Fundamentals of Solid State Physics

Electronic Devices

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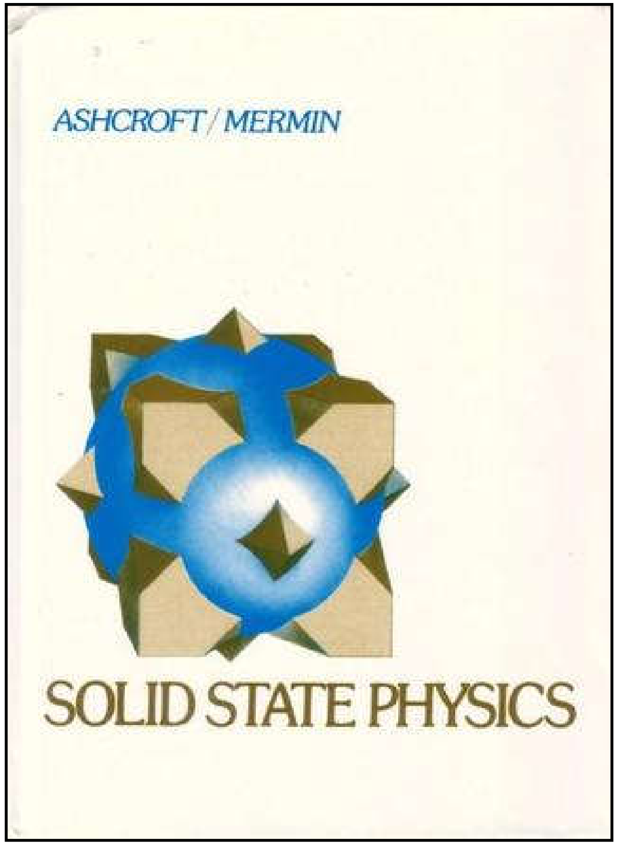
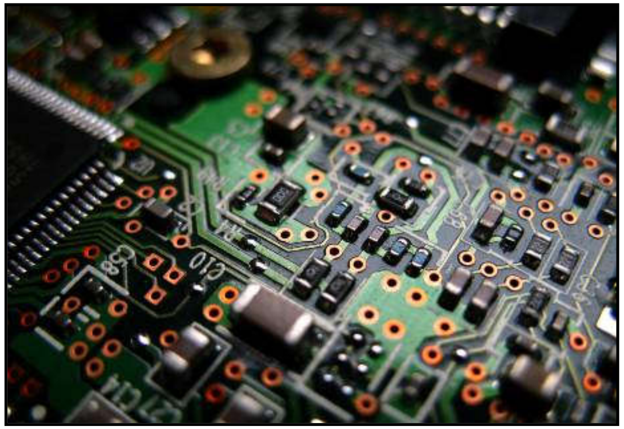
Further Reading

- **Ashcroft & Mermin, Chapter 29**
- **PV Education online course, Chapter 3**
  - https://www.pveducation.org/



Semiconductors - Applications

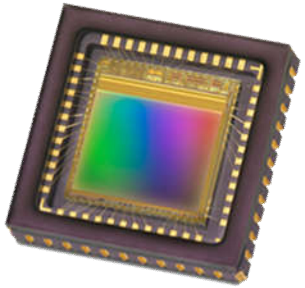
semiconductors are the basis of electronics and photonics



integrated circuits

LEDs

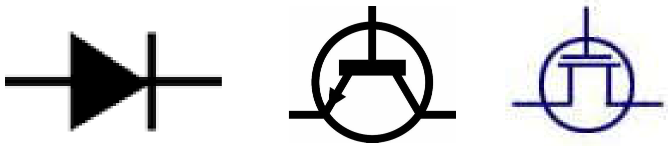
lasers



detectors

solar cells

key components: junctions

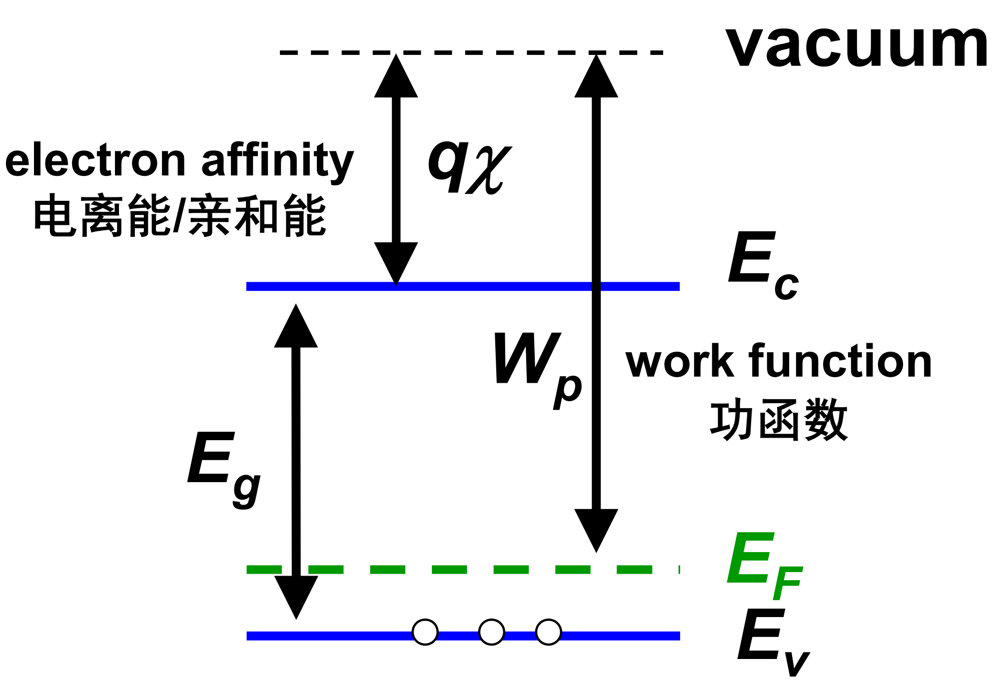


Junctions

- **Semiconductor-Semiconductor**
  - pn homojunction 同质结
  - heterojunction 异质结
- **Metal-Metal**
- **Metal-Semiconductor**
  - Ohmic contact
  - Schottky contact
- **Metal-Oxide-Semiconductor**
  - MOSFET 场效应晶体管

p-type and n-type semiconductor

p-Si

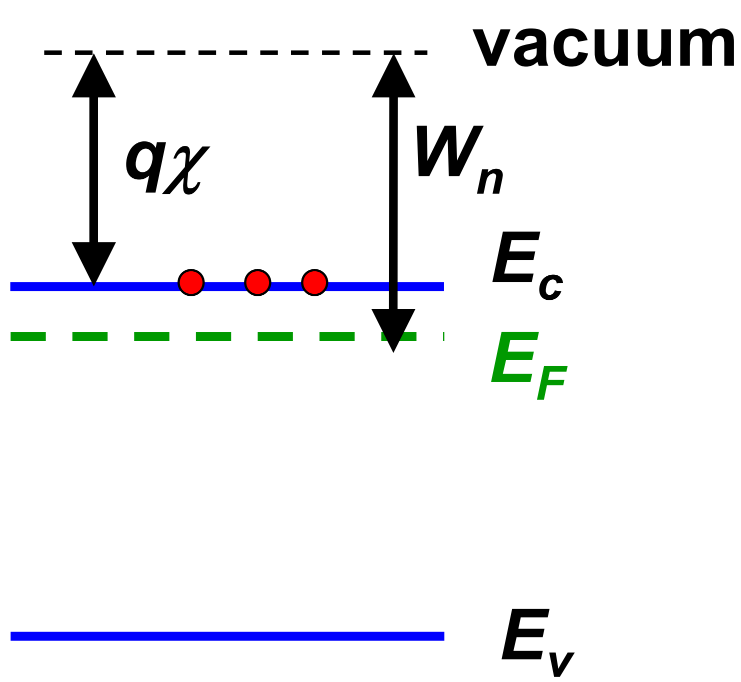


$$p_v = N_A$$

$$n_c = n_i^2 / p_v$$

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

n-Si



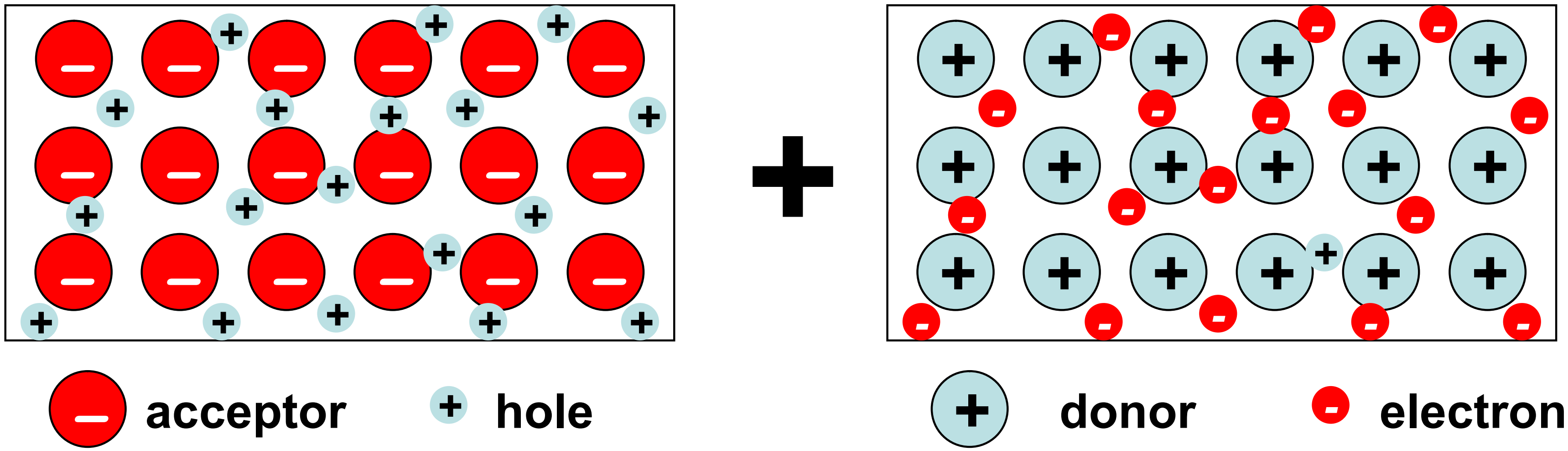
$$n_c = N_D$$

$$p_v = n_i^2 / n_c$$

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

p-type and n-type semiconductor

p-Si **n-Si**



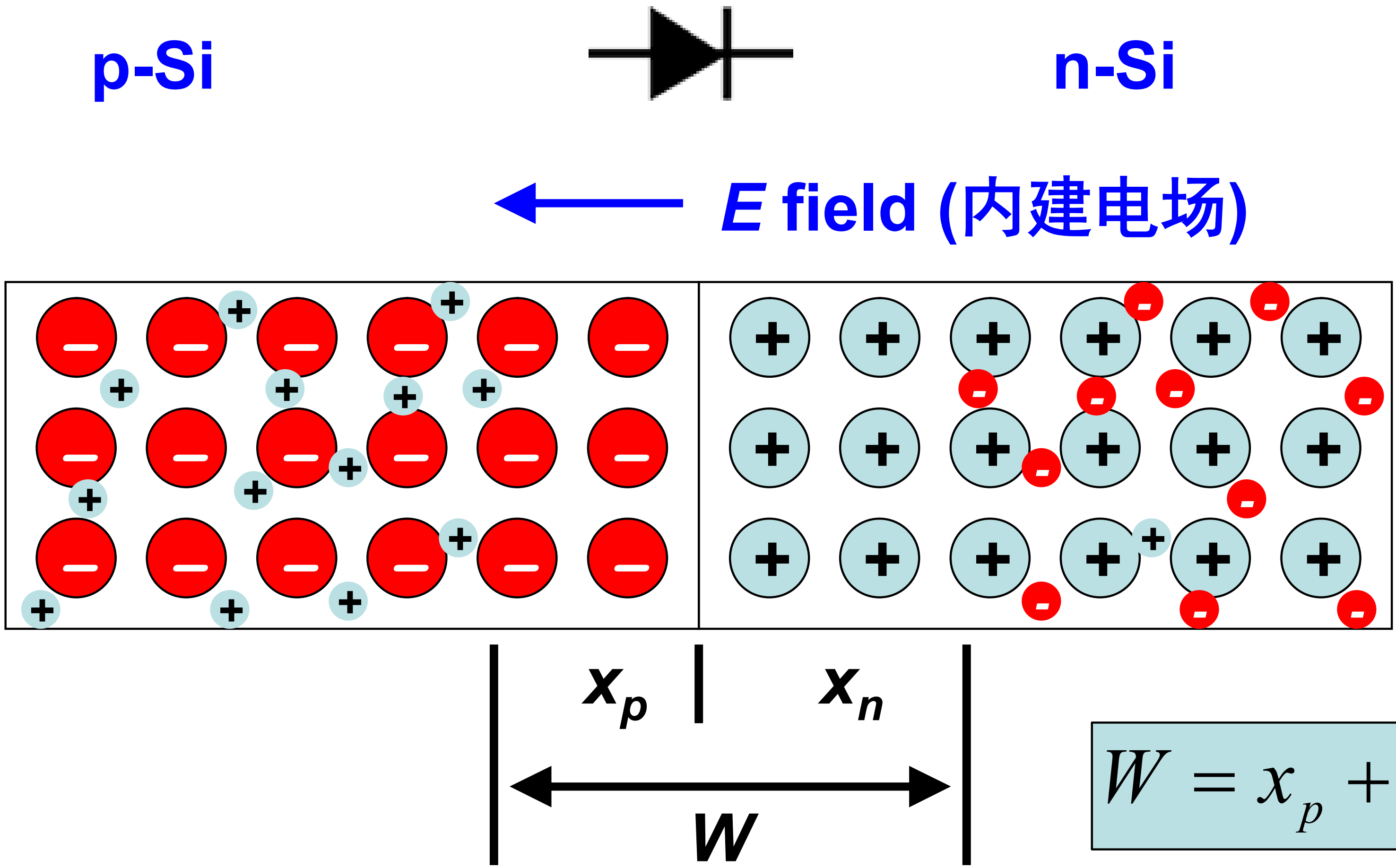
$$p_v = N_A \qquad n_c = n_i^2 / p_v$$

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

$$n_c = N_D \qquad p_v = n_i^2 / n_c$$

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

pn homojunction 同质结

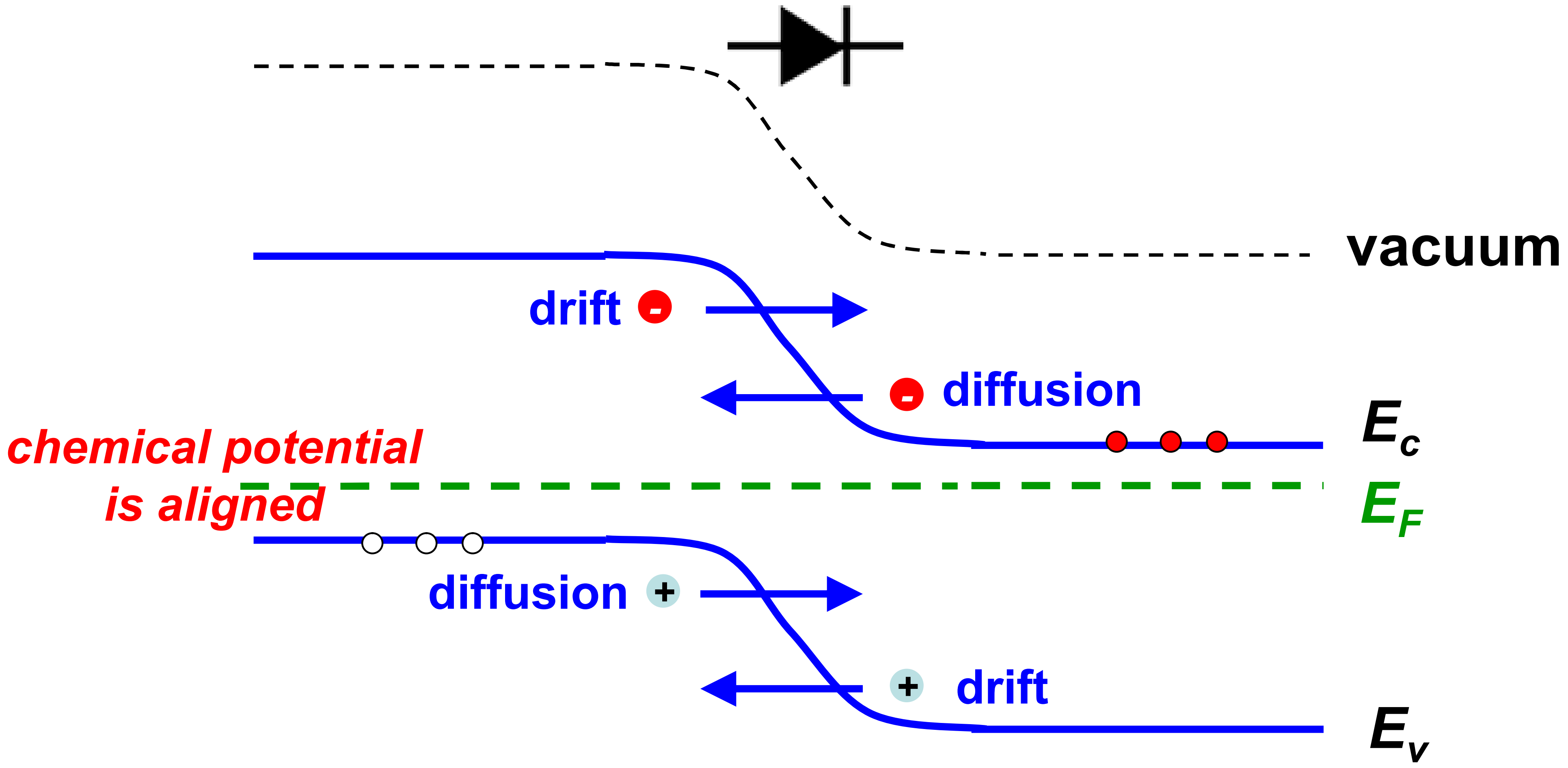


$$W = x_p + x_n$$

depletion region
耗尽区

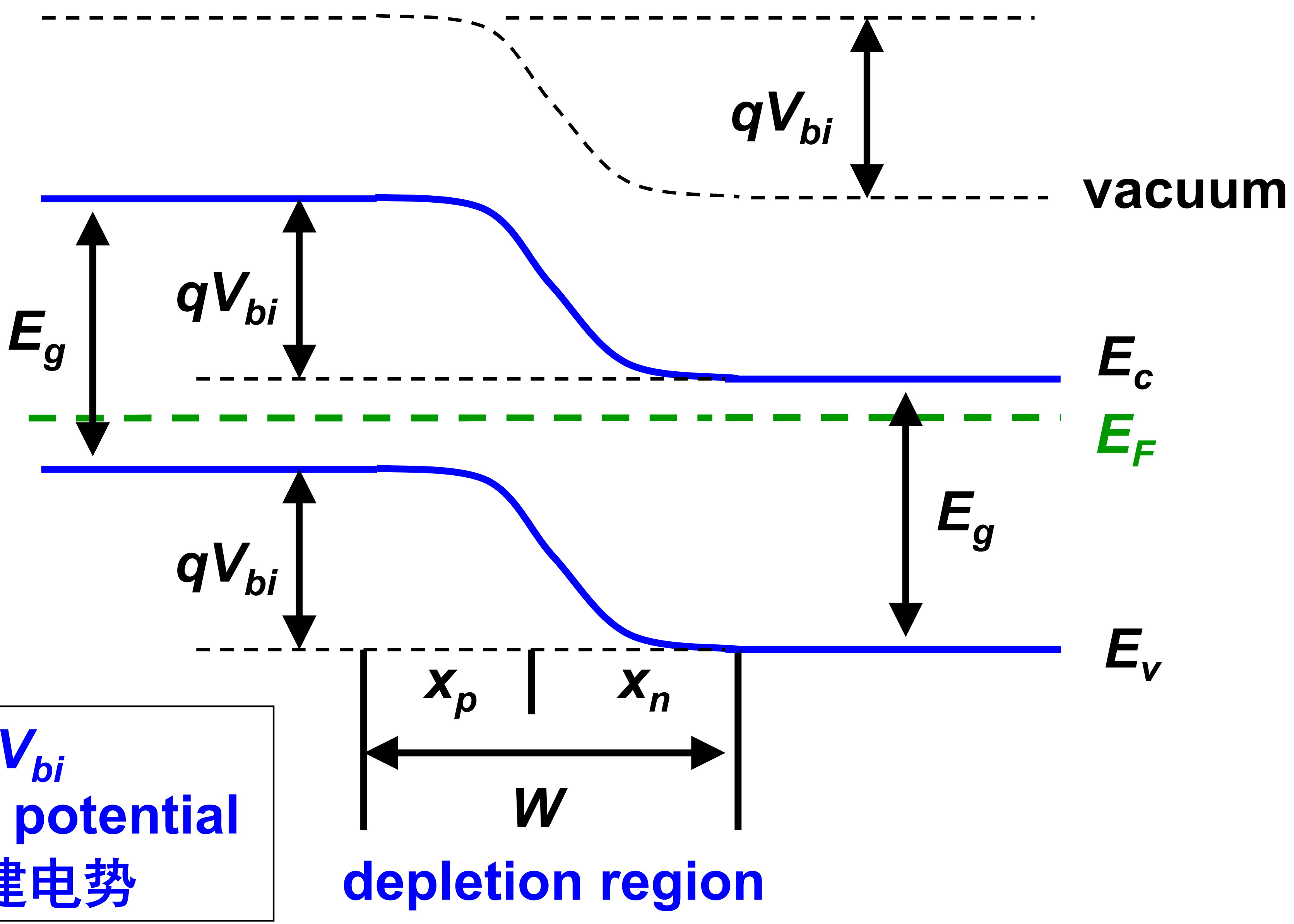
electrons and holes recombine

pn homojunction 同质结



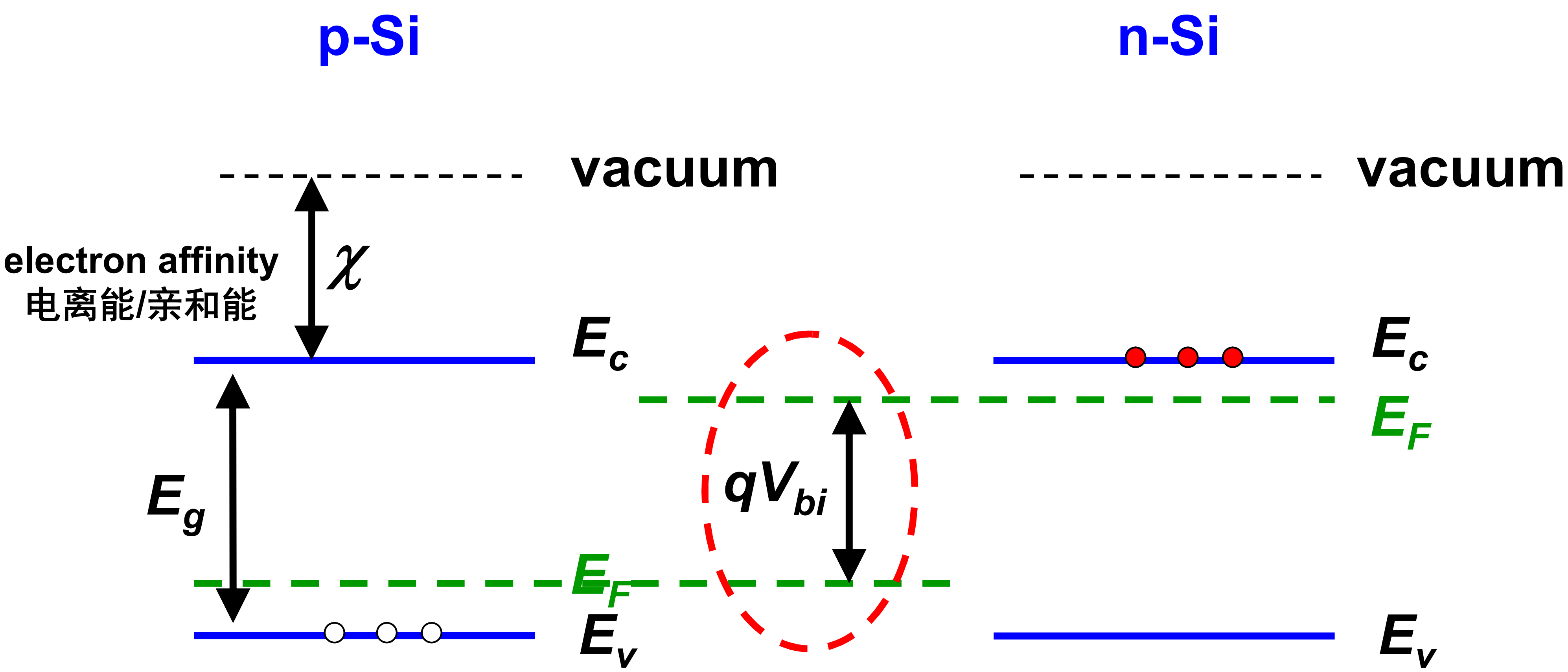
at thermal equilibrium, carrier diffusion is balanced by drift caused by the built-in field. Overall current = 0

pn homojunction 同质结



V_{bi}
built-in potential
内建电势

p-type and n-type semiconductor



$$p_v = N_A$$

$$n_c = n_i^2 / p_v$$

$$n_c = N_D$$

$$p_v = n_i^2 / n_c$$

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

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

V_{bi} - built-in potential 内建电势

$$V_{bi} = \frac{k_B T}{q} \cdot \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

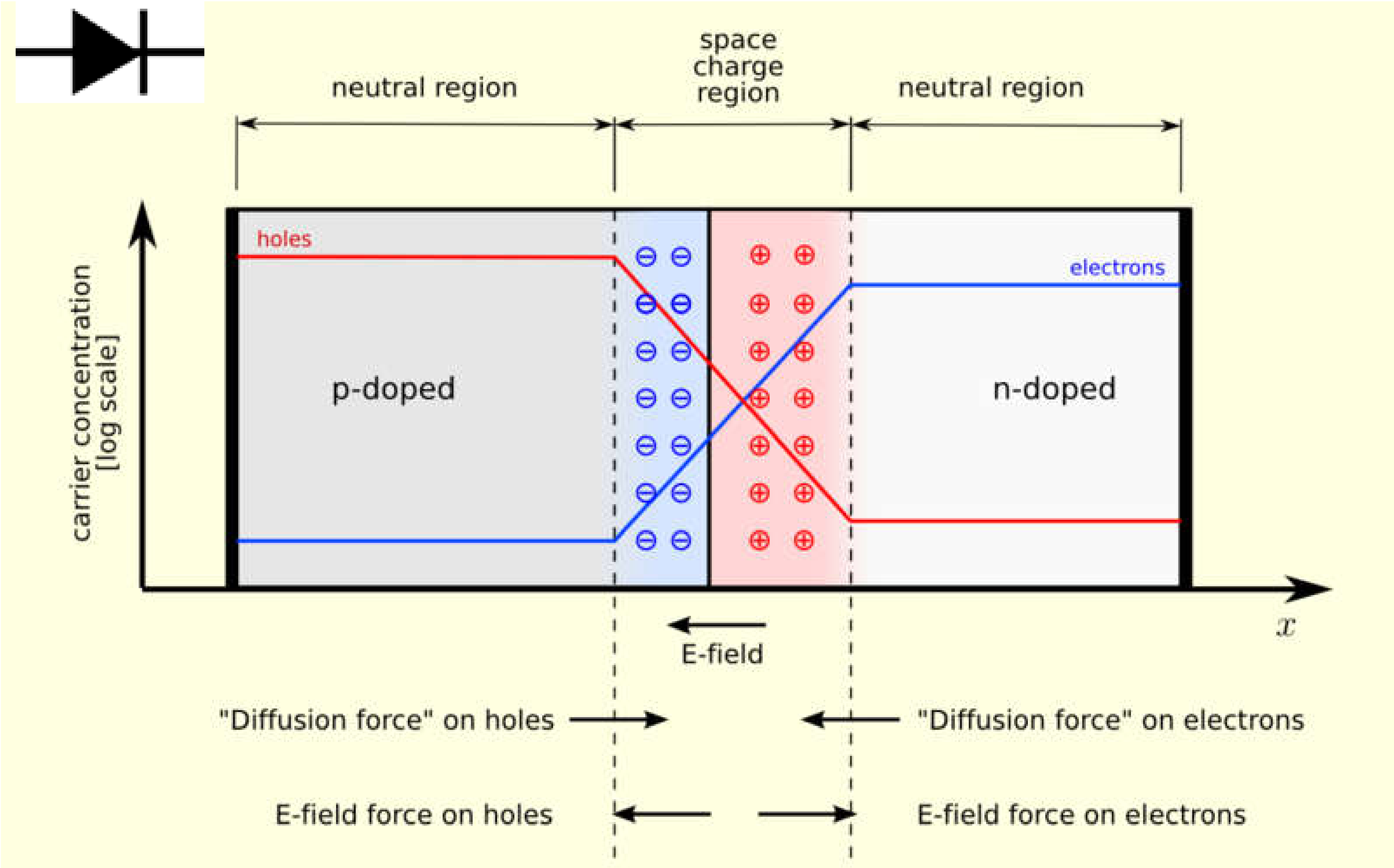
Example:

For a Si pn junction, if N_A = 1e18 cm^{-3}, N_D = 1e15 cm^{-3}, and n_i = 1.5e10 cm^{-3}, T = 300 K

$\rightarrow$ $$\boxed{V_{bi} = 0.75\ \mathrm{V}}$$

$$\boxed{qV_{bi} = 0.75\ \mathrm{eV}} < \boxed{E_g = 1.12\ \mathrm{eV}}$$

pn homojunction 同质结

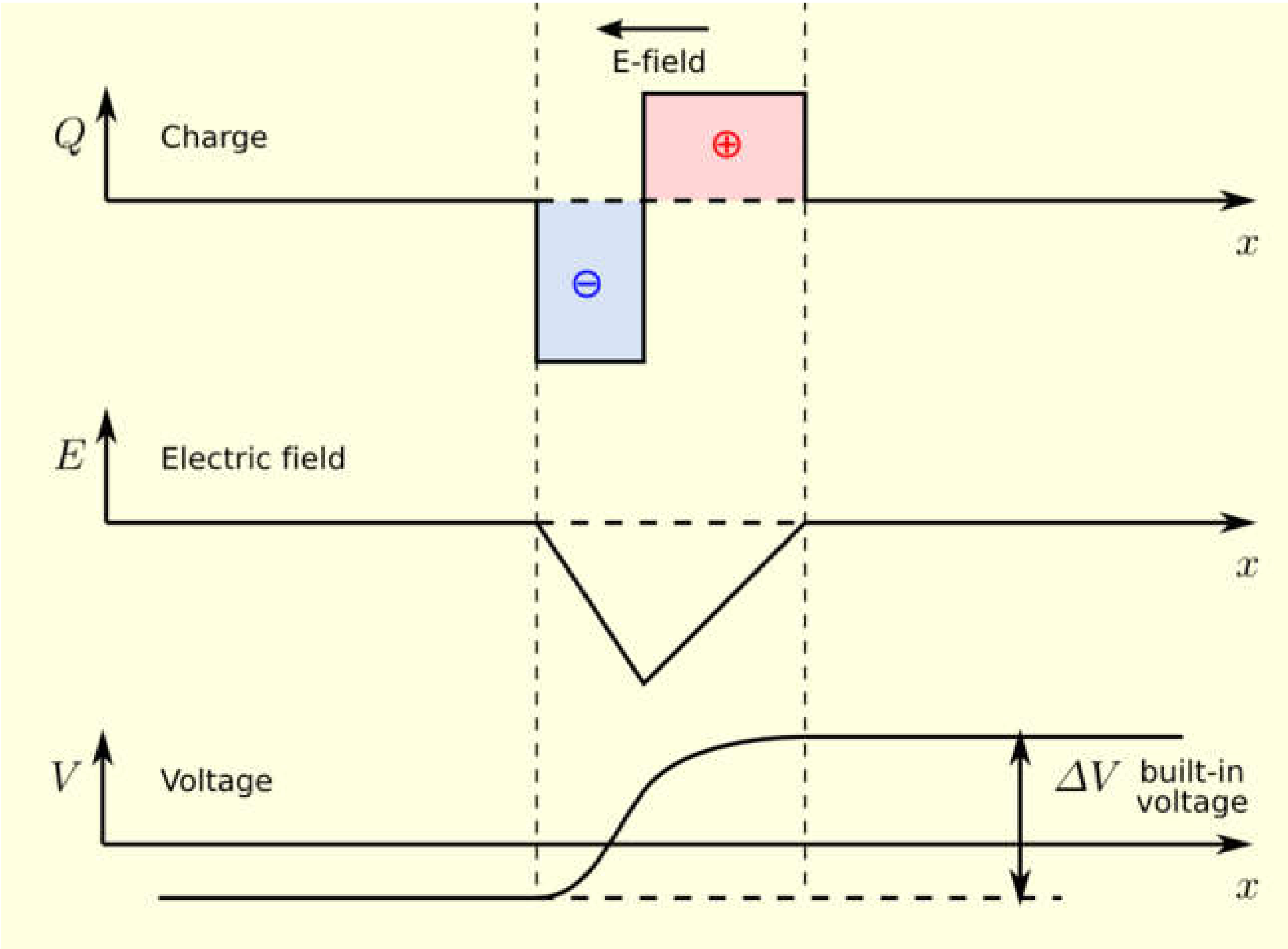


$$W = x_p + x_n$$

Q: How to calculate the depletion width W?

Full-depletion Approximation

Assume abrupt transition



$$N_A x_p = N_D x_n$$

$$\frac{\partial E}{\partial x} = \frac{e}{\varepsilon_s} n(x)$$

$$\frac{\partial V}{\partial x} = -E(x)$$

Full-depletion Approximation

Assume abrupt transition

$$V_{bi} = \frac{k_B T}{q} \cdot \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$N_A x_p = N_D x_n$$

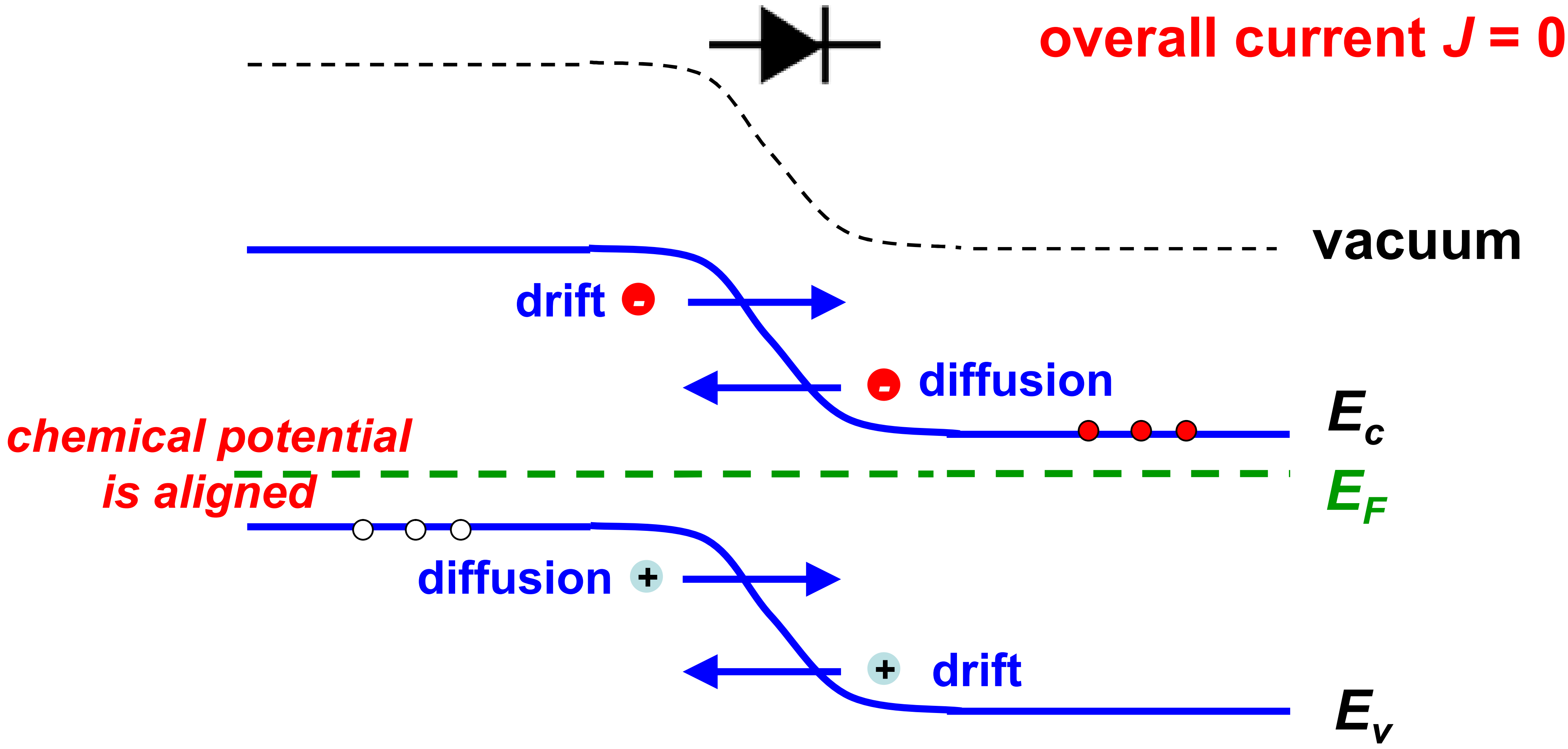
$$W = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_{bi}}$$

$$x_p = \frac{N_D}{N_A + N_D} W$$

$$x_n = \frac{N_A}{N_A + N_D} W$$

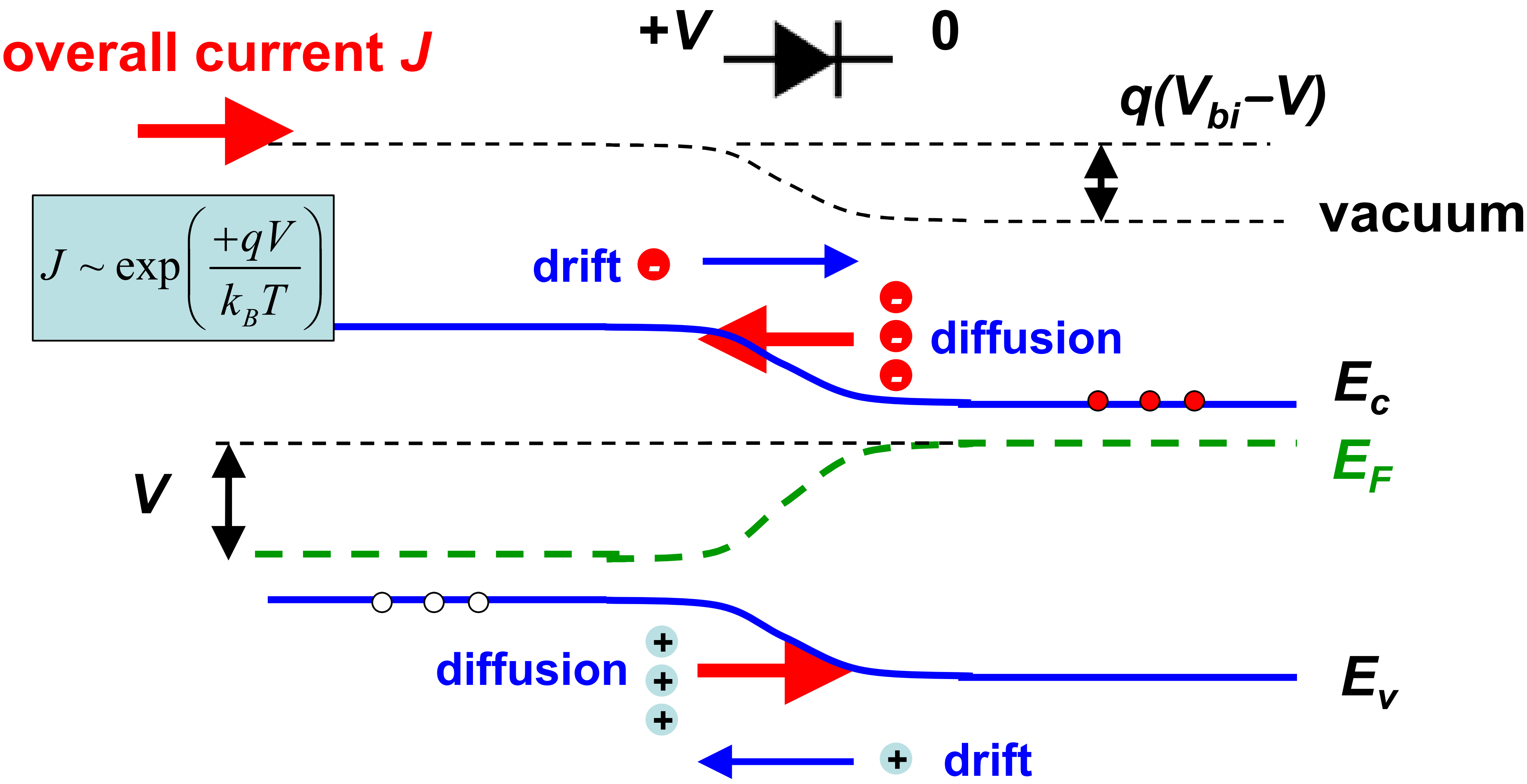
ε_s - dielectric constant / permittivity (F/m) 介电常数
q - electron charge 1.6×10^{-19} C

pn homojunction 同质结



at thermal equilibrium, carrier diffusion is balanced by drift caused by the built-in field. Overall current = 0

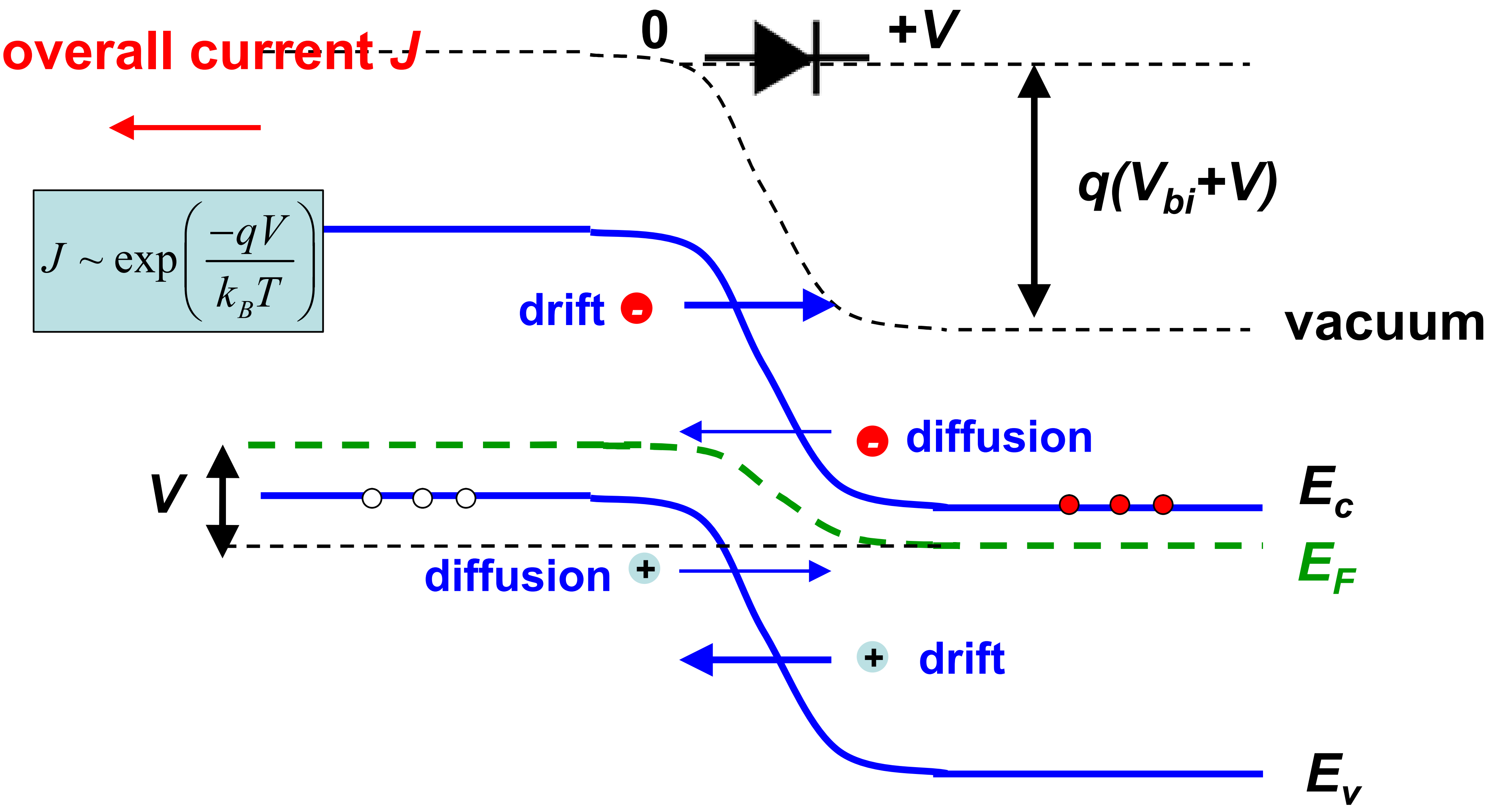
At Forward Bias (V > 0)



V_{bi} decreases by V, W decreases

much more diffusion current, the junction is conductive

At Reverse Bias ($V < 0$)



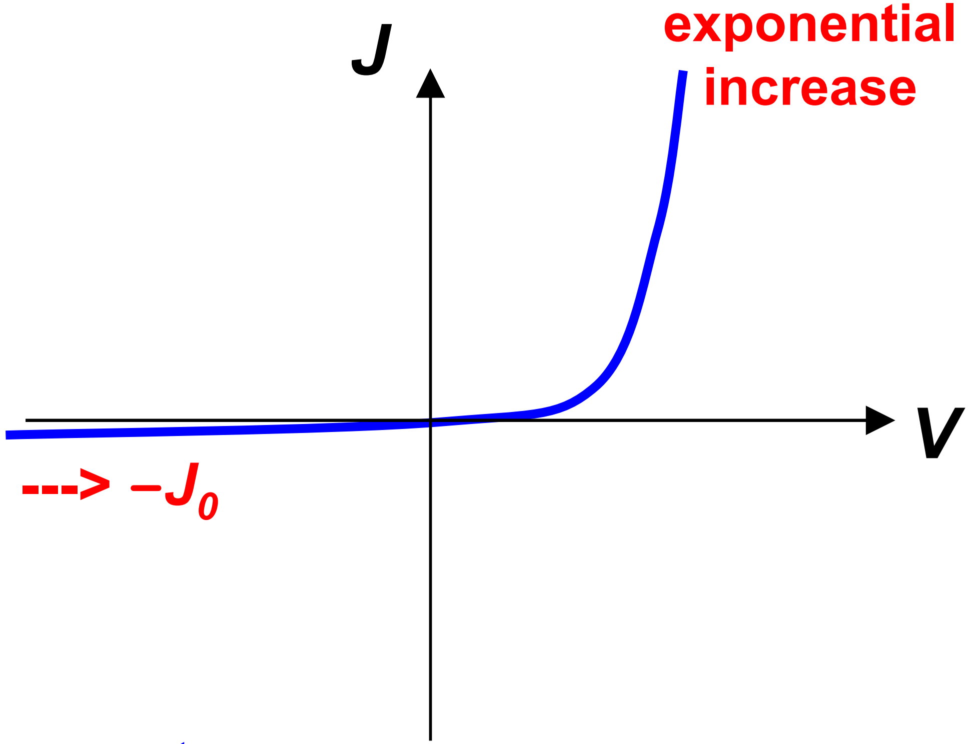
V_{bi} increases by V, W increases

little drift current, the junction is slightly conductive

Current-Voltage Relation

pn junction - diode 二极管

$$J = J_0\left[\exp\left(\frac{qV}{nk_BT}\right) - 1\right]$$



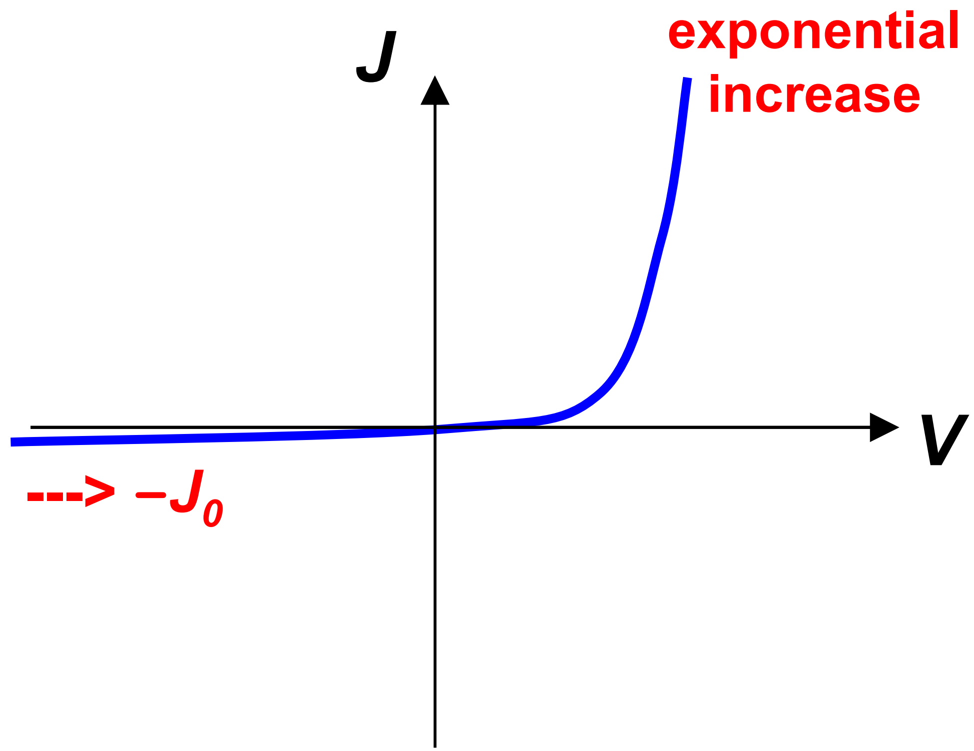
J_0 - dark/leakage/saturation current
depend on bandgap, defects, temperature, ...

n - ideality factor (for ideal case, n = 1)

Current-Voltage Relation

pn junction - diode 二极管

$$J = J_0 \left[\exp\left(\frac{qV}{nk_B T} \right) - 1 \right]$$



ideal diode model

$$J_0 = q \frac{D_n}{L_n} \frac{n_i^2}{N_A} + q \frac{D_p}{L_p} \frac{n_i^2}{N_D}$$

D **- diffusivity (m²/s) 扩散率**
τ **- carrier lifetime (s)**
L **- diffusion length (m)**

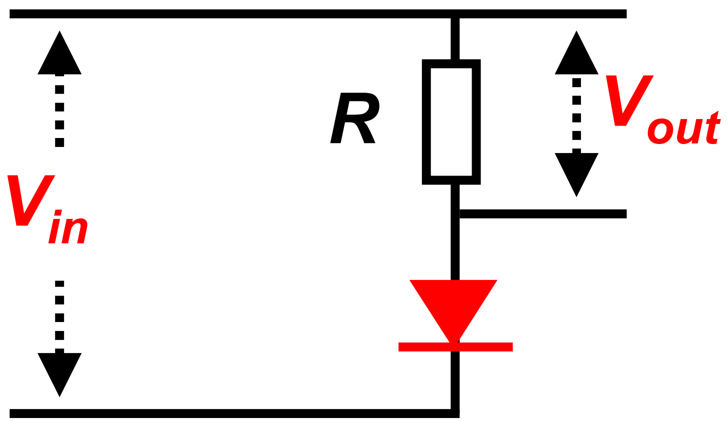
$$L = \sqrt{D\tau}$$

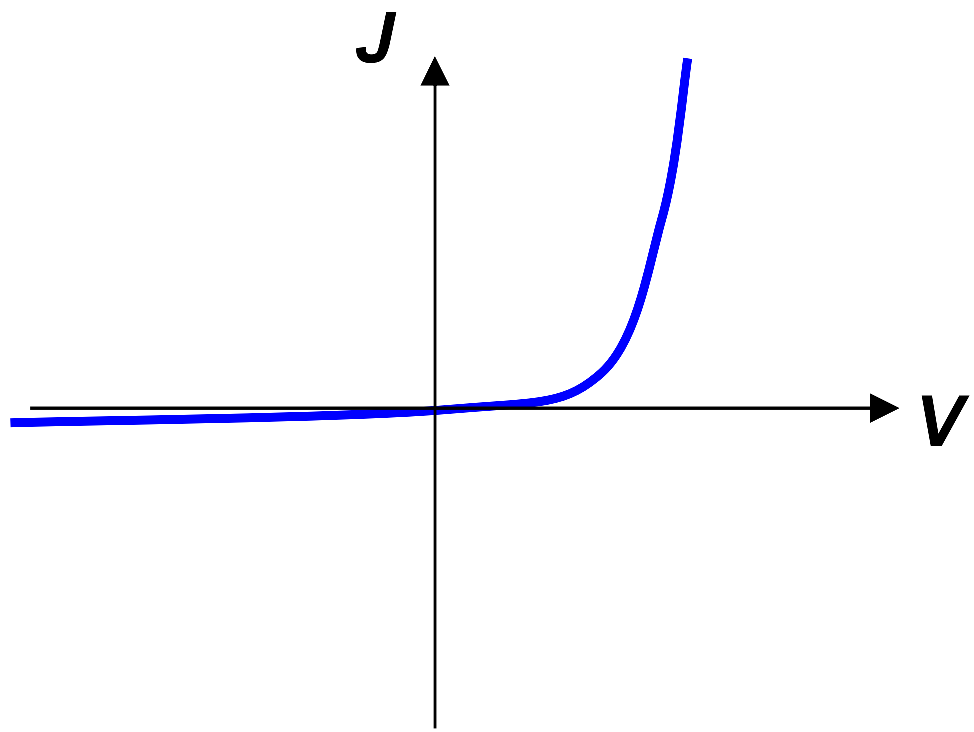
https://www.pveducation.org/pvcdrom/pn-junctions/example-1-general-solution-for-wide-base-p-n-junction

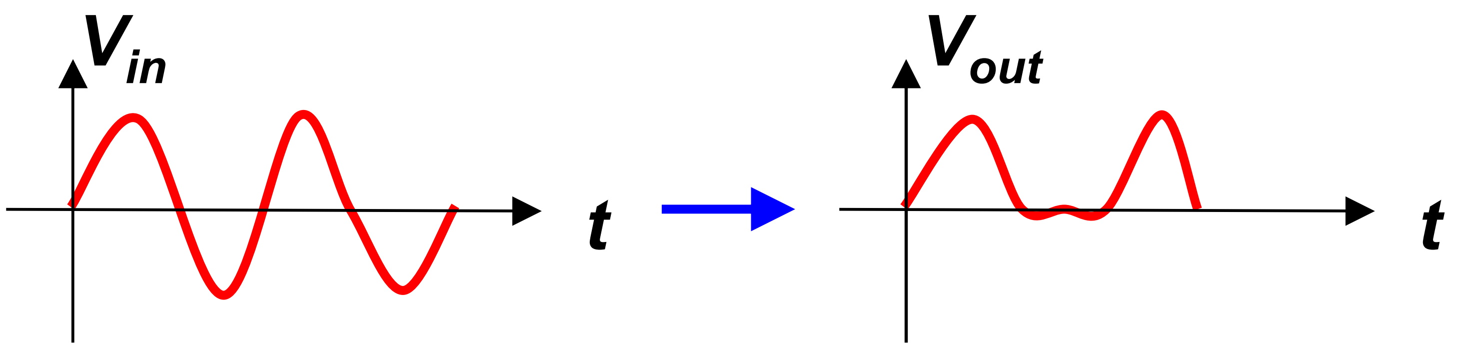
Current-Voltage Relation

pn junction - diode 二极管

rectifier 整流管



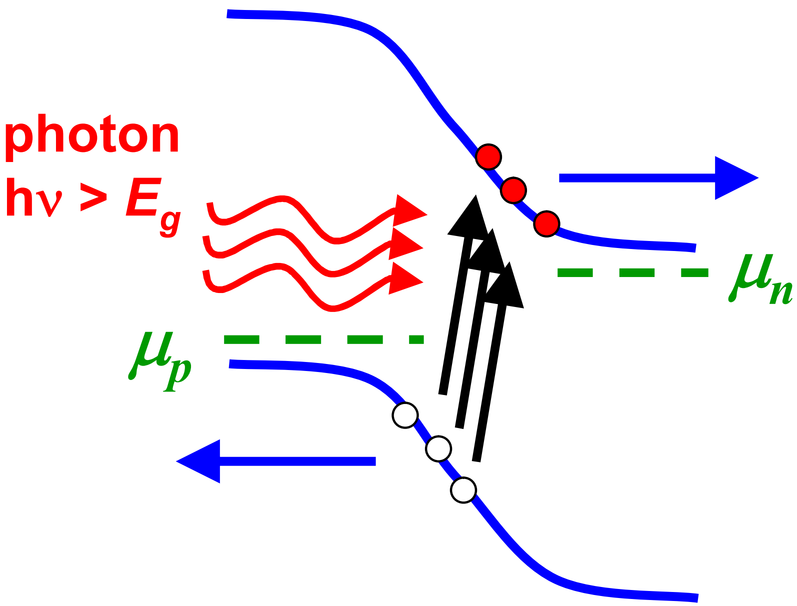


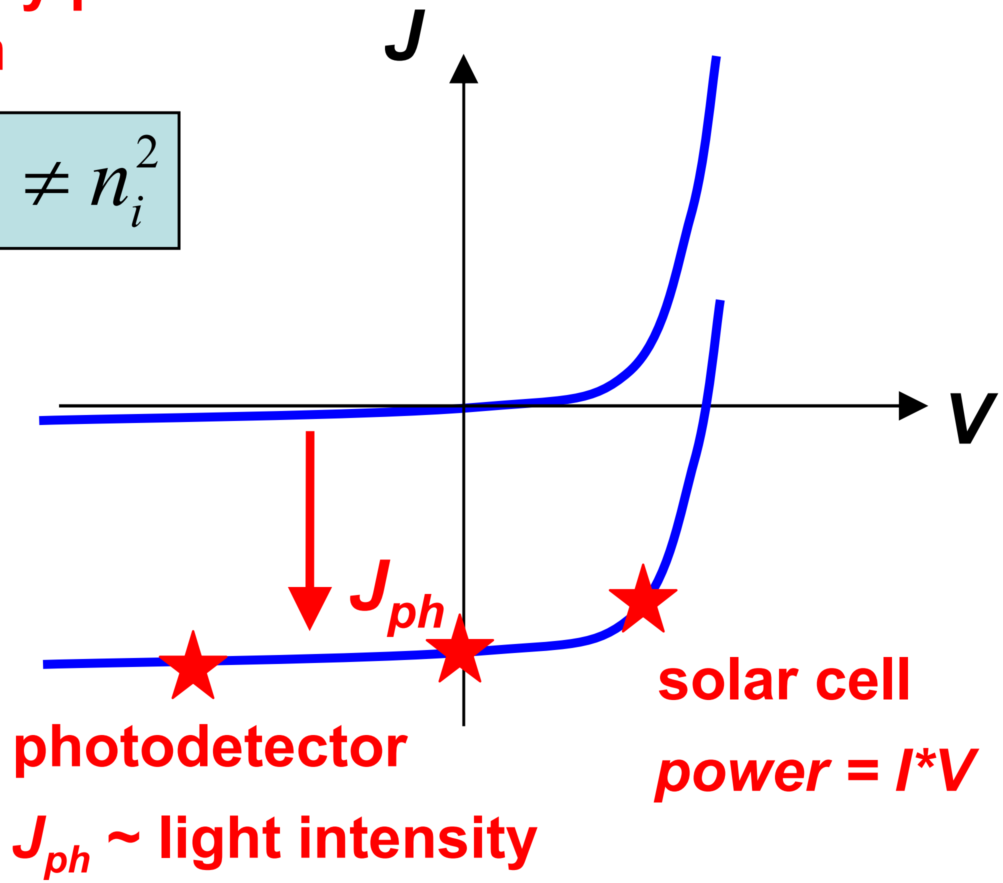


Solar Cell / Photodetector

extra carriers generated by photon
non-equilibrium

$$n_c p_v \neq n_i^2$$



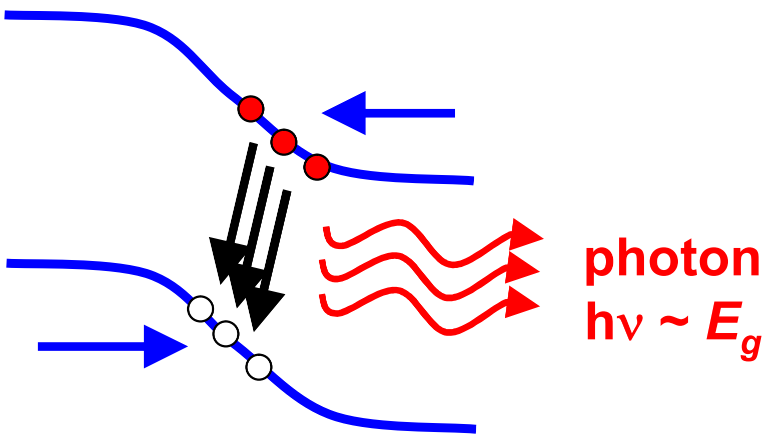


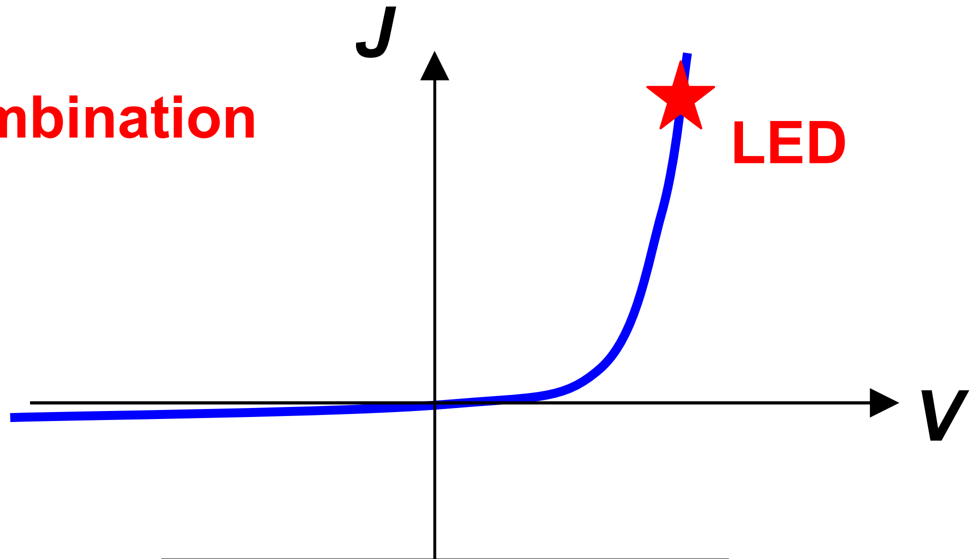
$$J = J_0\left[\exp\left(\frac{qV}{nk_BT}\right)-1\right]-J_{ph}$$

photocurrent

Light-Emitting Diode (LED)

at forward bias
photon generation by radiative recombination



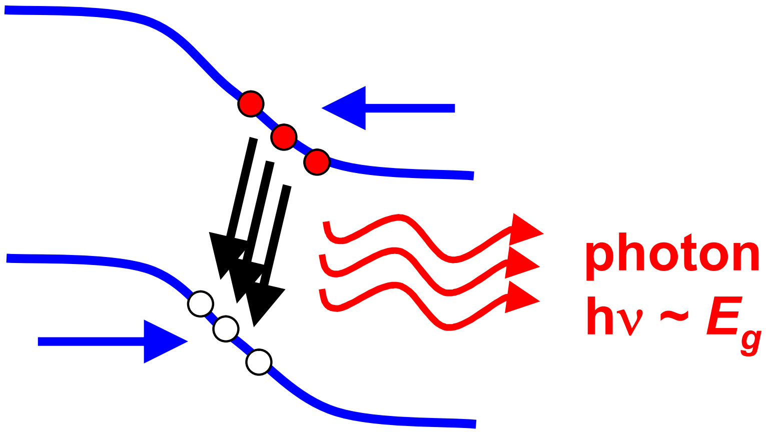


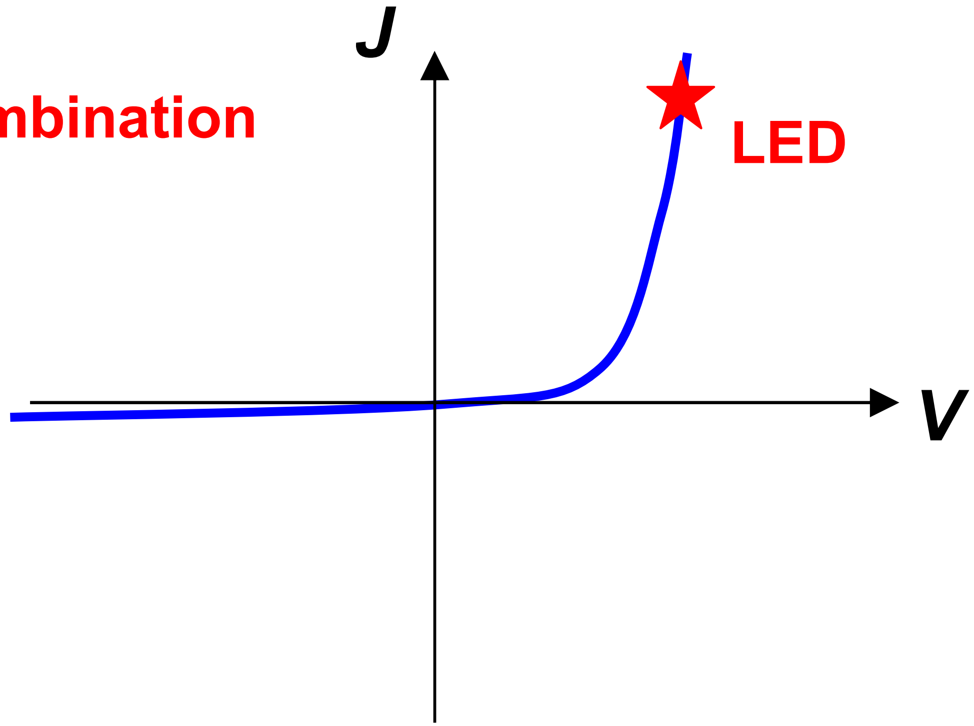
$$J = J_0 \left[\exp\left(\frac{qV}{nk_B T} \right) - 1 \right]$$

LEDs

Light-Emitting Diode (LED)

at forward bias
photon generation by radiative recombination





$$J = J_0\left[\exp\left(\frac{qV}{nk_BT}\right) - 1\right]$$

$$\text{optical power} = J \cdot \eta$$

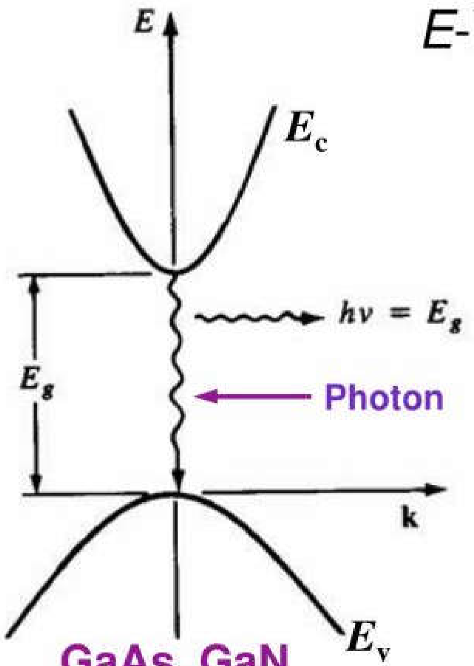
η - conversion efficiency

η < 100%, because of non-radiative recombination (generating heat)

Light Emission Efficiency

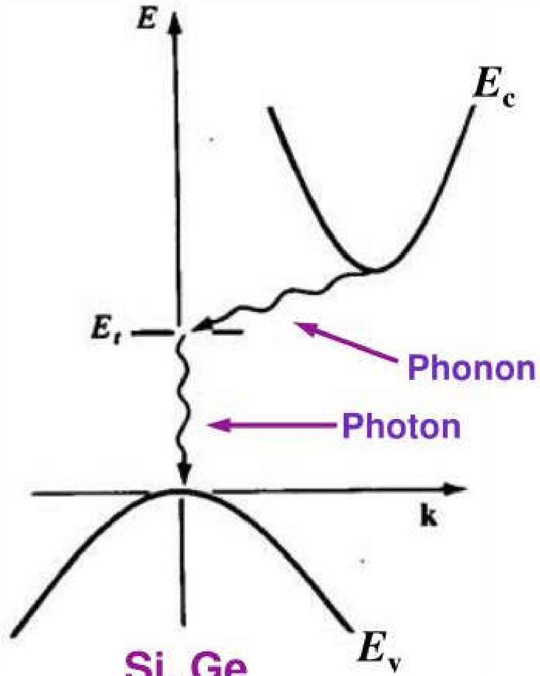
E-**k** Diagrams

radiative recombination



GaAs, GaN
(direct semiconductors)

- Little change in momentum is required for recombination
- Momentum is conserved by photon (light) emission



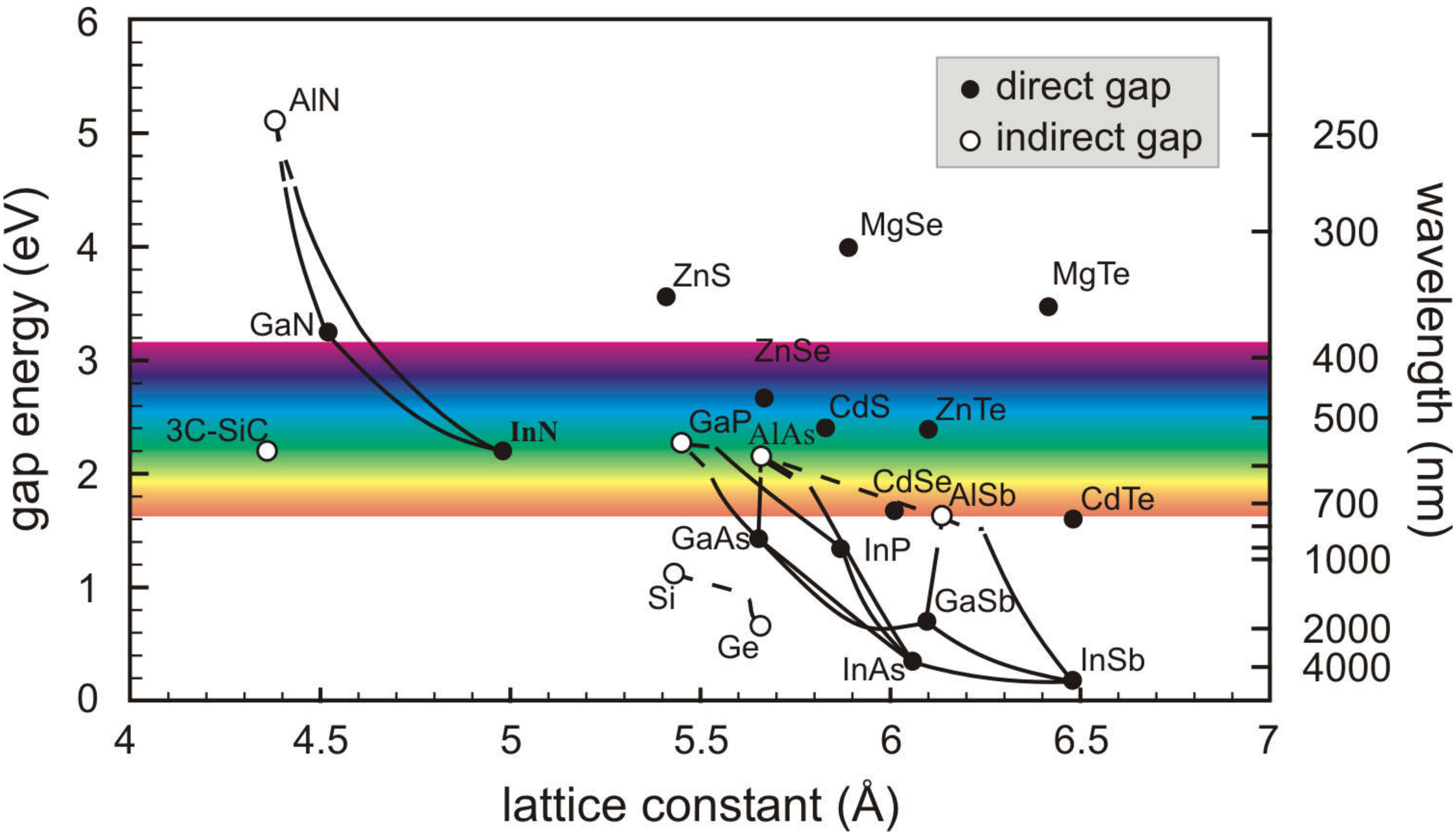
Si, Ge
(indirect semiconductors)

- Large change in momentum is required for recombination
- Momentum is conserved by mainly phonon (vibration) emission + photon emission

Direct bandgap semiconductors like GaAs, GaN are more suitable for LEDs and lasers, more radiative recombinations

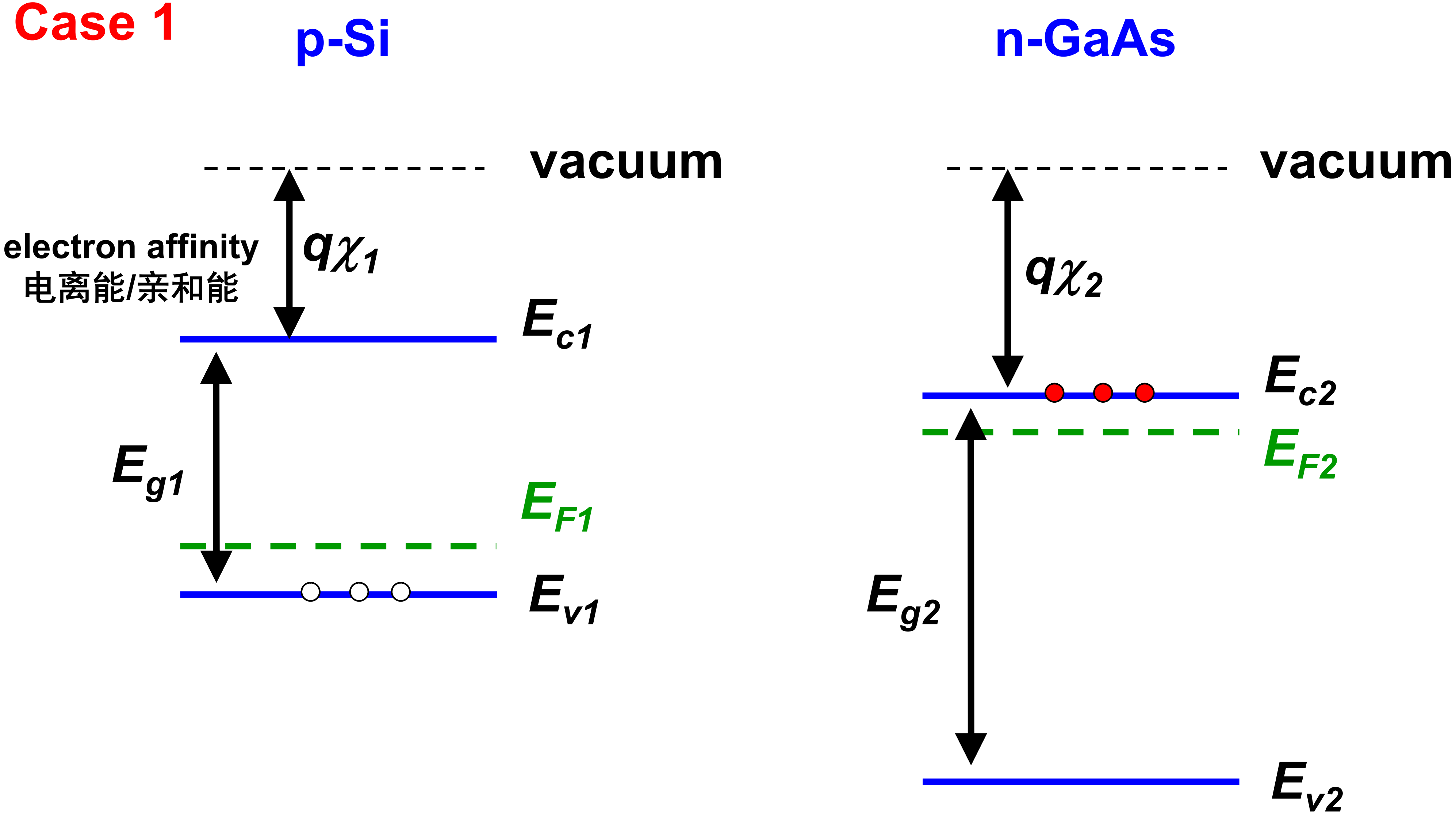
Indirect bandgap semiconductors like Si, Ge do not emit light efficiently more non-radiative recombinations

Materials Choices for Light Emission



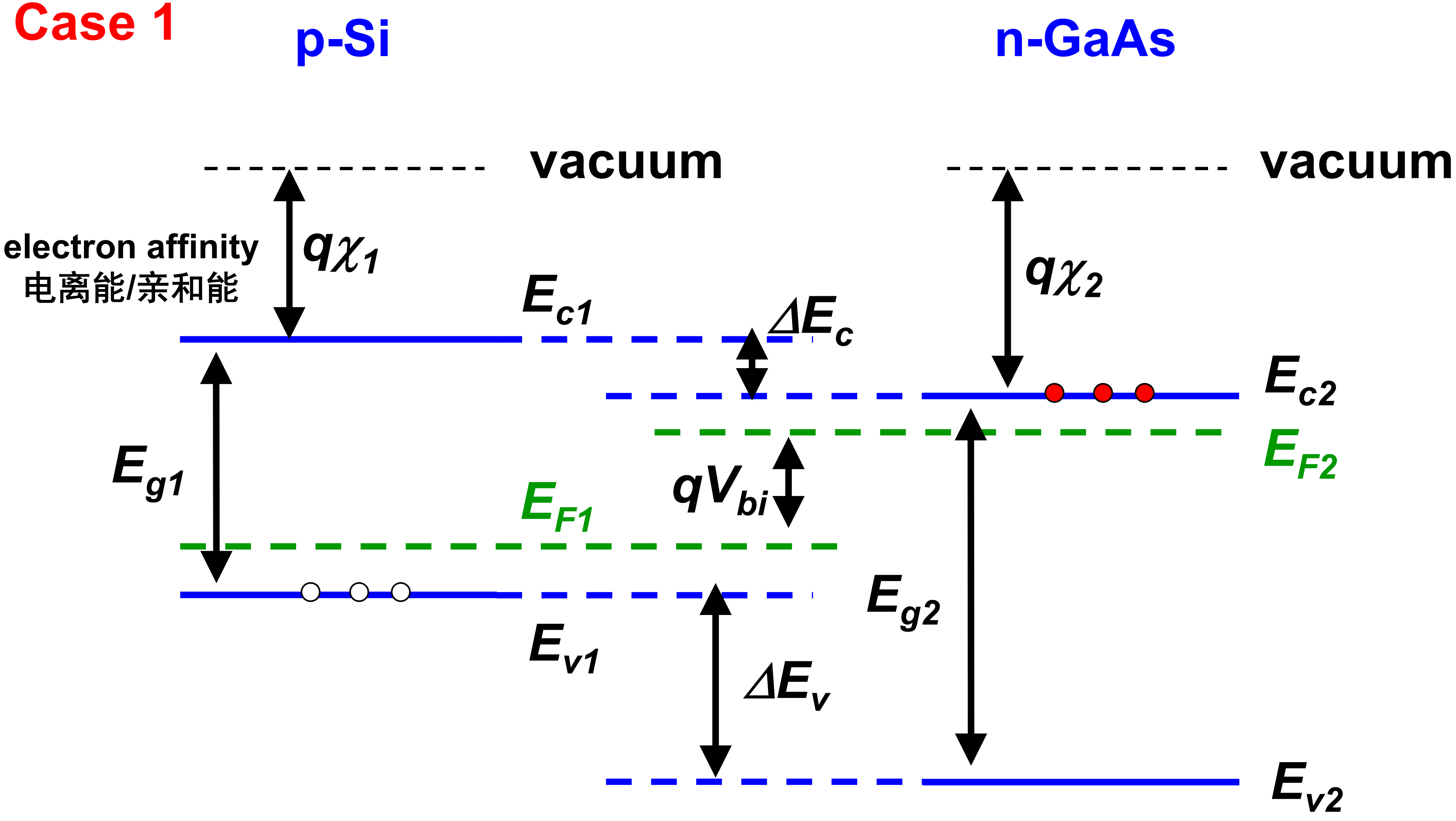
Heterojunction 异质结

Case 1



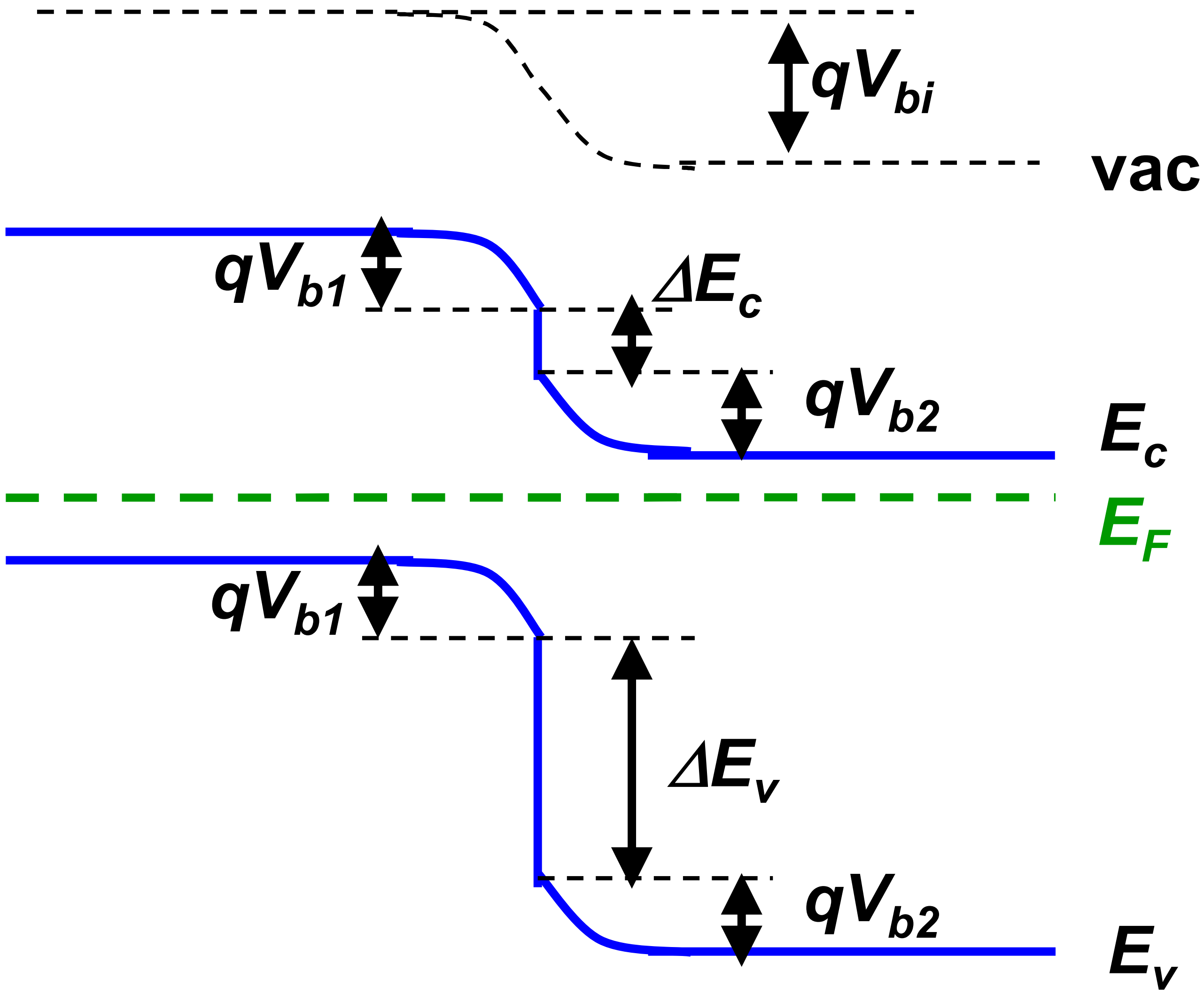
Heterojunction 异质结

Case 1



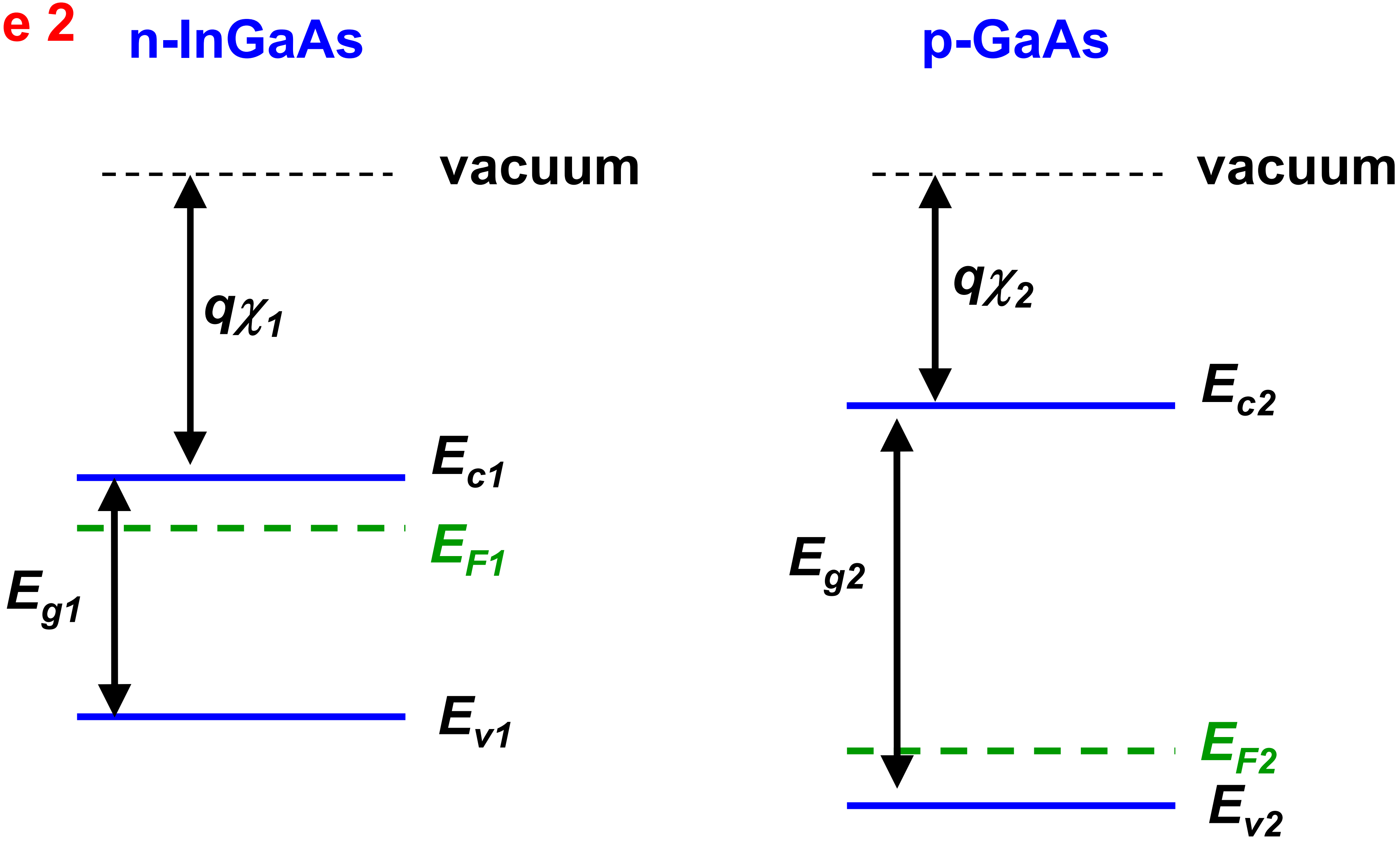
Heterojunction 异质结

Case 1



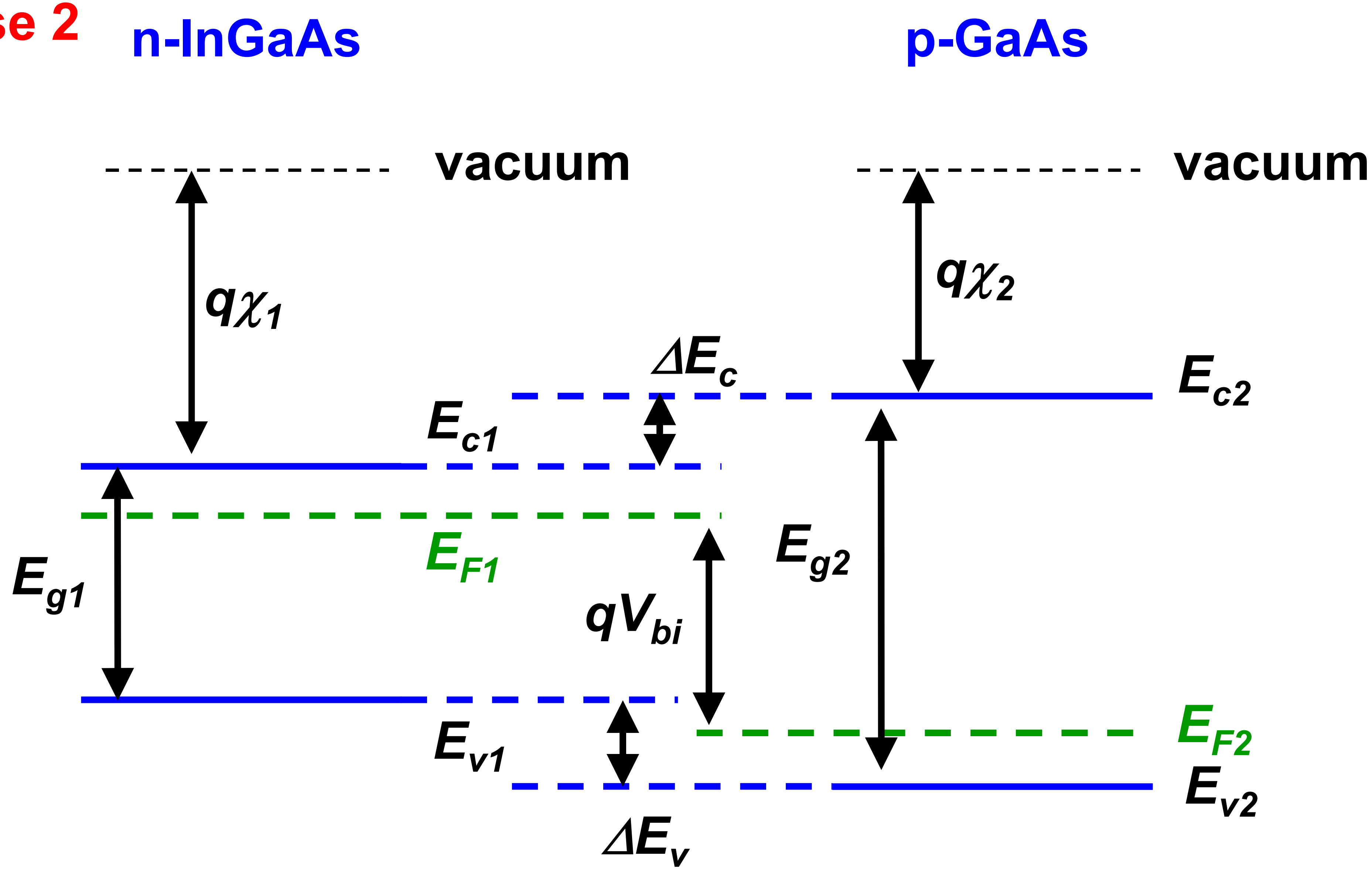
Heterojunction 异质结

Case 2



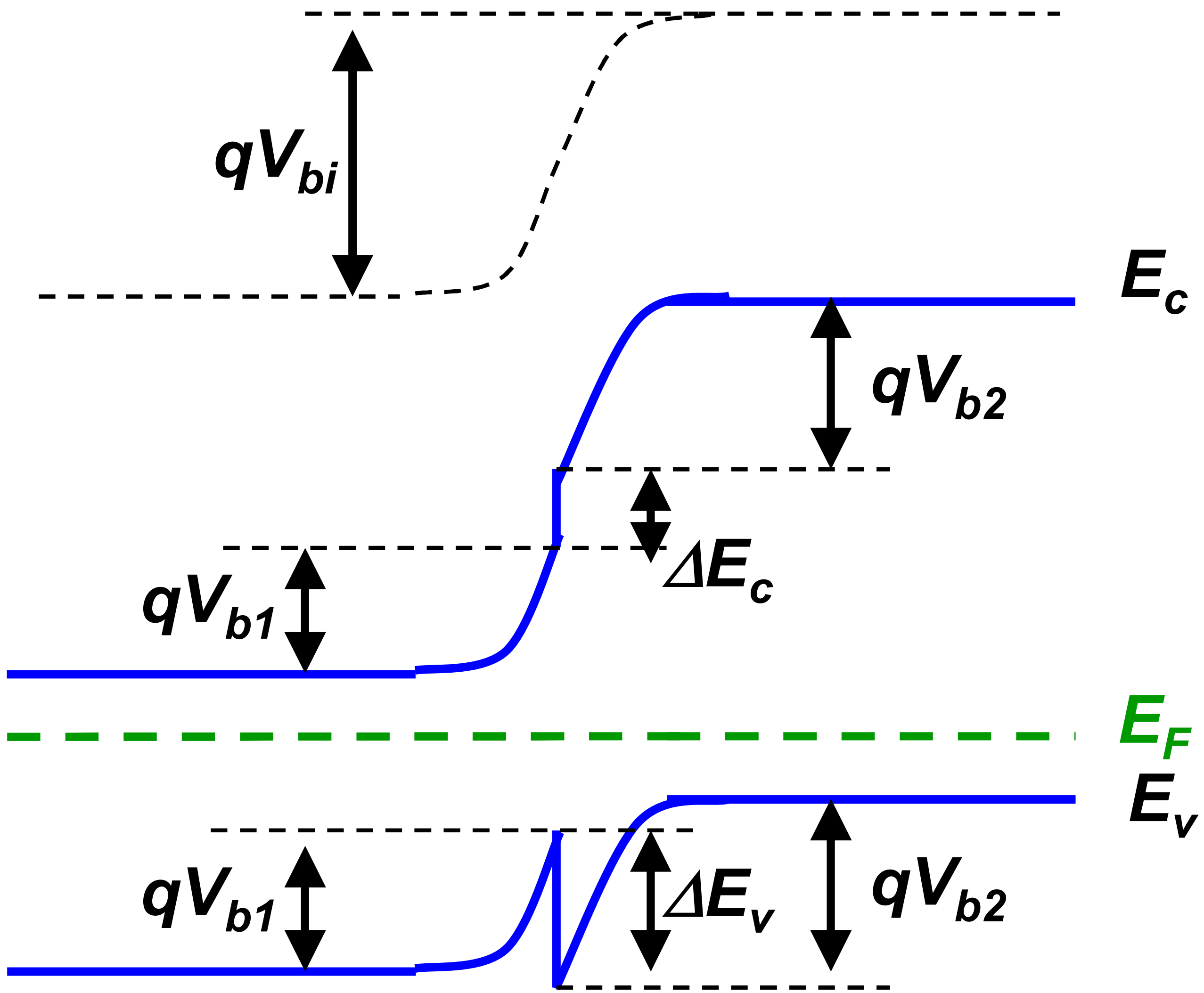
Heterojunction 异质结

Case 2

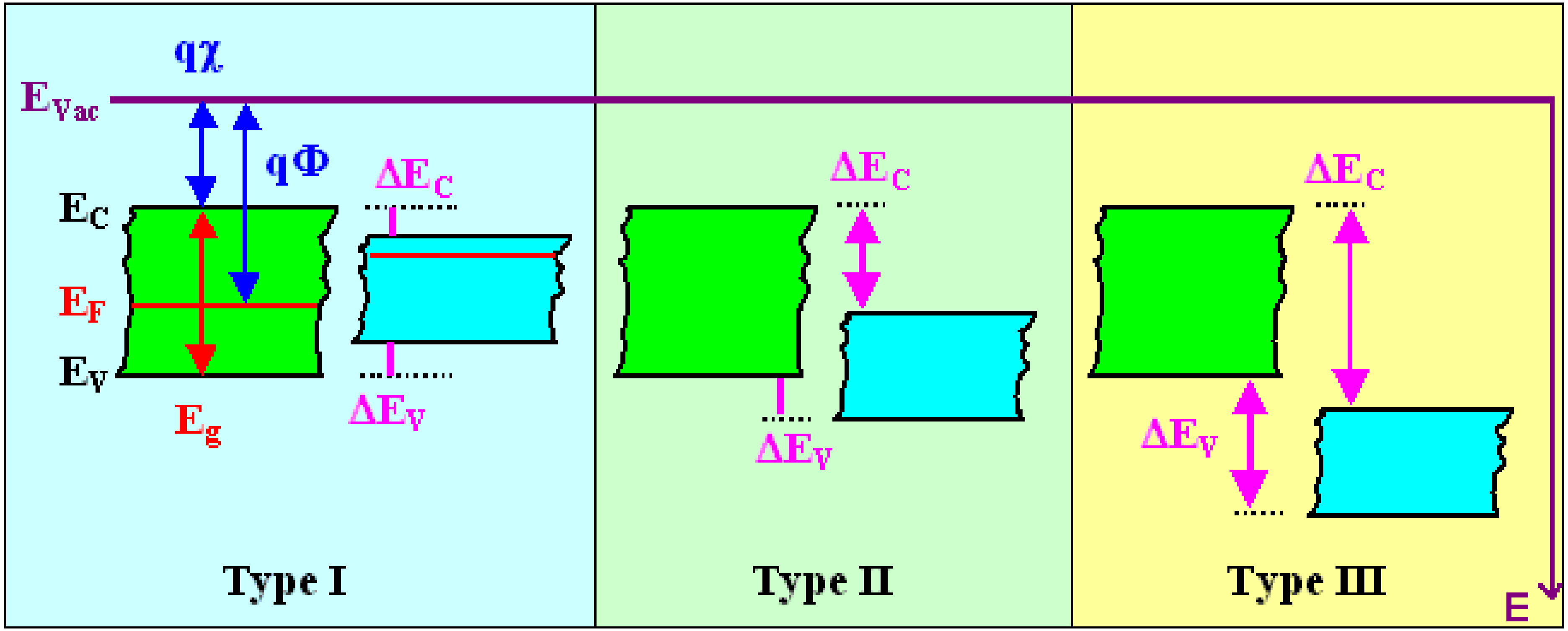


Heterojunction 异质结

Case 2

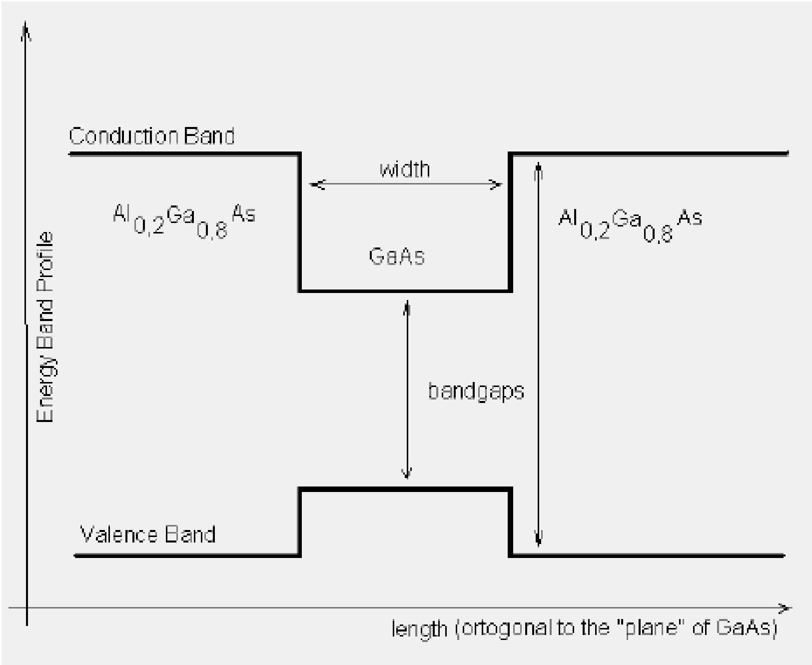


Heterojunction 异质结

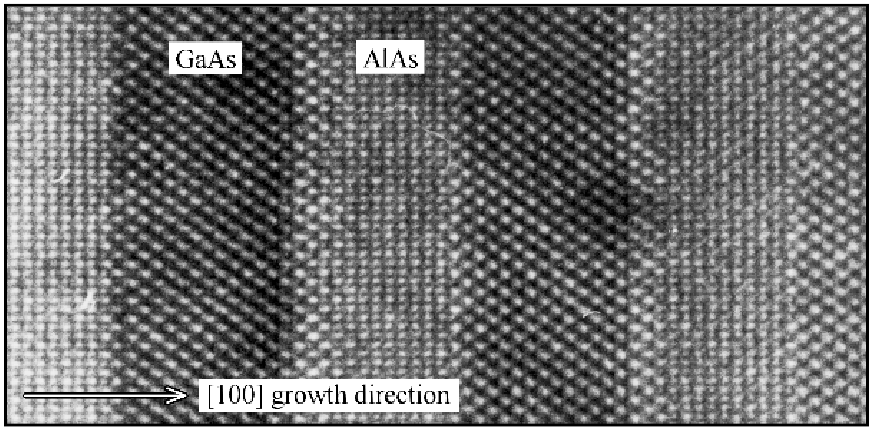


Straddling Gap **Staggered Gap** **Broken Gap**

Semiconductor Heterostructures



GaAs/AlGaAs heterostructure:
Type I junction
electron and hole confinement
enhanced radiative recombination
for better LEDs and lasers



Z. I. Alferov

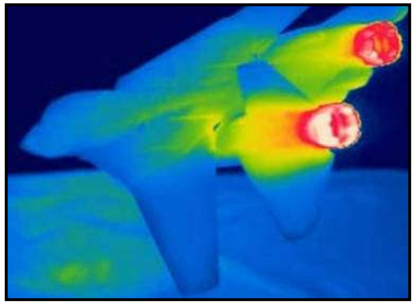
H. Kroemer

2000 Nobel Prize in Physics

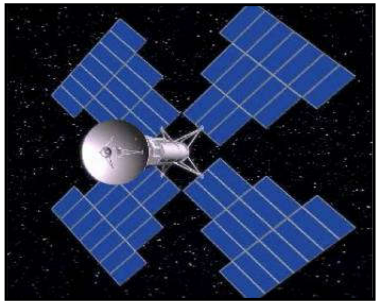
Optoelectronic Devices

LEDs

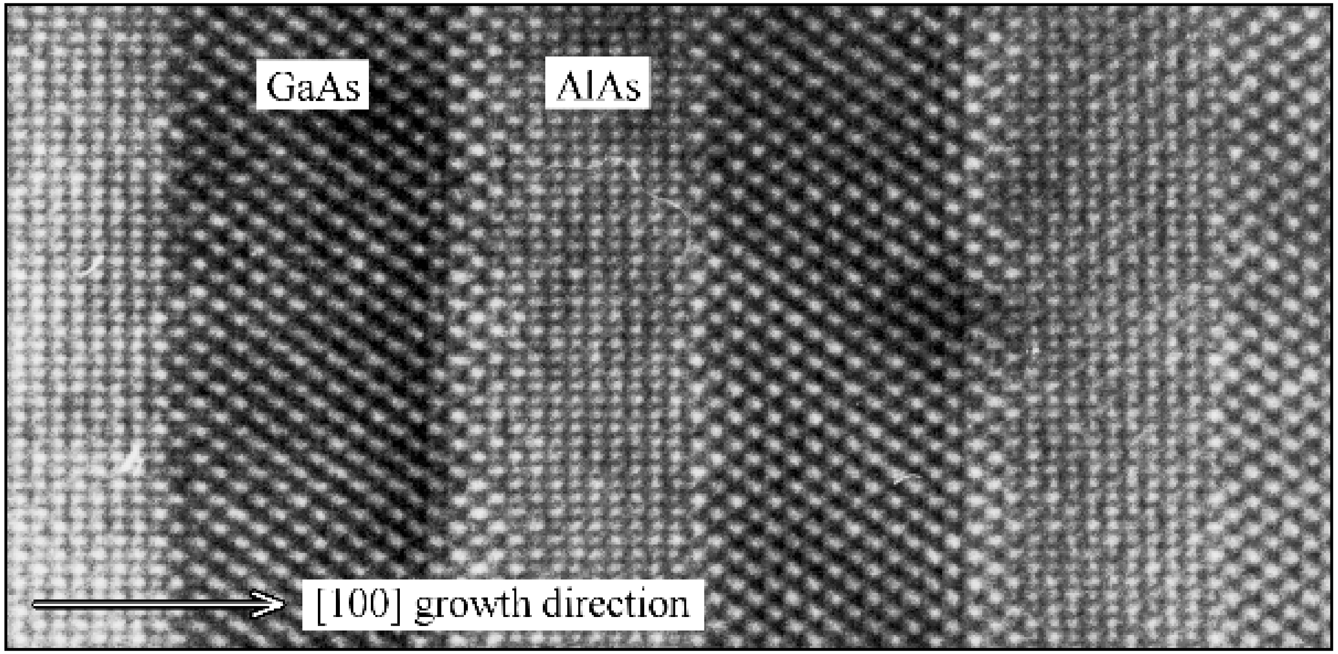
lasers



IR imaging

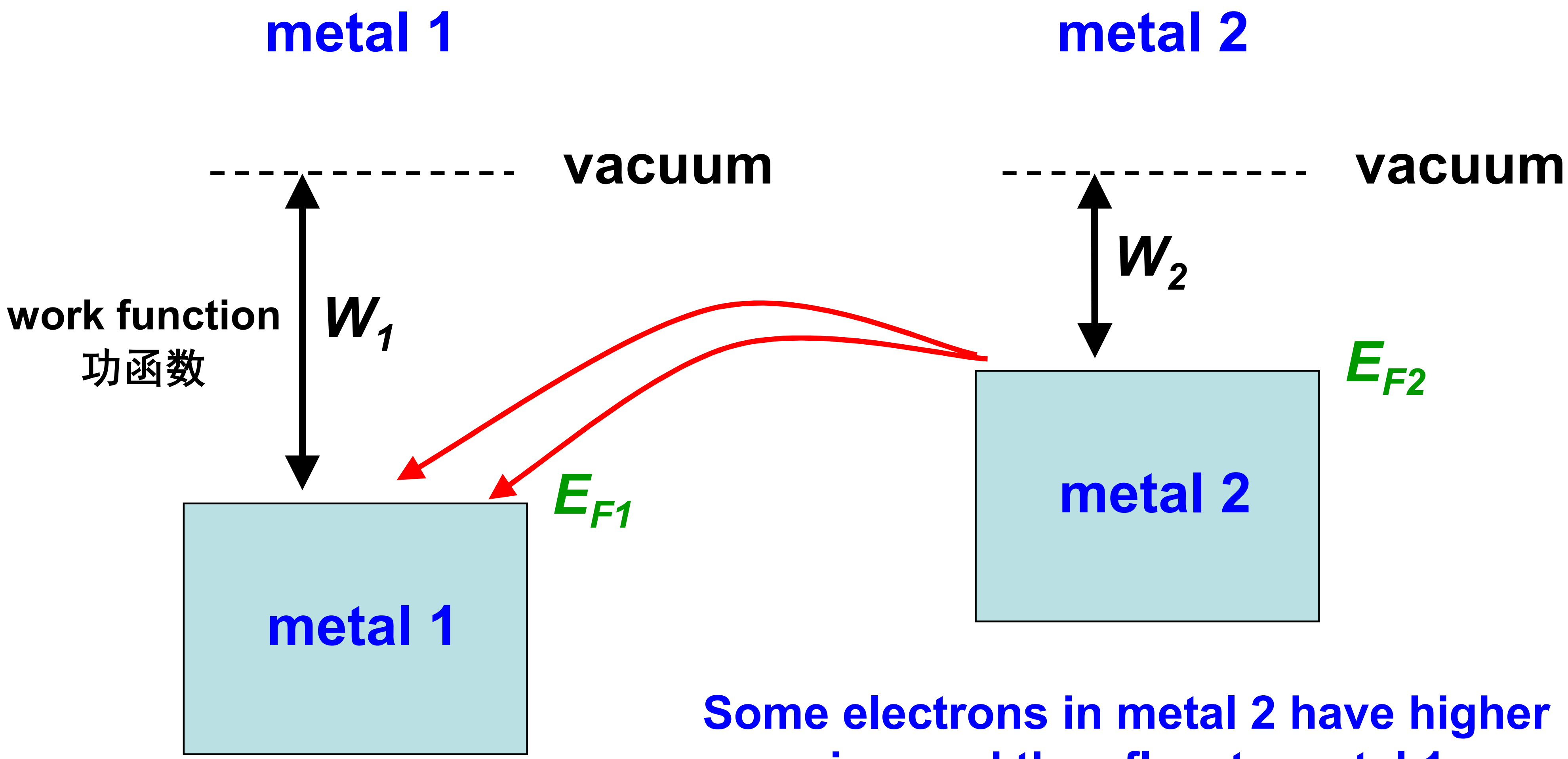


solar cells



Lattice matched GaAs/AlAs structure - perfect interface

Metal-Metal Junction

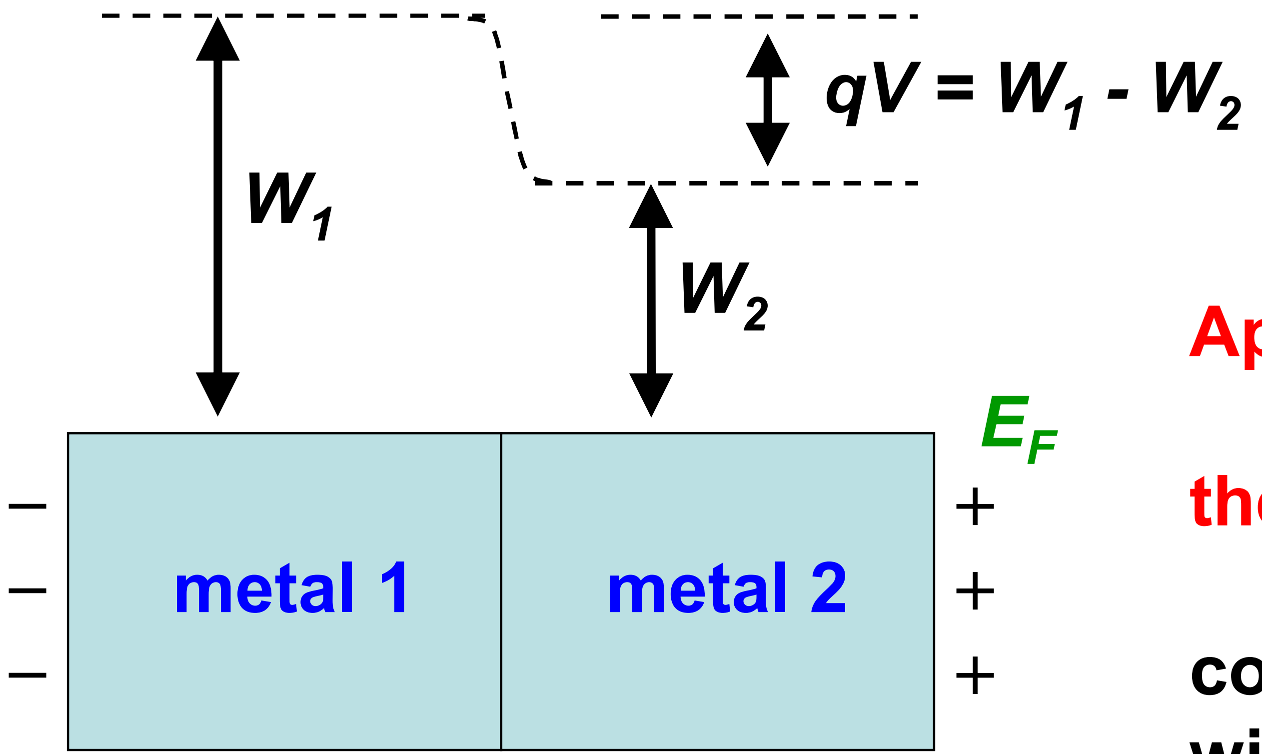


Some electrons in metal 2 have higher energies, and they flow to metal 1

metal 2 becomes more positive

Metal-Metal Junction

contact voltage (接触势)



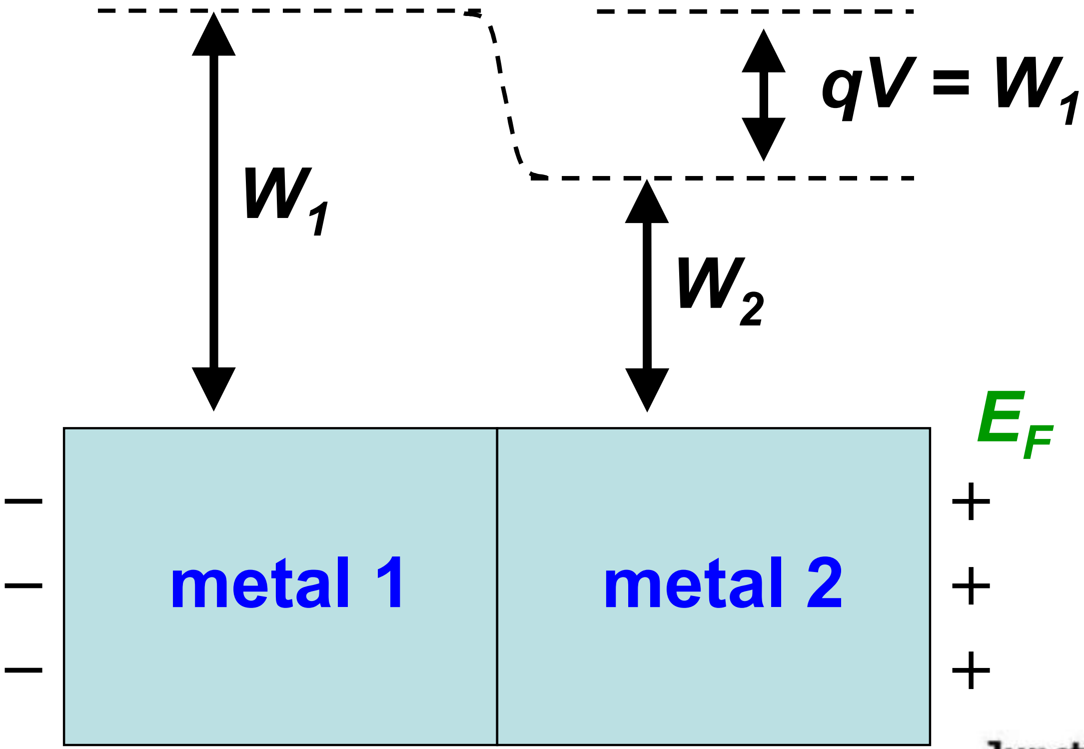
Application:

thermal couple 热电偶

contact voltage changes with temperature

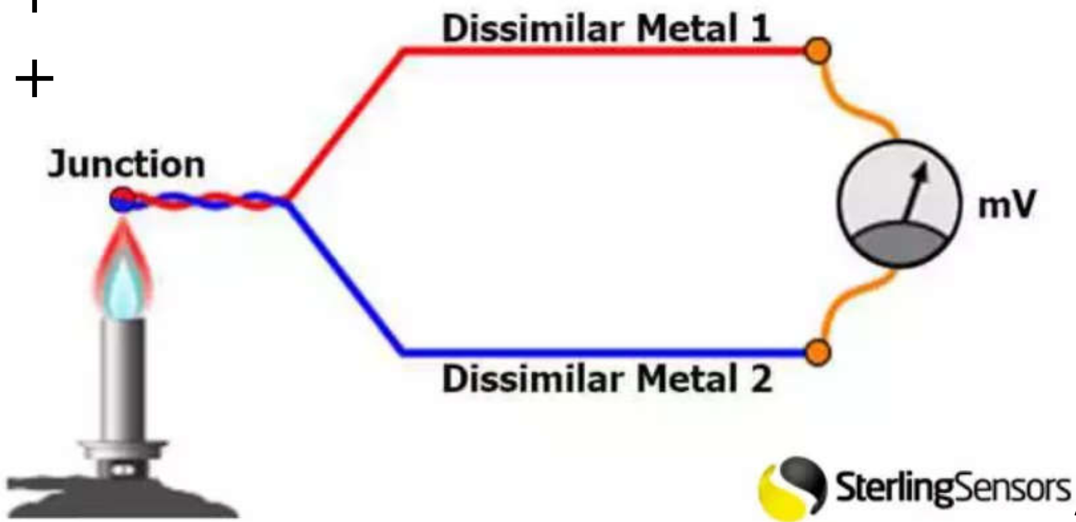
Metal-Metal Junction

contact voltage (接触势)



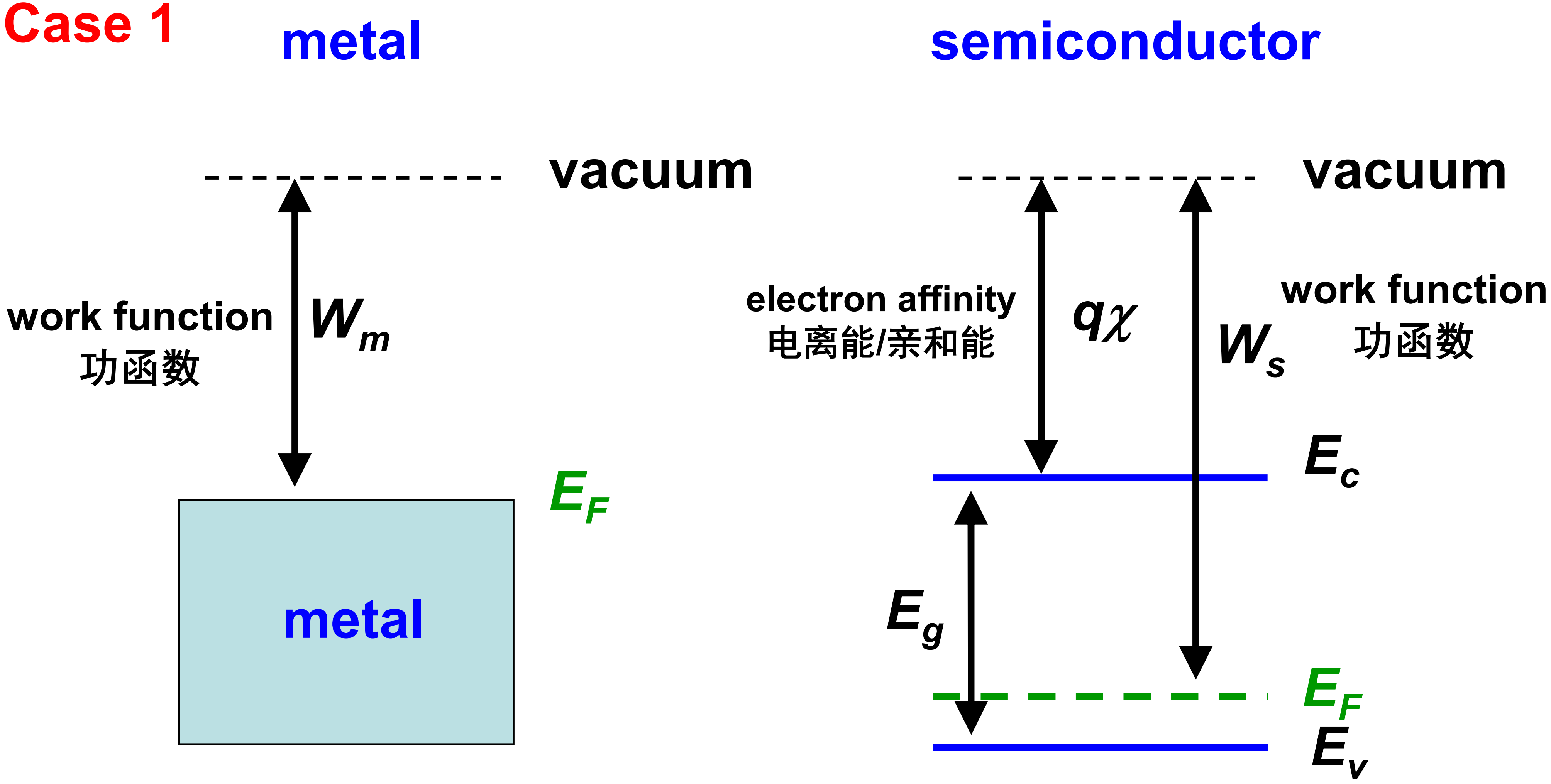
Application:

thermal couple 热电偶



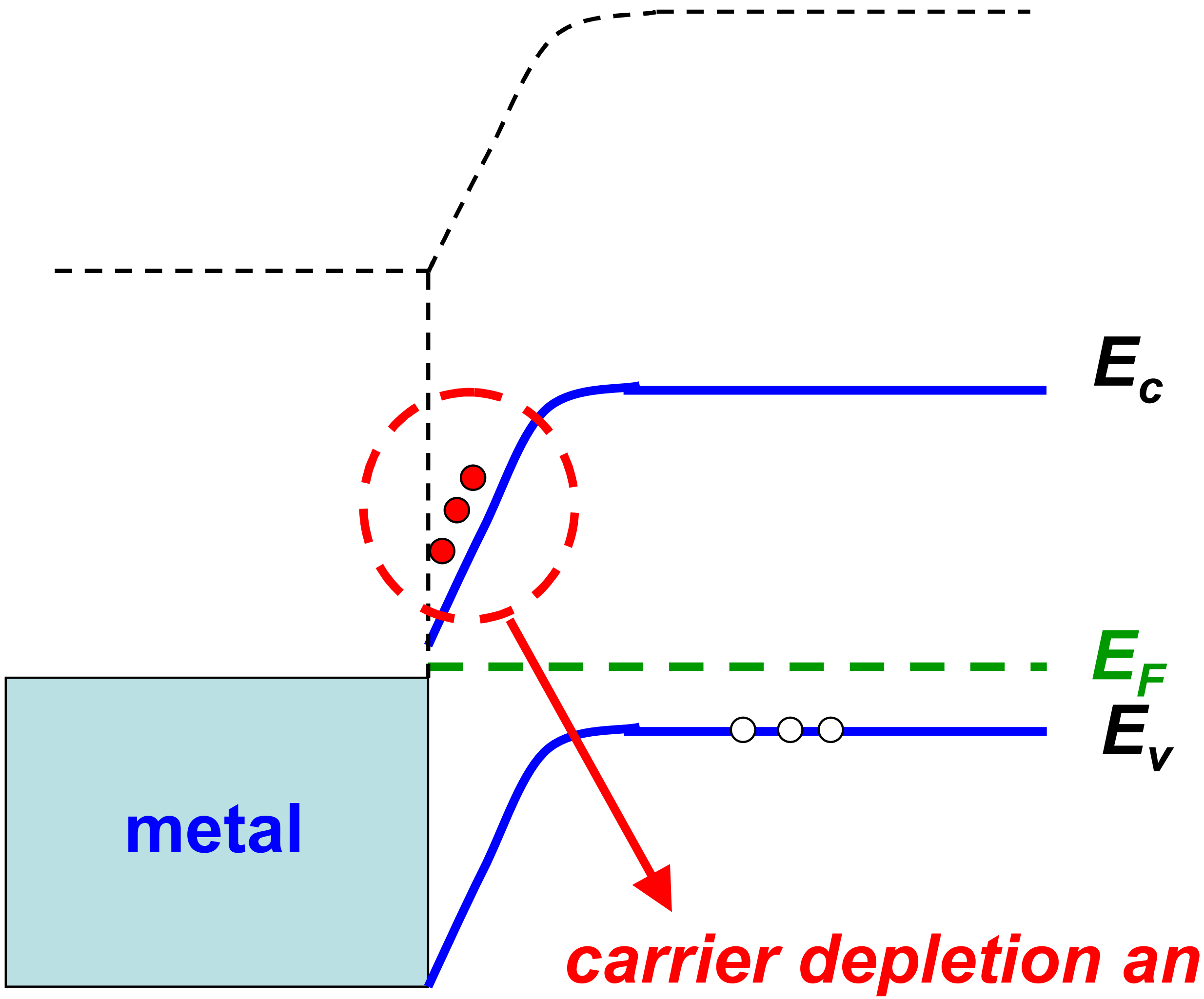
Metal-Semiconductor Junction

Case 1



Metal-Semiconductor Junction

Case 1 **Schottky contact 肖特基接触**

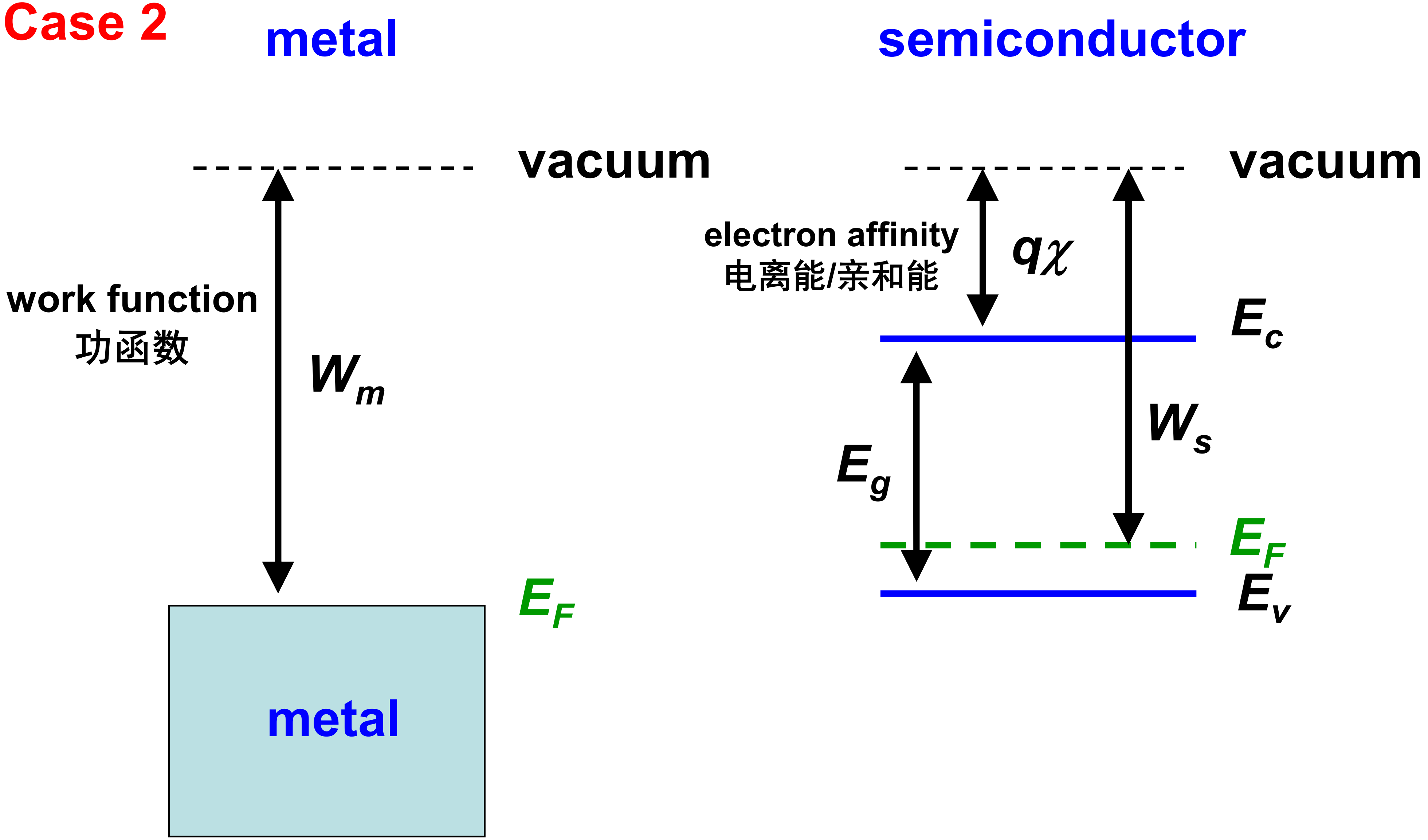


carrier depletion and inversion

(behave like a pn junction)

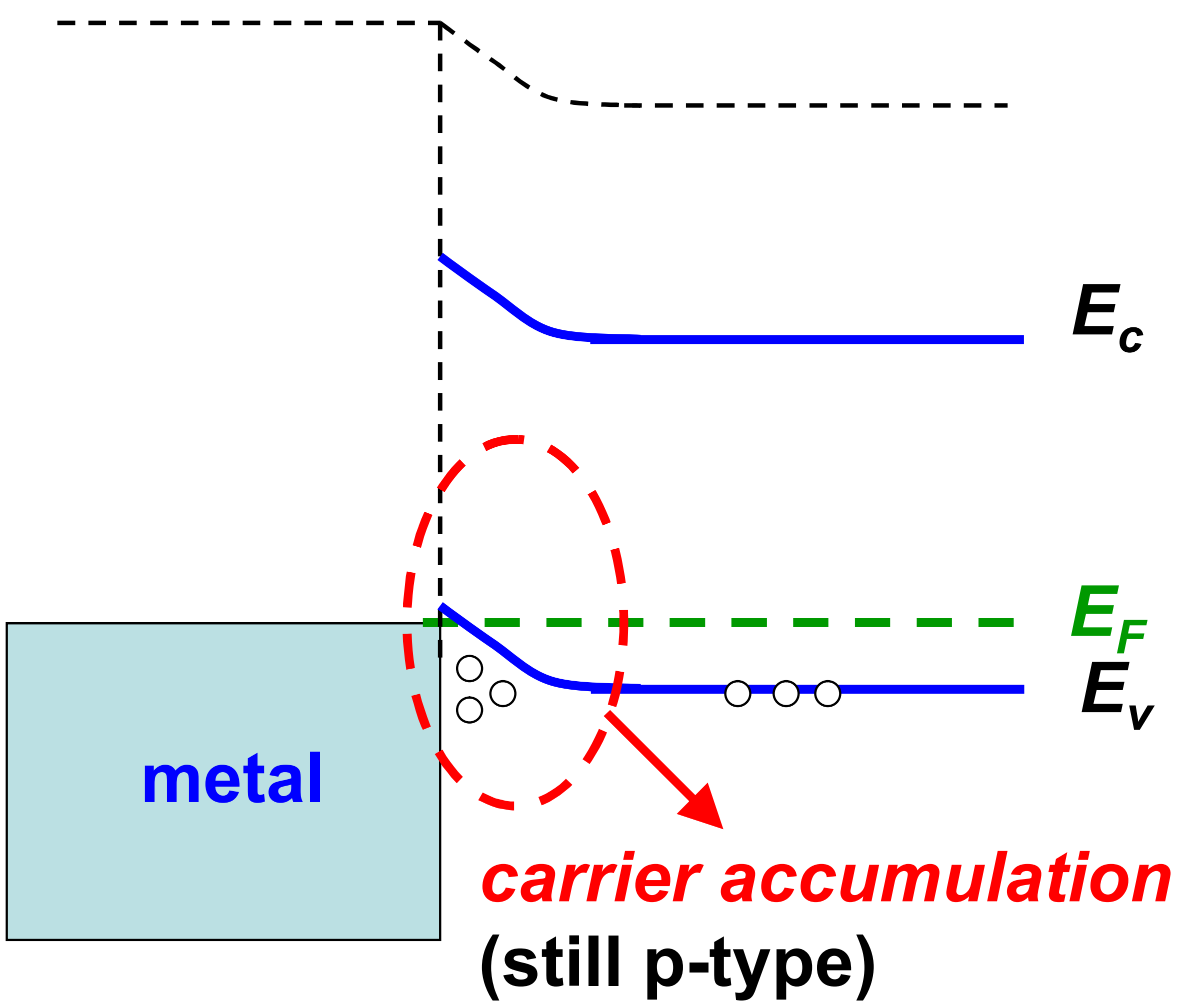
Metal-Semiconductor Junction

Case 2



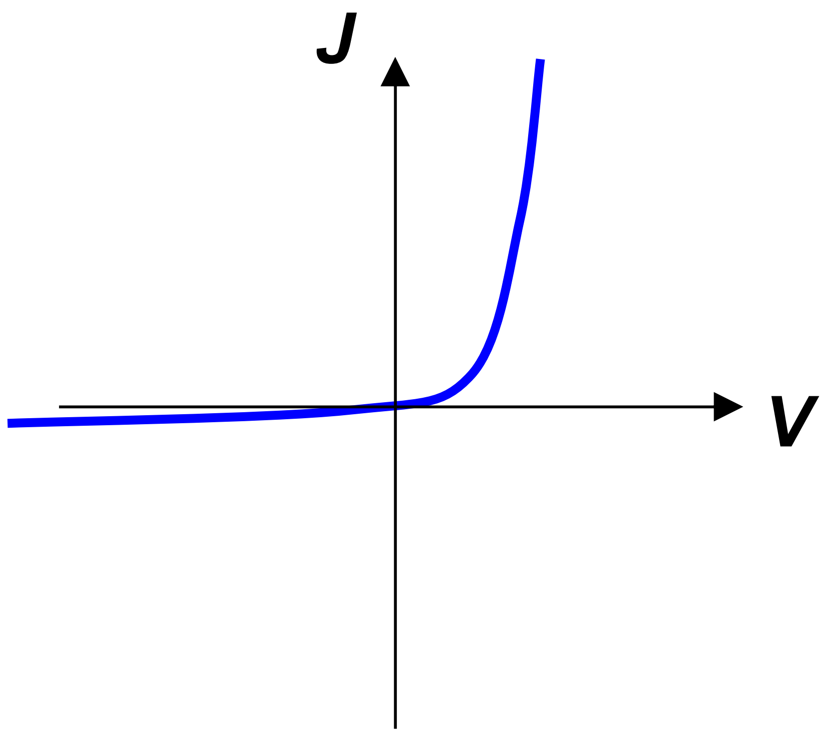
Metal-Semiconductor Junction

Case 2 **Ohm contact 欧姆接触**

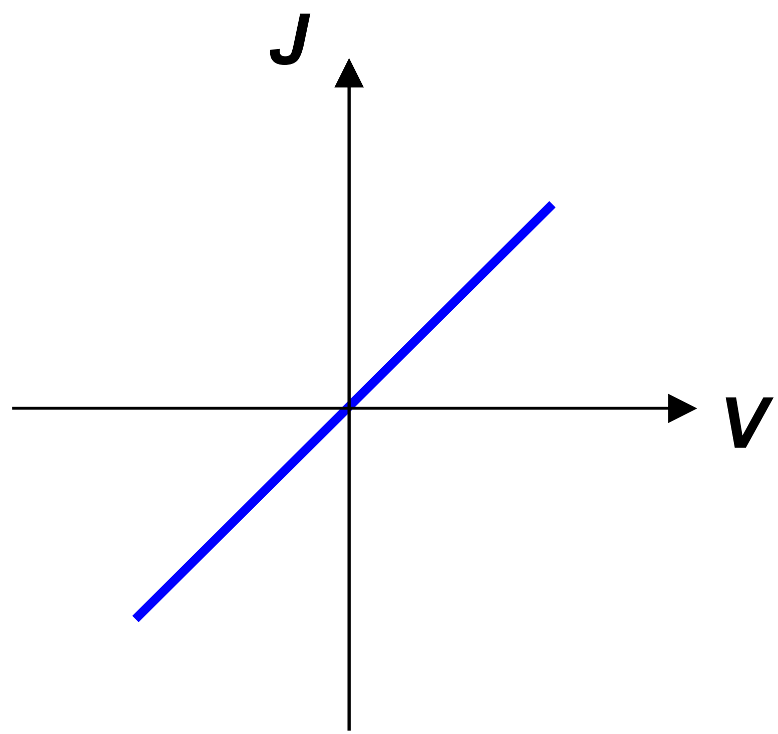


Metal-Semiconductor Junction

Schottky contact 肖特基接触

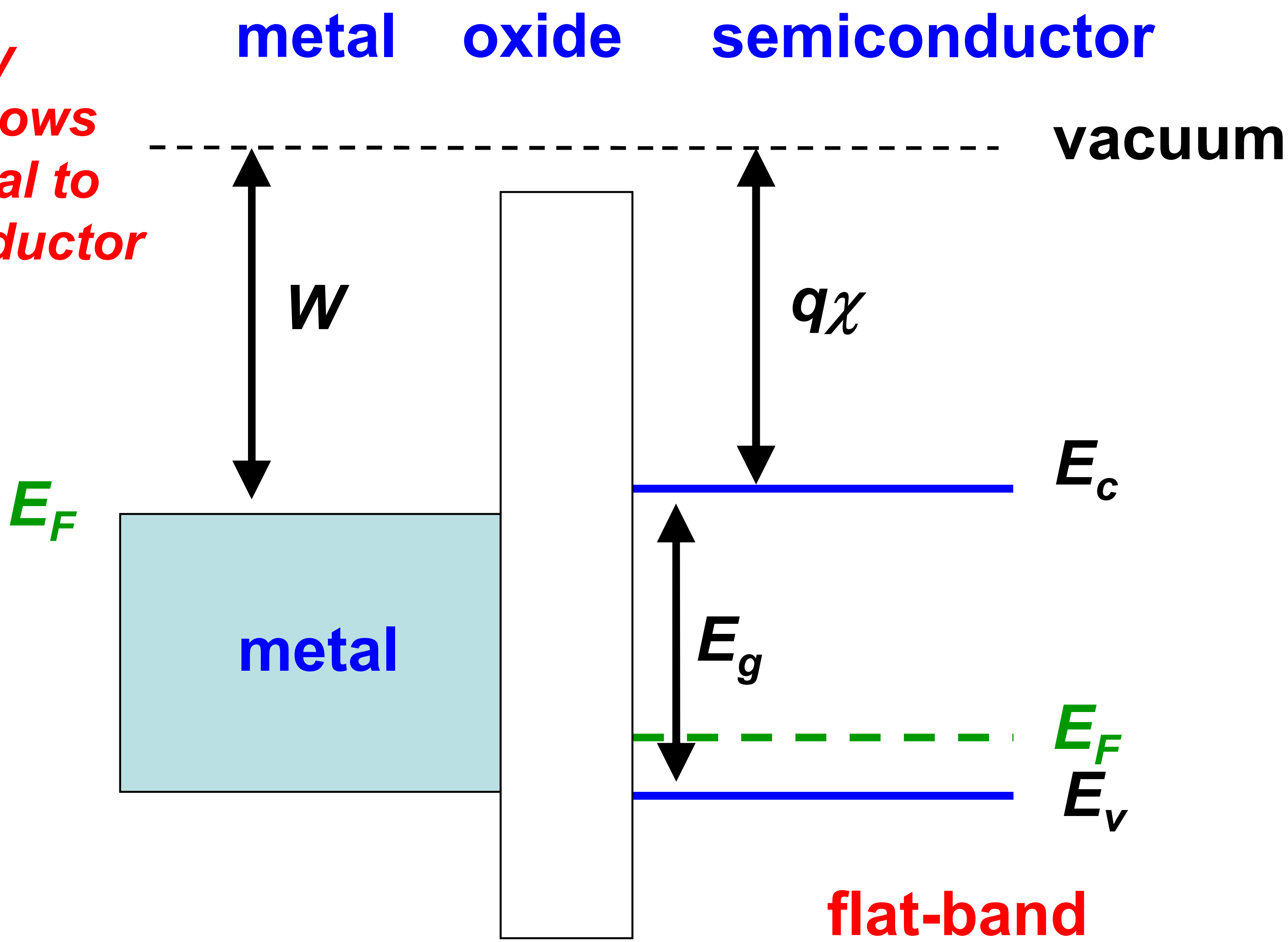


Ohm contact 欧姆接触



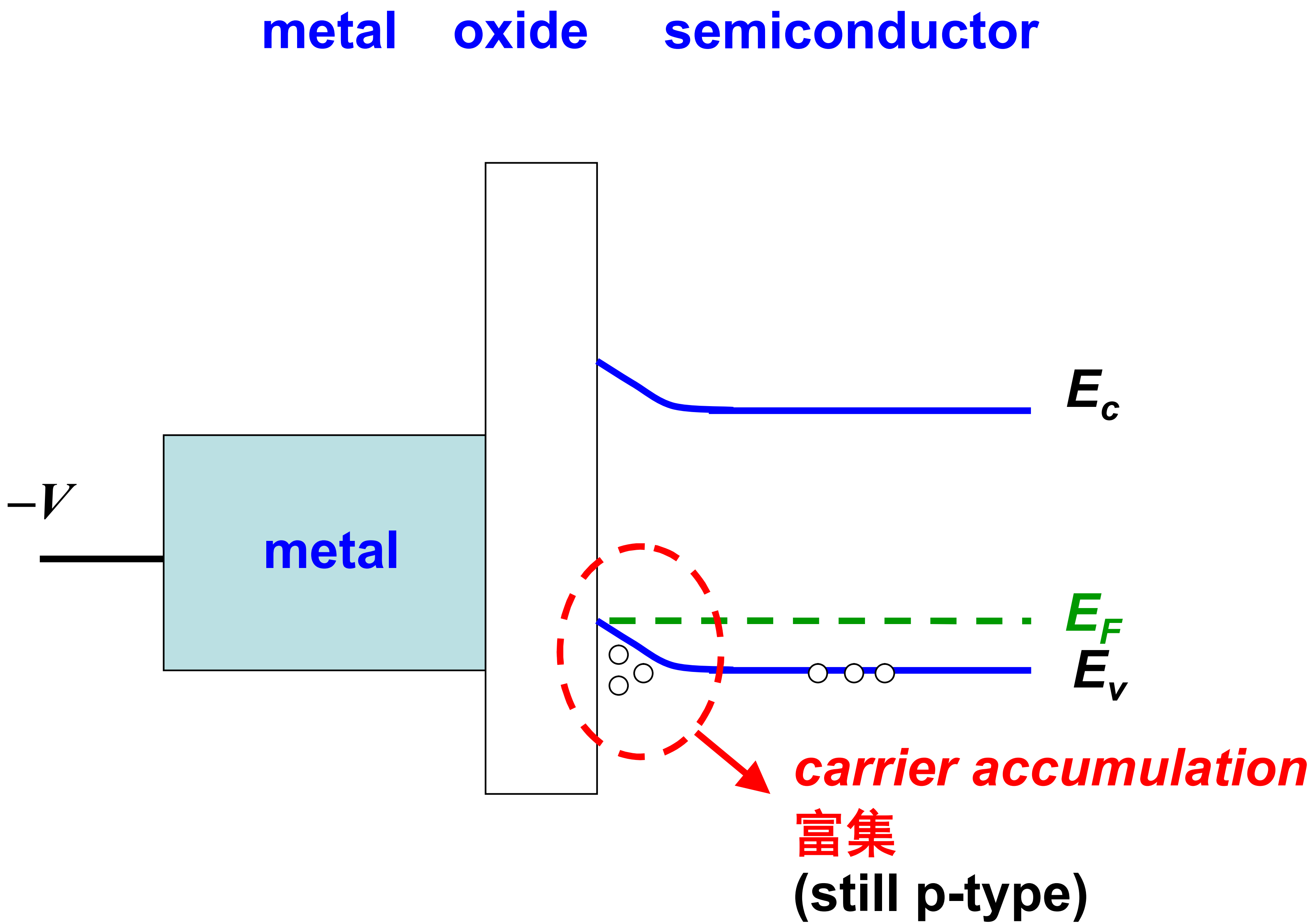
Metal-Oxide-Semiconductor Junction

no steady current flows from metal to semiconductor

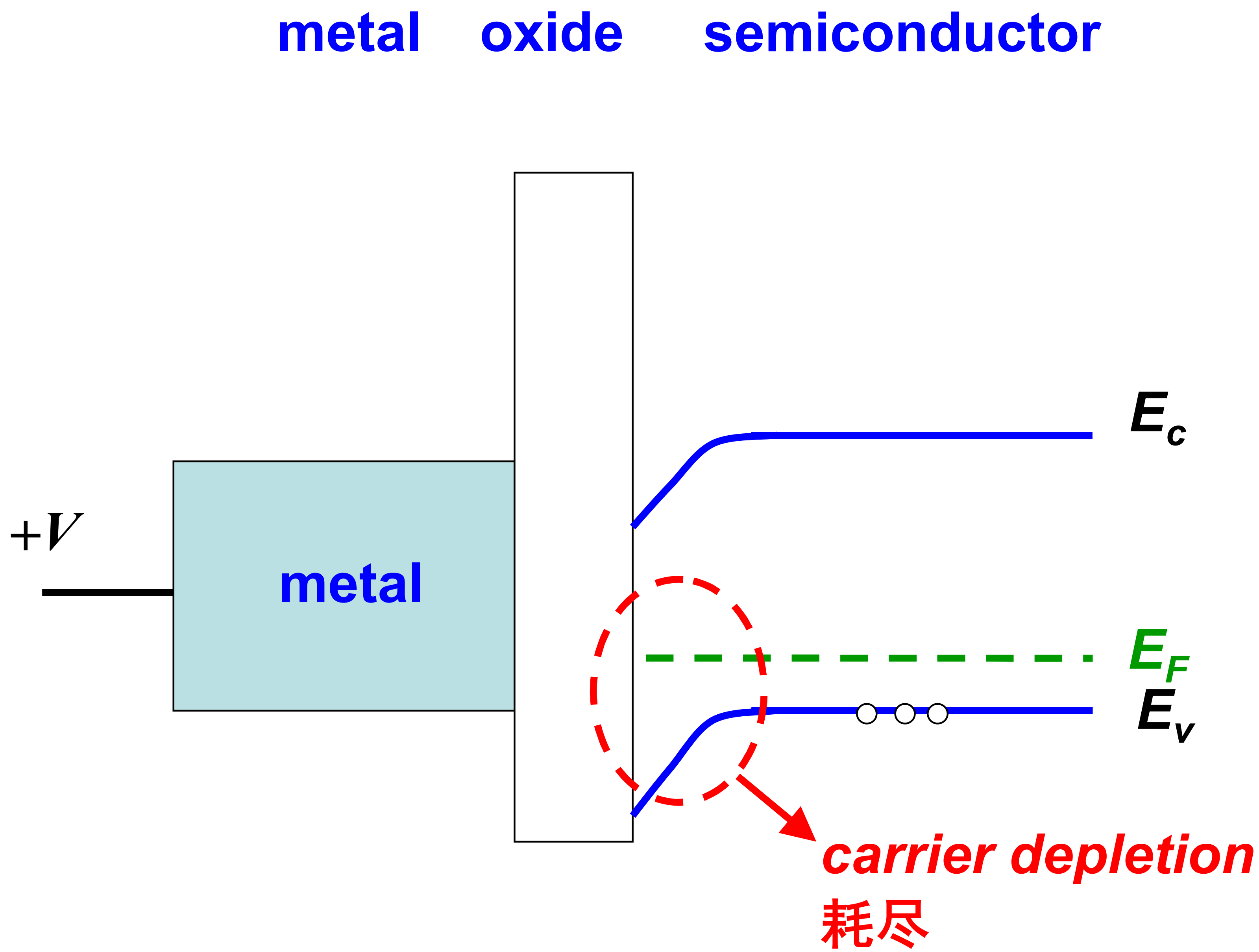


insulator / capacitor

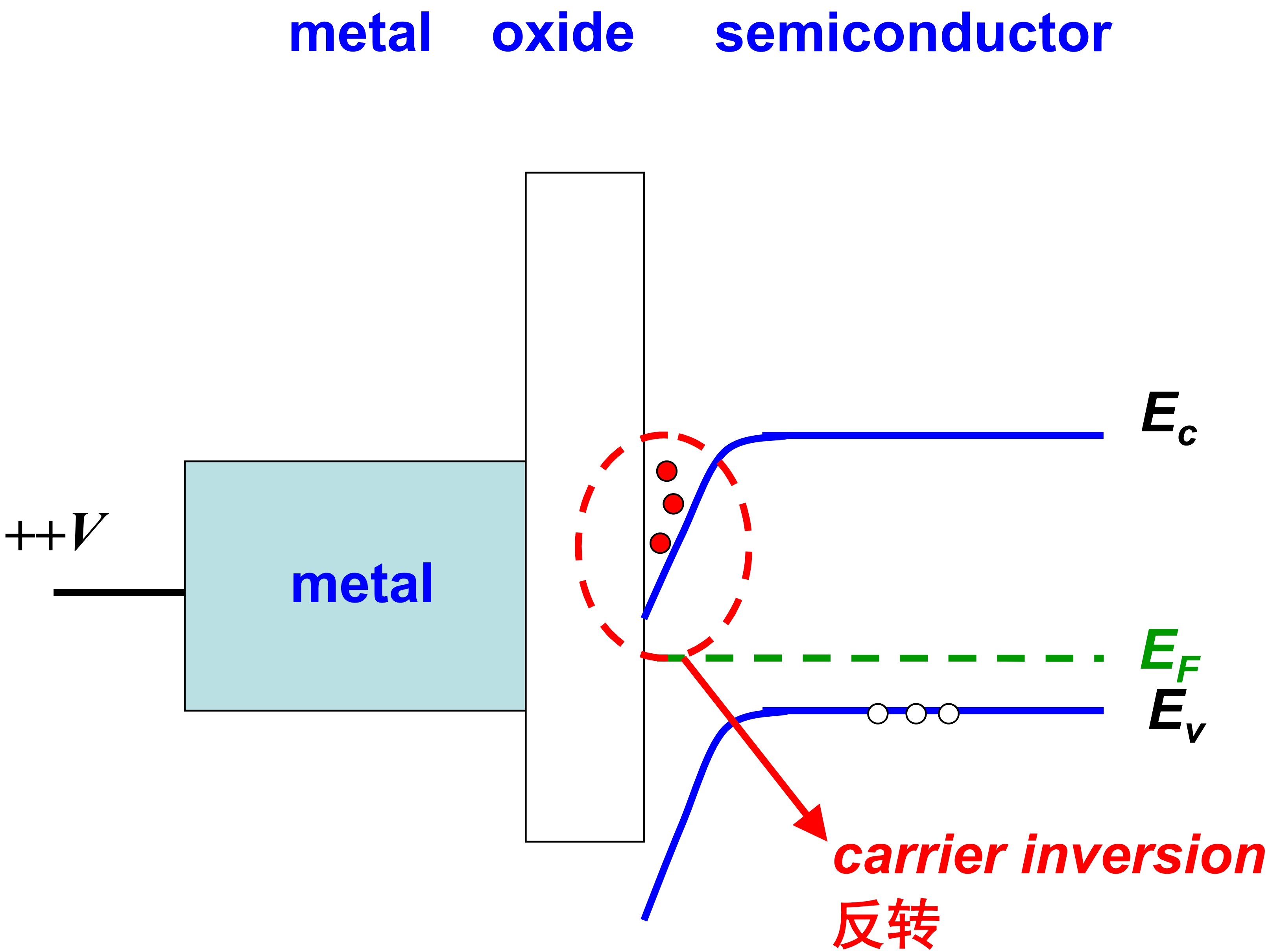
Metal-Oxide-Semiconductor Junction



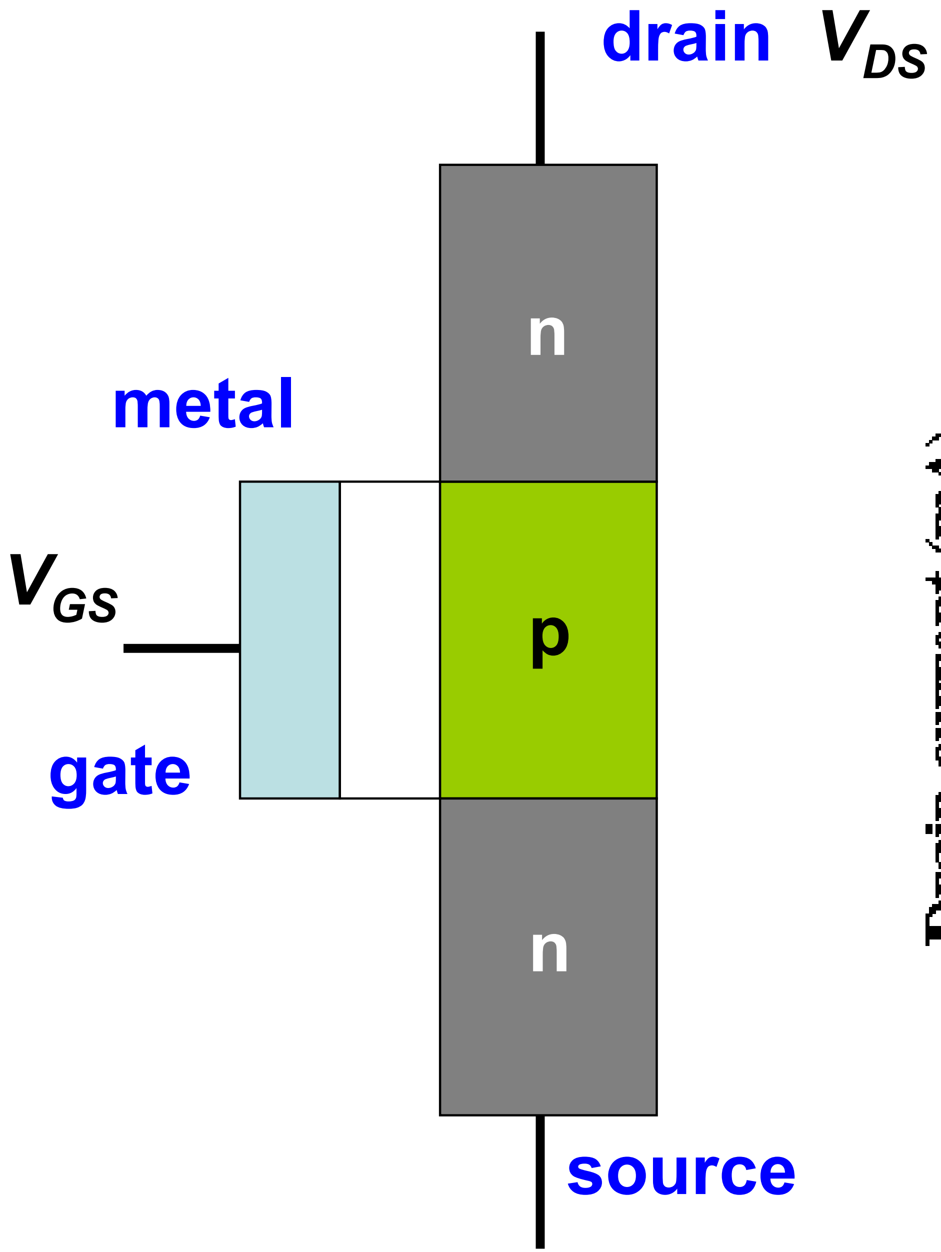
Metal-Oxide-Semiconductor Junction



Metal-Oxide-Semiconductor Junction

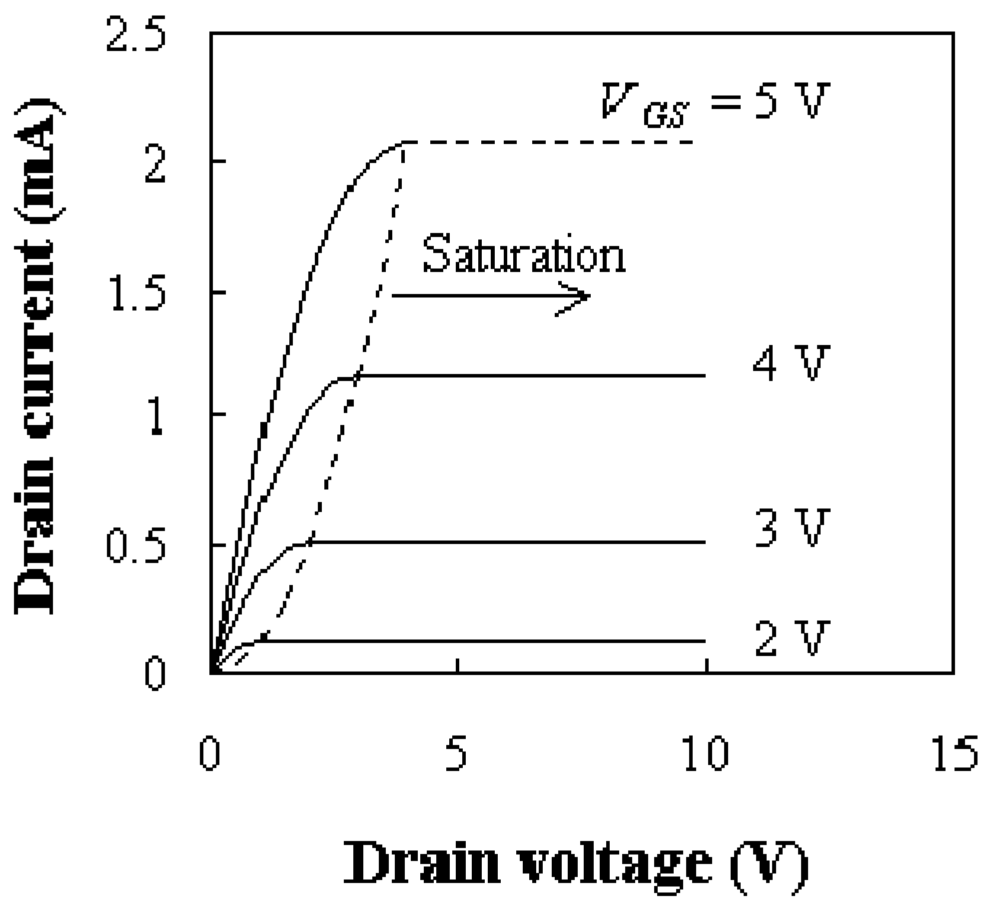


Metal-Oxide-Semiconductor Junction

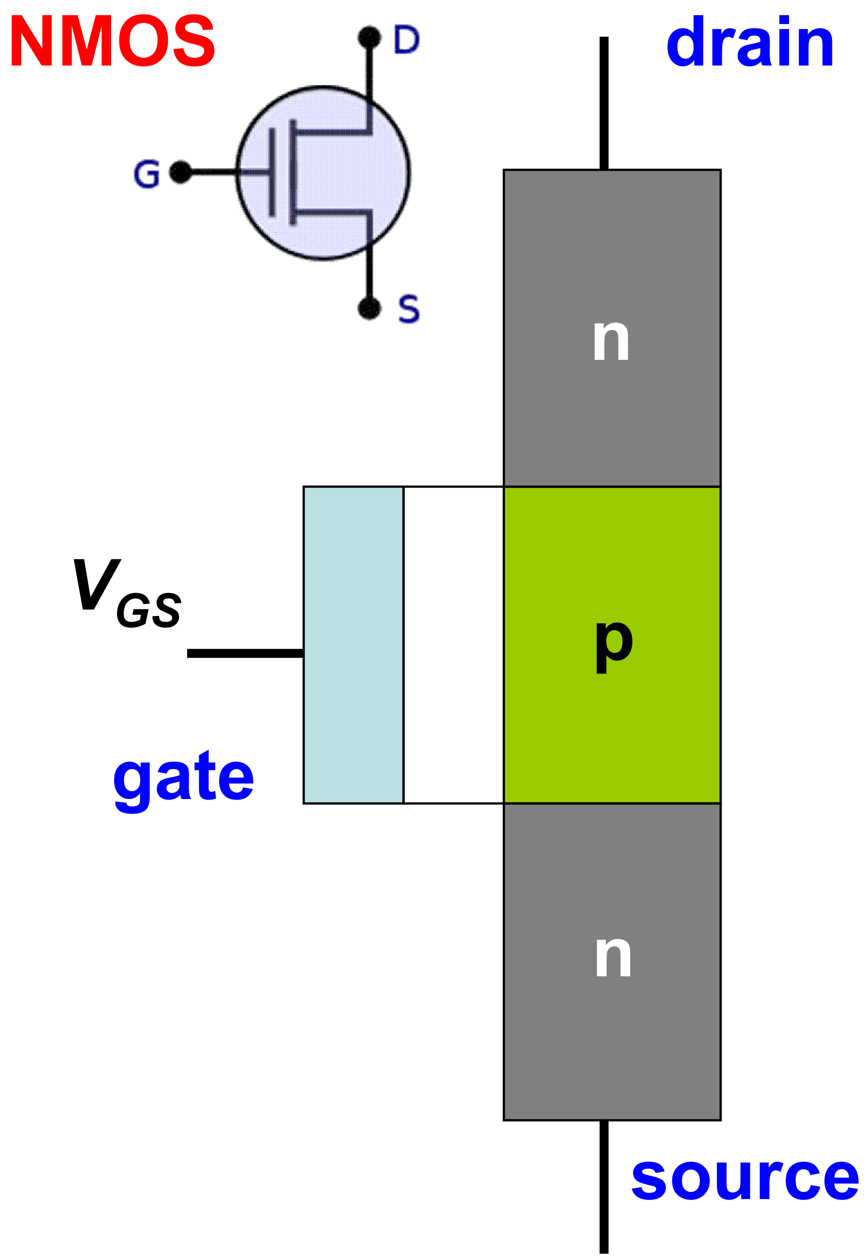


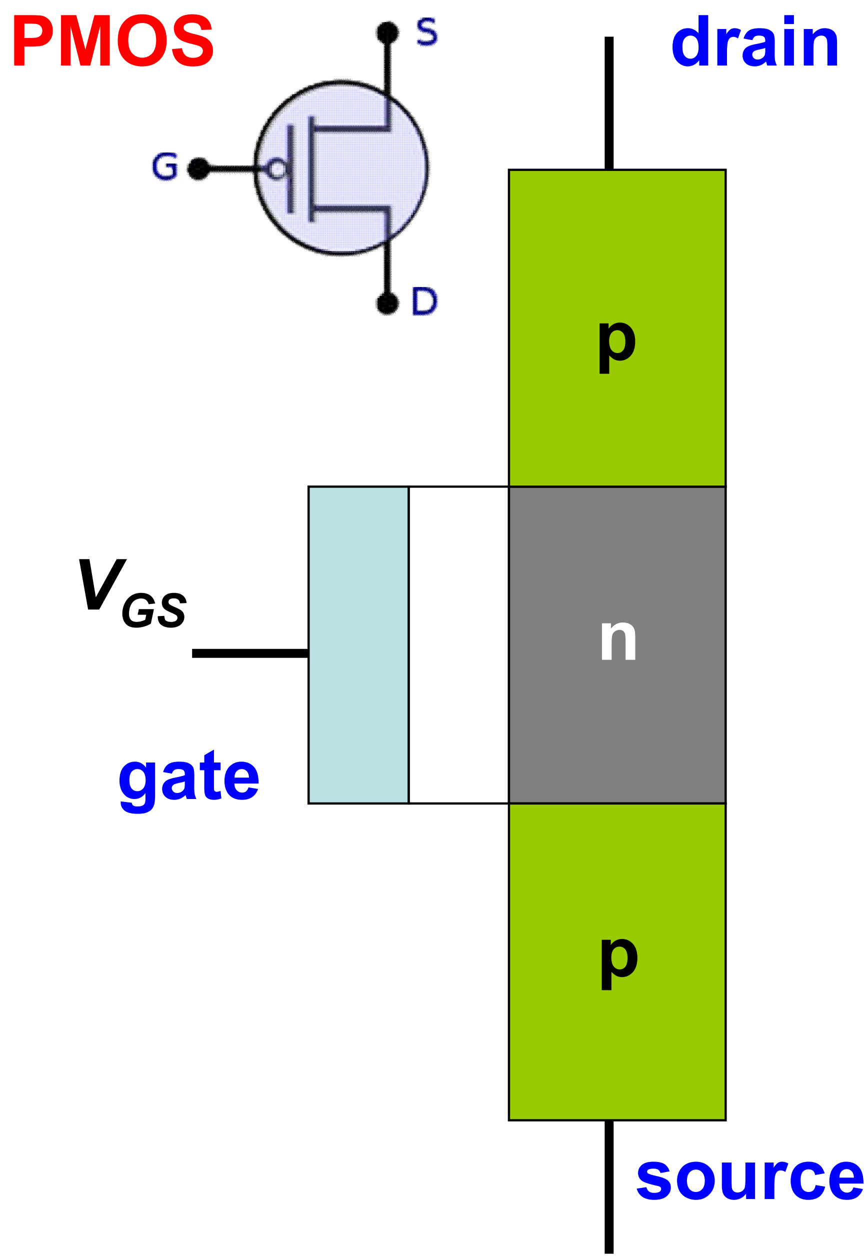
Metal-Oxide-Semiconductor Field-Effect Transistor

MOSFET 场效应晶体管



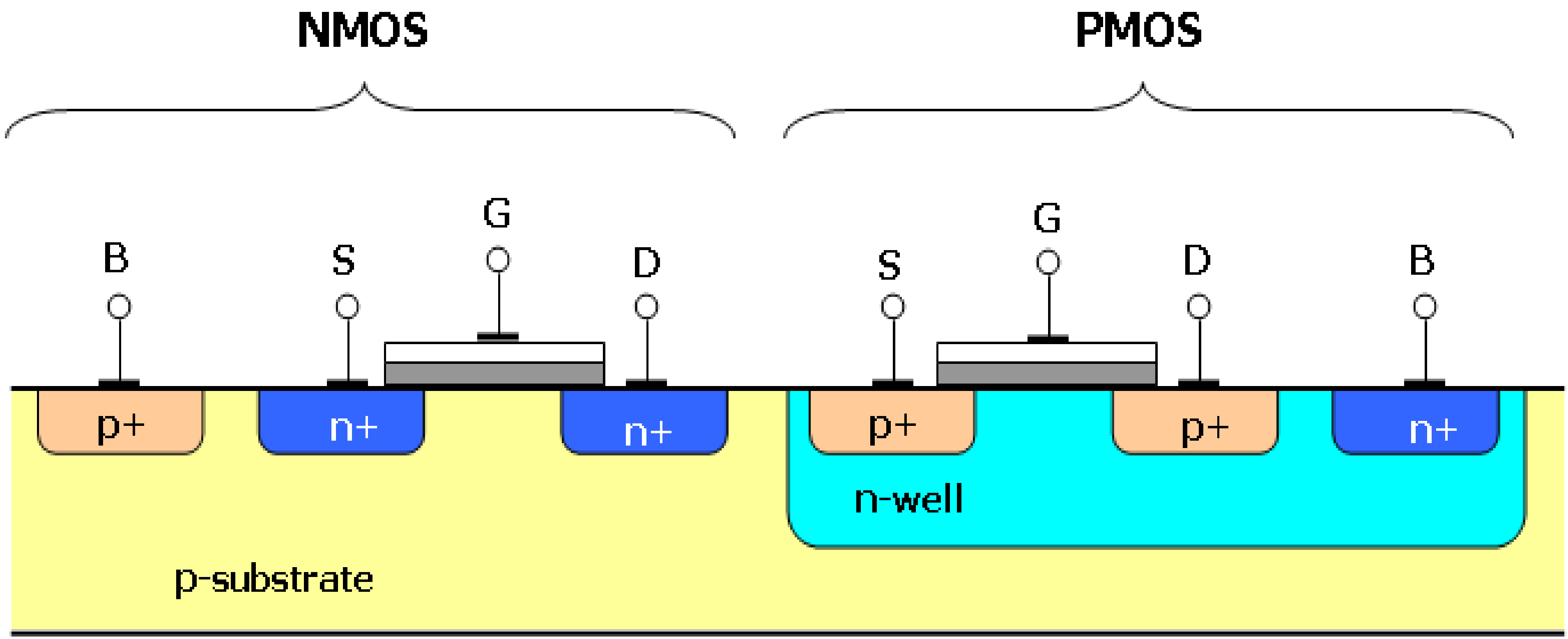
MOSFET


NMOS
D
G
S
drain
n
p
n
V_{GS}
gate
source


PMOS
S
G
D
drain
p
n
p
V_{GS}
gate
source

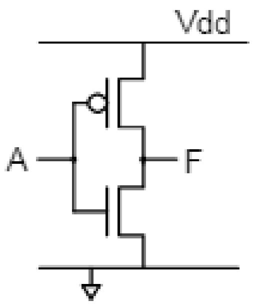
CMOS Technology

- **Complementary Metal-Oxide-Semiconductor**



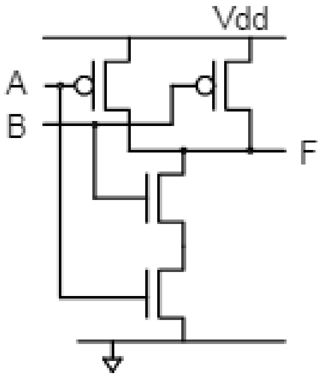
Video MOSFET

CMOS Logics



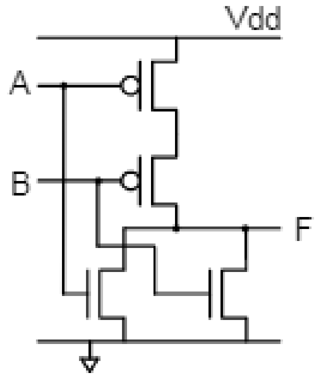
A	F
L	H
H	L

CMOS INVERTER



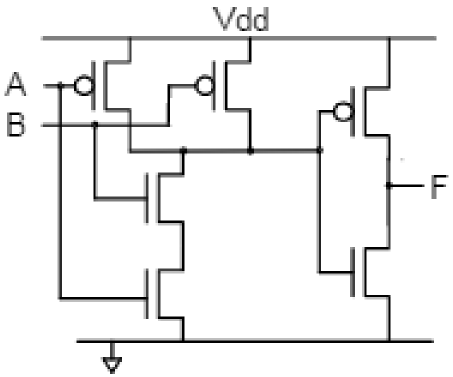
A	B	F
L	L	H
L	H	H
H	L	H
H	H	L

CMOS NAND



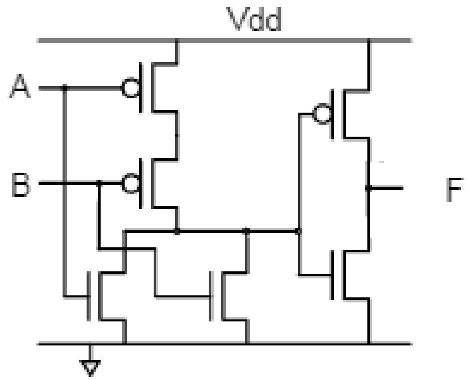
A	B	F
L	L	H
L	H	L
H	L	L
H	H	L

CMOS NOR



A	B	F
L	L	L
L	H	L
H	L	L
H	H	H

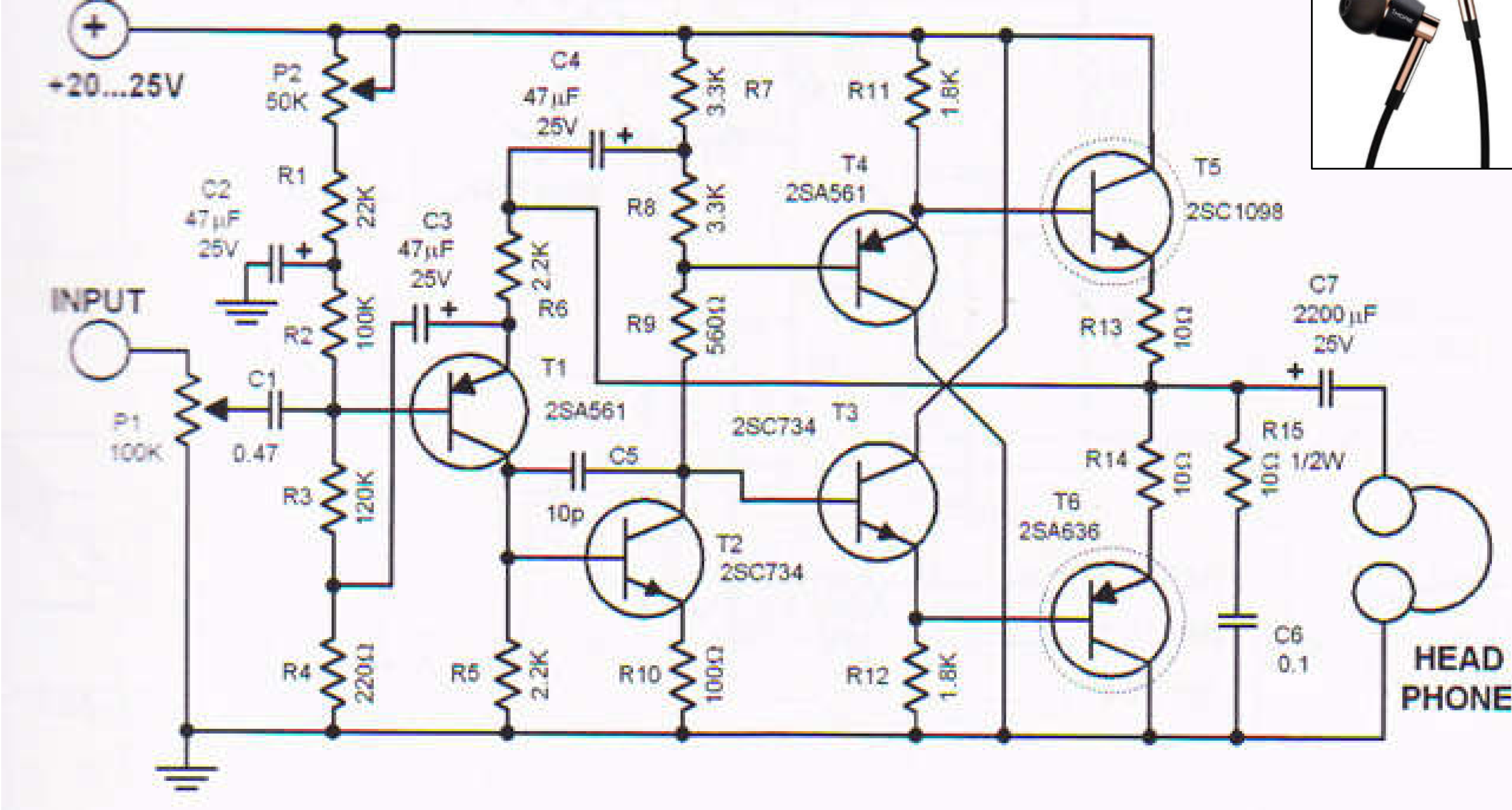
CMOS AND



A	B	F
L	L	L
L	H	H
H	L	H
H	H	H

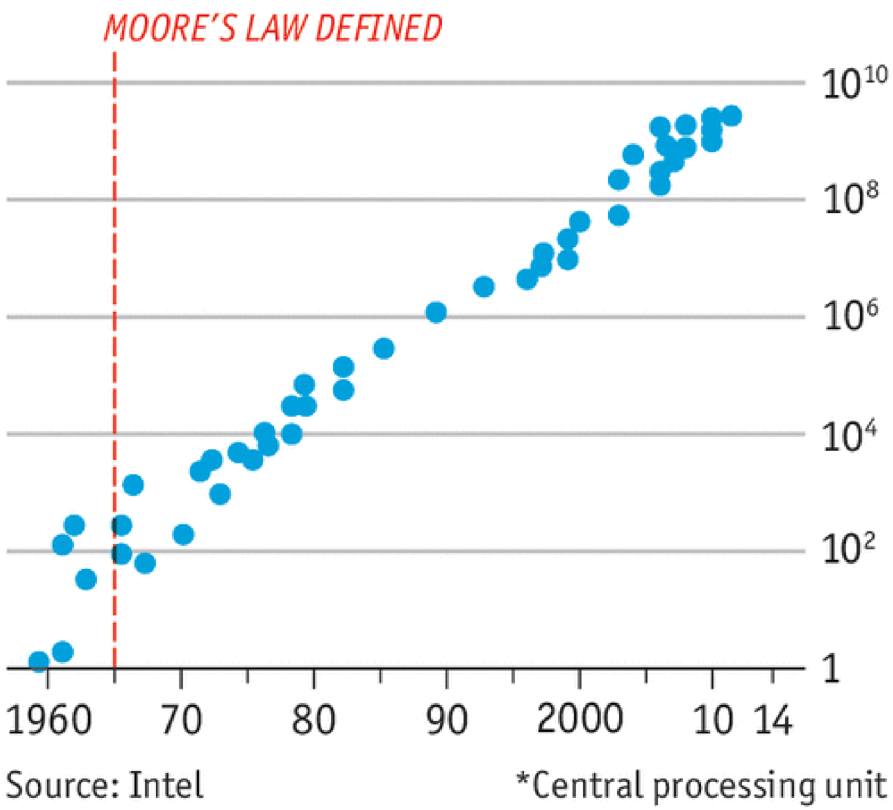
CMOS OR

CMOS Circuits

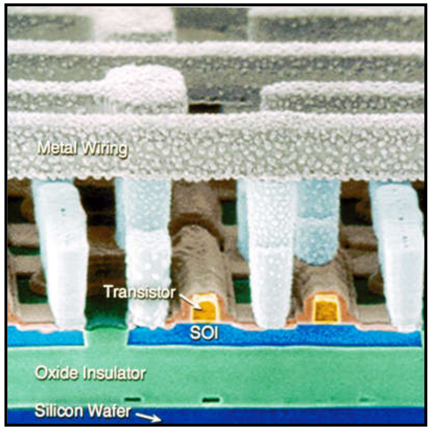


Integrated Circuits

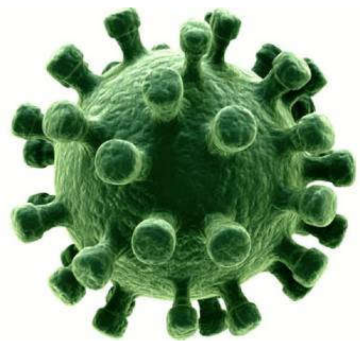
- **Moore's law, Fairchild, 1965**



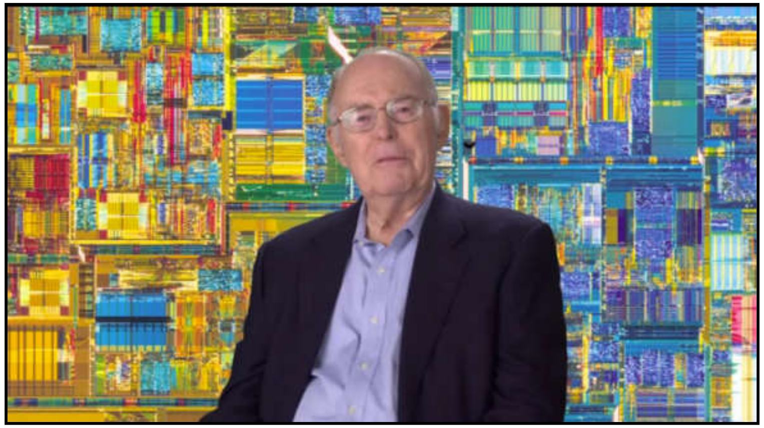
Economist.com



< 100 nm



coronavirus

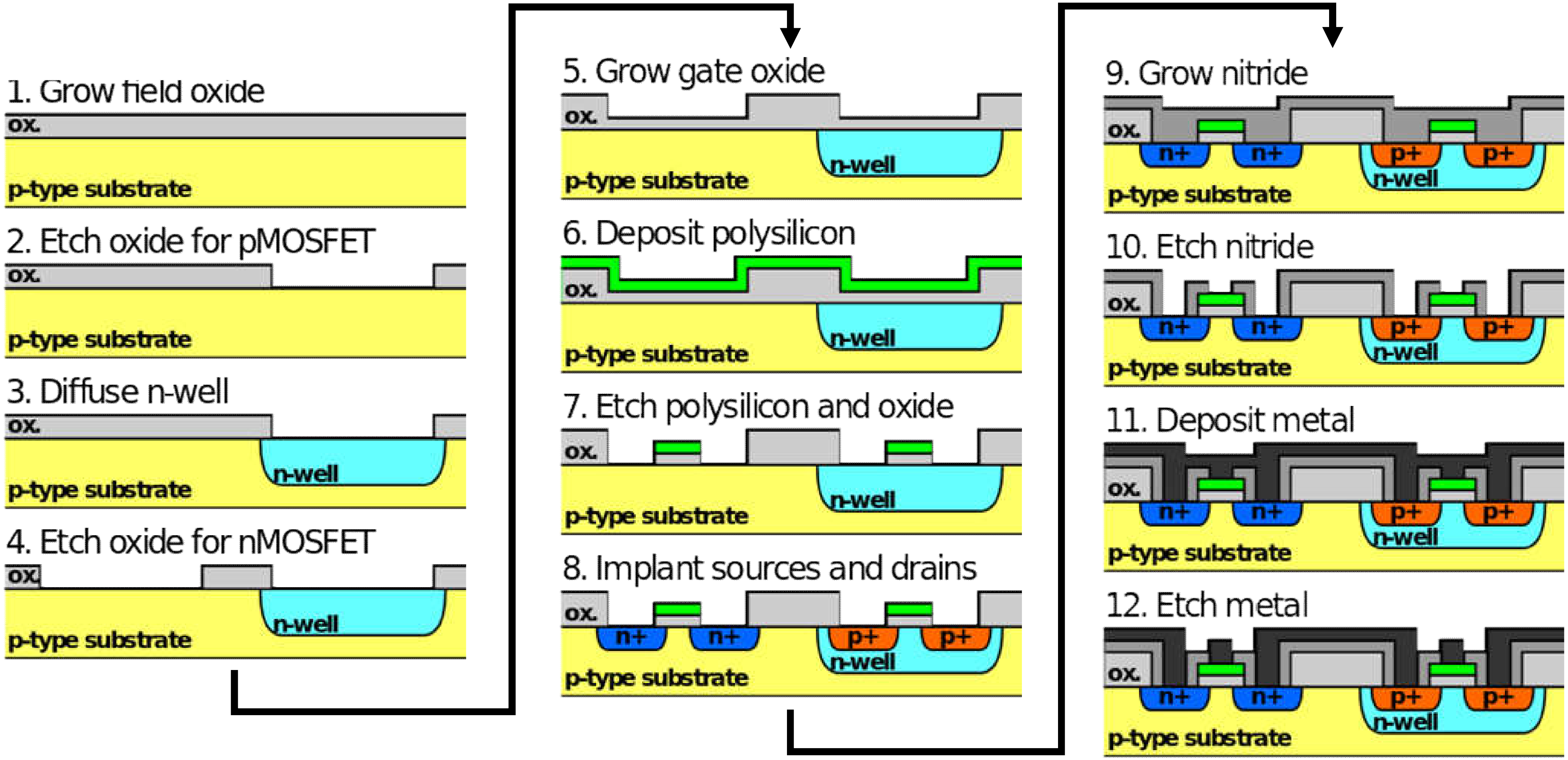


Gordon Moore

Intel i7 CPU, ~ 10^9 transistors

Modern Electronics is a real Nanotechnology

CMOS Process



[Video Fabrication]

Thank you for your attention