

➢ Dopants (掺杂物)

❖ Electron donors (电子施主):

- A dopant that donates electrons to the doped semiconductors;
- The **energy level** of an electron donor is **in the band gap** and more **close to the edge of conduction band**;
- The electrons of donor levels can be thermally activated to conduction band at finite temperature.

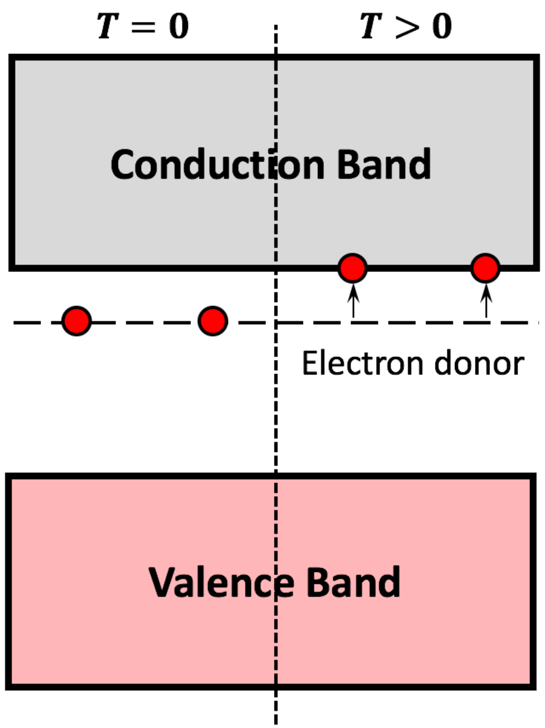
➢ Dopants (掺杂物)

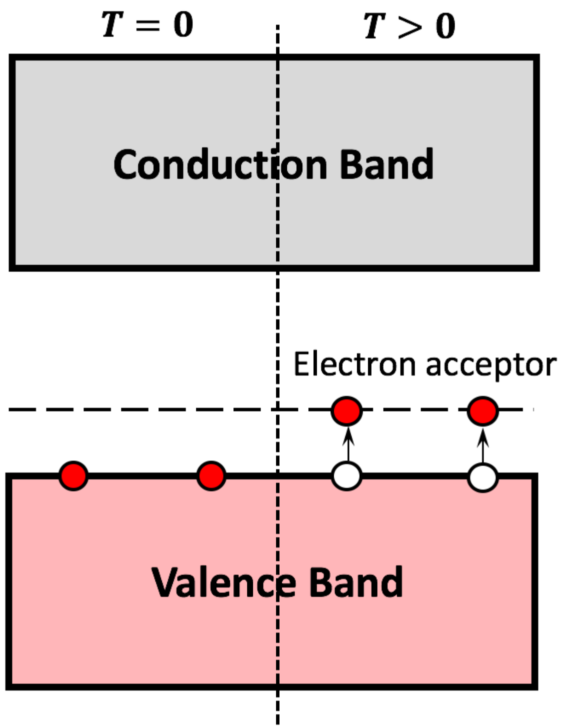
❖ Electron acceptors (电子受主):

- A dopant that accepts electrons from the doped semiconductors;
- The **energy level** of an electron acceptor is **in the band gap** and more **close to the edge of valence band**;
- The electrons of valence band can be thermally activated to acceptor levels at finite temperature.

➢ Dopants (掺杂物)

❖ The dopant energy levels with respect to the band structures of semiconductors:

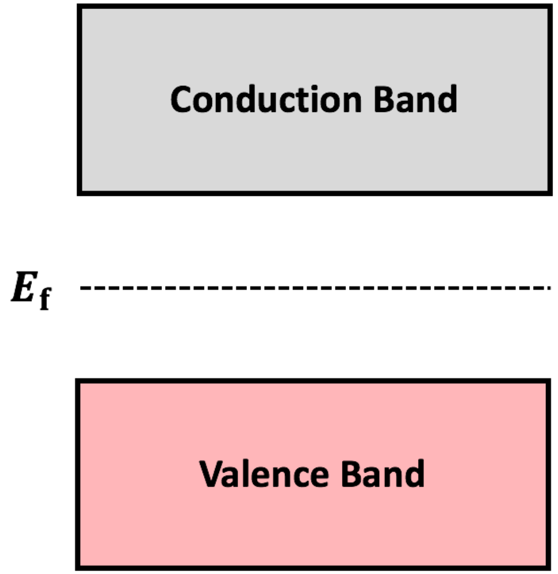




➢ Intrinsic and Extrinsic Semiconductors (本征与非本征半导体)

❖ Intrinsic semiconductors (本征半导体)

- Undoped semiconductors (未掺杂半导体);
- **The Fermi level is in the middle of band gap;**
- The amounts of electrons and holes are equal.



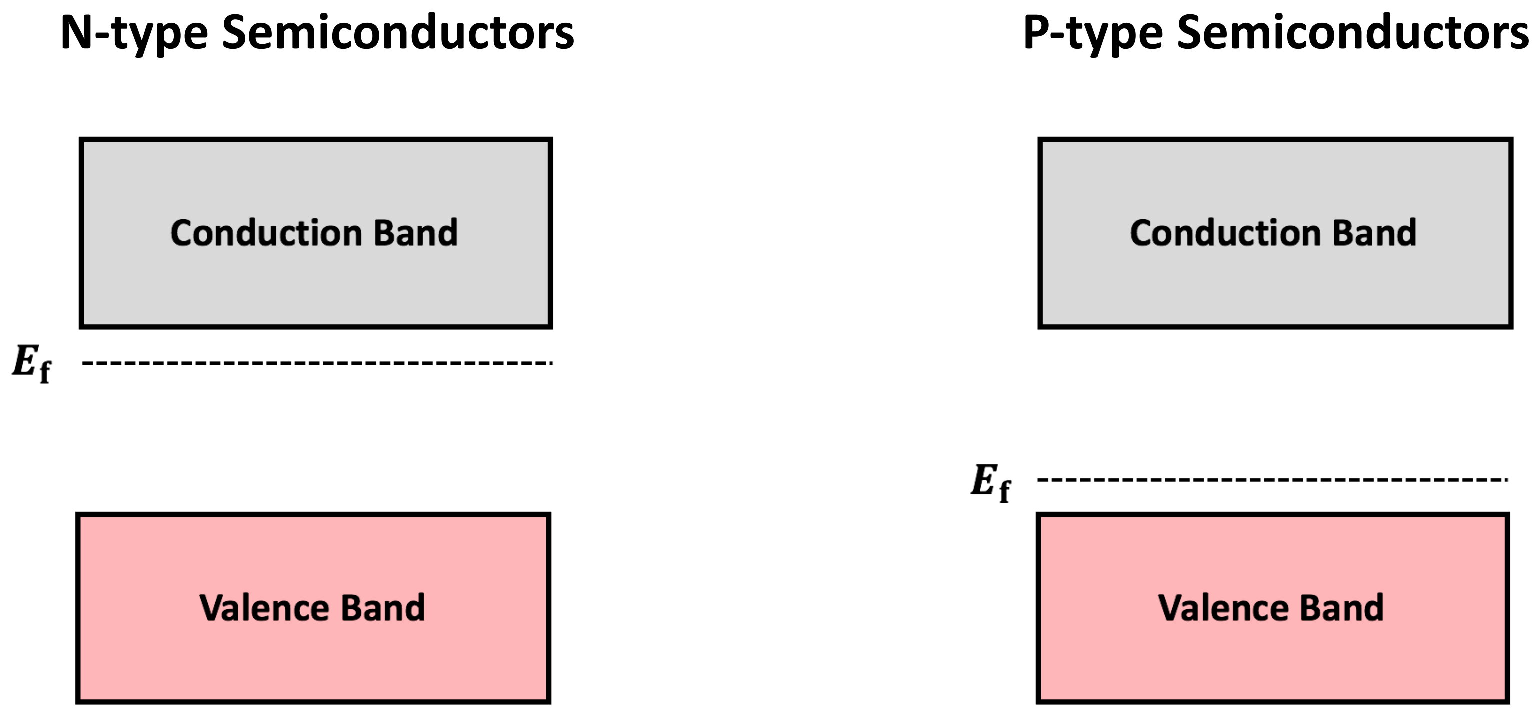
➢ Intrinsic and Extrinsic Semiconductors (本征与非本征半导体)

❖ Extrinsic semiconductors (非本征半导体)

- Doped semiconductors (掺杂半导体);
- **The Fermi level is more close to conduction band (N-type) or valence band (P-type);**
- There are more electrons in **N-type semiconductors (N型半导体)** and more holes in **P-type semiconductors (P型半导体)**.

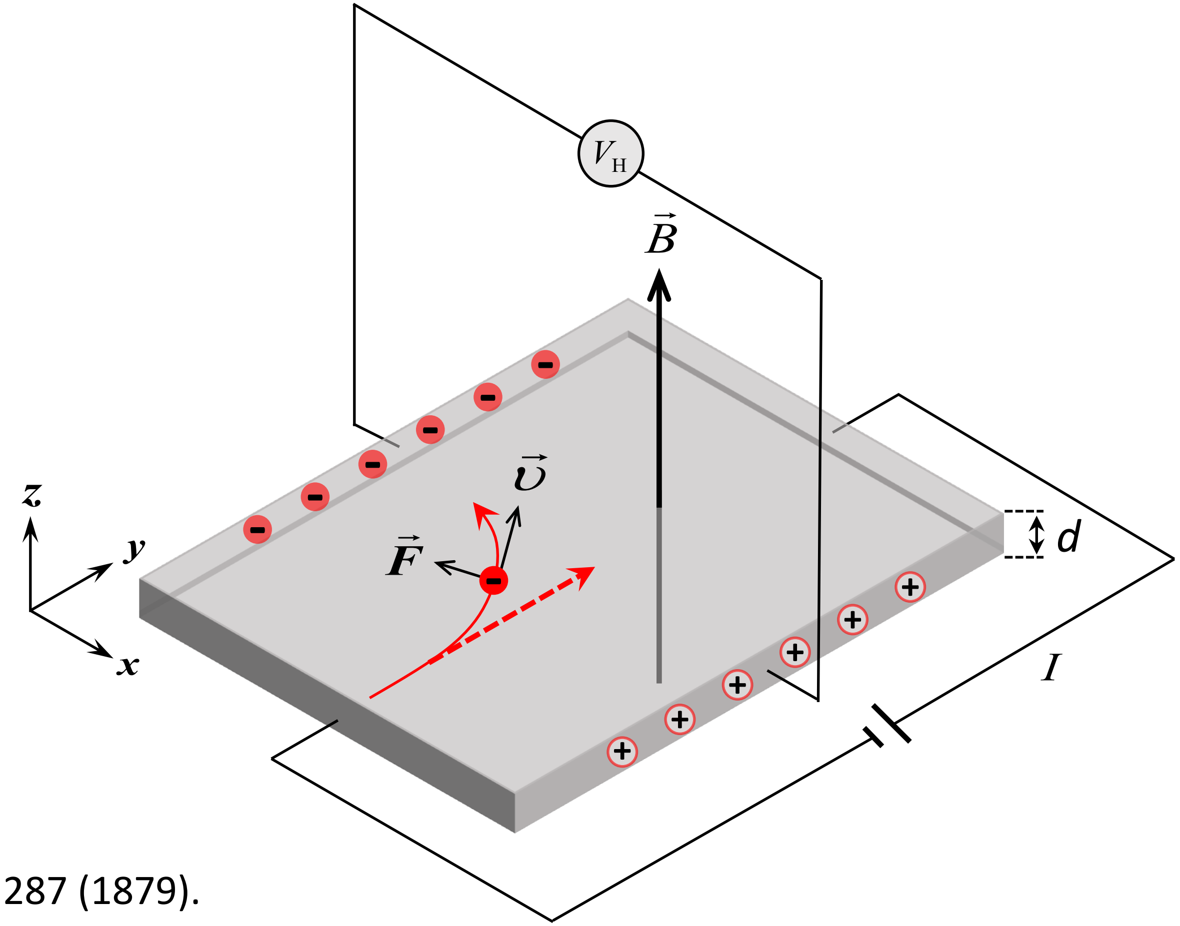
➢ Intrinsic and Extrinsic Semiconductors (本征与非本征半导体)

❖ Extrinsic semiconductors (非本征半导体)



➢ Hall Effect (霍尔效应)

❖ The generation of transverse voltage by longitudinal electric current and perpendicular magnetic field.



E. Hall, **Am. J. Math.** 2, 287 (1879).

➢ Hall Effect (霍尔效应)

❖ The Hall effect is usually used to probe the **types (electron or hole) and density of charge carriers** in semiconductors.

Hall voltage (霍尔电压):

$$V_{\mathrm{H}} = \frac{BI}{ned} = R\frac{BI}{d}$$

Hall coefficient (霍尔系数):

$$\boldsymbol{R} = \frac{\mathbf{1}}{\boldsymbol{ne}} \longrightarrow \boxed{\boldsymbol{n} = \frac{\mathbf{1}}{\boldsymbol{Re}}}$$

E. Hall, **Am. J. Math.** 2, 287 (1879).

➢ Hall Effect (霍尔效应)

❖ The Hall effect family (霍尔效应家族)

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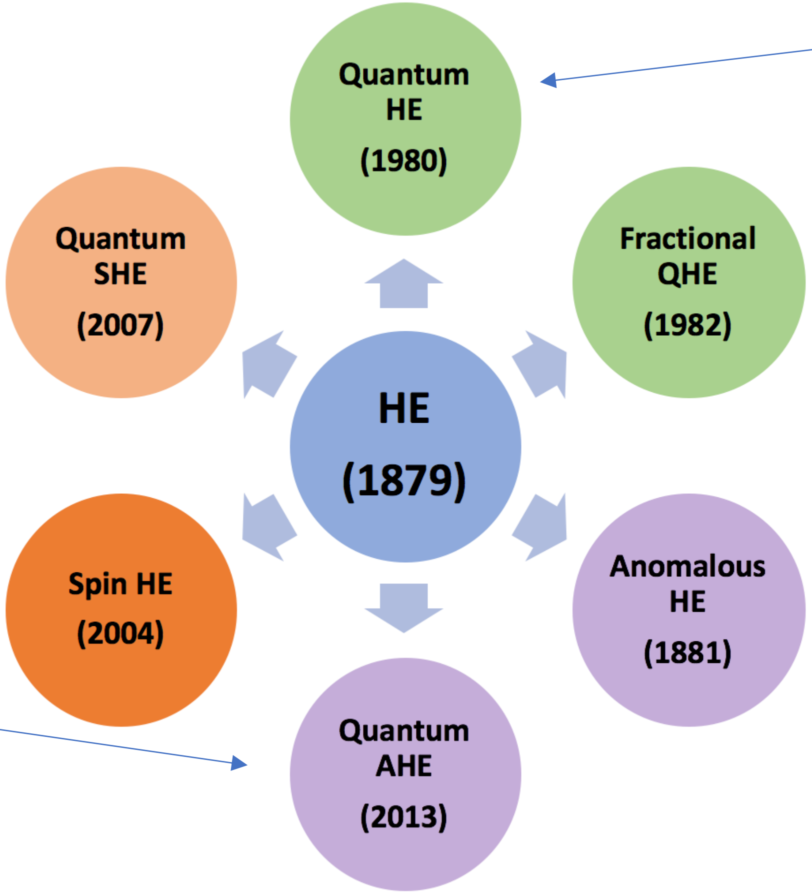
(1963-2018)
Chinese-American Theoretical Physicist

Q. K. Xue 薛其坤
(1963-)
Chinese Physicist



Nobel Prize in Physics 1985

K. von Klitzing
(1943-)
German Physicist

Nobel Prize in Physics 1998

R. B. Laughlin
(1950-)
American Physicist

H. L. Stormer
(1949-)
American Physicist

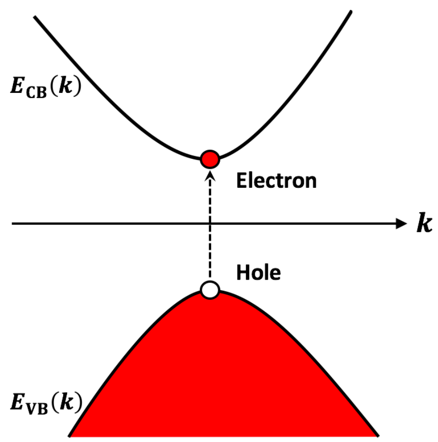
D. Tsui 崔琦
(1939-)
Chinese-American Physicist

Summary (总结)

➢ Summary

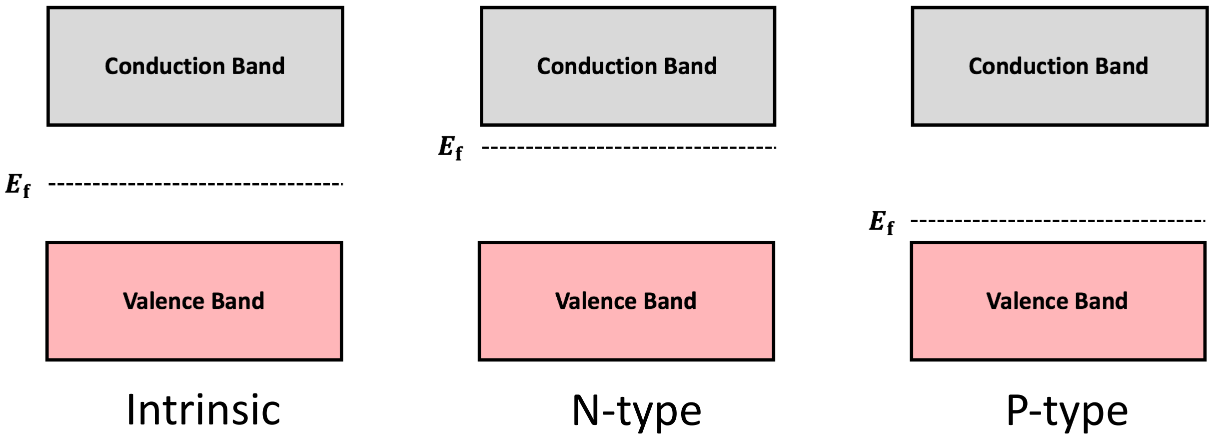
❖ Important properties of semiconductors:

- **Band gap**
- Charge-carrier types: **electrons and holes**
- Charge-carrier **effective mass** at band edges
- **Dopants**



❖ Classification of semiconductors:

- **Intrinsic** semiconductors
- **Extrinsic** semiconductors
  - **N-type** semiconductors
  - **P-type** semiconductors



Thank you!