Chap 11

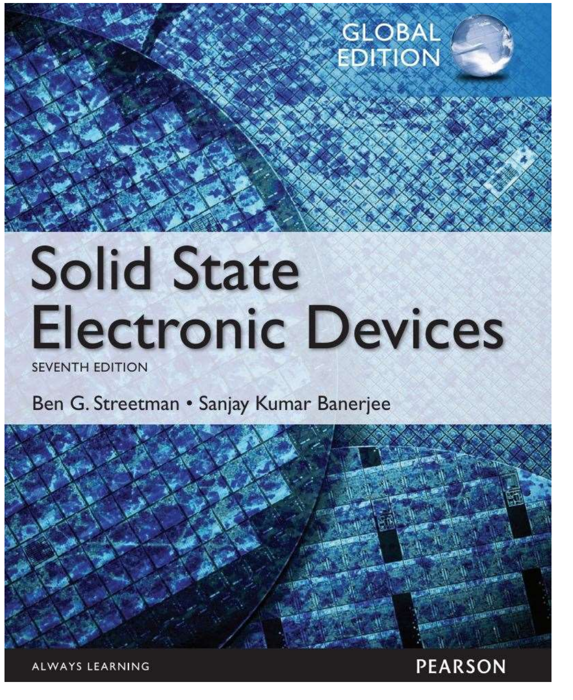
# Semiconductor Theory and Devices

- Band Theory of Solids
- Semiconductor Theory
- Semiconductor Devices

*Diodes, Rectifiers, Zener Diodes, Light-Emitting Diodes, Photovoltaic Cells, Transistors, Field Effect Transistors, Schottky Barriers, Semiconductor Lasers, Integrated Circuits*

- Nanotechnology

If you're interested in this subject, take Solid State Physics, and read the textbook on the right



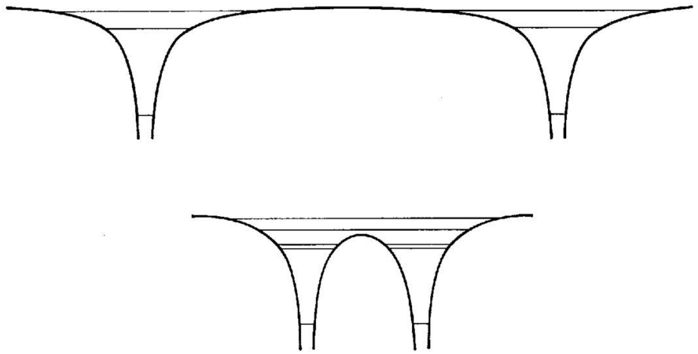
**Energy bands** in solids

Opposite viewpoints:

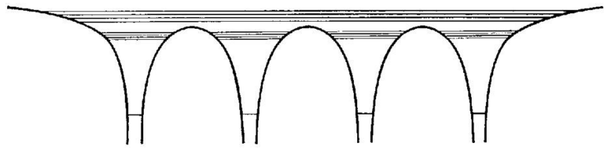
1. Tight-binding electrons (this page)

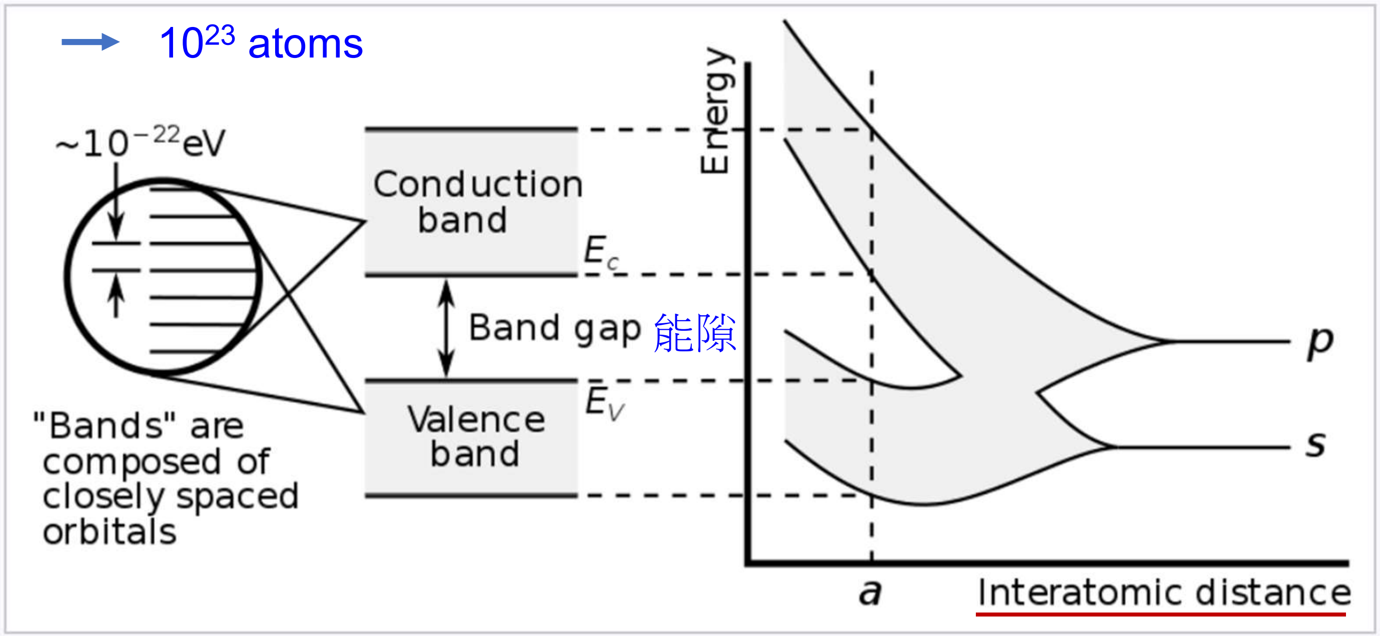
2. Nearly free electrons (next page)

2 atoms



→ 4 atoms

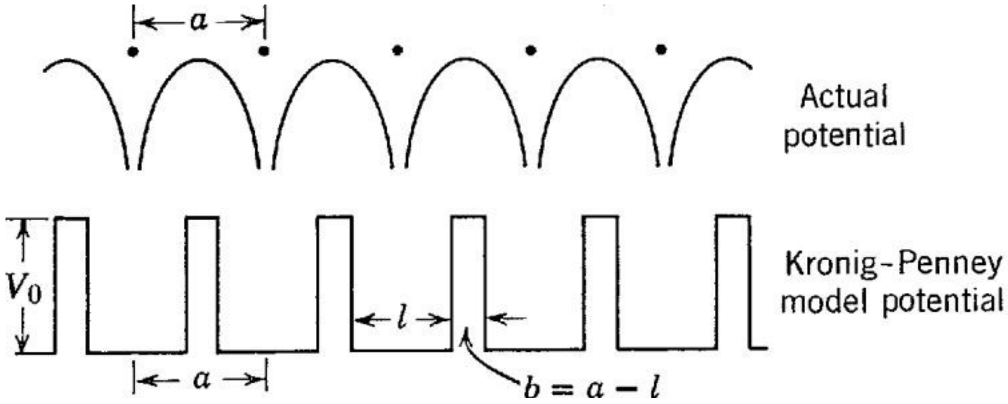


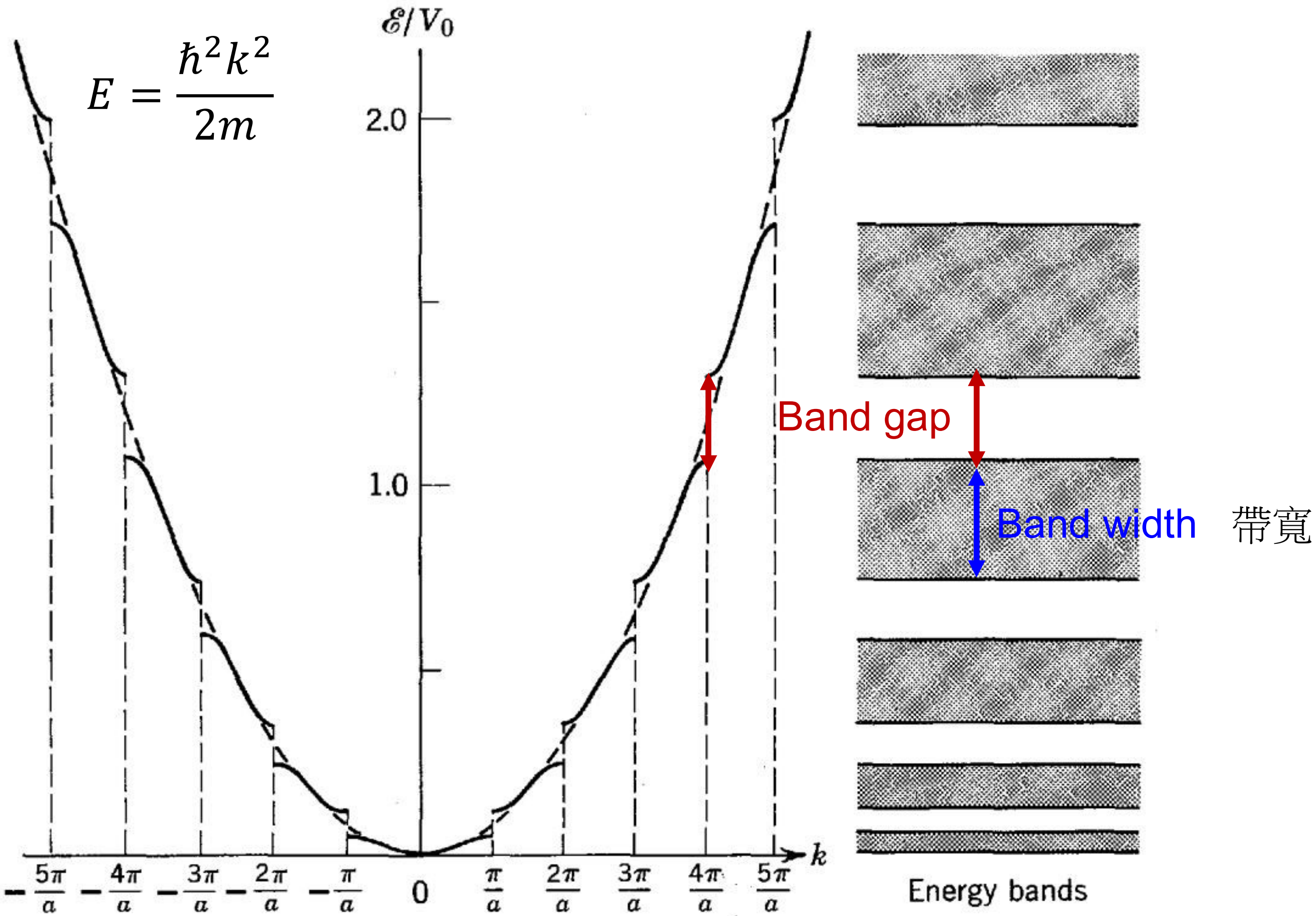


## Kronig-Penny model

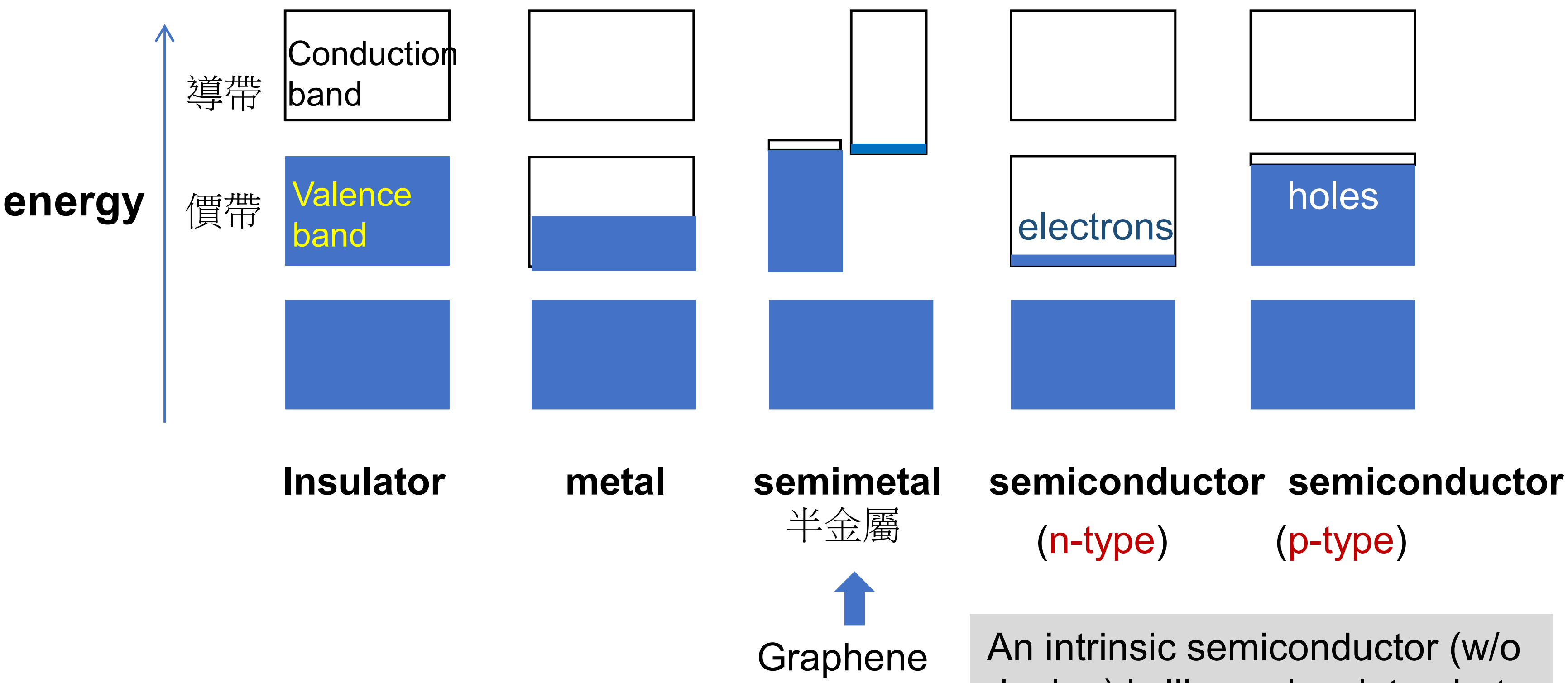
(1930)

Electrons in a periodic potential



Filling energy bands with electrons




An intrinsic semiconductor (w/o doping) is like an insulator, but with a smaller energy gap.

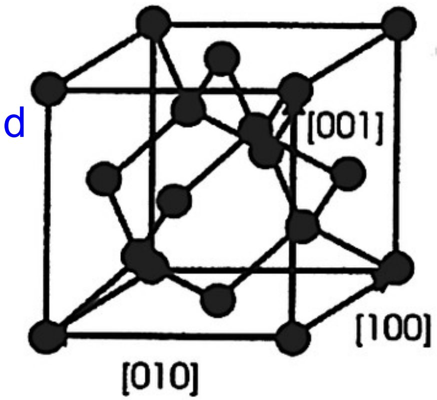
Basic properties of some semiconductor materials

| (at 300K) | Ge | Si | GaAs | GaN |
|---|---|---|---|---|
| energy gap (eV) | 0.67 (i) | 1.11 (i) | 1.43 (d) | 3.39 (d) |
| lattice type | Diamond | Diamond | Zincblend | Wurtzite |

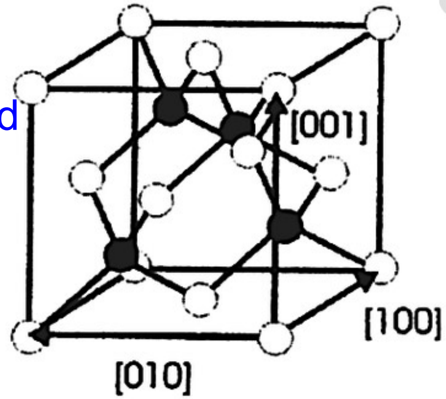
ZnS 閃鋅    纖鋅礦

2 overlapping hcp lattices

Diamond lattice




Zincblend structure




- Semiconductor is insulator at 0 K, but because of its smaller energy gap (Cf: insulator, diamond = 5.4 eV), some electrons can be thermally excited to the conduction band (and transport current).

**Ex 11.1:**

Find the relative number of electrons with energies 0.10 eV, 1.0 eV, and 10 eV above the ~~valence band~~ Fermi energy at room temperature (293 K).

**Solution** For $E - E_F = 1.0$ eV, $(E - E_F)/kT = (1.60 \times 10^{-19}\ \text{J})/(1.38 \times 10^{-23}\ \text{J/K})(293\ \text{K}) = 39.61$. Then

$$F_{FD} = \frac{1}{\exp\left[\beta\left(E - E_F\right)\right] + 1}$$

$$F_{\text{FD}}(0.10\ \text{eV}) = \frac{1}{e^{3.961} + 1} = 0.019$$

$$F_{\text{FD}}(1.0\ \text{eV}) = \frac{1}{e^{39.61} + 1} = 6.27 \times 10^{-18}$$

$$F_{\text{FD}}(10\ \text{eV}) = \frac{1}{e^{396.1} + 1} = 1.0 \times 10^{-172}$$

This example illustrates how strongly the Fermi-Dirac factor depends on the size of the band gap. The number of electrons available for conduction drops off sharply as the band gap increases.

掺雜

# Dopants for Si and Ge

| period | group | | | | | |
|---|---|---|---|---|---|---|
| | II | III | IV | V | VI | VII |
| 2 | Be | B | C | N | O | F |
| 3 | Mg | Al | Si | P | S | Cl |
| 4 | Ca Zn | Ga | Ge | As | Se | Br |
| 5 | Sr Cd | In | Sn | Sb | Te | I |

p-type (group III) n-type (group V)

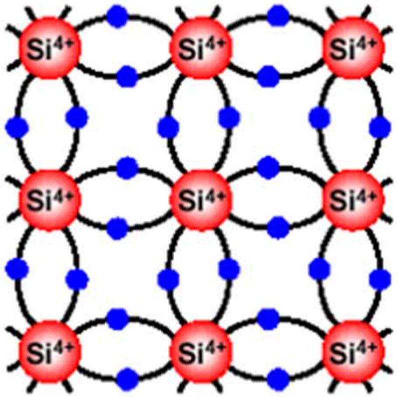
- dopants for Si and Ge

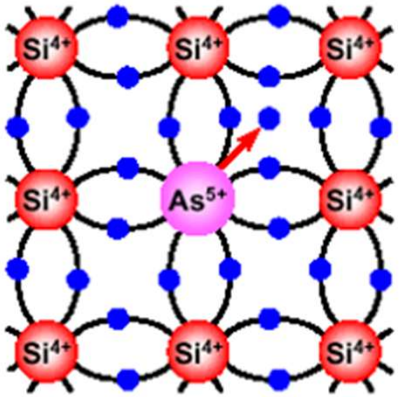
A silicon single crystal

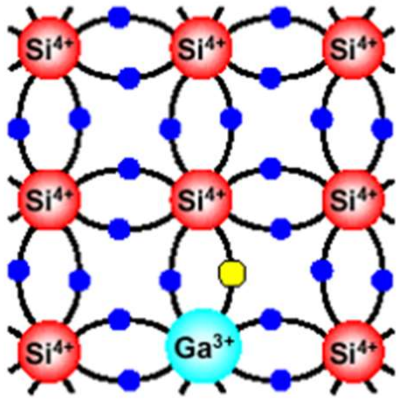
載子 (electrons or holes)

Electric carriers by doping

本質半導體 Intrinsic | extrinsic (n-type) 雜質半導體 | extrinsic (p-type)

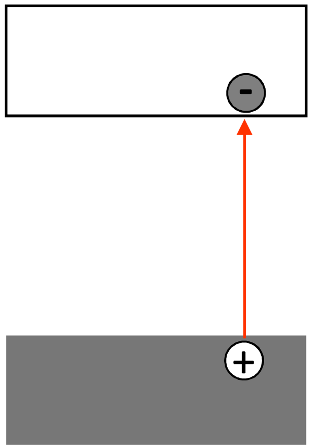


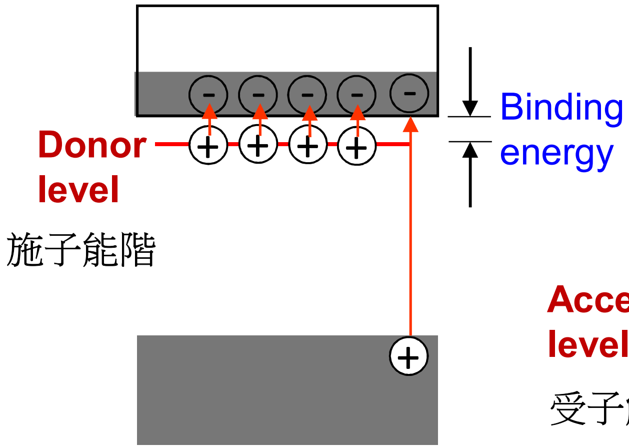




**Impurity levels**

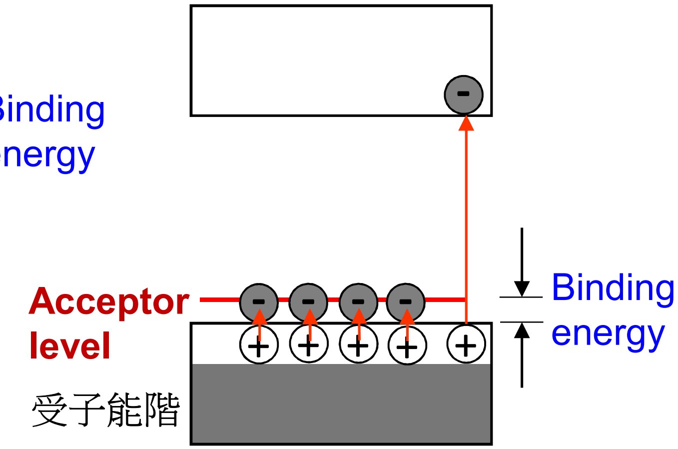
Intrinsic



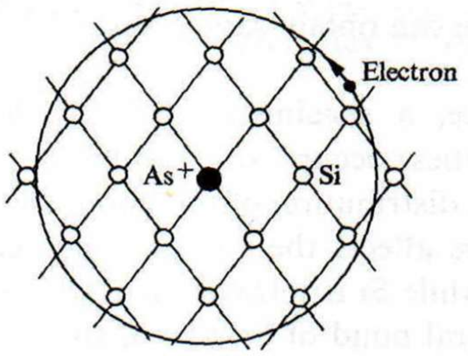
n-type doping




p-type doping



# Bohr model of Impurity level




• Assume an ionized donor atom has a hydrogen-like potential

($m \rightarrow m_e$, $\varepsilon_0 \rightarrow \varepsilon$)

$$E_D = \frac{e^4 m_e}{2\varepsilon^2 \hbar^2} = \left( \frac{13.6}{\varepsilon^2} \frac{m_e}{m} \right) \text{eV}$$

Dielectric constant of Si = 11.7

Effective mass for Si = 0.2 m.

Donor ionization energy = 20 meV.

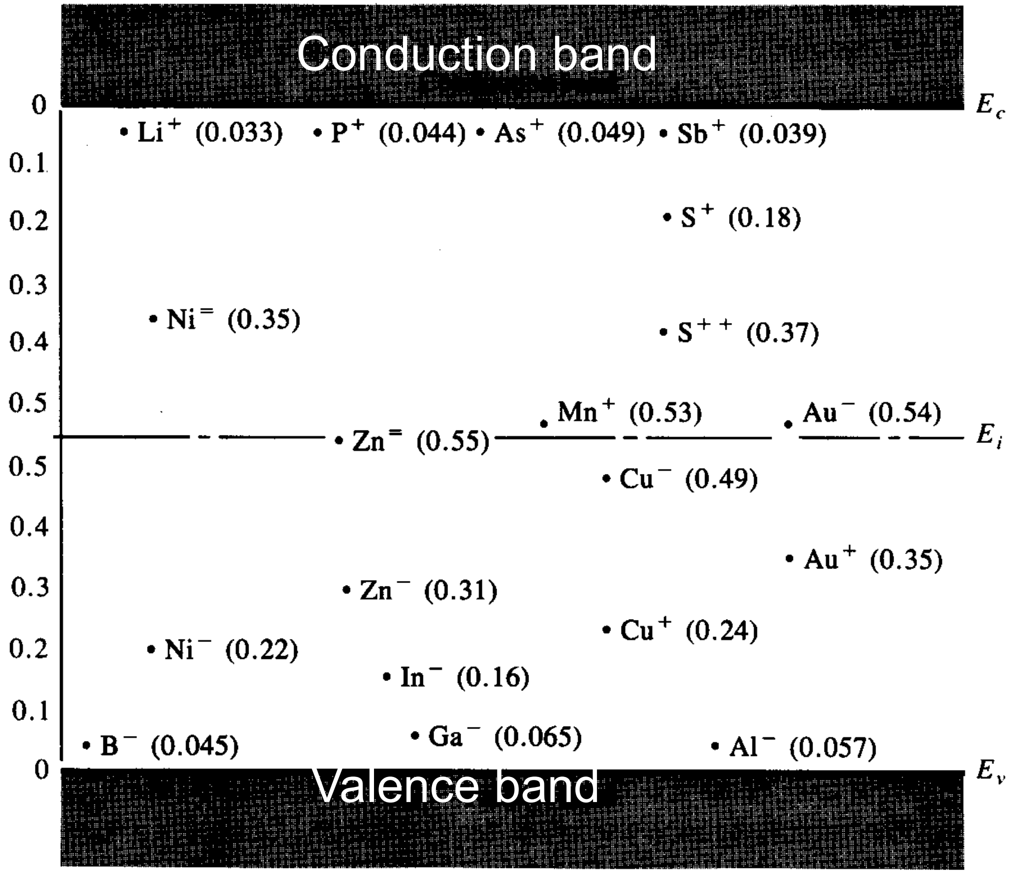
• Bohr radius of the donor electron:

$$a_D = \frac{\varepsilon \hbar^2}{m_e e^2} = \left( \frac{0.53\varepsilon}{m_e / m} \right) \text{A}$$

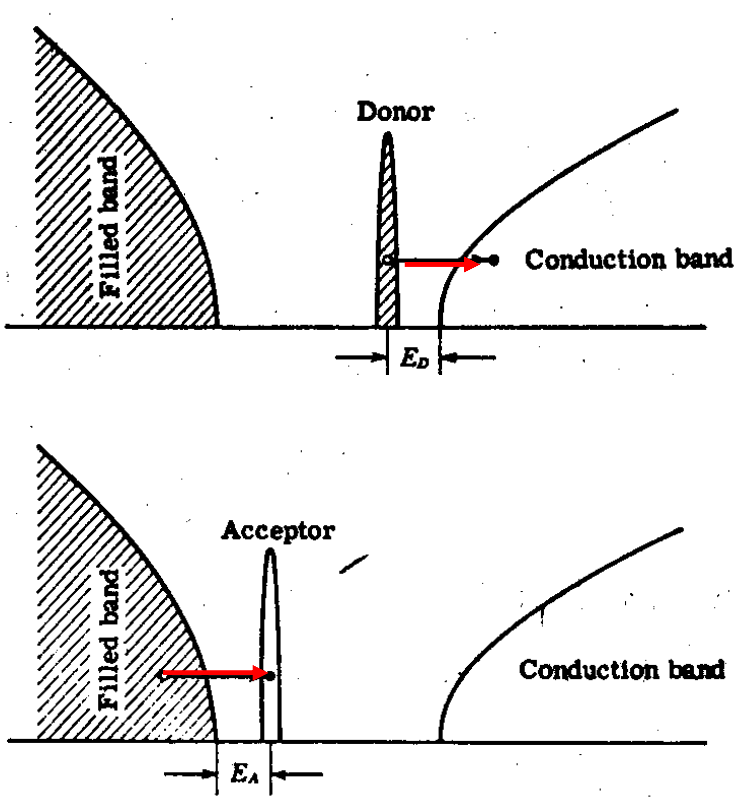
For Si, it's about 50 A (justifies the use of a constant ε).

optional

- Impurity levels in Si



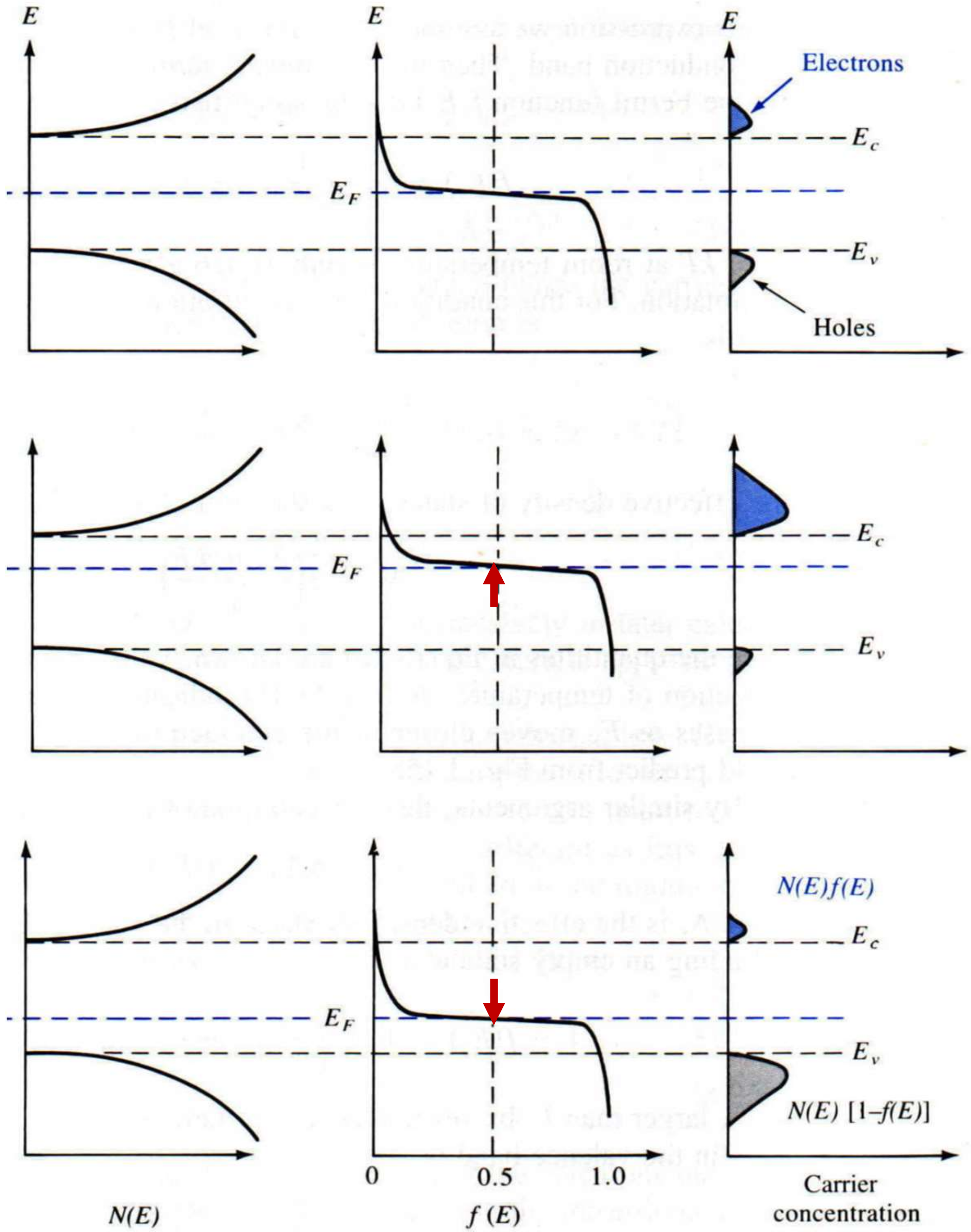

- Density of states



optional

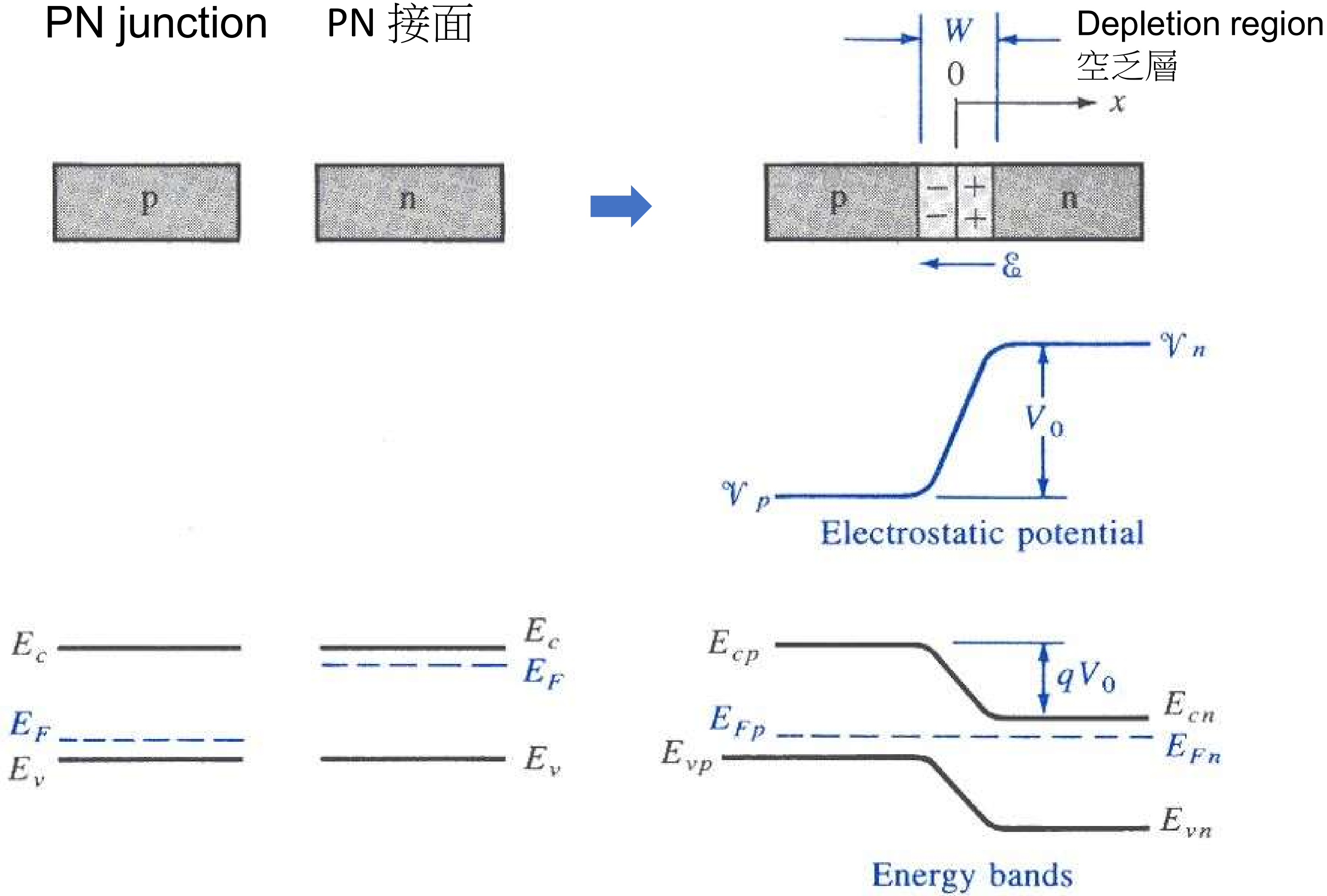
# Position of Fermi energy

- Intrinsic
- N-doped
- P-doped



optional

PN junction　　PN 接面

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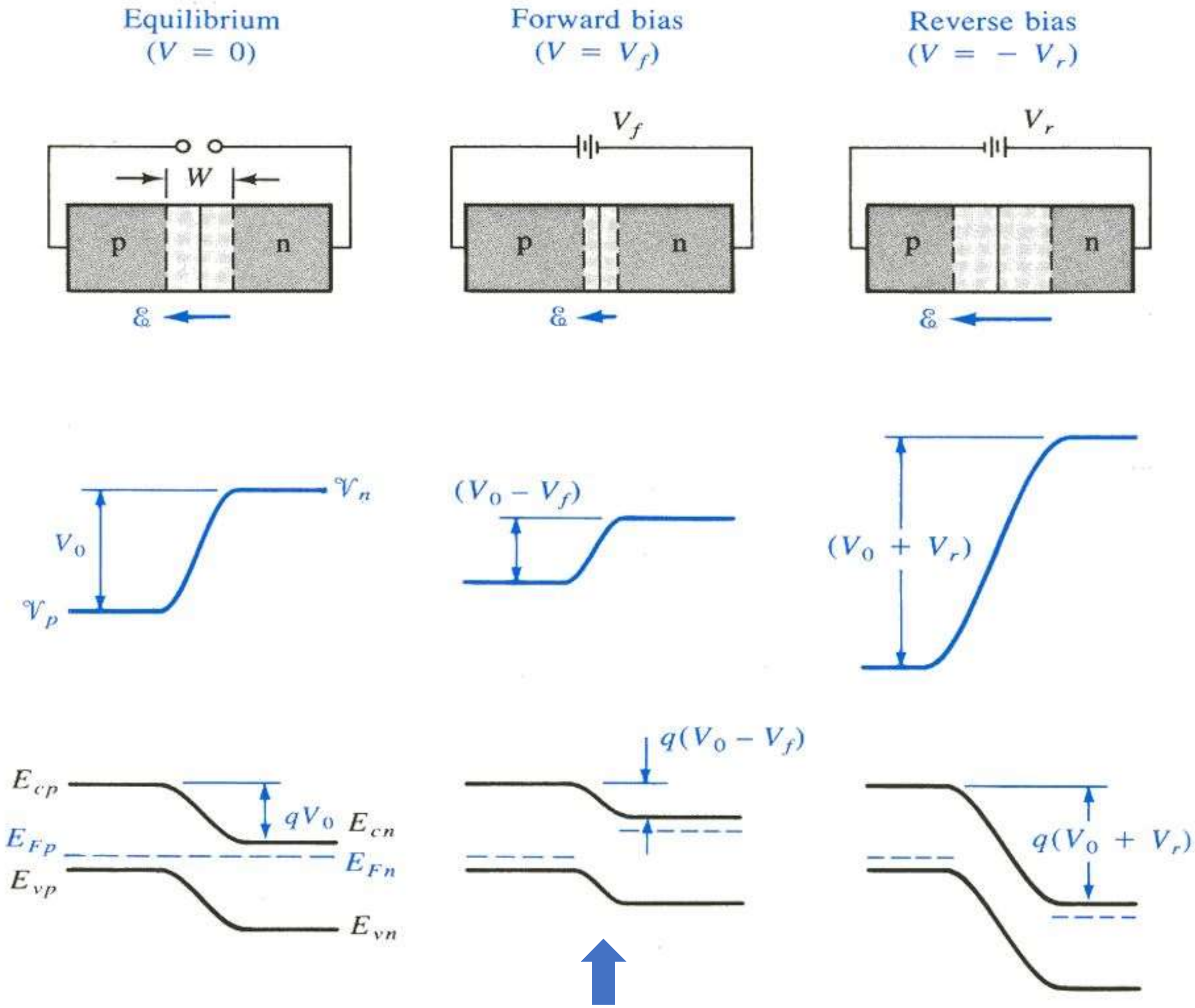
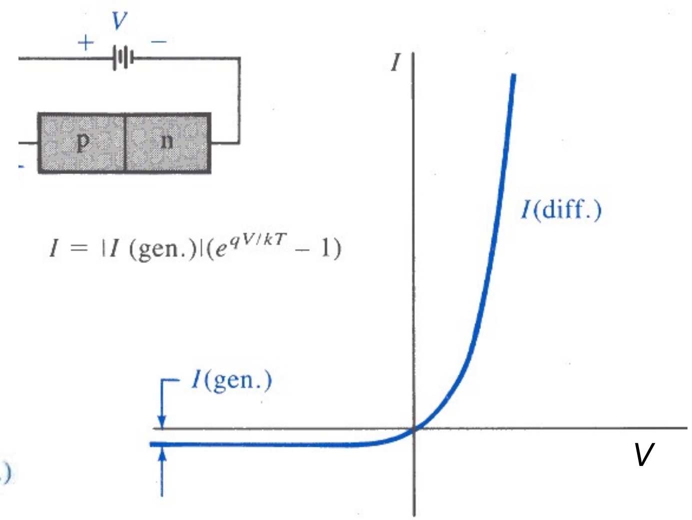
optional

Equilibrium    With external bias




(easier for e ← and h → to go through the barrier)

Rectification 整流

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optional

**Light emitting diode**
(LED)