Fundamentals of Solid State Physics

Electronic Devices

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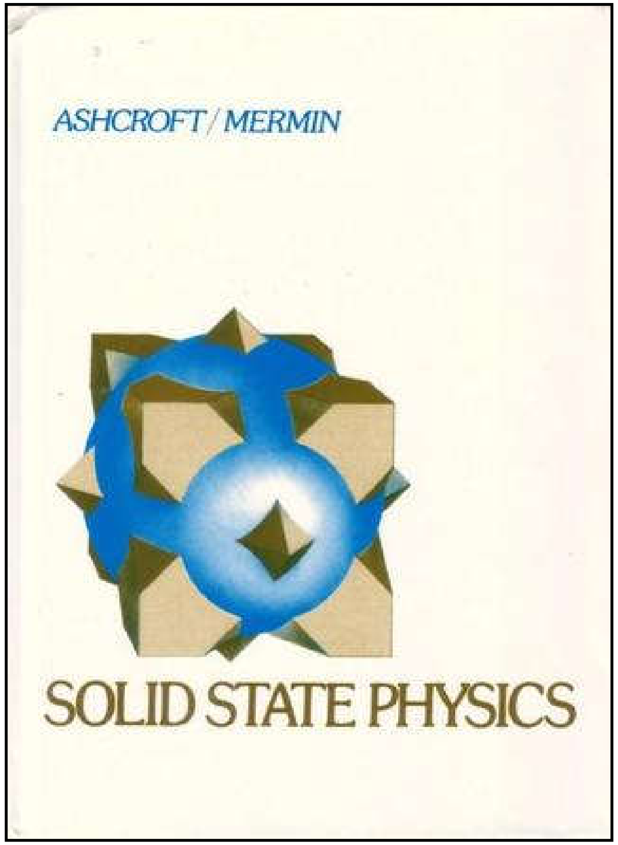
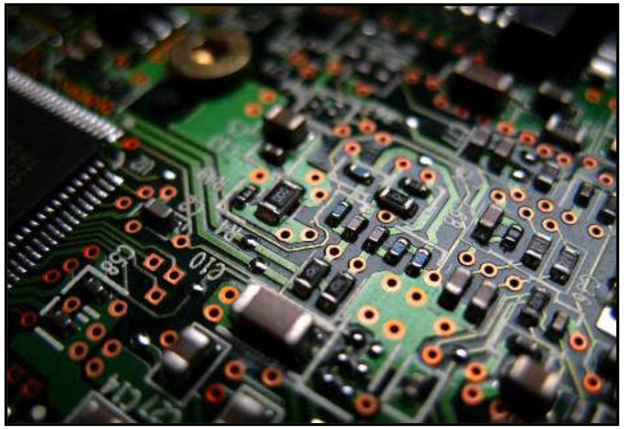
Further Reading

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



Semiconductors - Applications

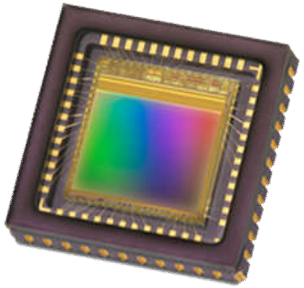
semiconductors are the basis of electronics and photonics



integrated circuits

LEDs

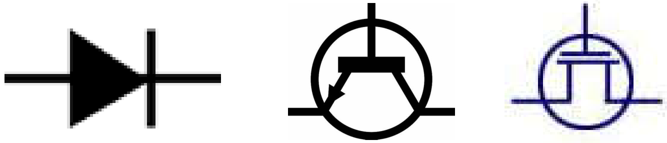
lasers



detectors

solar cells

key components: junctions

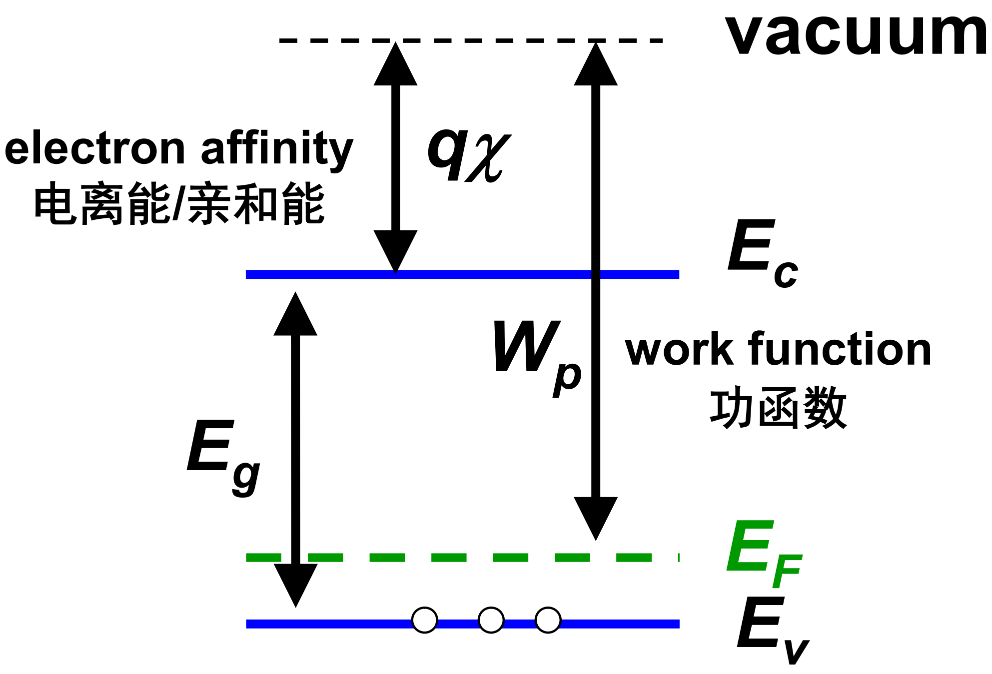


Junctions

- **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

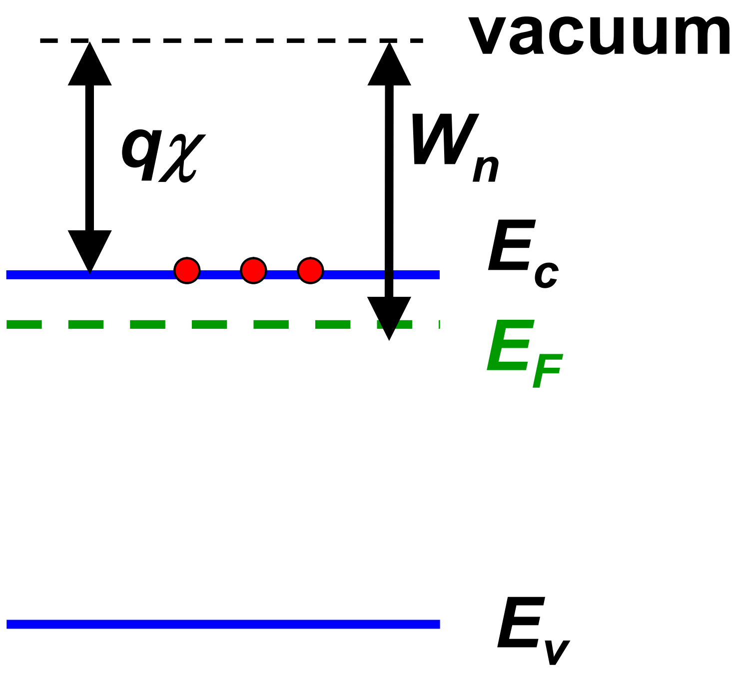


$$p_v = N_A$$

$$n_c = n_i^2 / p_v$$

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

n-Si



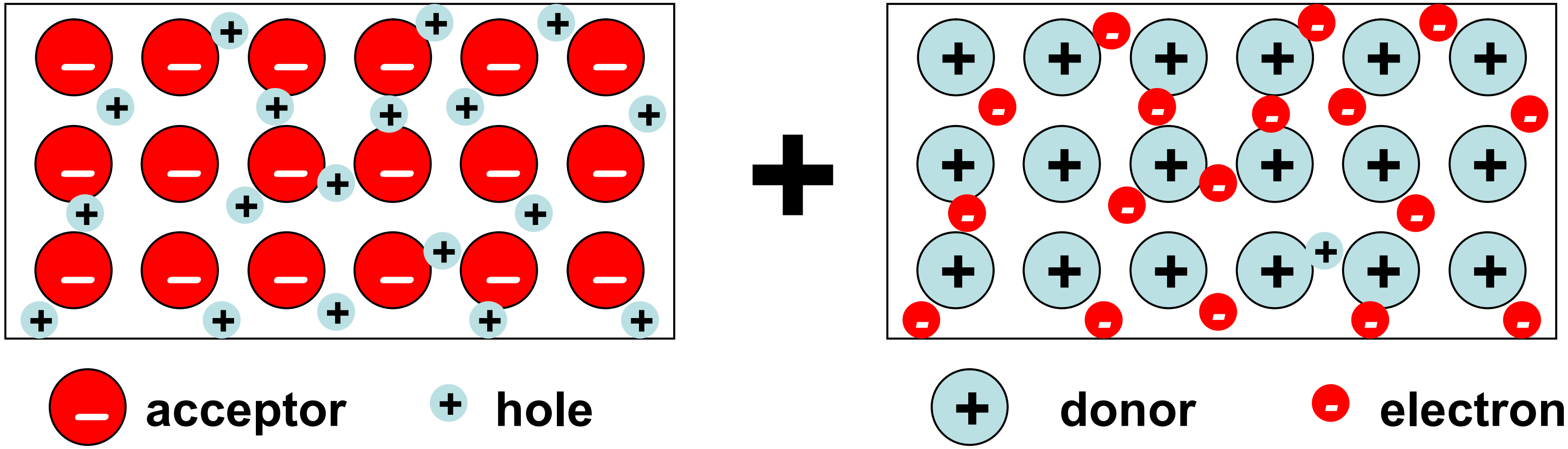
$$n_c = N_D$$

$$p_v = n_i^2 / n_c$$

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

p-type and n-type semiconductor

p-Si **n-Si**



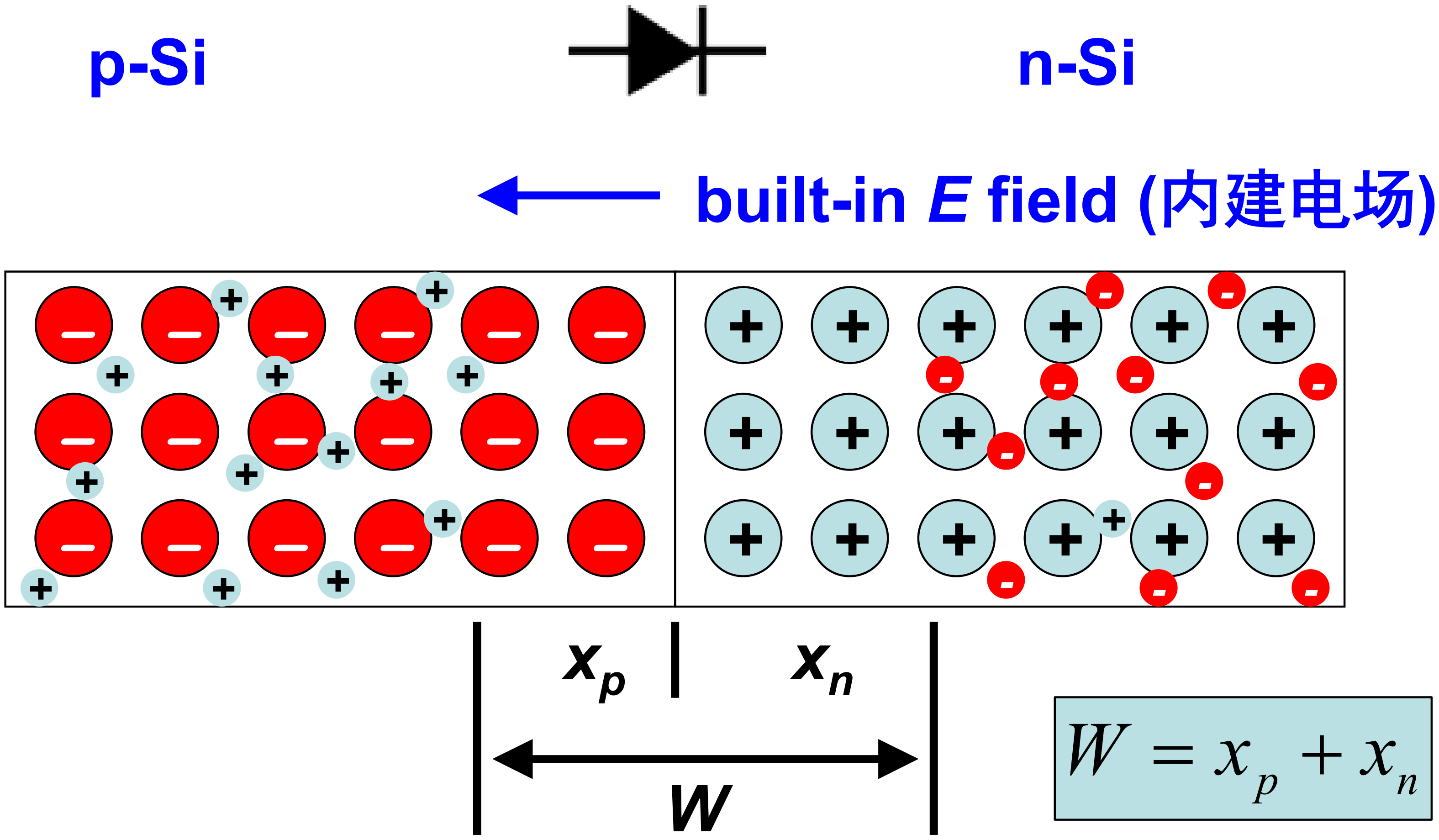
$$p_v = N_A \qquad n_c = n_i^2 / p_v$$

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

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

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

pn homojunction 同质结



p-Si

n-Si

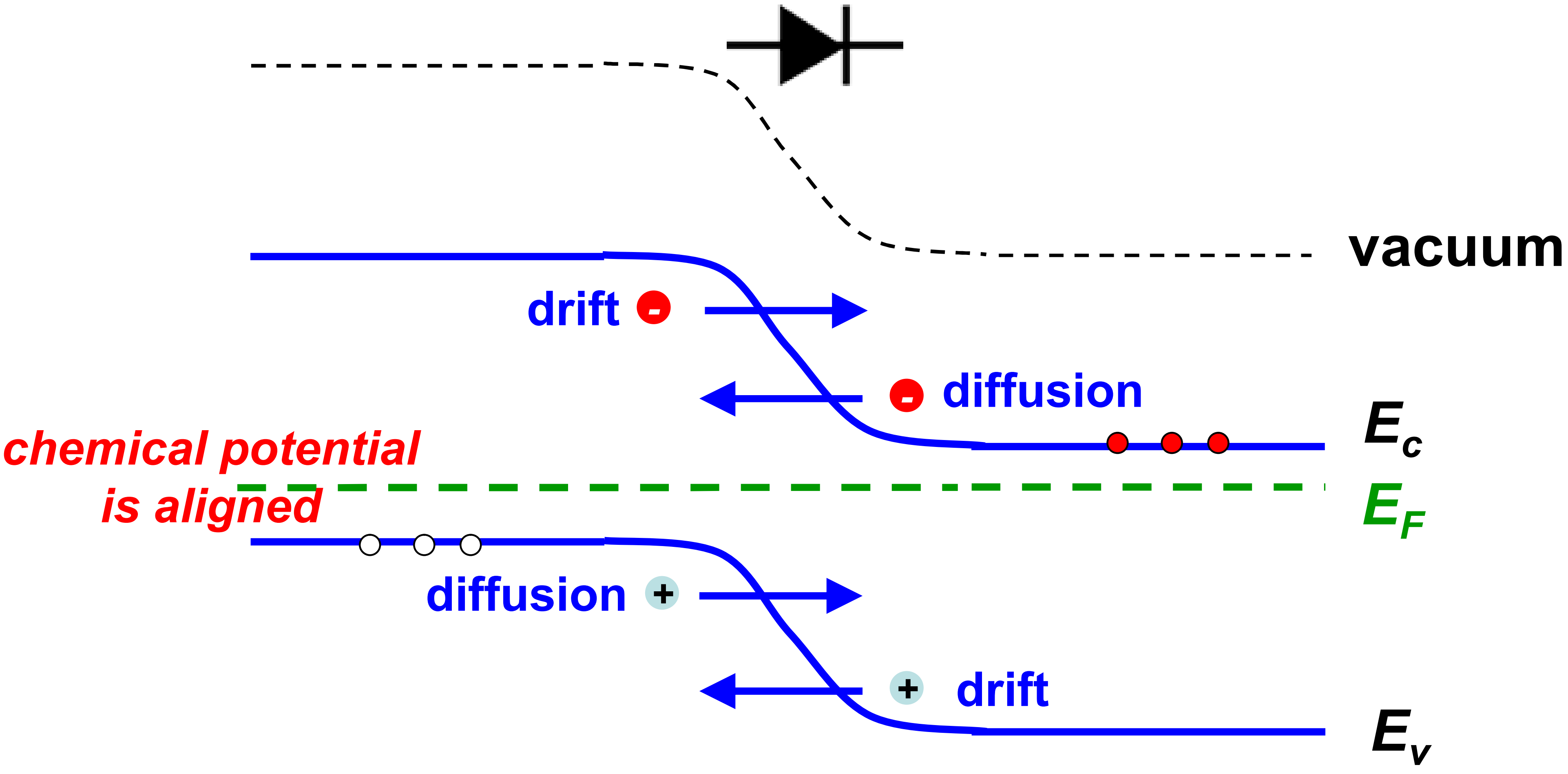
built-in *E* field (内建电场)

$$W = x_p + x_n$$

depletion region
耗尽区

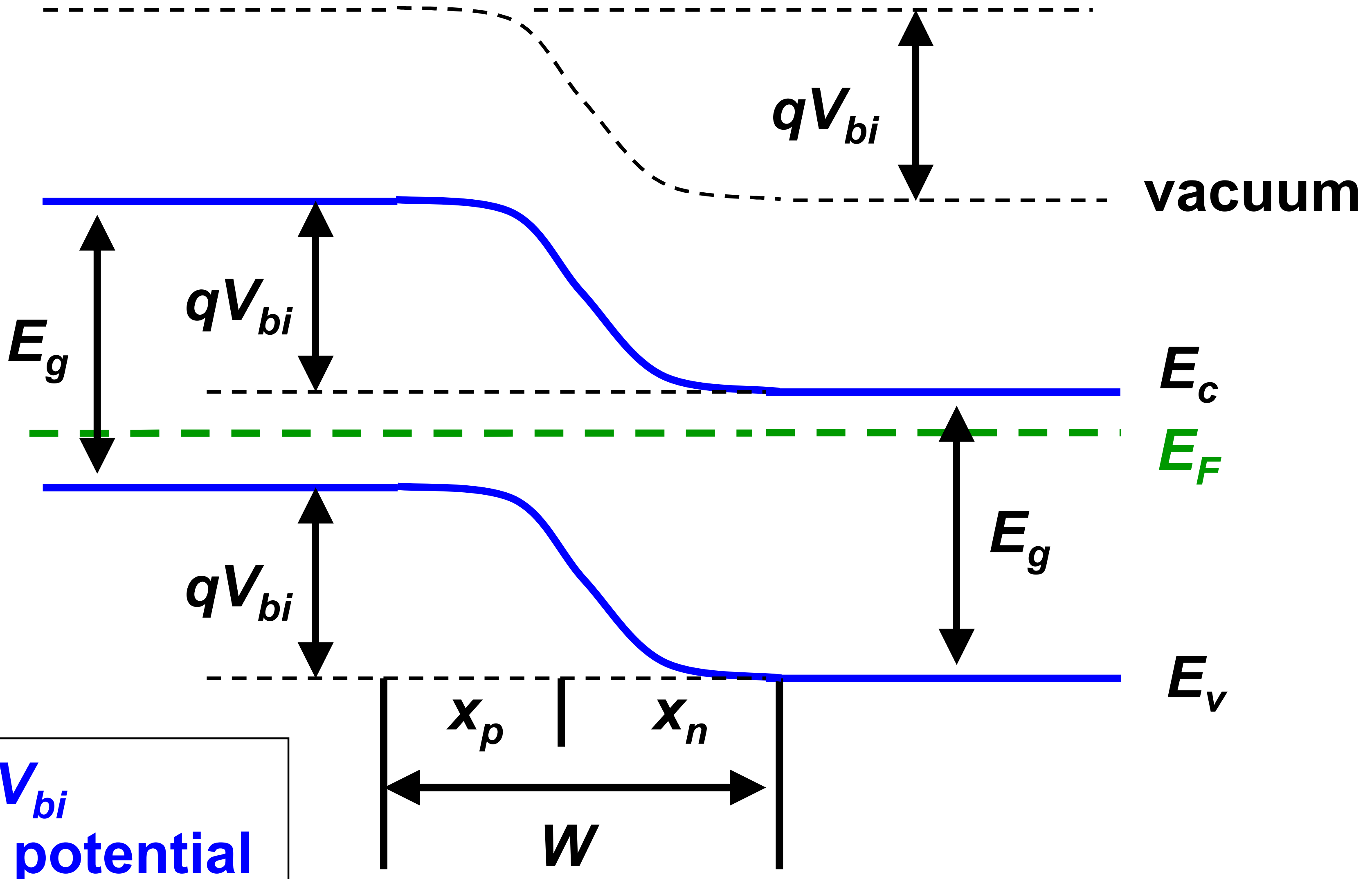
electrons and holes recombine

pn homojunction 同质结



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

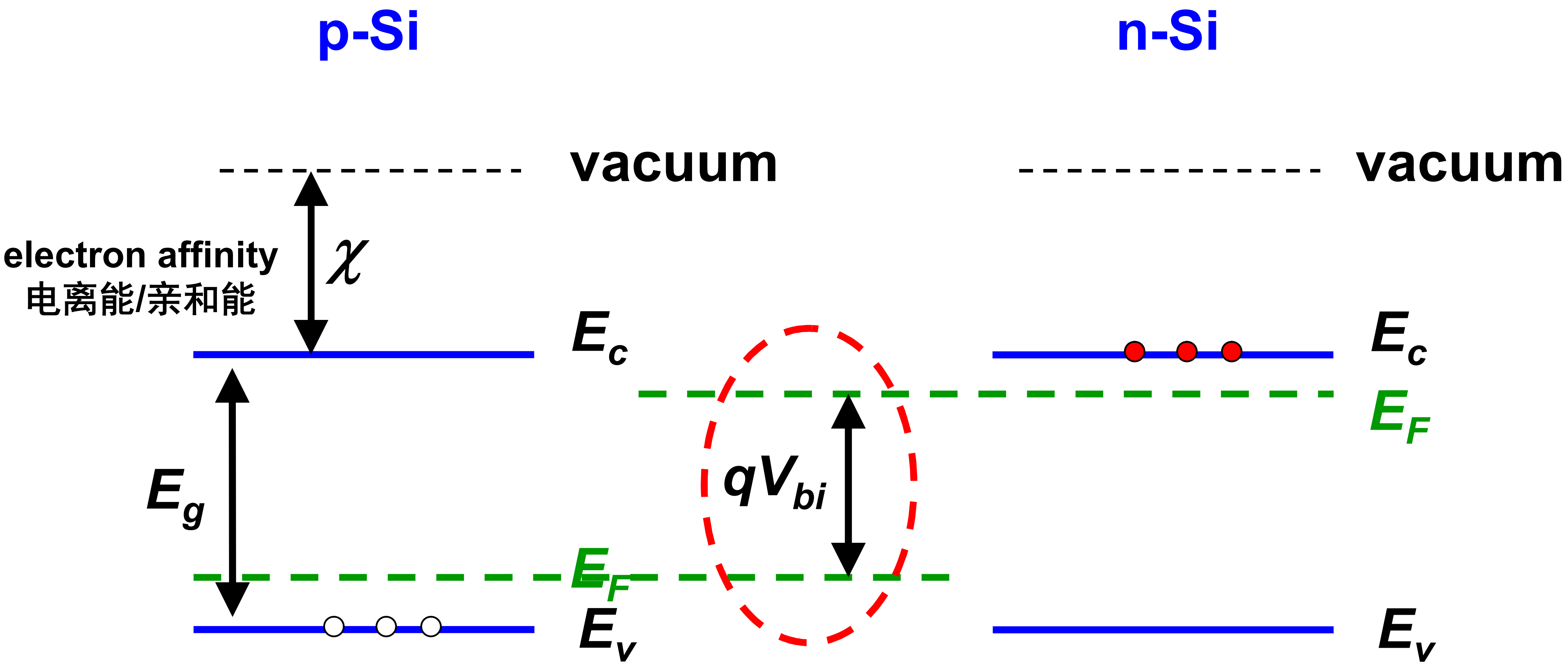
pn homojunction 同质结



V_{bi}
built-in potential
内建电势

depletion region

p-type and n-type semiconductor



$$p_v = N_A$$

$$n_c = n_i^2 / p_v$$

$$n_c = N_D$$

$$p_v = n_i^2 / n_c$$

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

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

V_{bi} - built-in potential 内建电势

p-Si

$$N_A = P_v(T)e^{-(\mu_p - E_v)/k_B T}$$

$$\mu_p = E_v + k_B T \ln\left(\frac{P_v(T)}{N_A}\right)$$

n-Si

$$N_D = N_c(T)e^{-(E_c - \mu_n)/k_B T}$$

$$\mu_n = E_c - k_B T \ln\left(\frac{N_c(T)}{N_D}\right)$$

$$\longrightarrow \quad qV_{bi} = \mu_n - \mu_p$$

q **- electron charge 1.6*10^{-19} C**

V_{bi} - built-in potential 内建电势

$$
\begin{aligned}
qV_{bi} &= \mu_n - \mu_p \\
&= E_c - E_v - k_B T \cdot \ln\left(\frac{N_c(T)P_v(T)}{N_A N_D}\right) \\
&= E_g - k_B T \cdot \ln\left(\frac{n_i^2 e^{+E_g/k_BT}}{N_A N_D}\right) \\
&= k_B T \cdot \ln\left(\frac{N_A N_D}{n_i^2}\right)
\end{aligned}
$$

$$n_i = \sqrt{N_v(T)P_v(T)} \cdot e^{-E_g/2k_BT}$$

V_{bi} - built-in potential 内建电势

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

q - electron charge $1.6*10^{-19}$ C

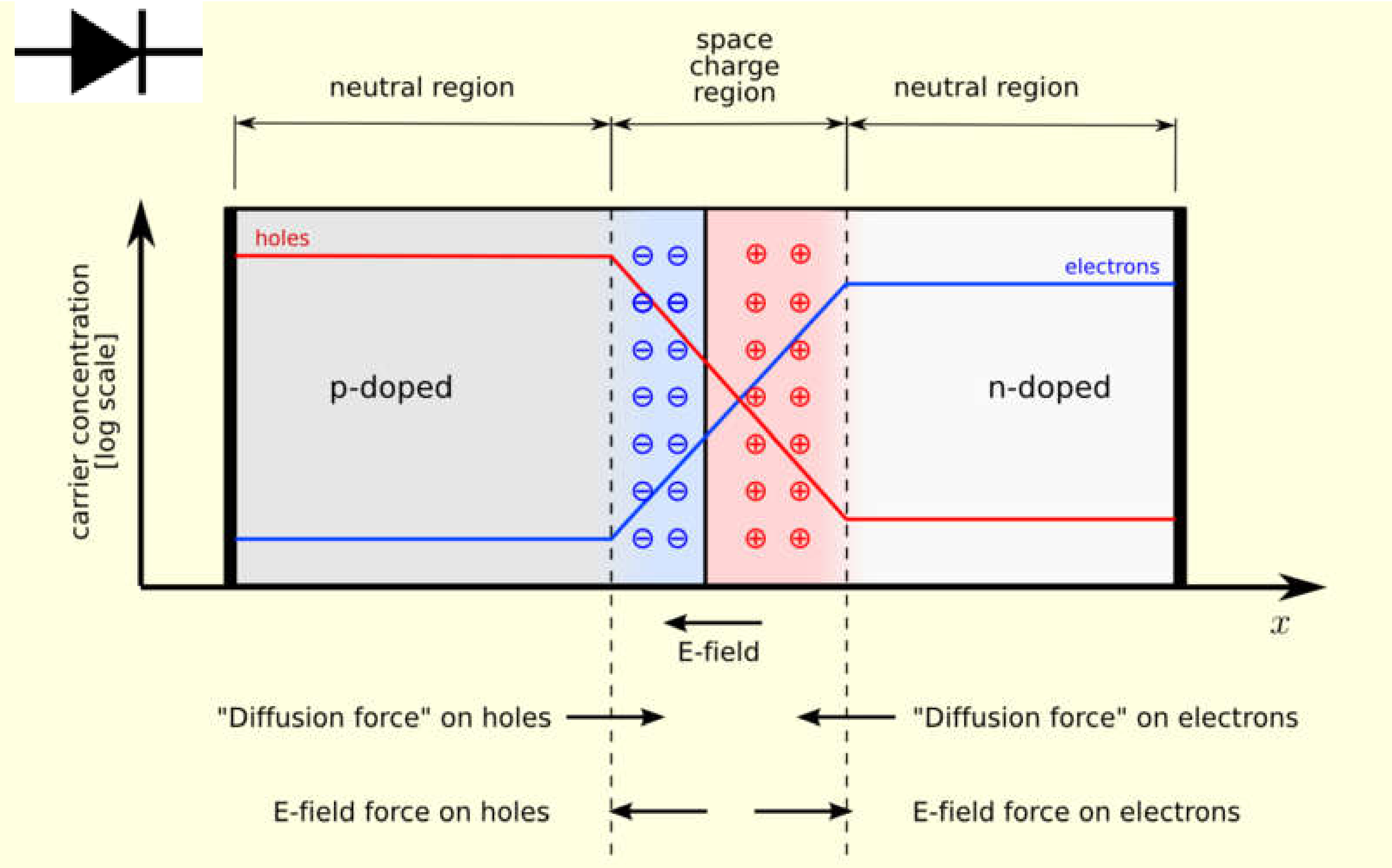
Example:

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

$$\longrightarrow \quad \boxed{V_{bi} = 0.75 \text{ V}}$$

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

pn homojunction 同质结



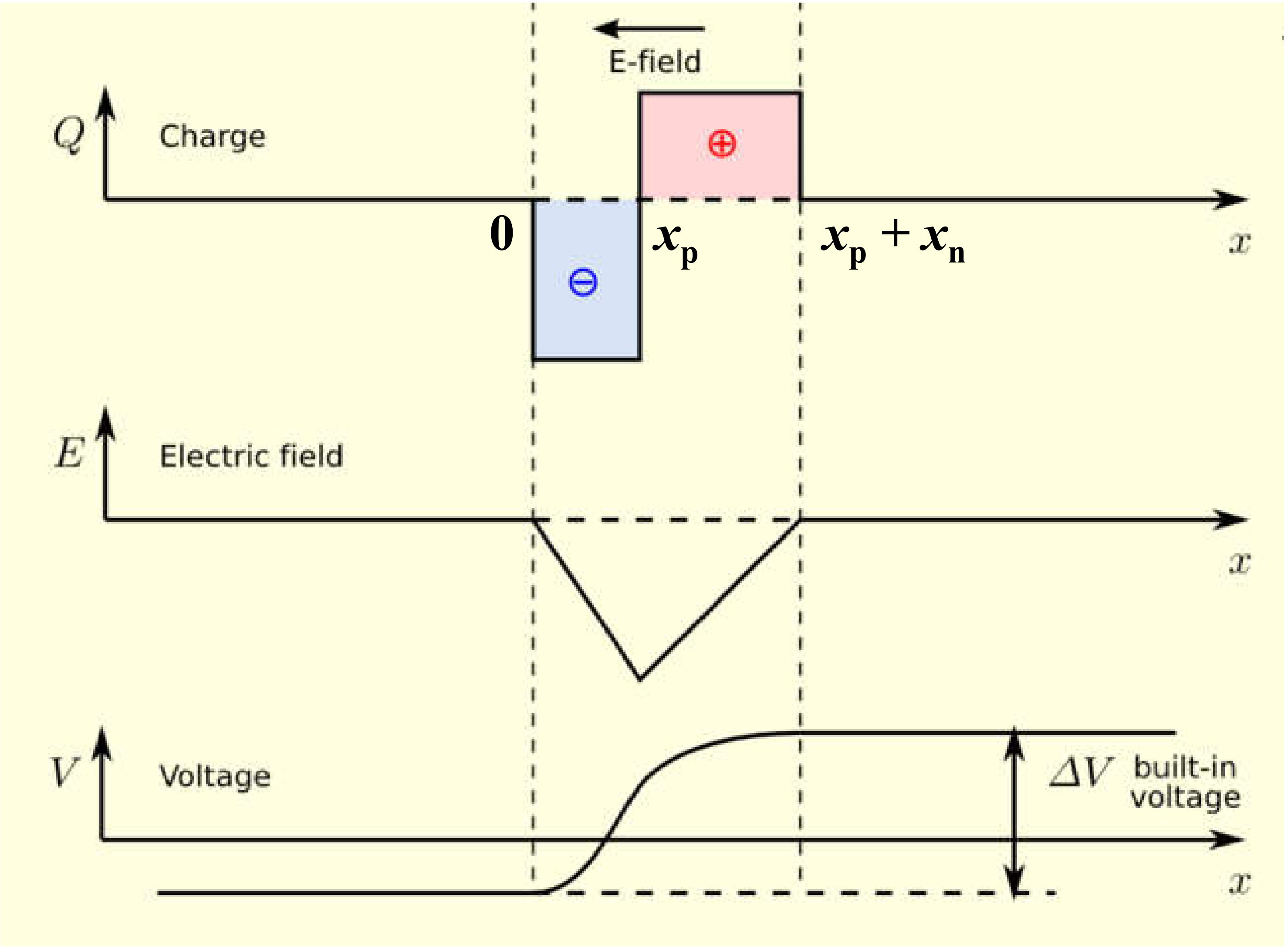
$$W = x_p + x_n$$

$$\boxed{W = x_p + x_n}$$

Q: How to calculate the depletion width W?

Full-depletion Approximation

Assume abrupt transition



Charge Balance

$$N_A x_p = N_D x_n$$

Gauss's Law

$$\frac{\partial E}{\partial x} = \frac{q}{\varepsilon_s} Q(x)$$

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

Full-depletion Approximation

Assume abrupt transition

and

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

Lecture Note 3.12

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

$$\varepsilon_s = \varepsilon_0 \varepsilon_r$$

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

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

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

Full-depletion Approximation

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, ε_r = 11.2

→ $$V_{bi} = 0.75 \text{ V}$$

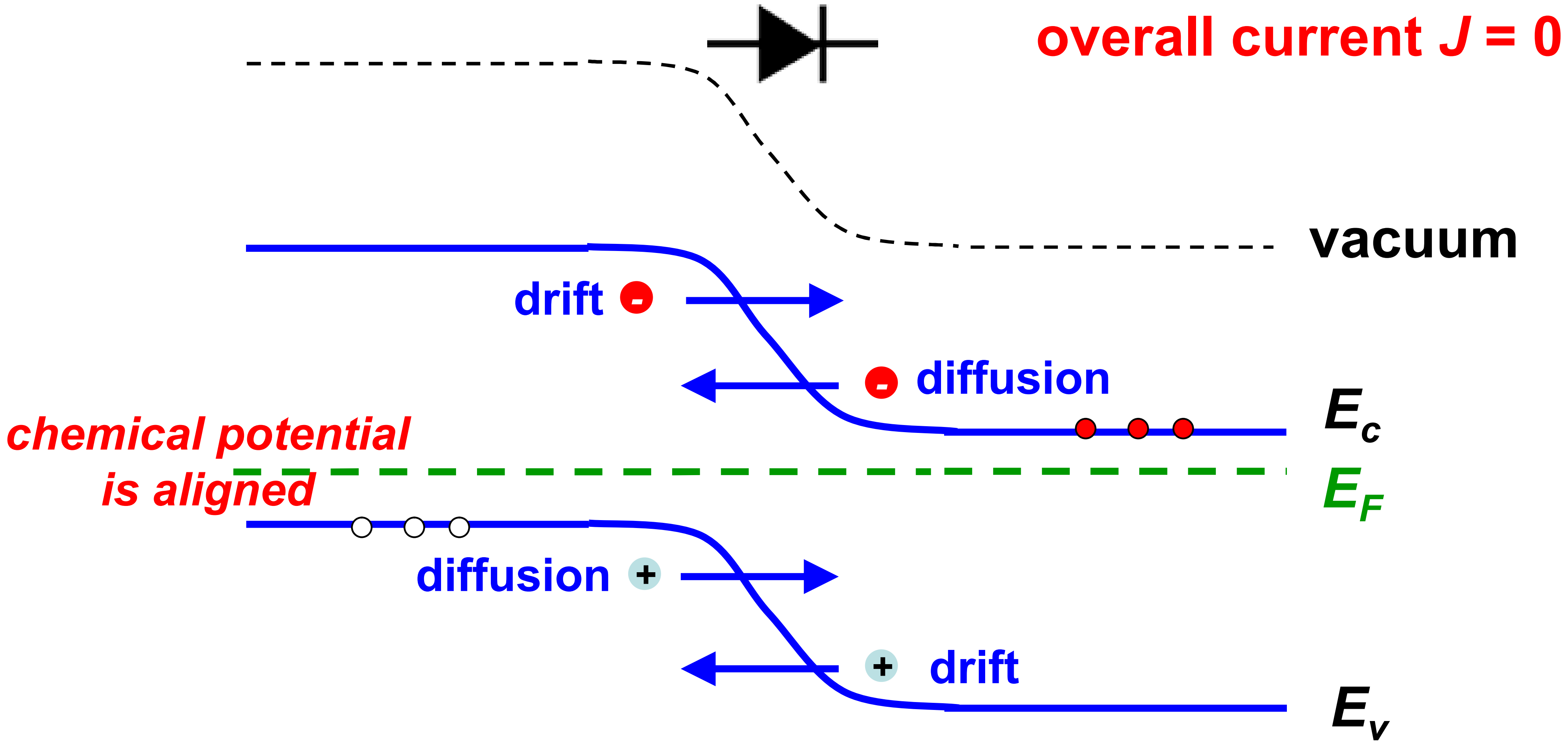
→ $$W = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_{bi}} = 964 \text{ nm}$$

$$x_p = 0.9 \text{ nm}$$

$$x_n = 963 \text{ nm}$$

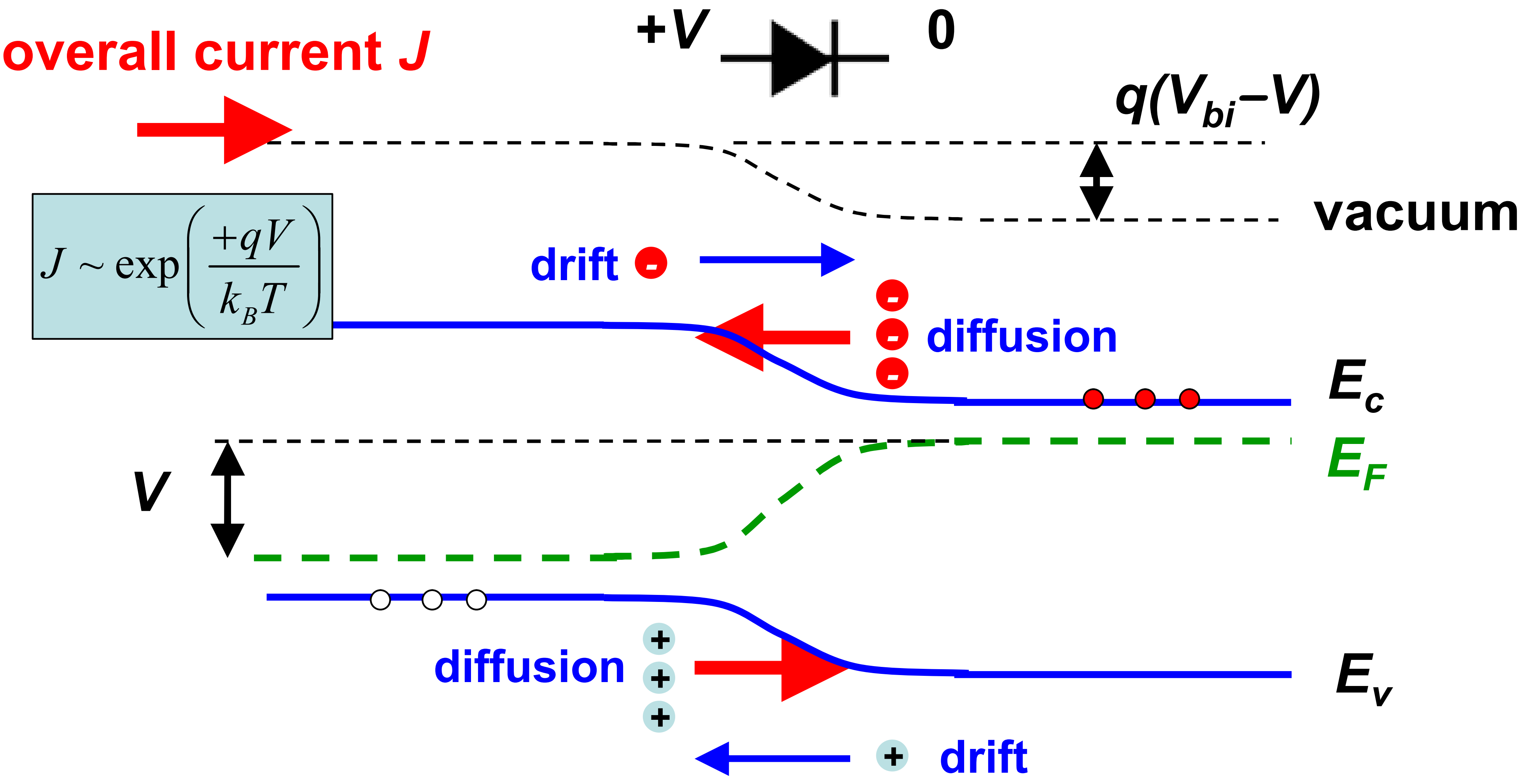
higher doping -> smaller width

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 ($V > 0$)

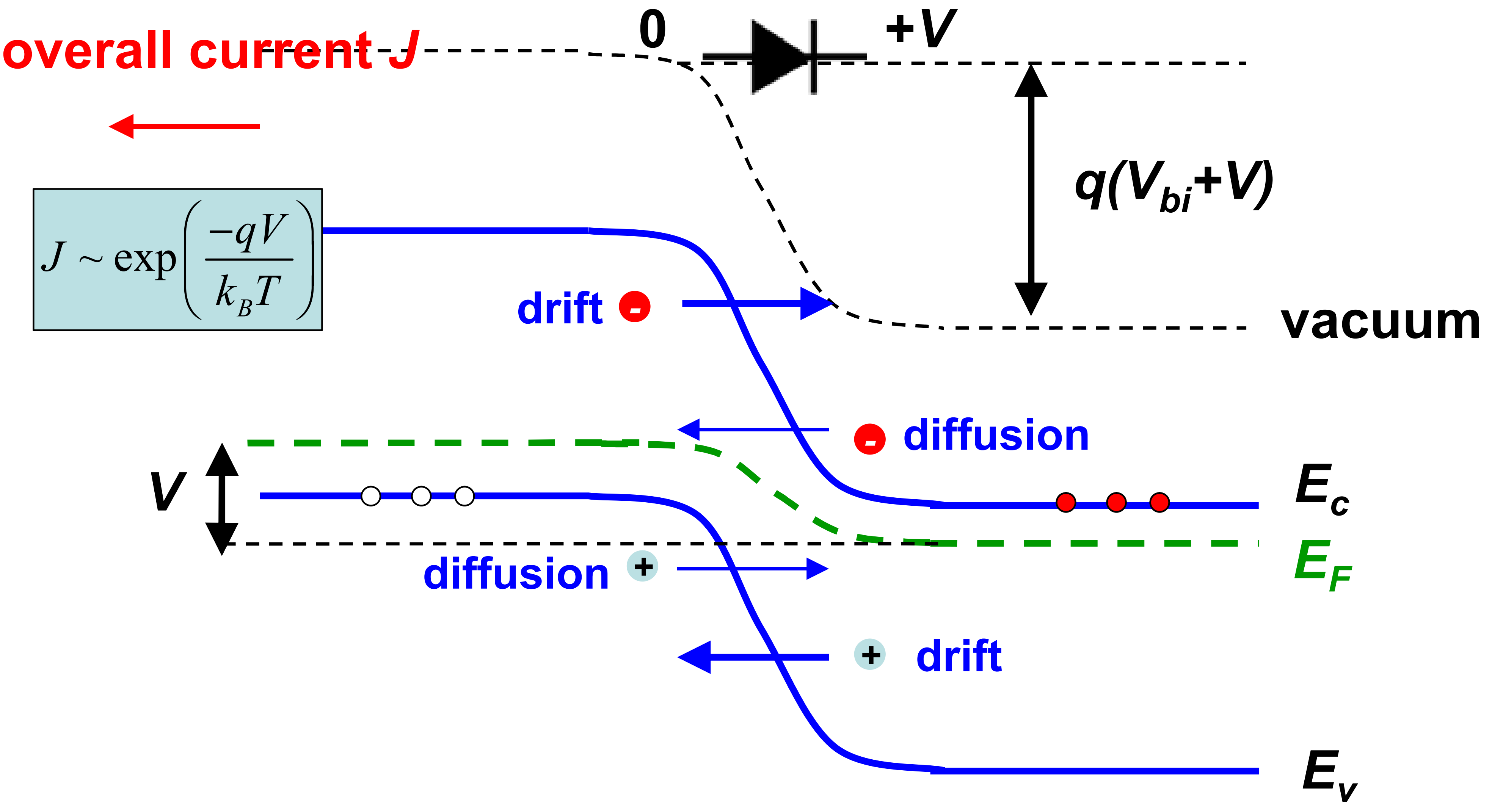


$$J \sim \exp\left(\frac{+qV}{k_B T}\right)$$

V_{bi} decreases by V, W decreases

much more diffusion current, the junction is conductive

At Reverse Bias ($V < 0$)



overall current J

$$J \sim \exp\left(\frac{-qV}{k_B T}\right)$$

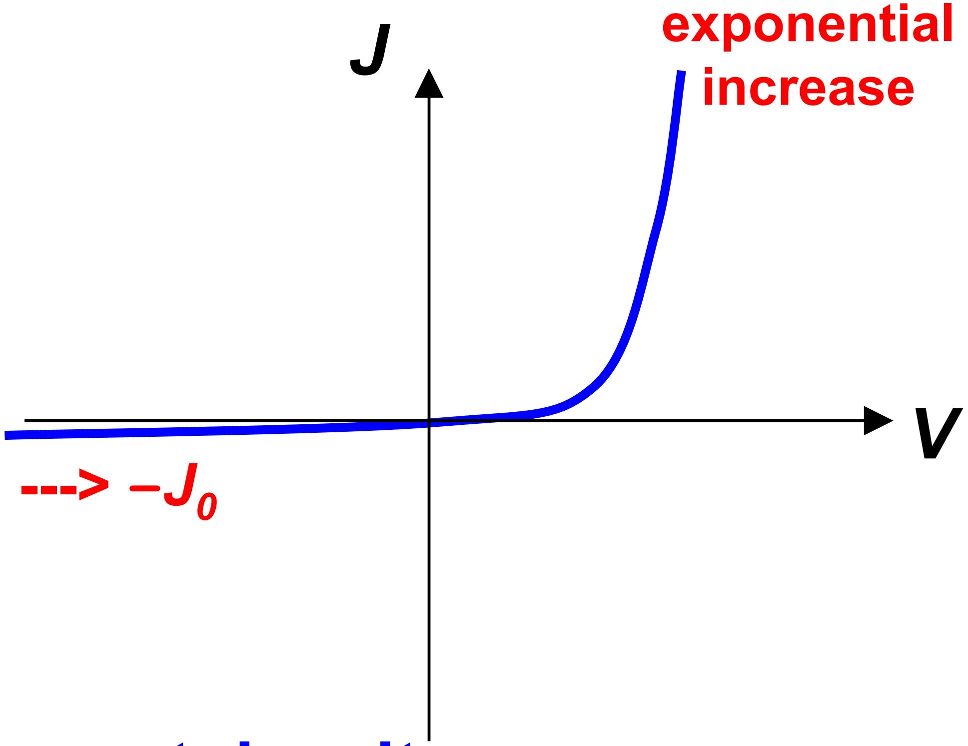
V_{bi} increases by V, W increases

little drift current, the junction is slightly conductive

Current-Voltage Relation

pn junction - diode 二极管

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



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

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

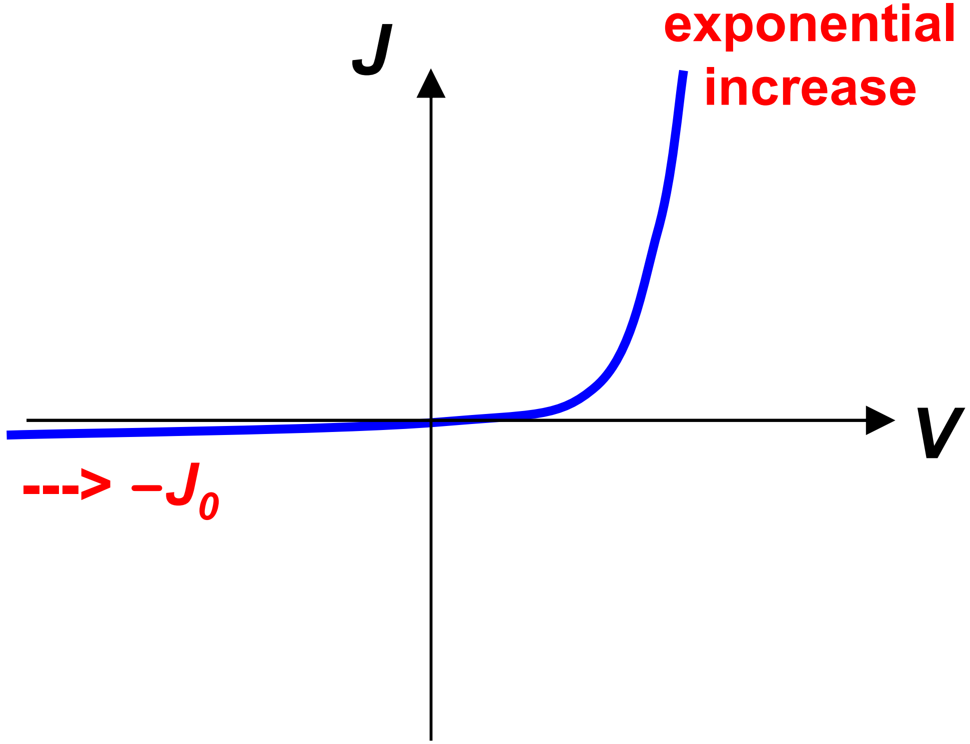
Current-Voltage Relation

pn junction - diode 二极管

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

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 (m^2/s) 扩散系数**
τ **- carrier lifetime (s)**
L **- diffusion length (m)**

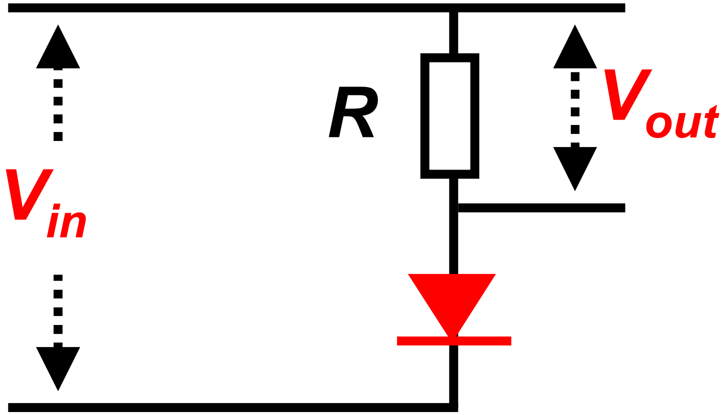
$$L = \sqrt{D\tau}$$

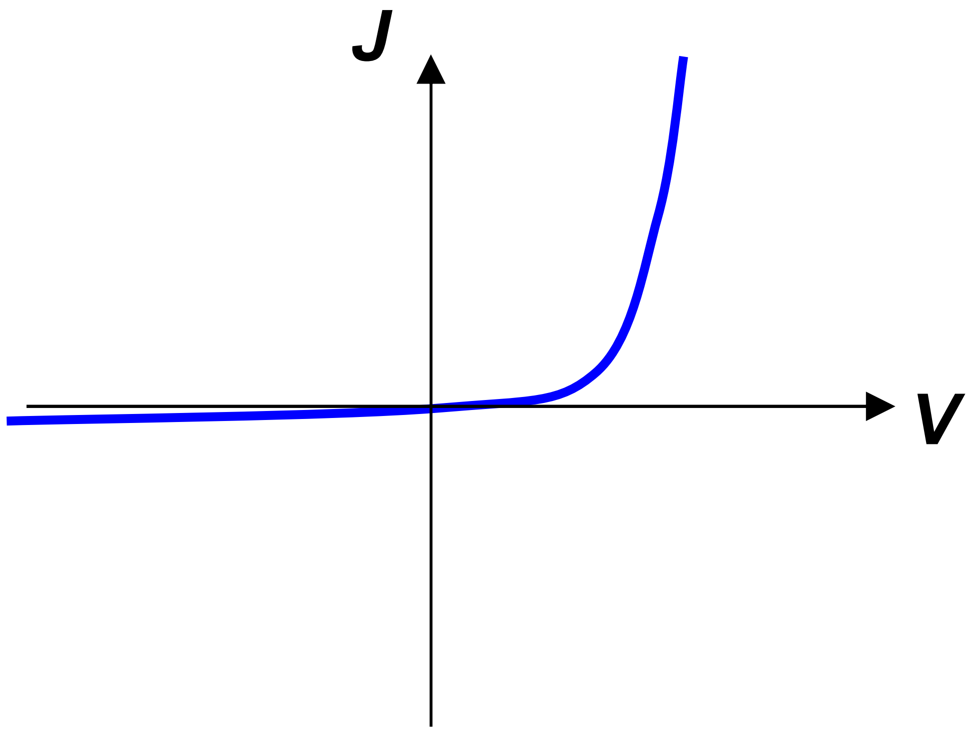
https://www.pveducation.org/pvcdrom/pn-junctions/example-1-general-solution-for-wide-base-p-n-junction

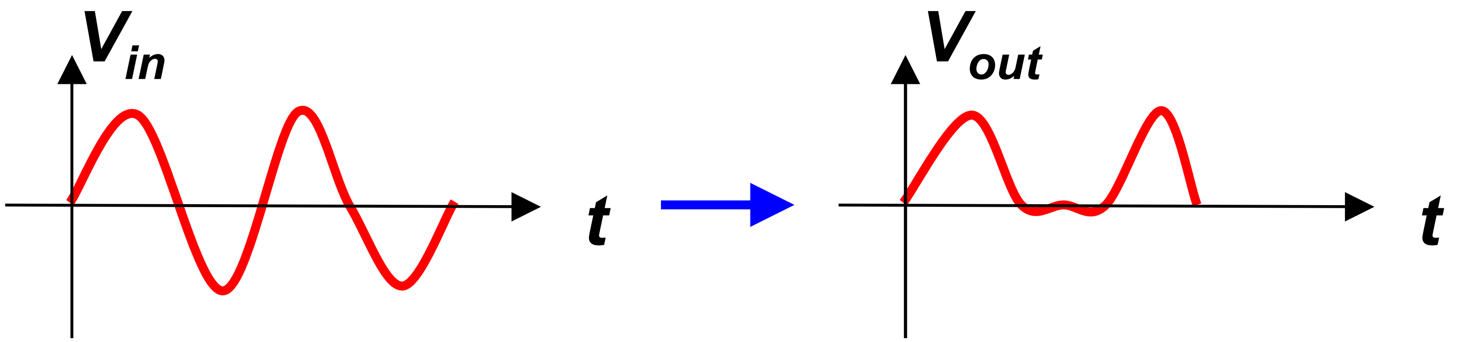
Current-Voltage Relation

pn junction - diode 二极管

rectifier 整流管

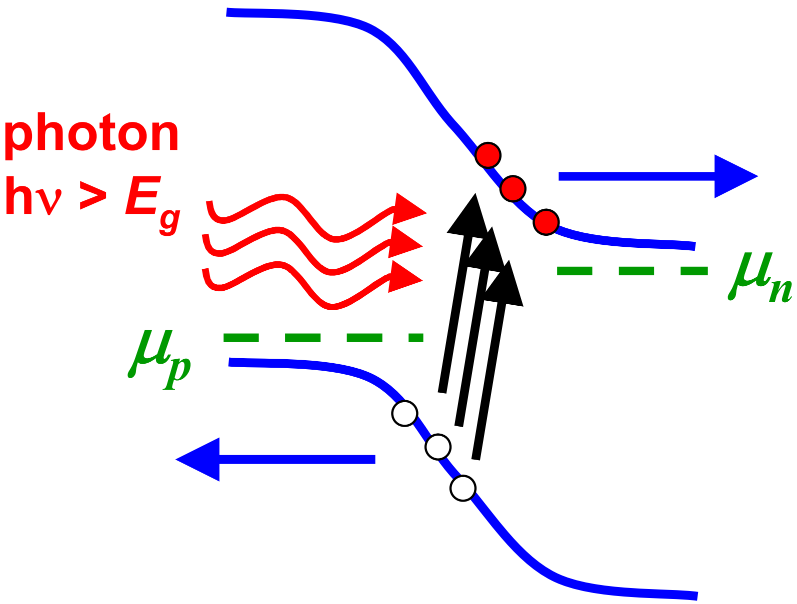




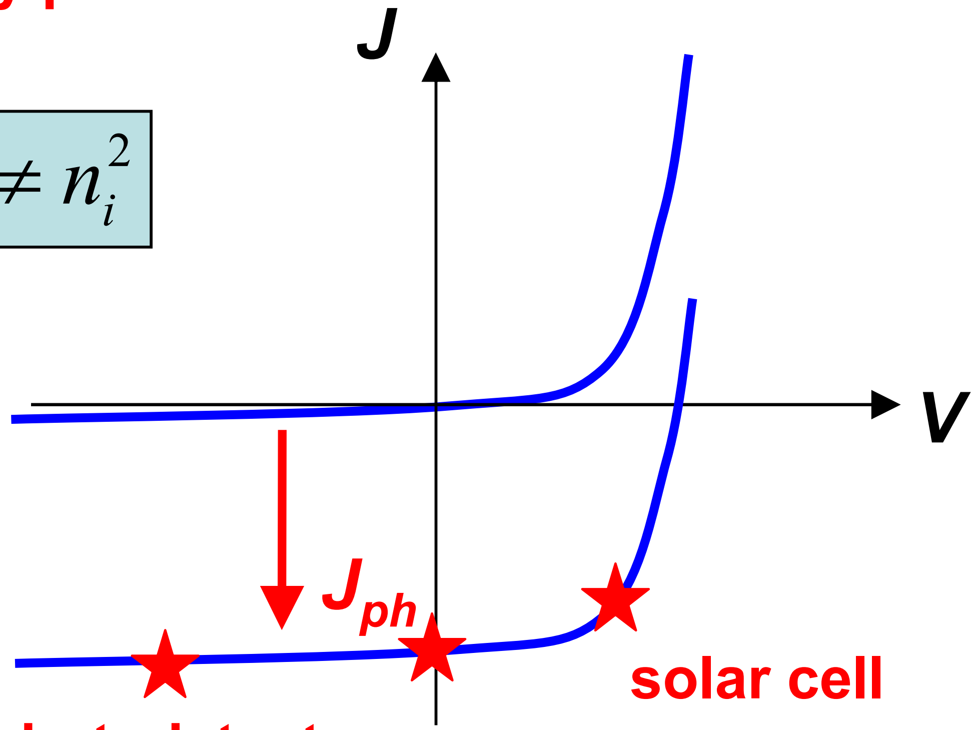


Solar Cell / Photodetector

extra carriers generated by photon
non-equilibrium



$$n_c p_v \neq n_i^2$$



solar cell

*power = I*V*

photodetector

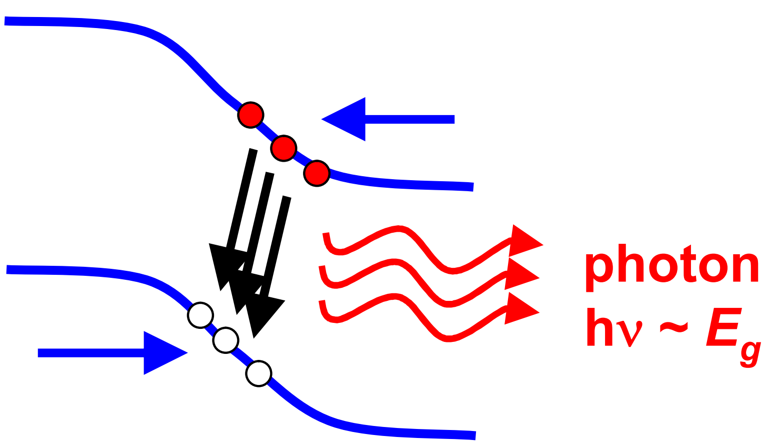
J_{ph} ~ light intensity

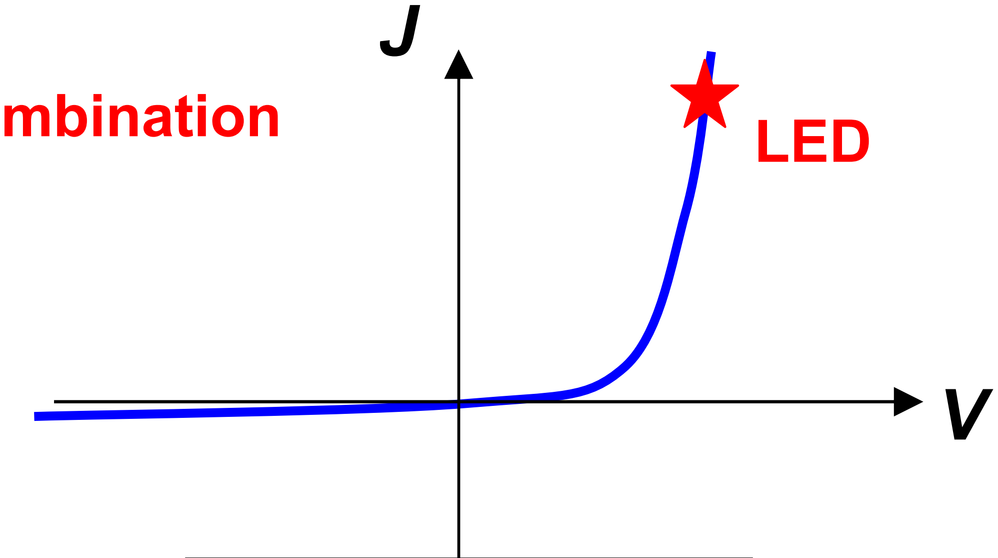
$$J = J_0\left[\exp\left(\frac{qV}{nk_BT}\right) - 1\right] - J_{ph}$$

photocurrent

Light-Emitting Diode (LED)

at forward bias
photon generation by radiative recombination



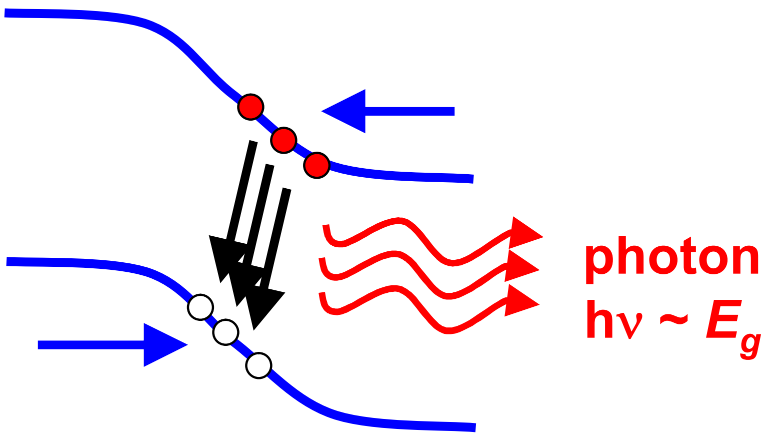


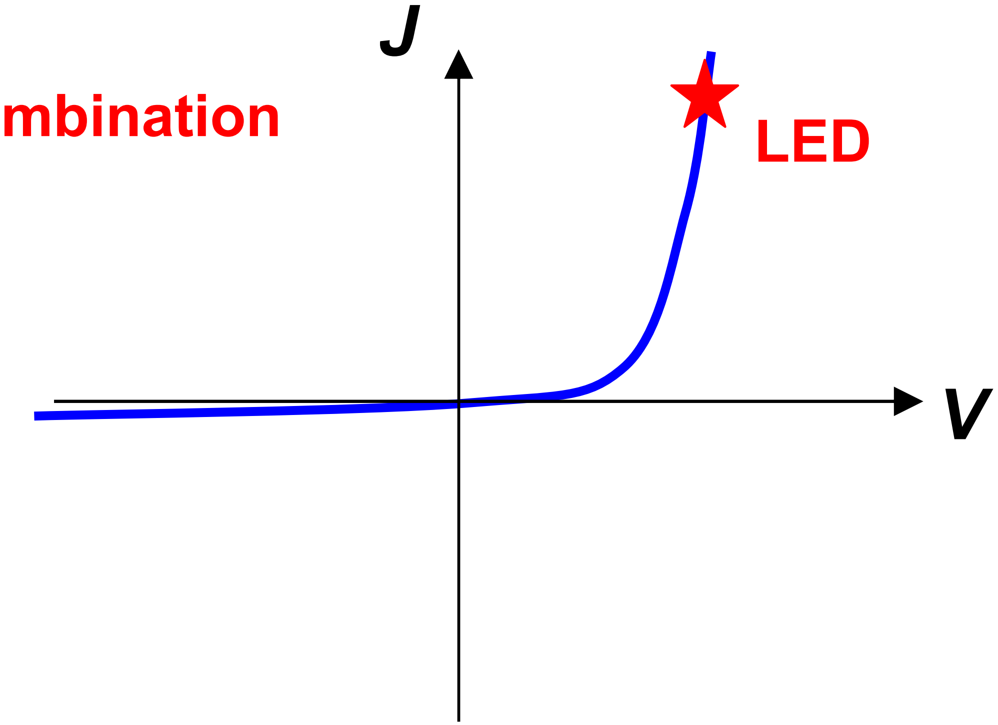
LEDs

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

Light-Emitting Diode (LED)

at forward bias
photon generation by radiative recombination





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

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

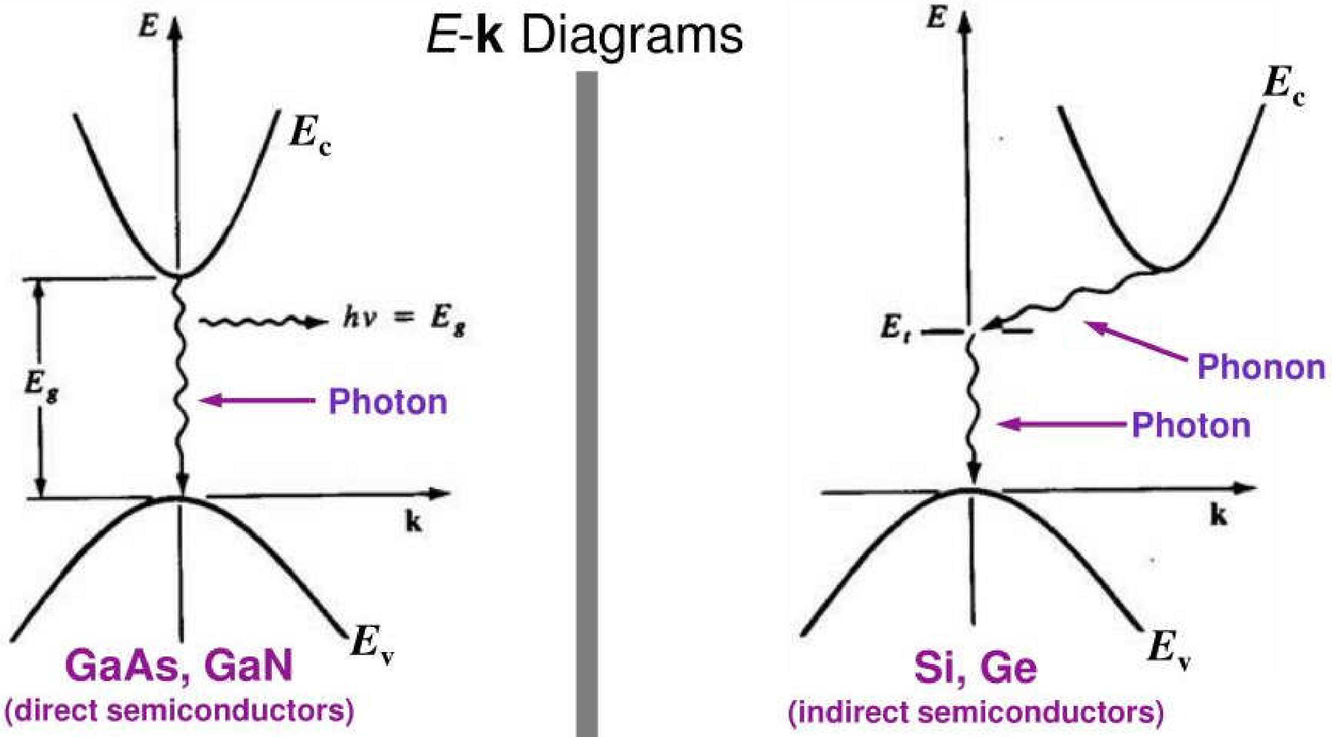
η - conversion efficiency

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

Light Emission Efficiency

E-**k** Diagrams

radiative recombination



GaAs, GaN
(direct semiconductors)

Si, Ge
(indirect semiconductors)

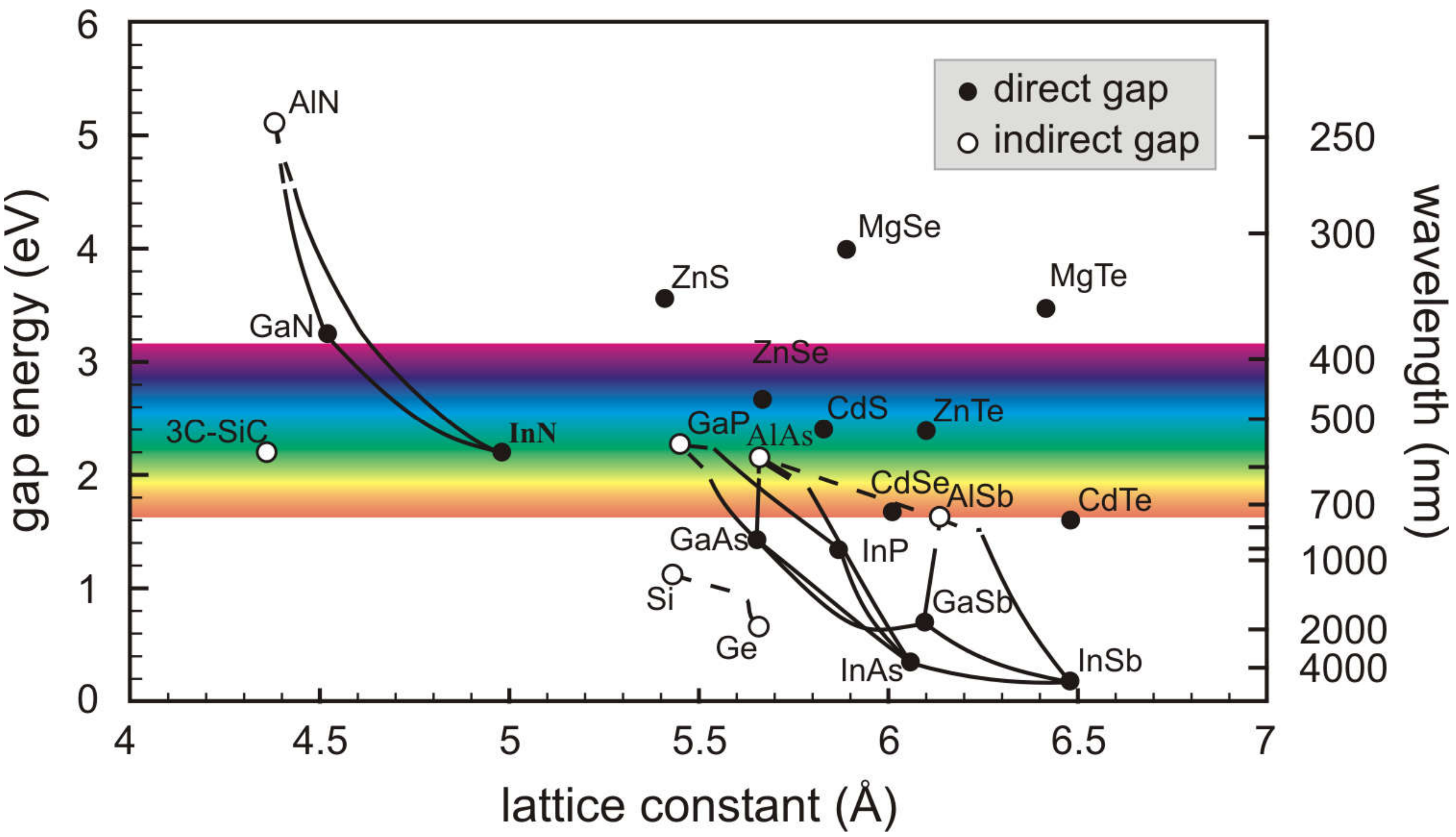
- Little change in momentum is required for recombination
- Momentum is conserved by photon (light) emission

- 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

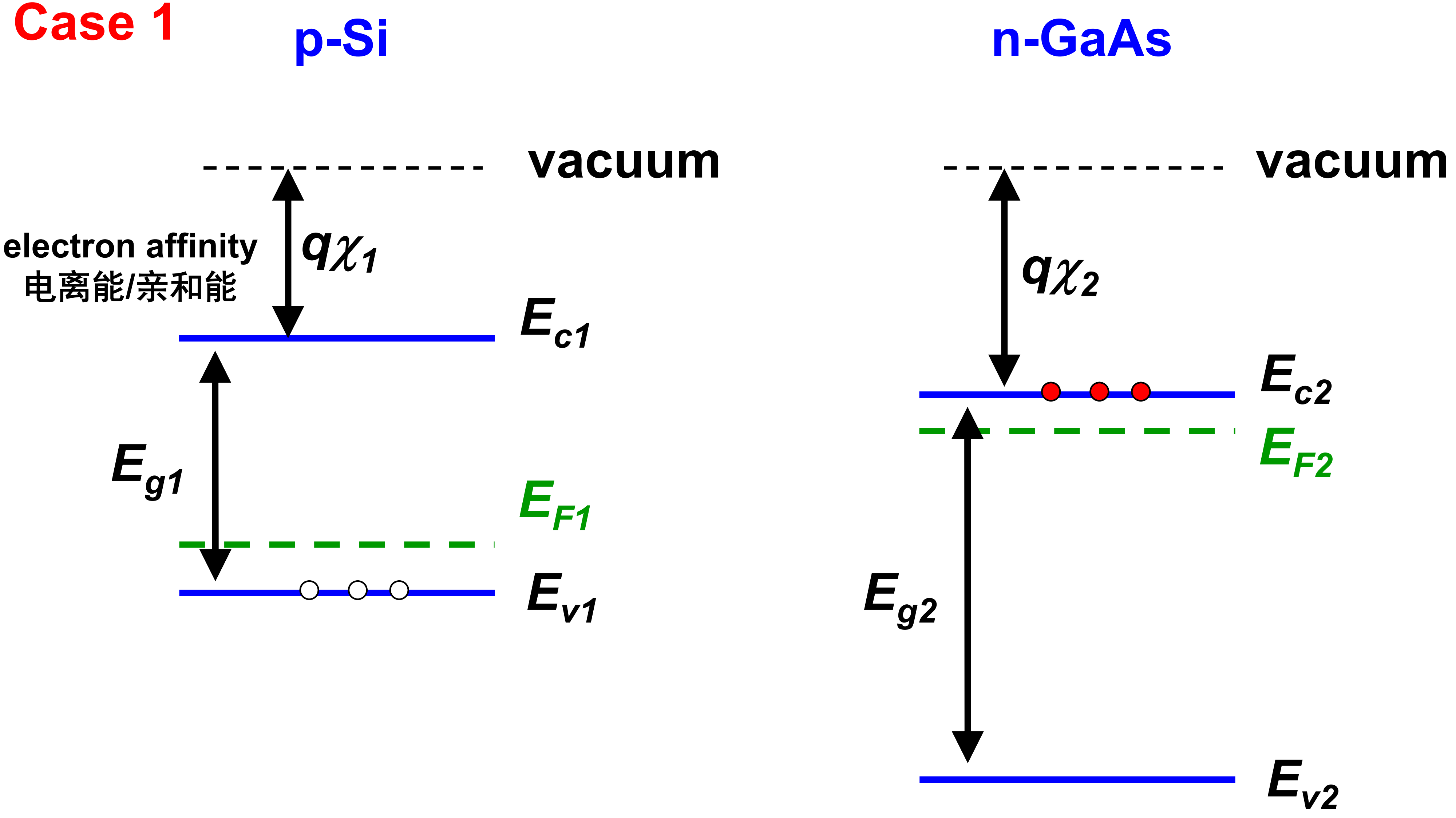
Materials Choices for Light Emission



Semiconductors with direct gaps are more suitable for LEDs and lasers

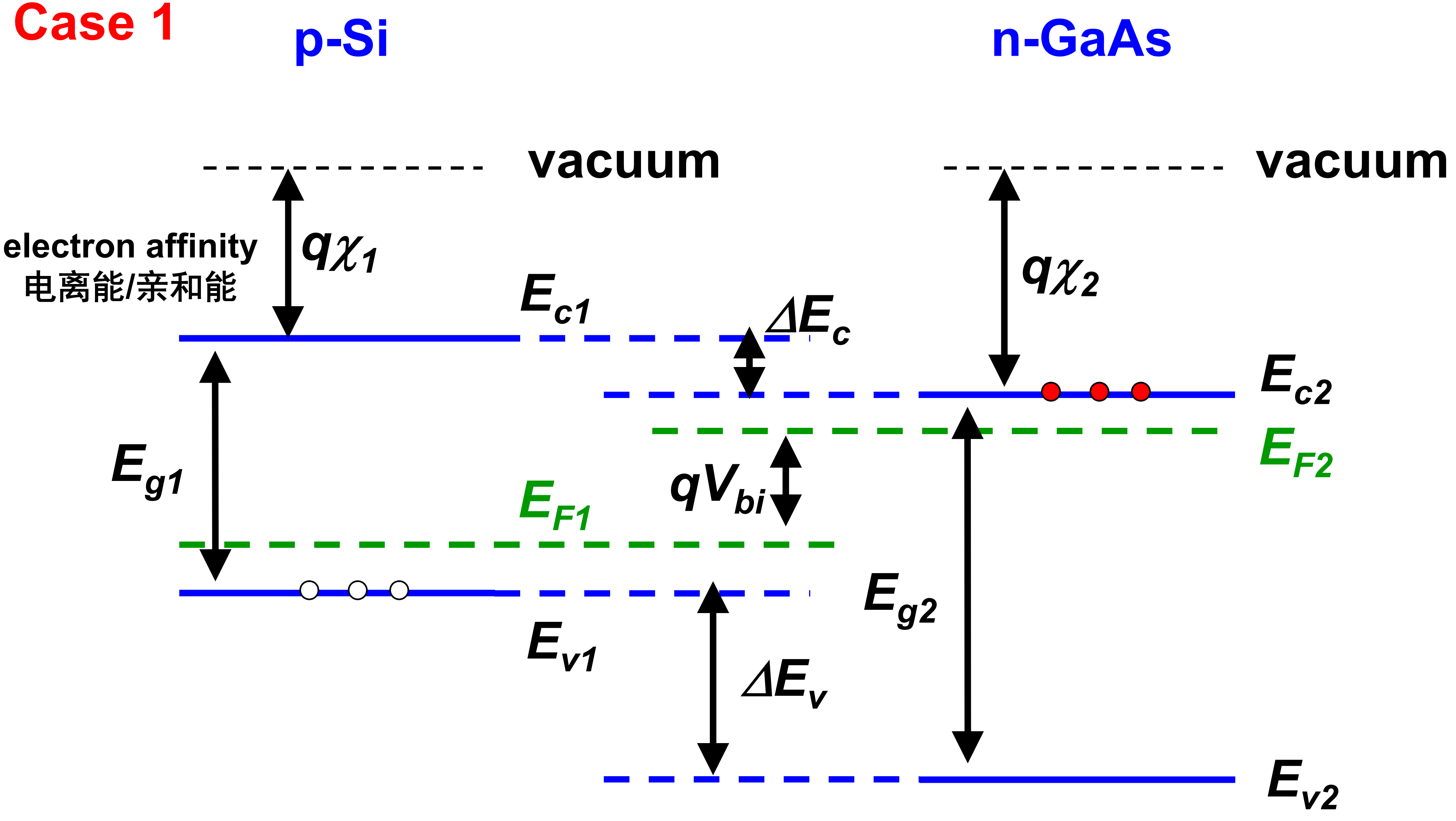
Heterojunction 异质结

Case 1



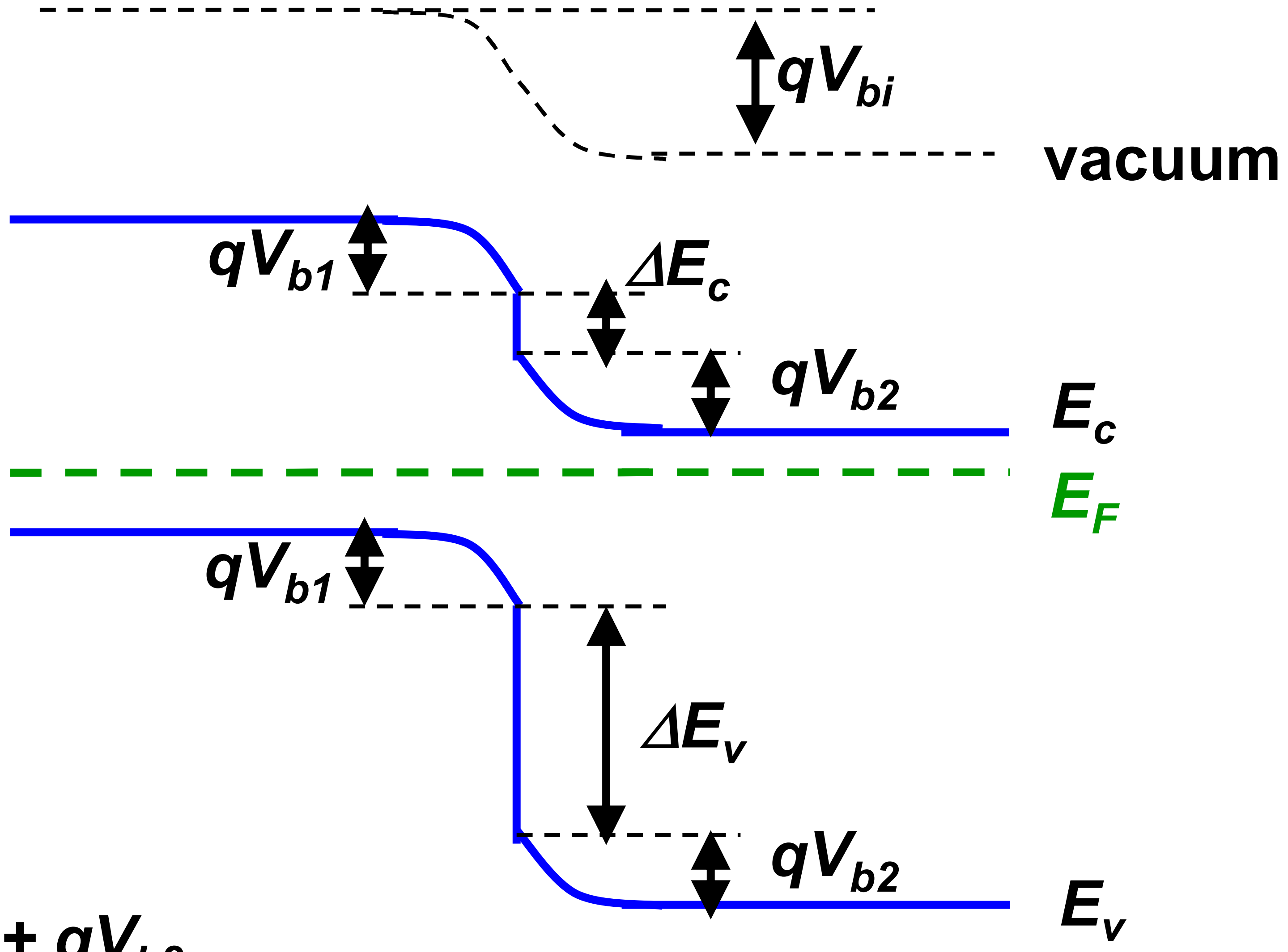
Heterojunction 异质结

Case 1



Heterojunction 异质结

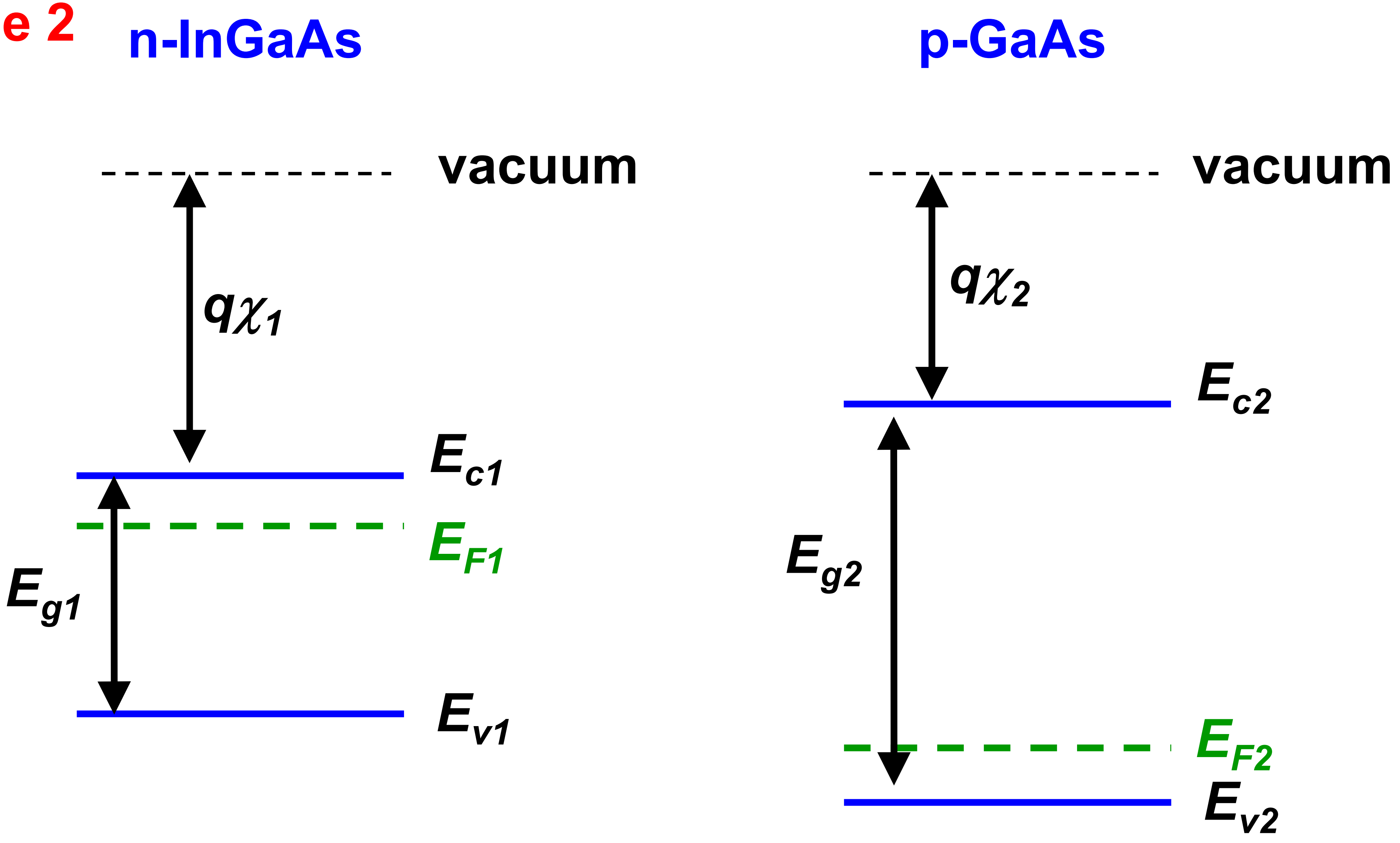
Case 1



$qV_b = qV_{b1} + qV_{b2}$

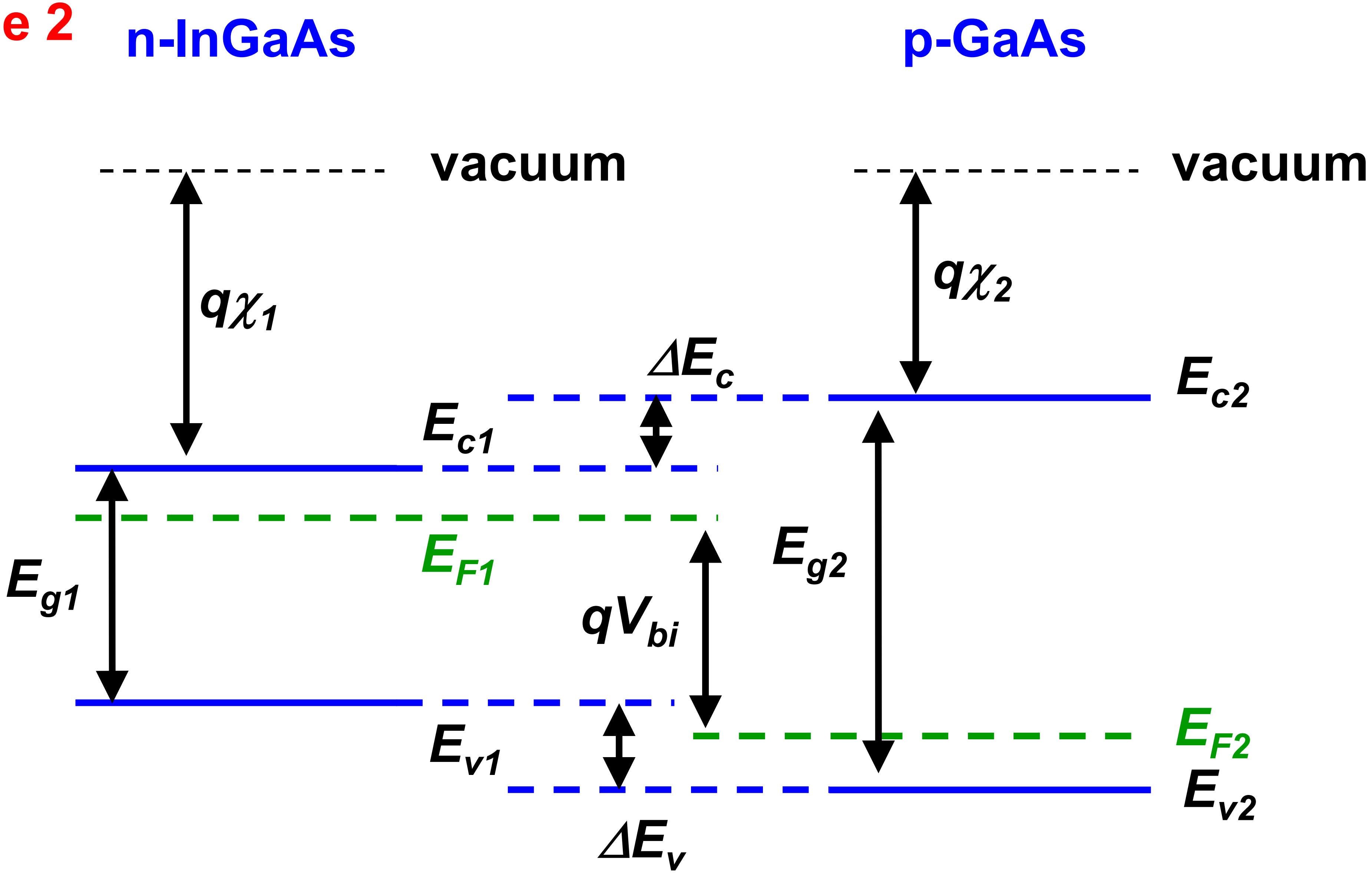
Heterojunction 异质结

Case 2



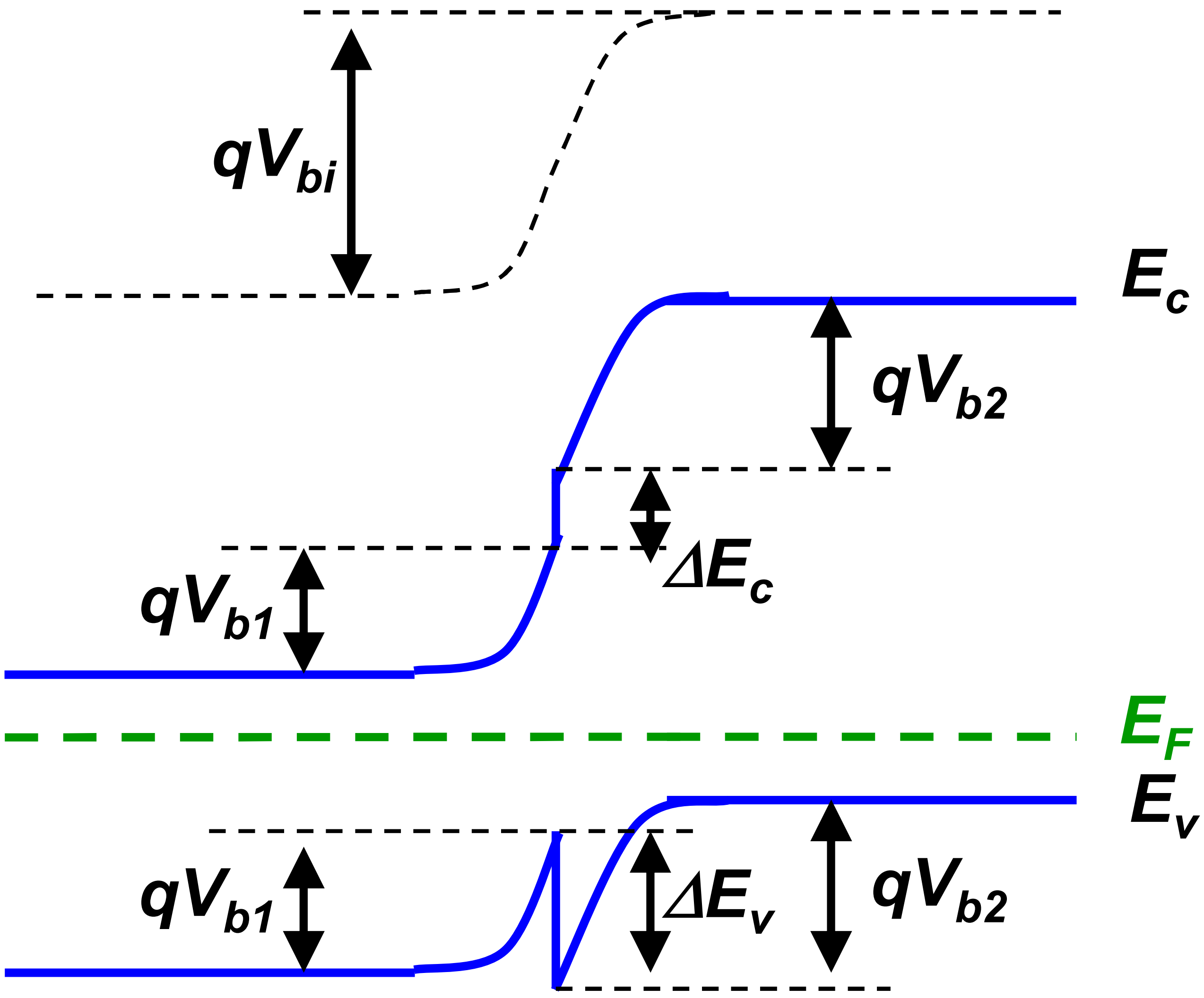
Heterojunction 异质结

Case 2



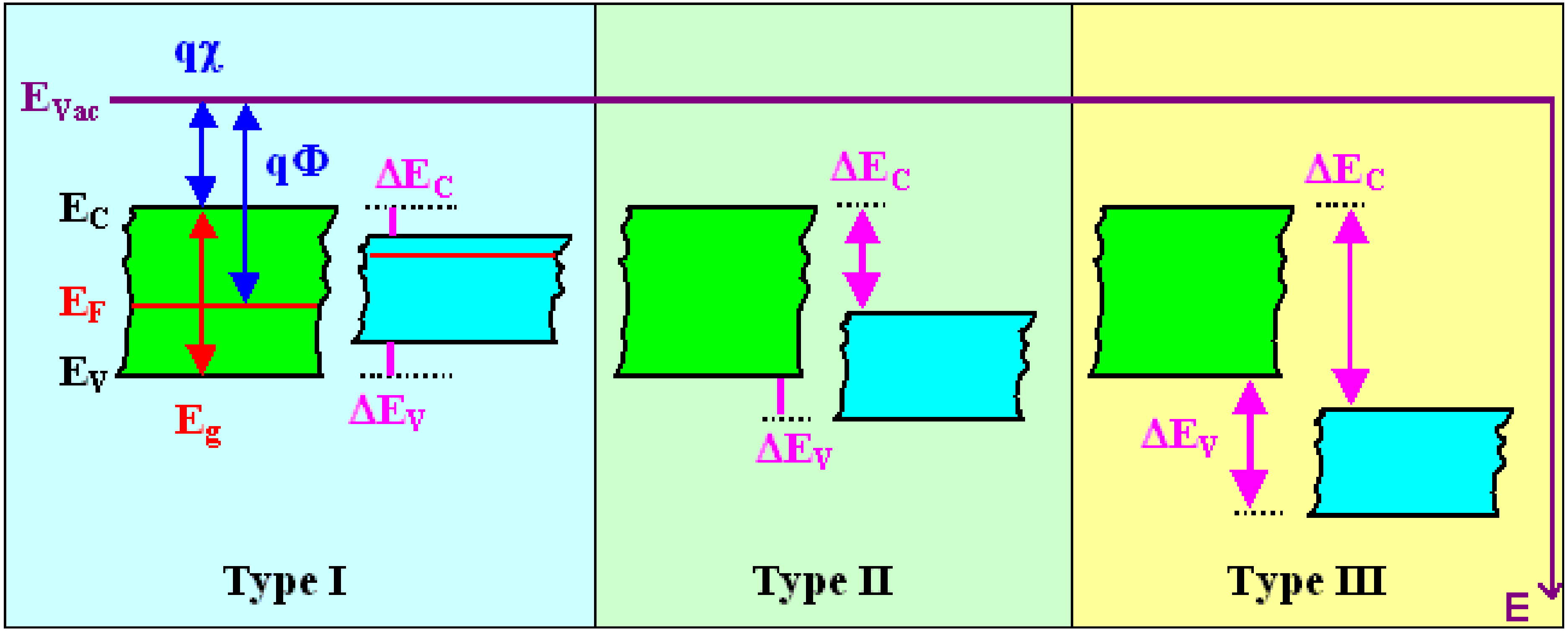
Heterojunction 异质结

Case 2



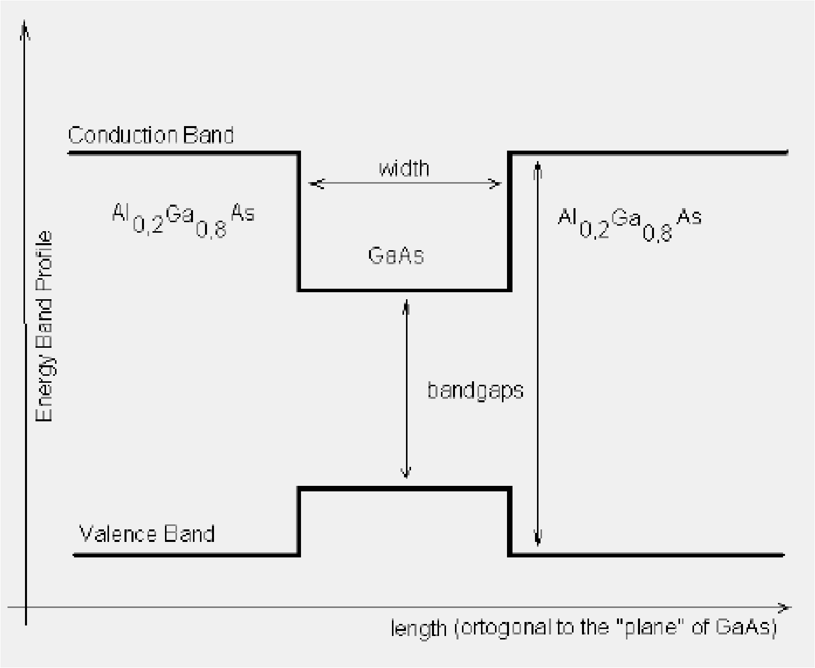
$$qV_b = qV_{b1} + qV_{b2}$$

Heterojunction 异质结



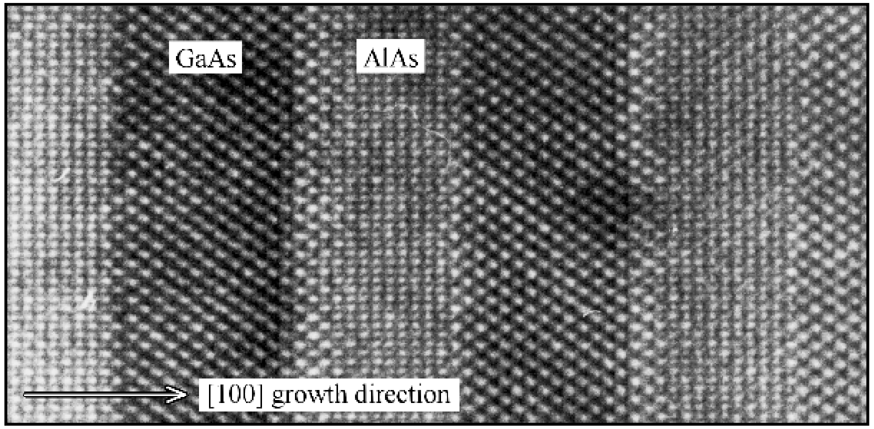
Straddling Gap **Staggered Gap** **Broken Gap**

Semiconductor Heterostructures



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

Z. I. Alferov



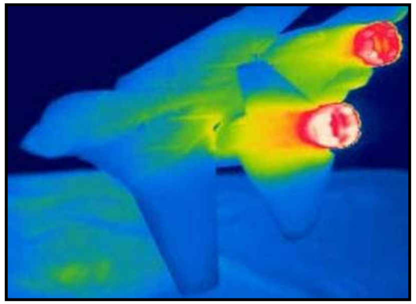
H. Kroemer

2000 Nobel Prize in Physics

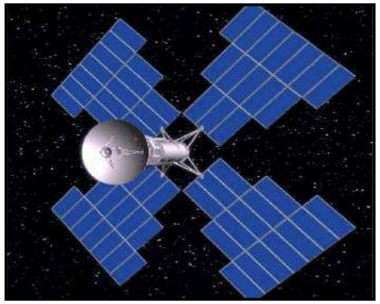
Optoelectronic Devices

LEDs

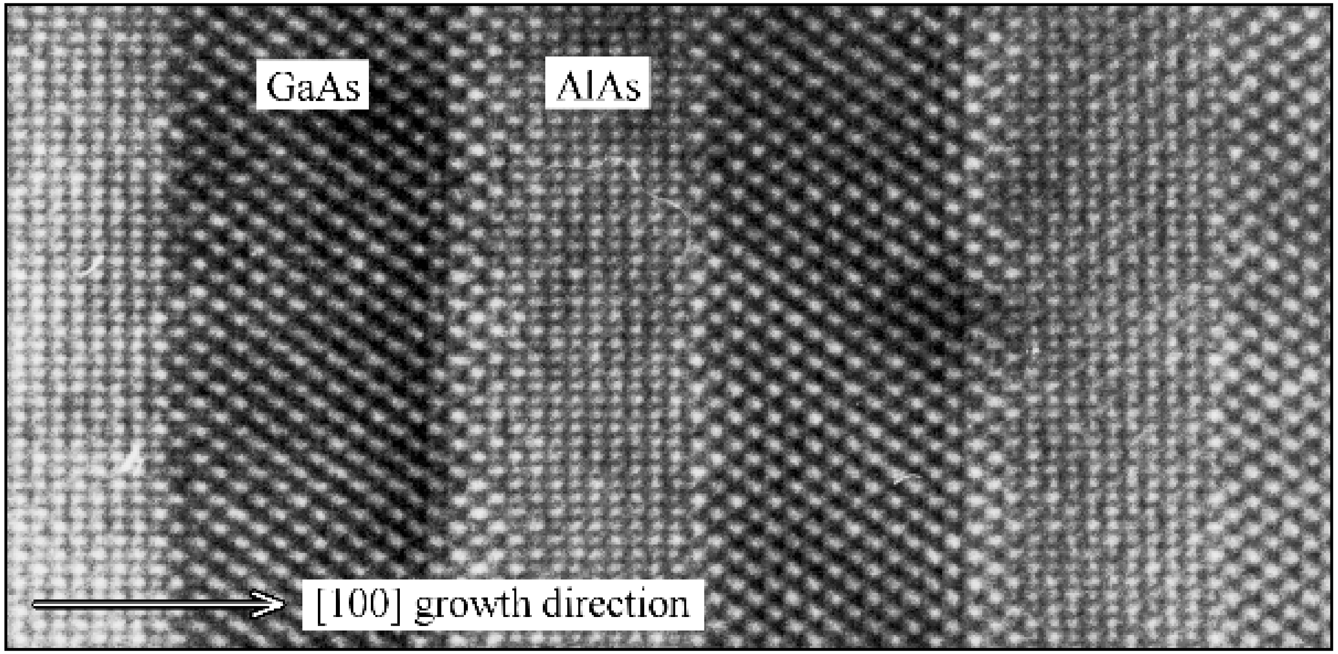
lasers



IR imaging

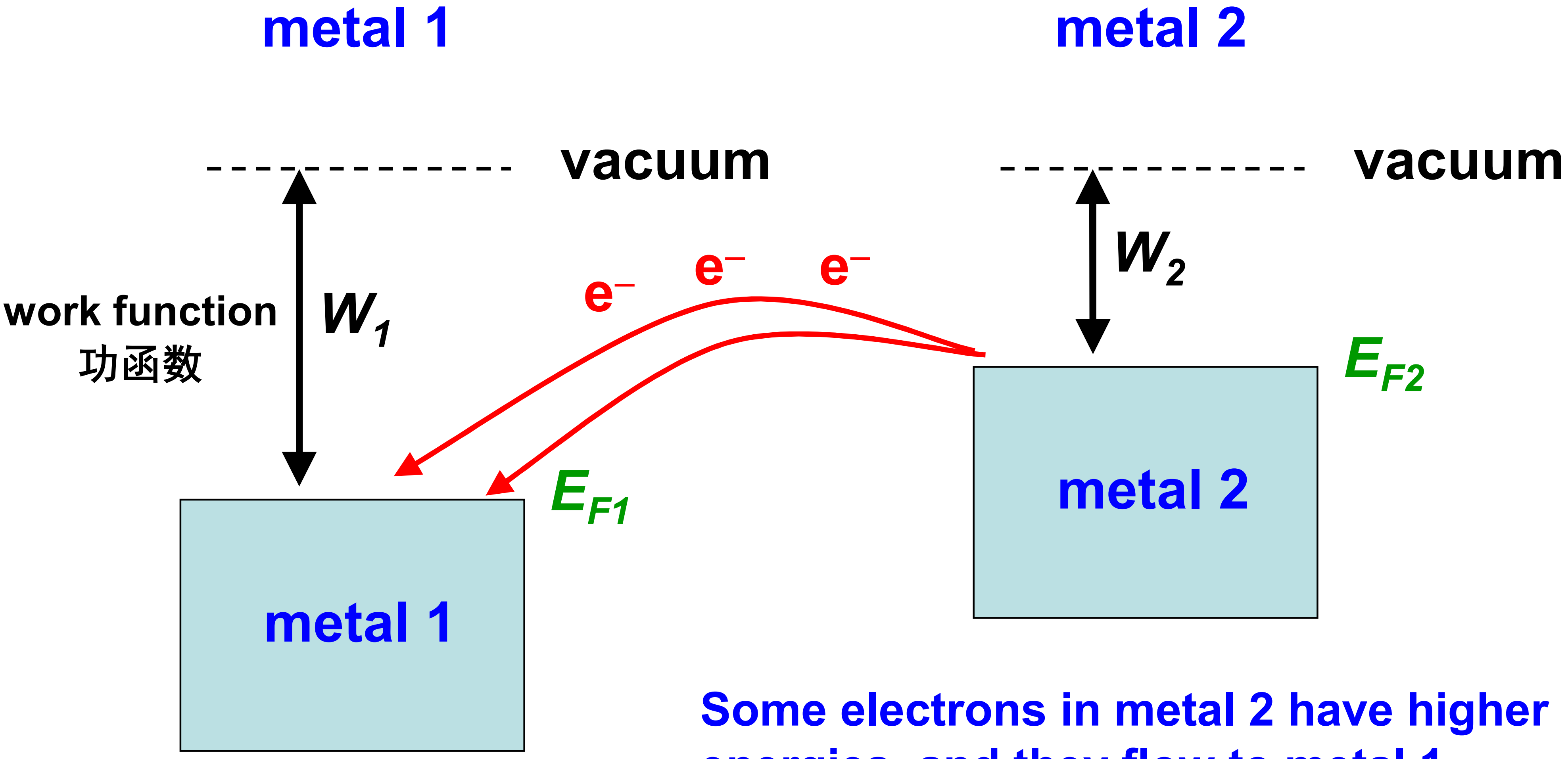


solar cells



Lattice matched GaAs/AlAs structure - perfect interface

Metal-Metal Junction

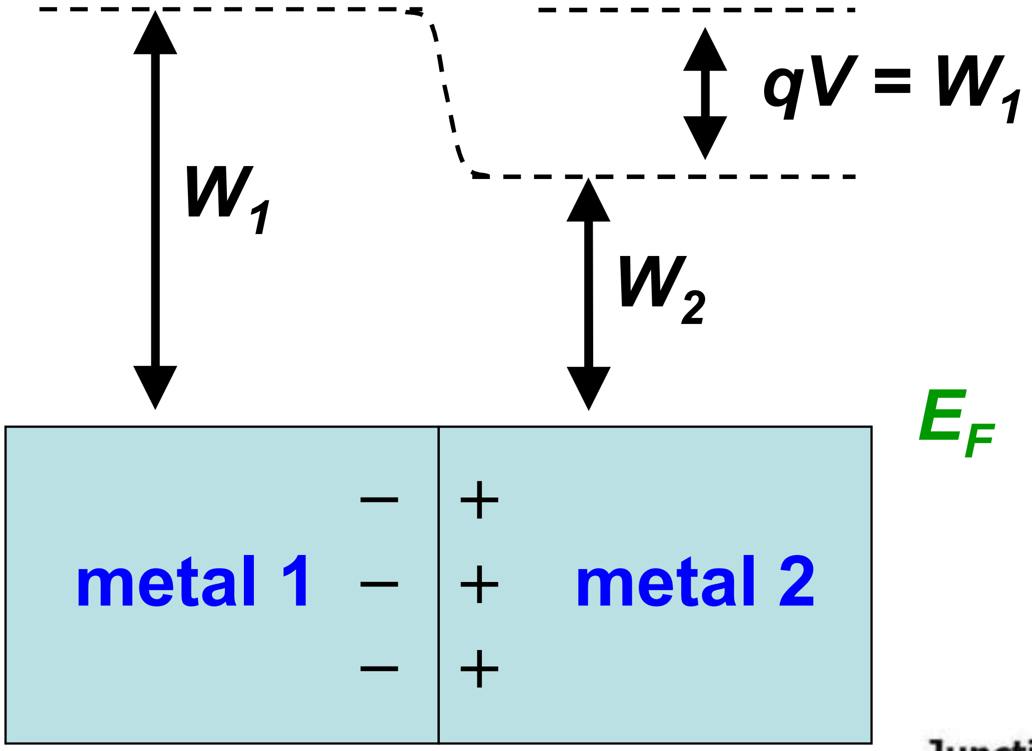


Some electrons in metal 2 have higher energies, and they flow to metal 1

metal 2 becomes more positive

Metal-Metal Junction

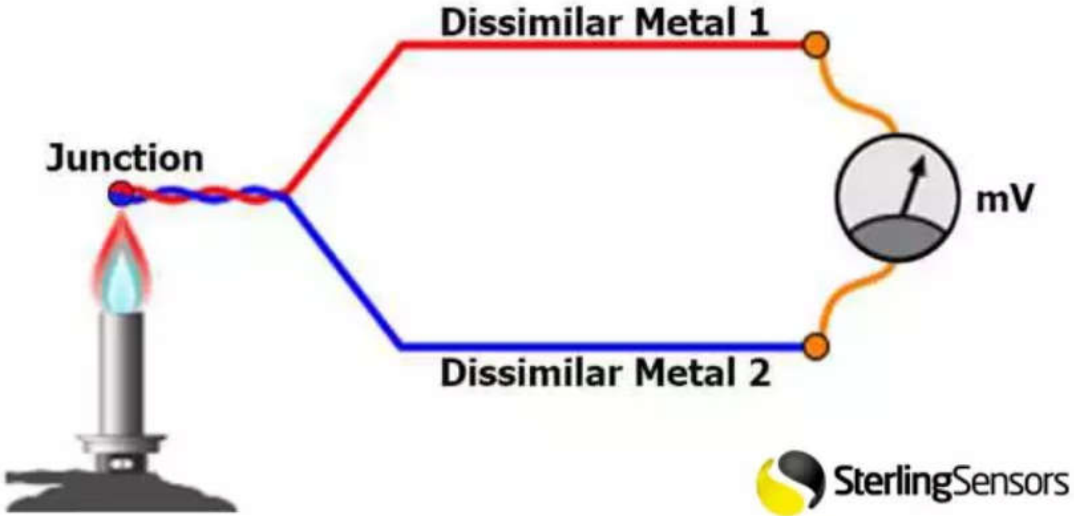
contact voltage (接触势)



$$qV = W_1 - W_2$$

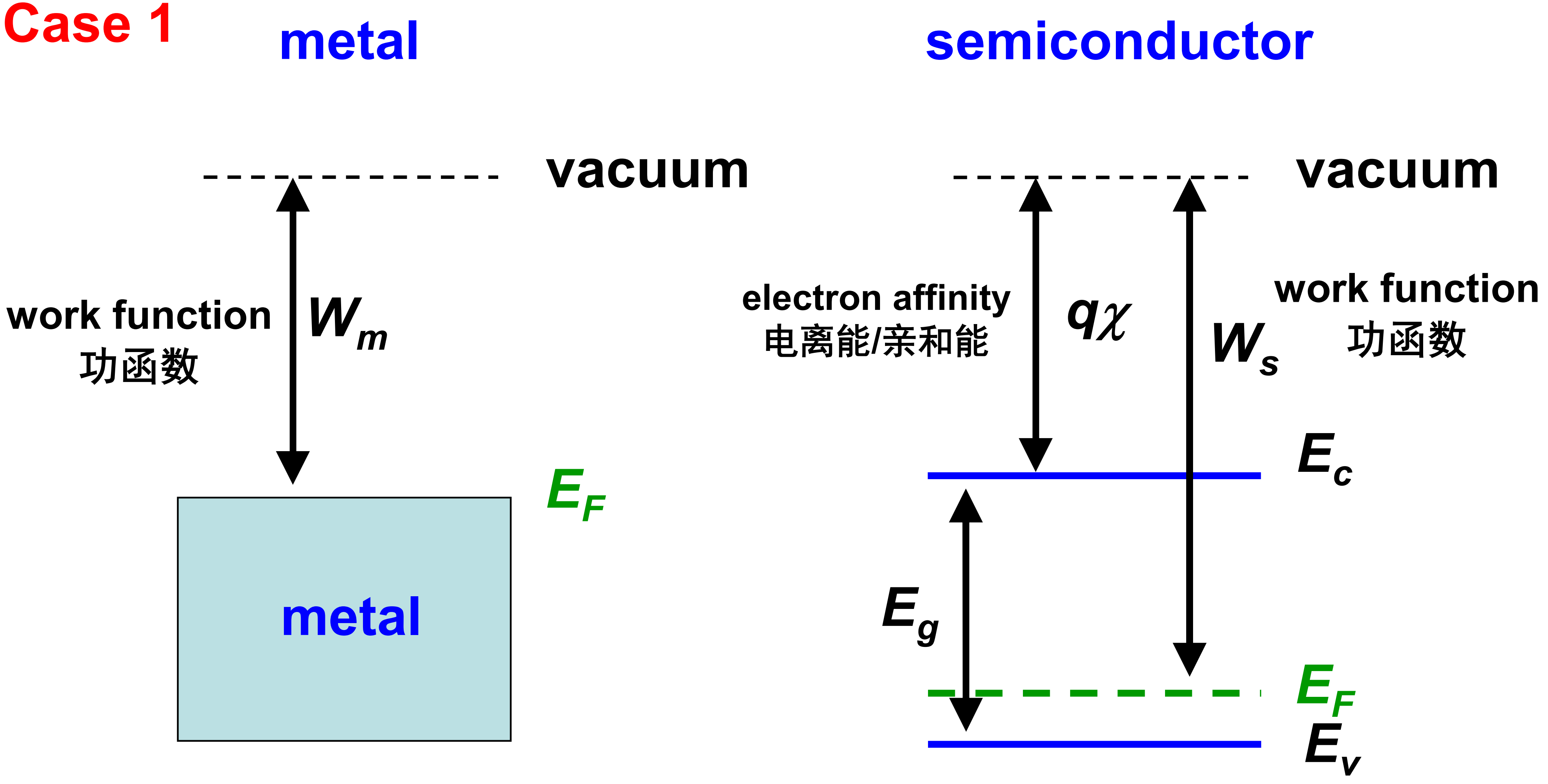
Application:

thermal couple 热电偶



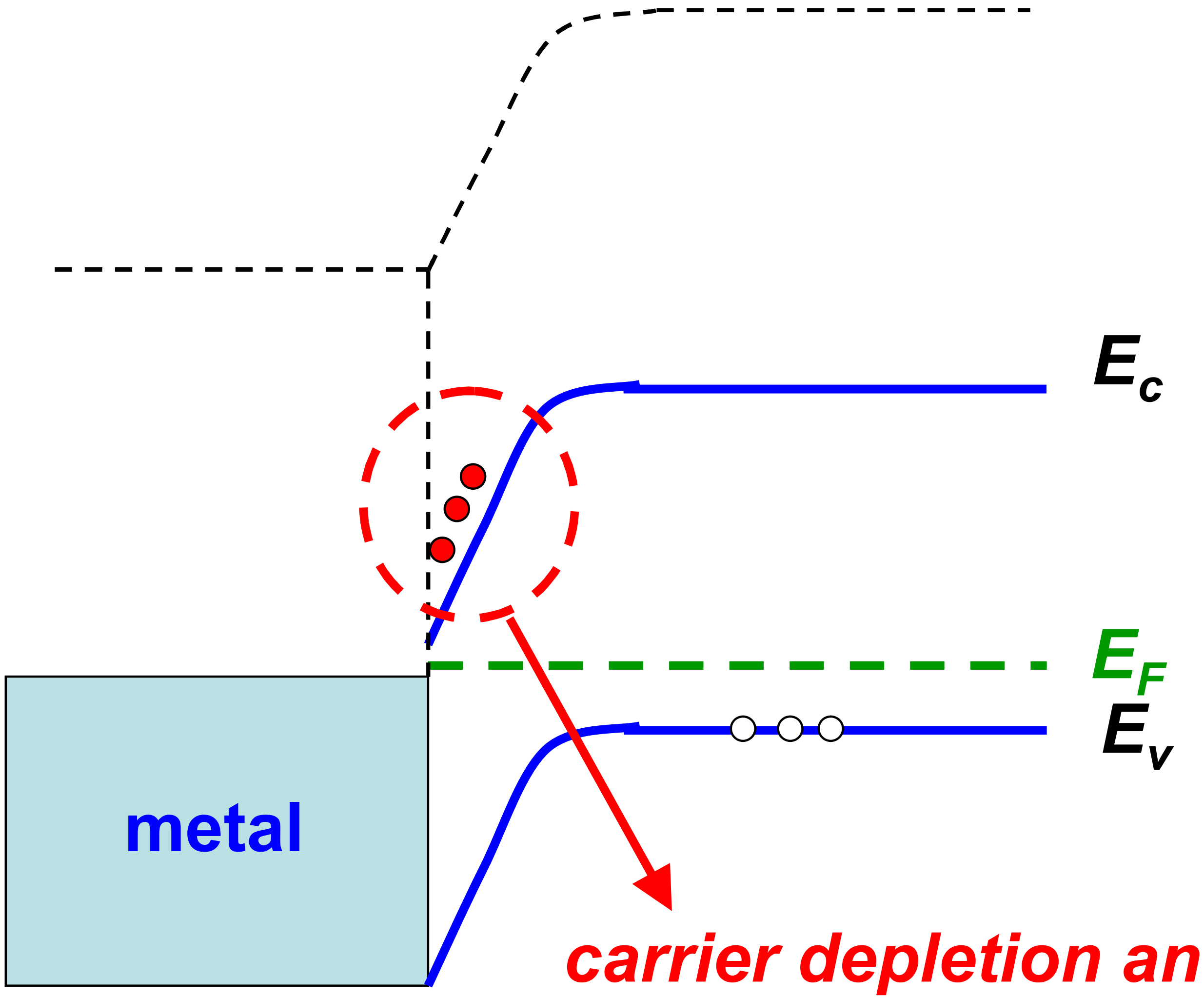
Metal-Semiconductor Junction

Case 1



Metal-Semiconductor Junction

Case 1 **Schottky contact 肖特基接触**

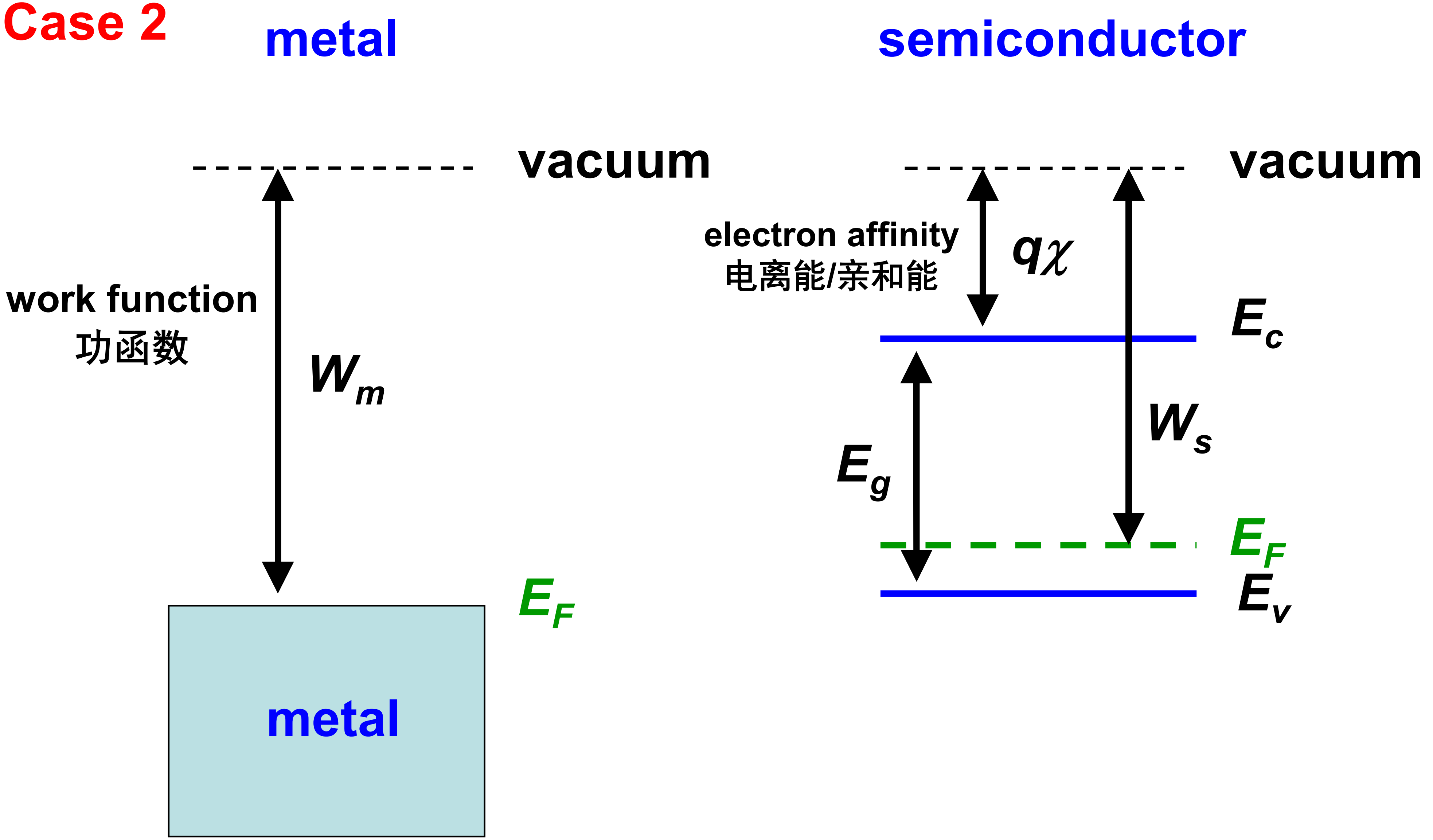


carrier depletion and inversion

(behave like a pn junction)

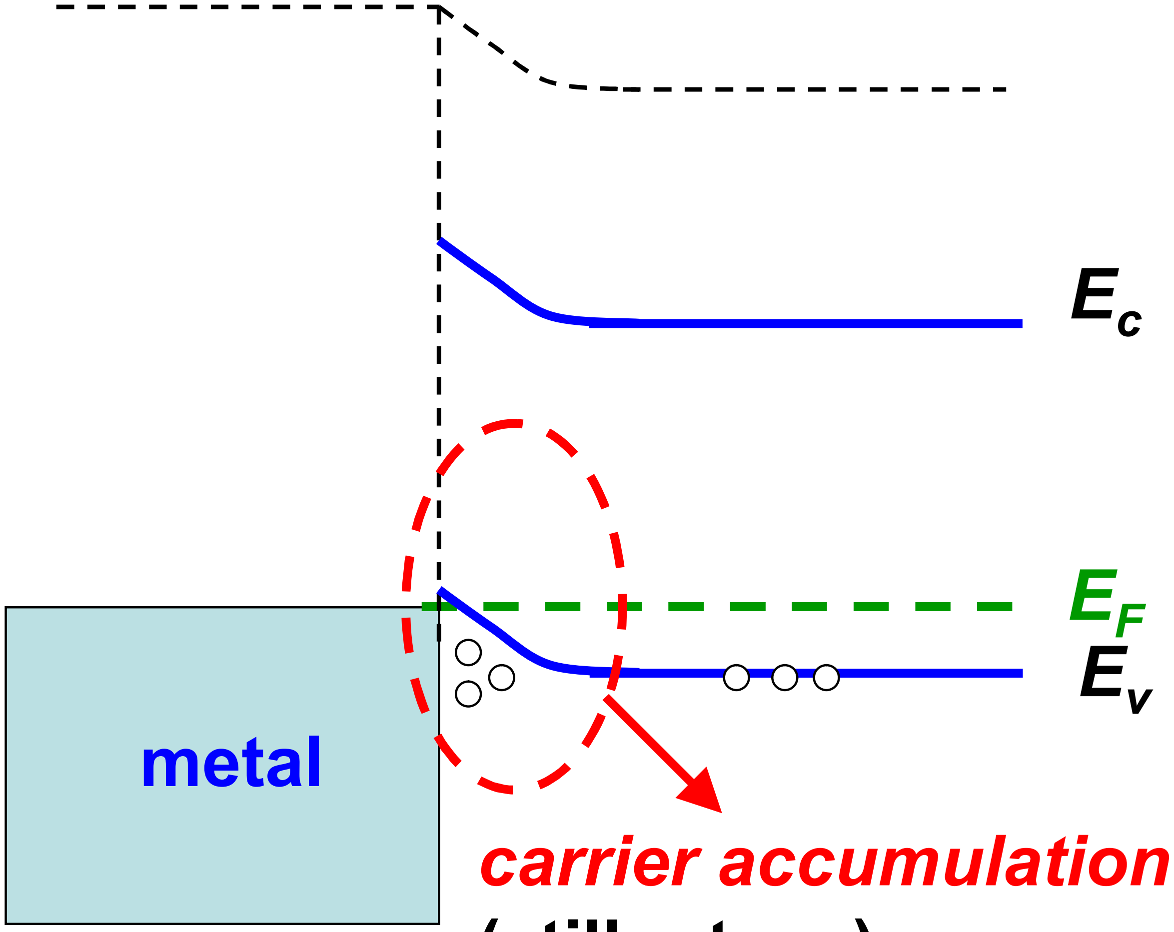
Metal-Semiconductor Junction

Case 2



Metal-Semiconductor Junction

Case 2 **Ohmic contact 欧姆接触**

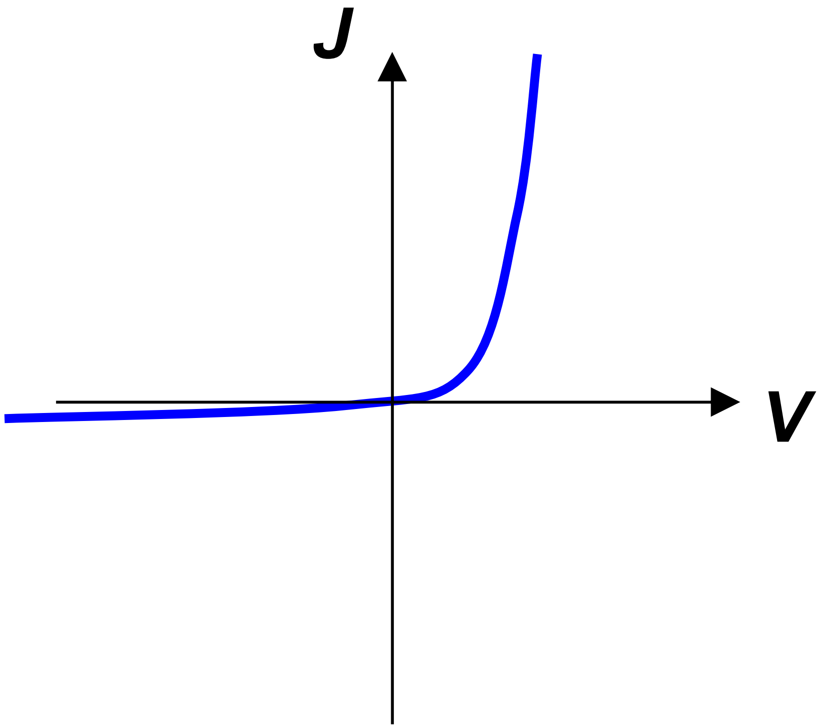


carrier accumulation

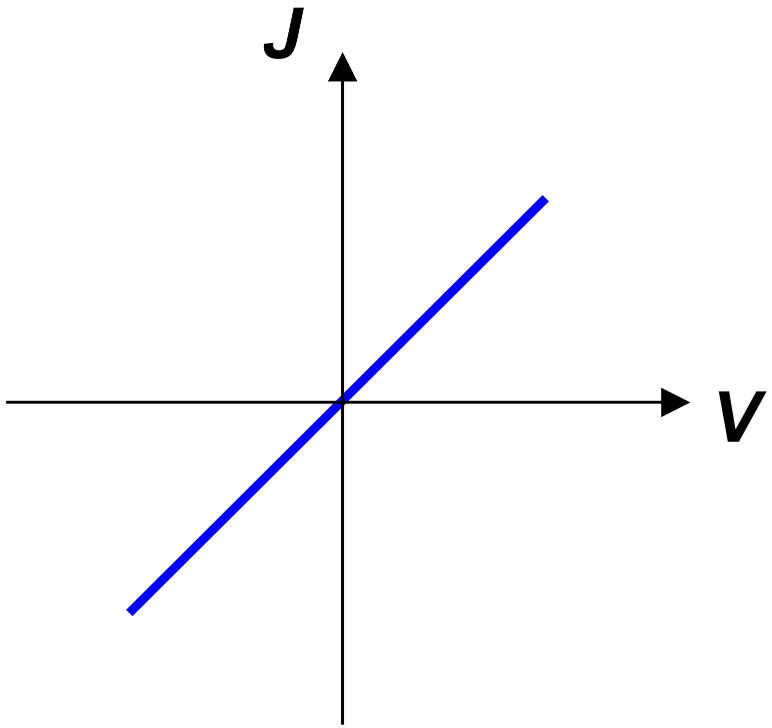
(still p-type)

Metal-Semiconductor Junction

Schottky contact 肖特基接触

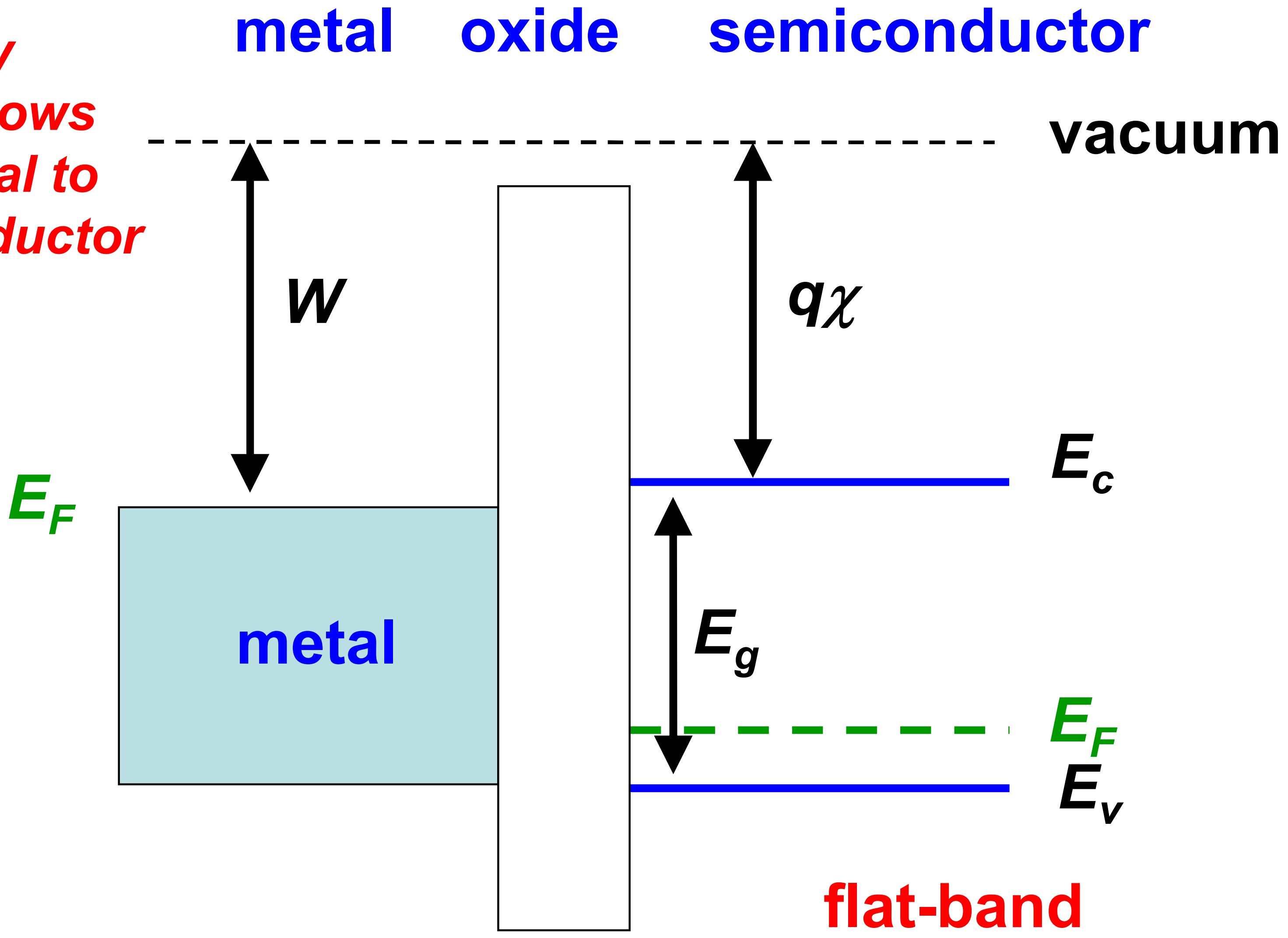


Ohmic contact 欧姆接触



Metal-Oxide-Semiconductor Junction

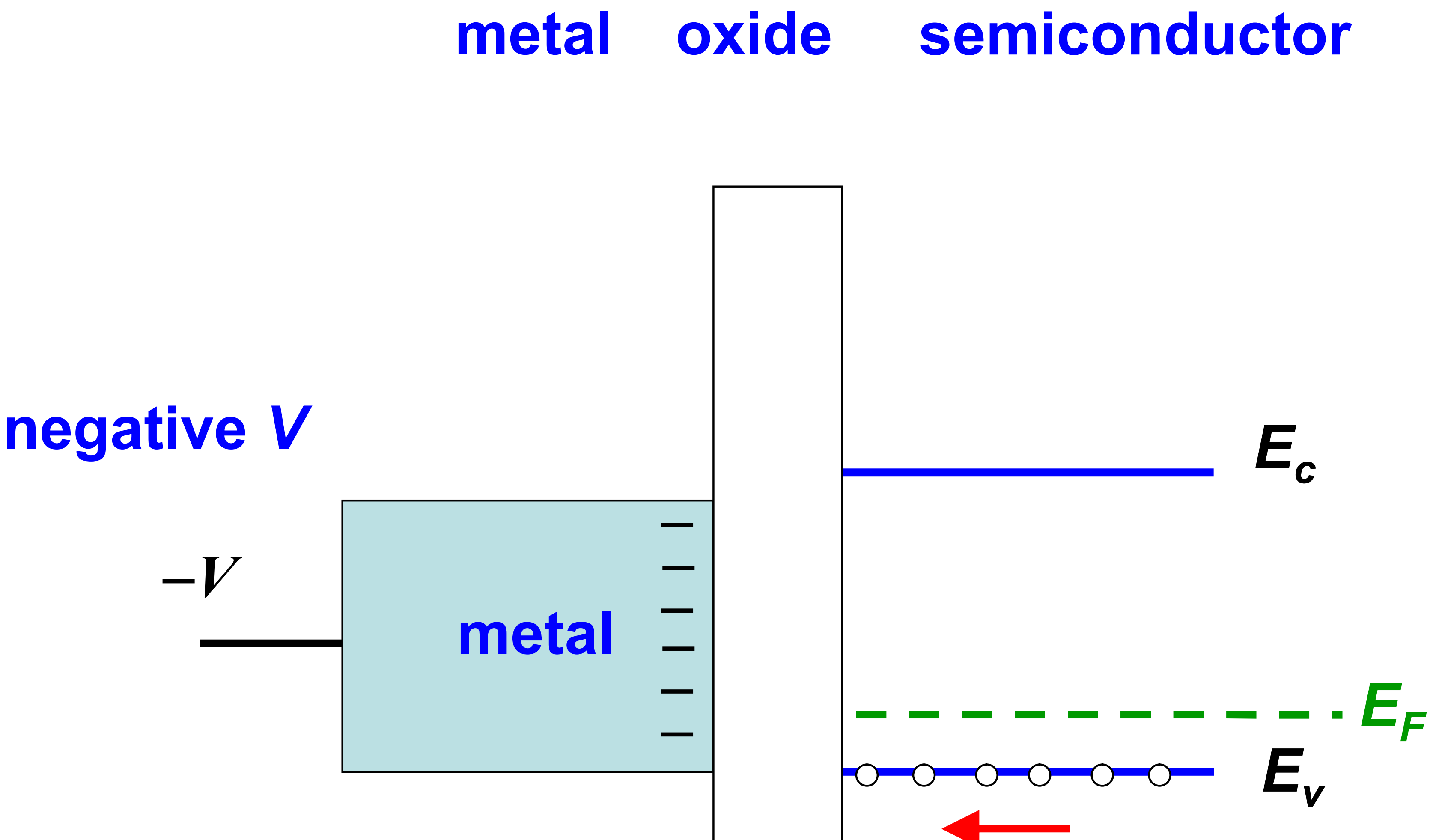
no steady current flows from metal to semiconductor



flat-band

insulator / capacitor

Metal-Oxide-Semiconductor Junction

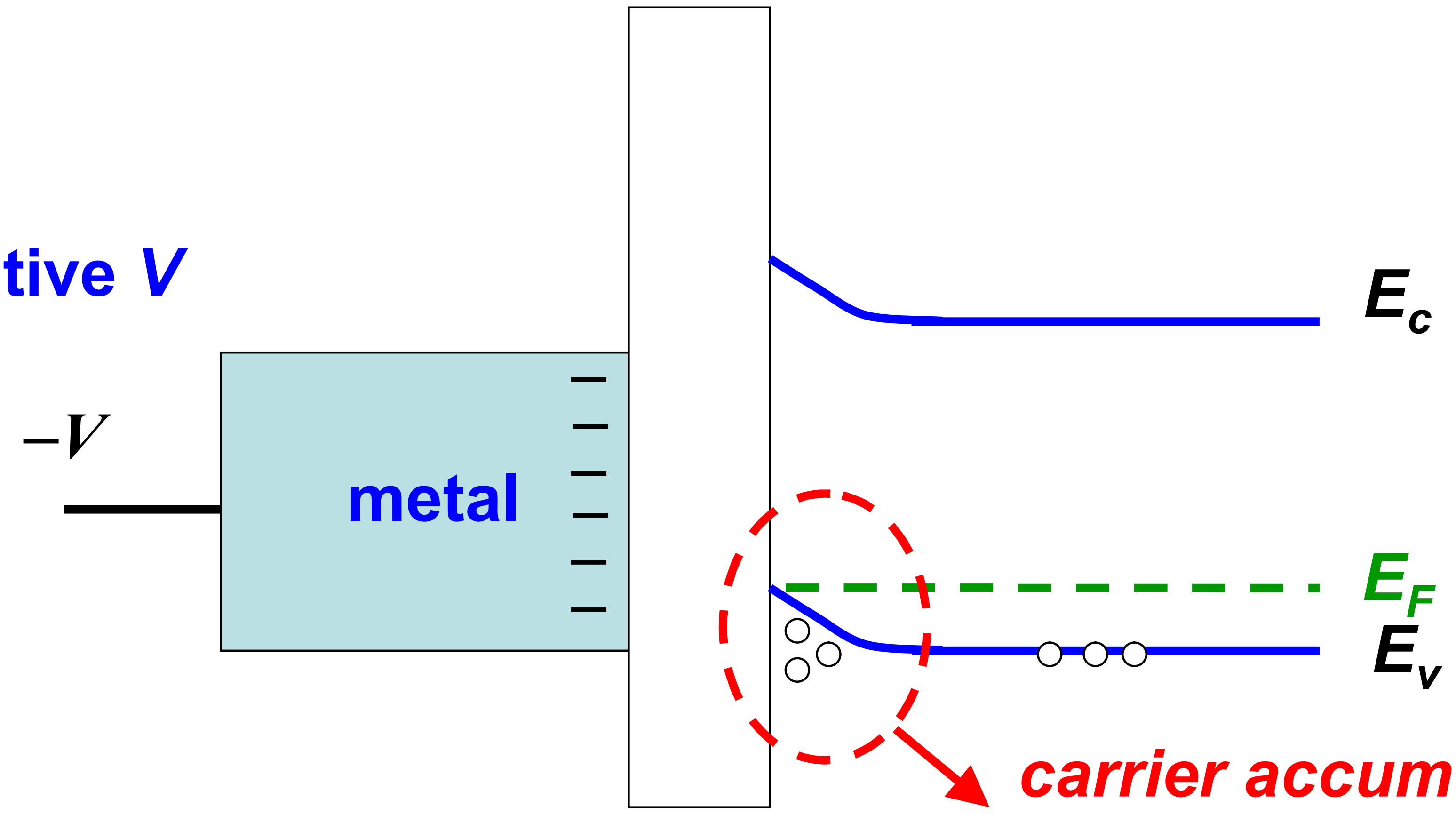


holes are attracted towards the junction

Metal-Oxide-Semiconductor Junction

metal **oxide** **semiconductor**

negative *V*

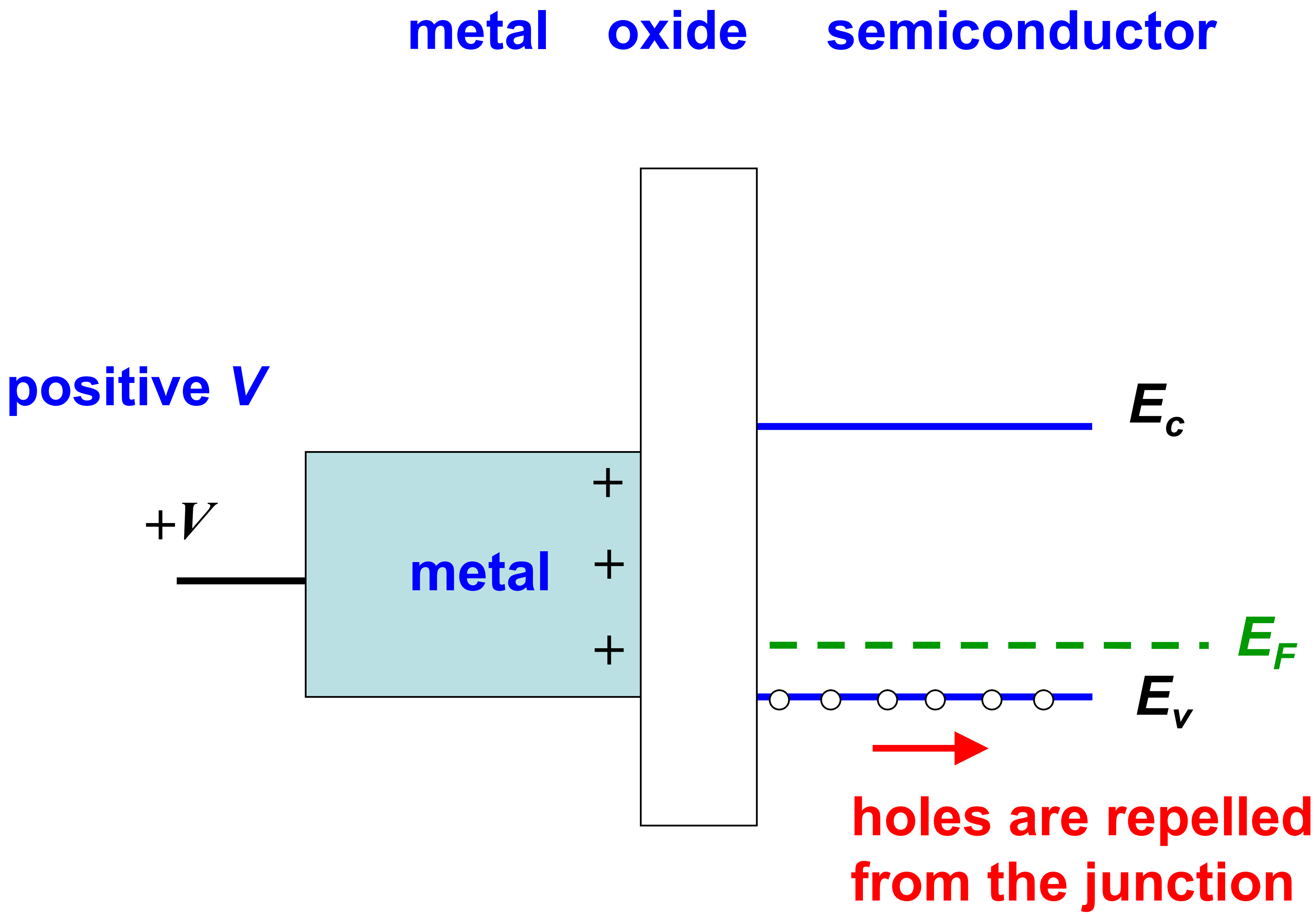


carrier accumulation

富集

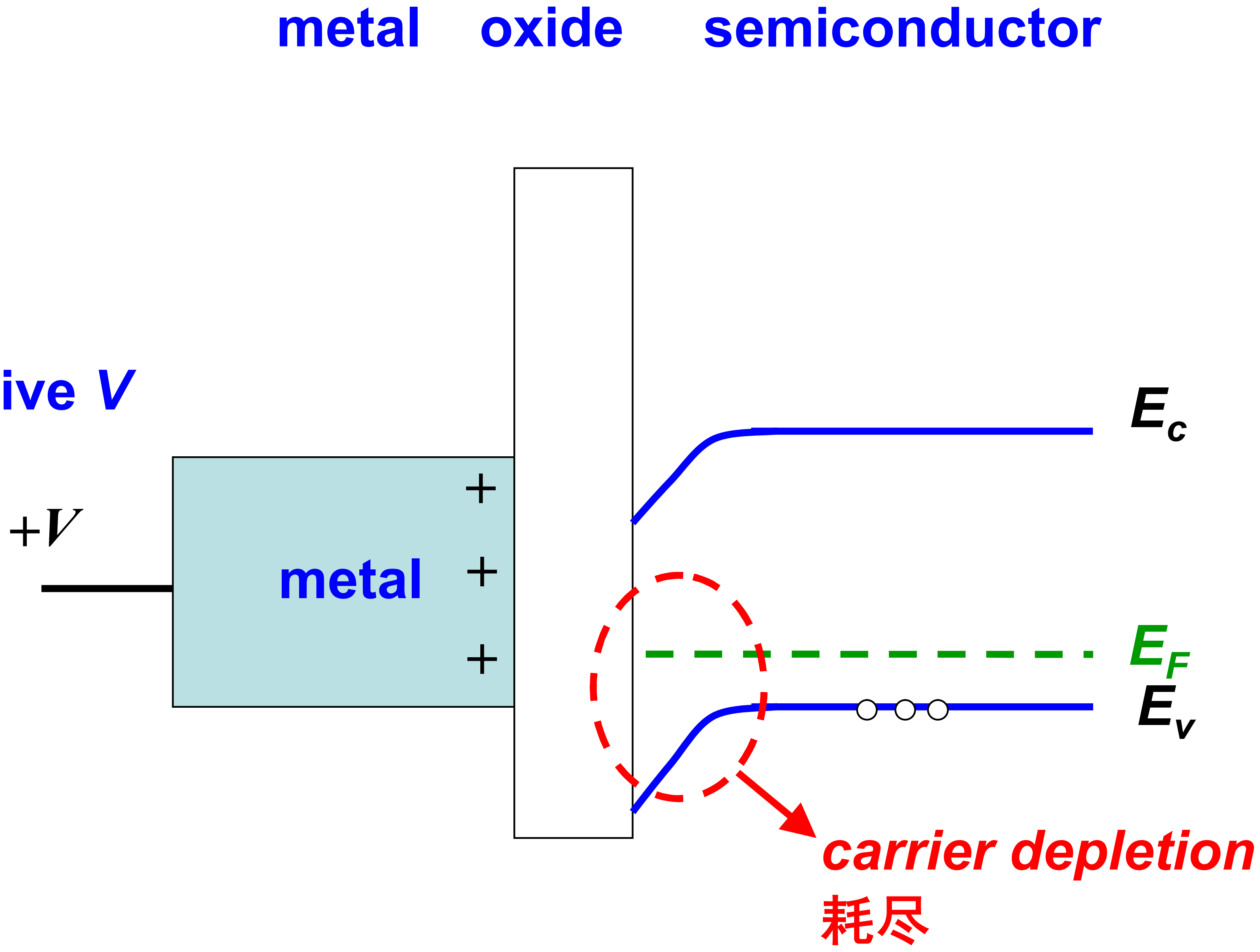
(still p-type)

Metal-Oxide-Semiconductor Junction

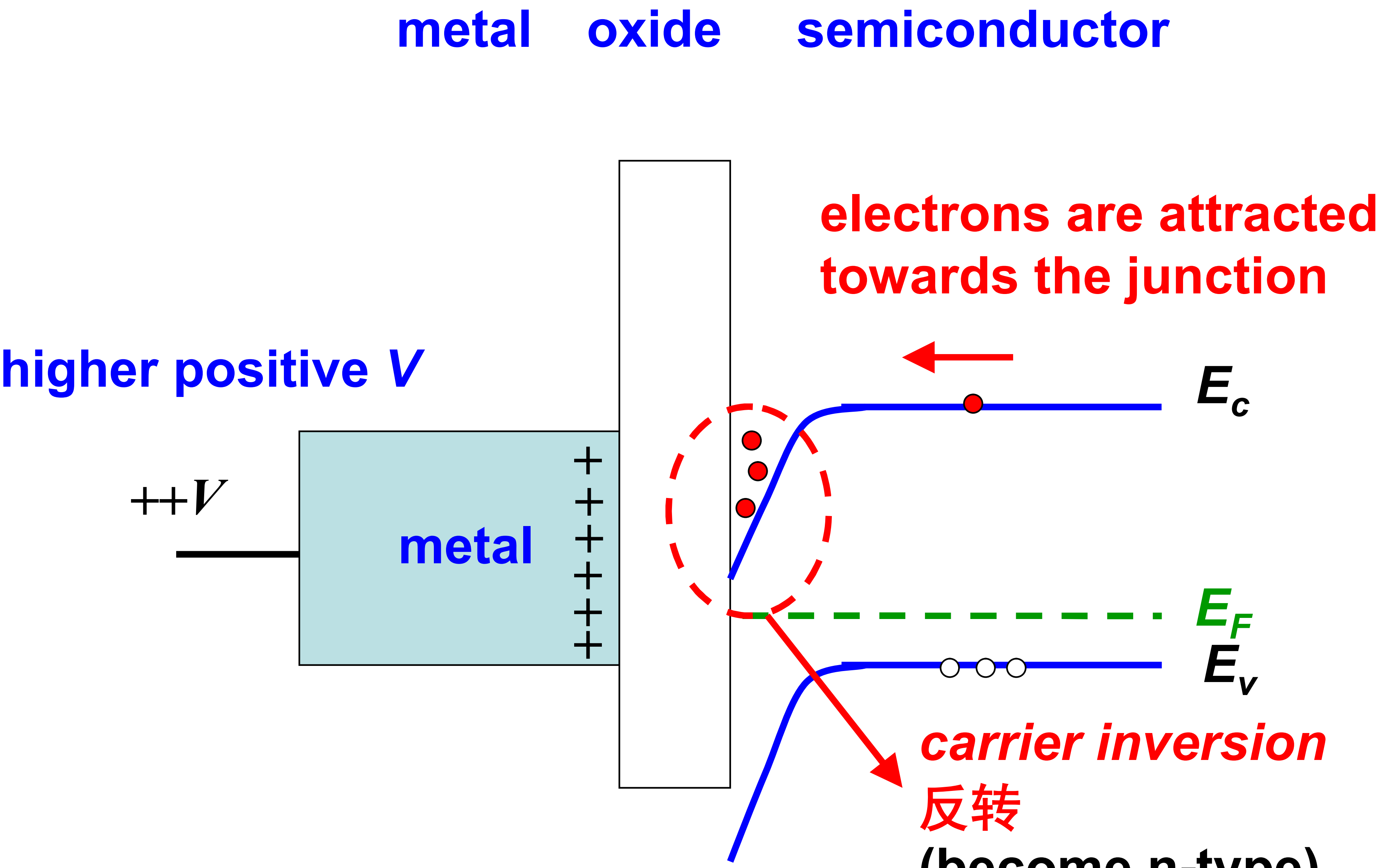


Metal-Oxide-Semiconductor Junction

positive *V*



Metal-Oxide-Semiconductor Junction



metal oxide semiconductor

electrons are attracted towards the junction

higher positive *V*

$++V$

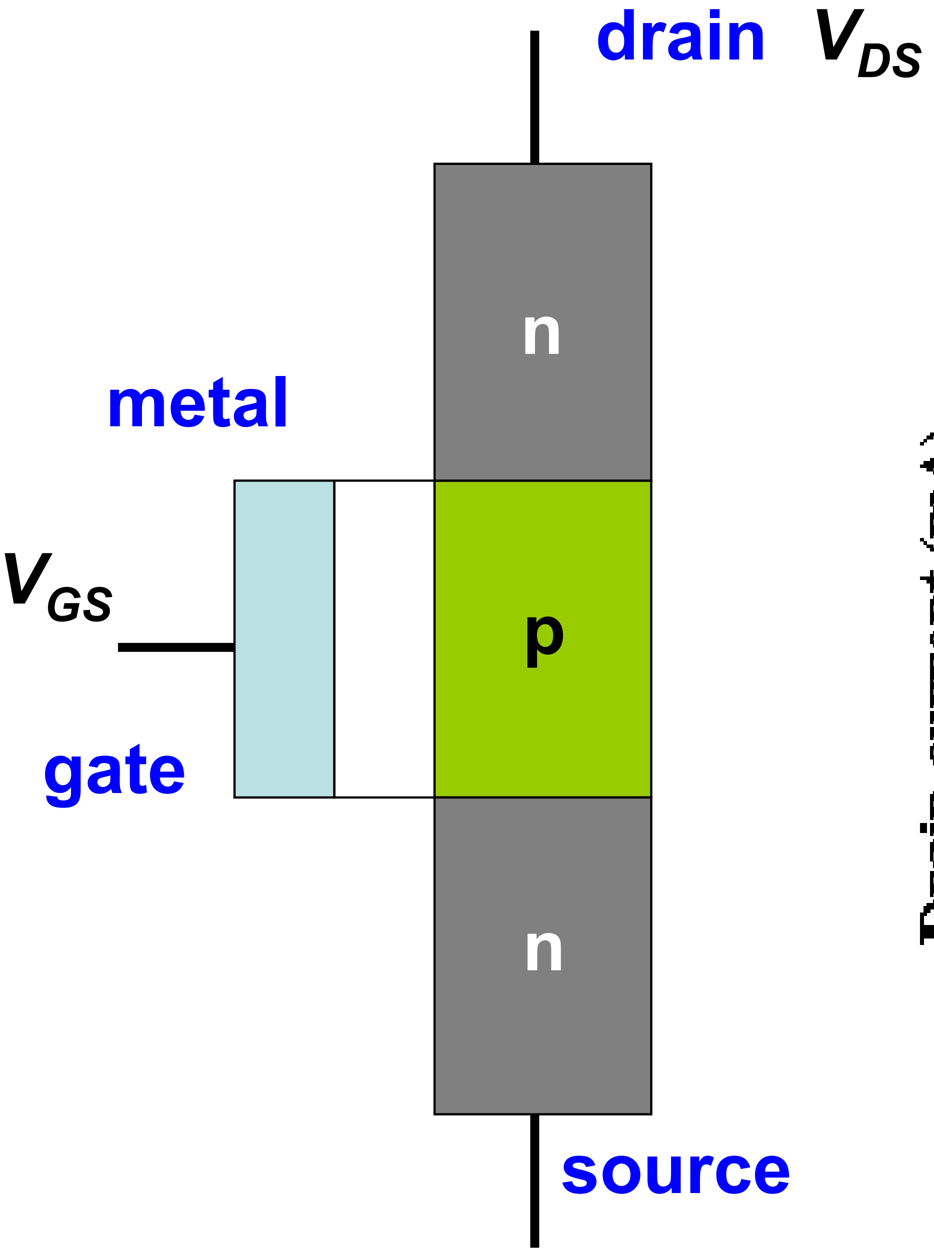
metal

carrier inversion

反转

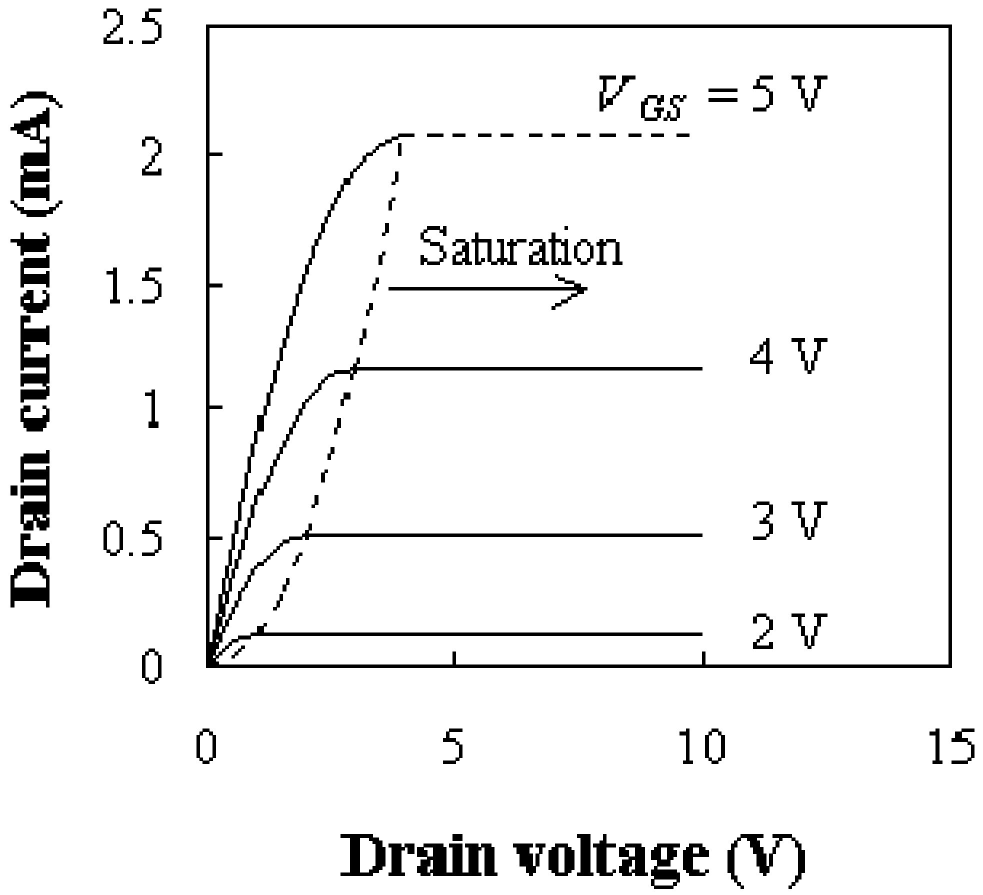
(become n-type)

Metal-Oxide-Semiconductor Junction



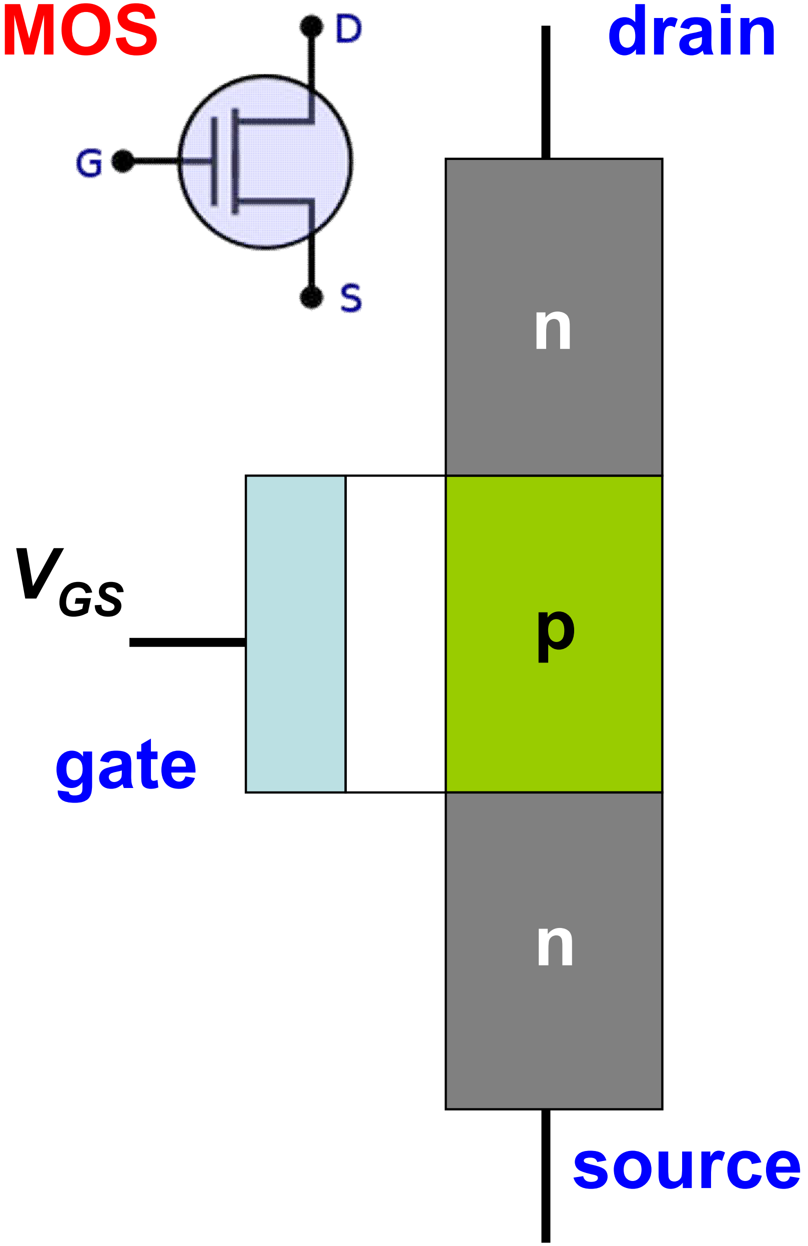
Metal-Oxide-Semiconductor Field-Effect Transistor

MOSFET 场效应晶体管

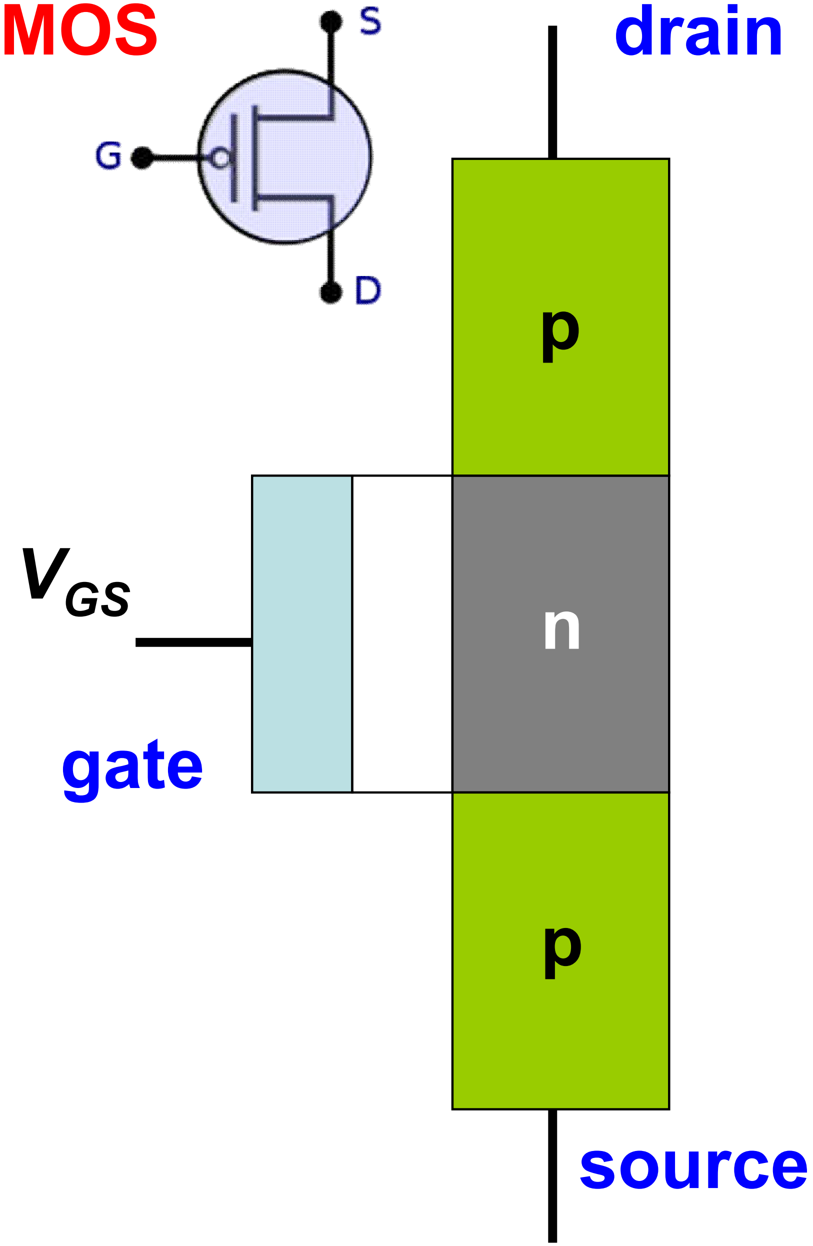


MOSFET

NMOS

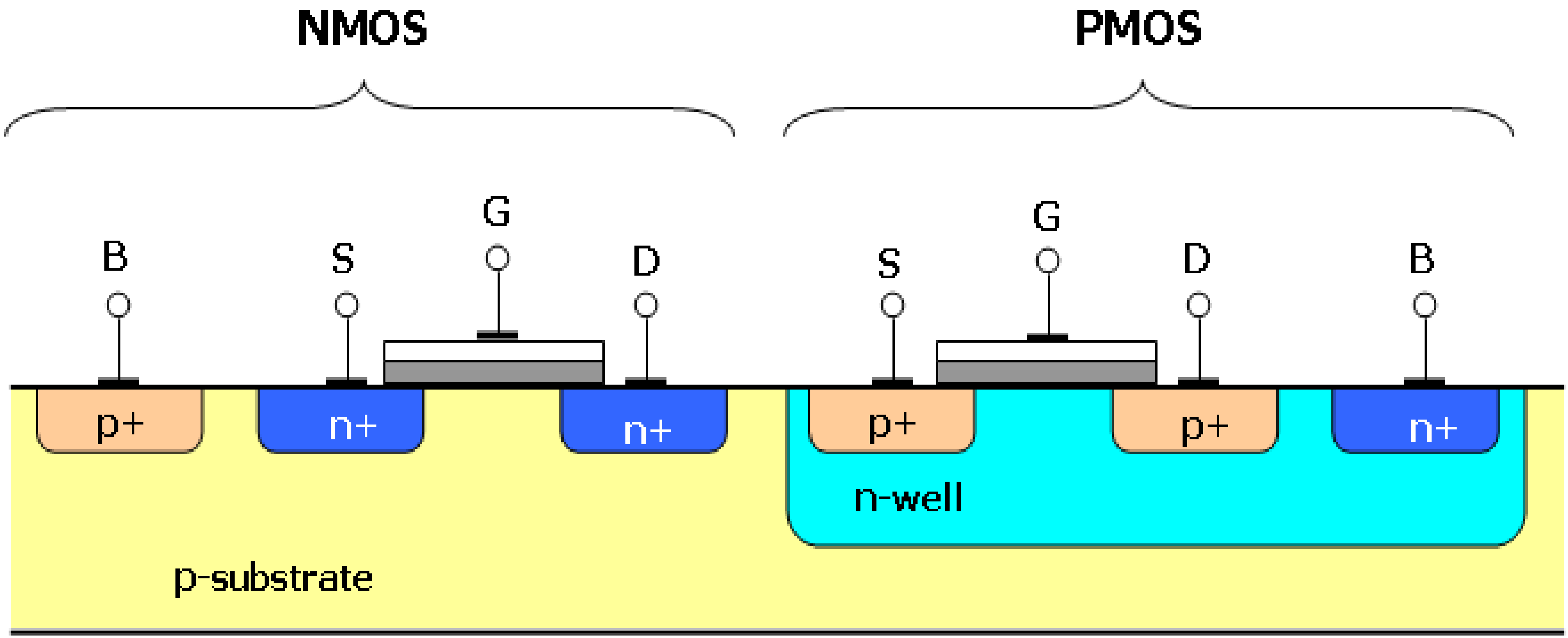


PMOS



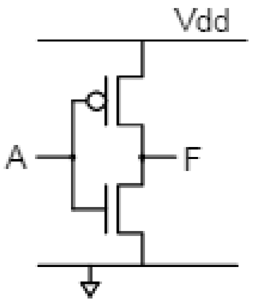
CMOS Technology

- **Complementary Metal-Oxide-Semiconductor**



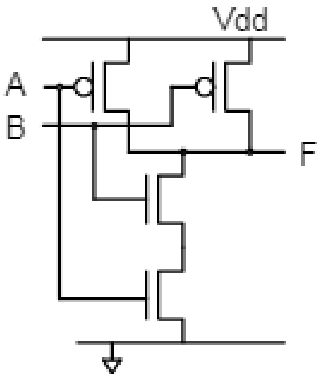
Video MOSFET

CMOS Logics



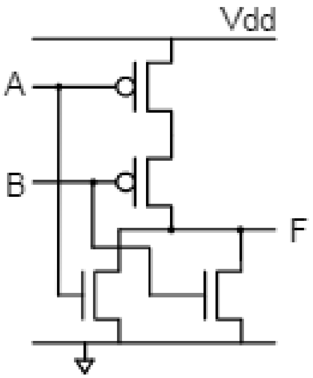
A	F
L	H
H	L

CMOS INVERTER



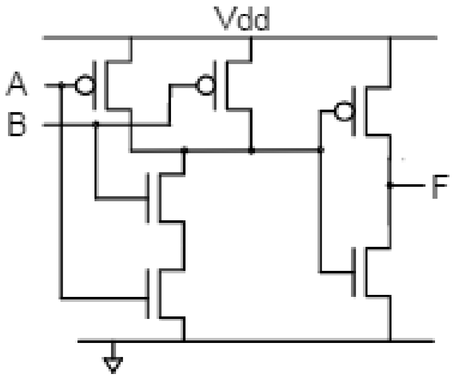
A	B	F
L	L	H
L	H	H
H	L	H
H	H	L

CMOS NAND



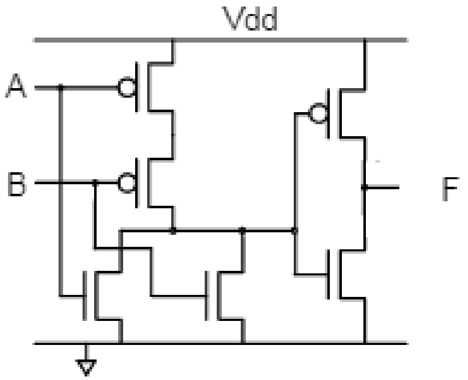
A	B	F
L	L	H
L	H	L
H	L	L
H	H	L

CMOS NOR



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

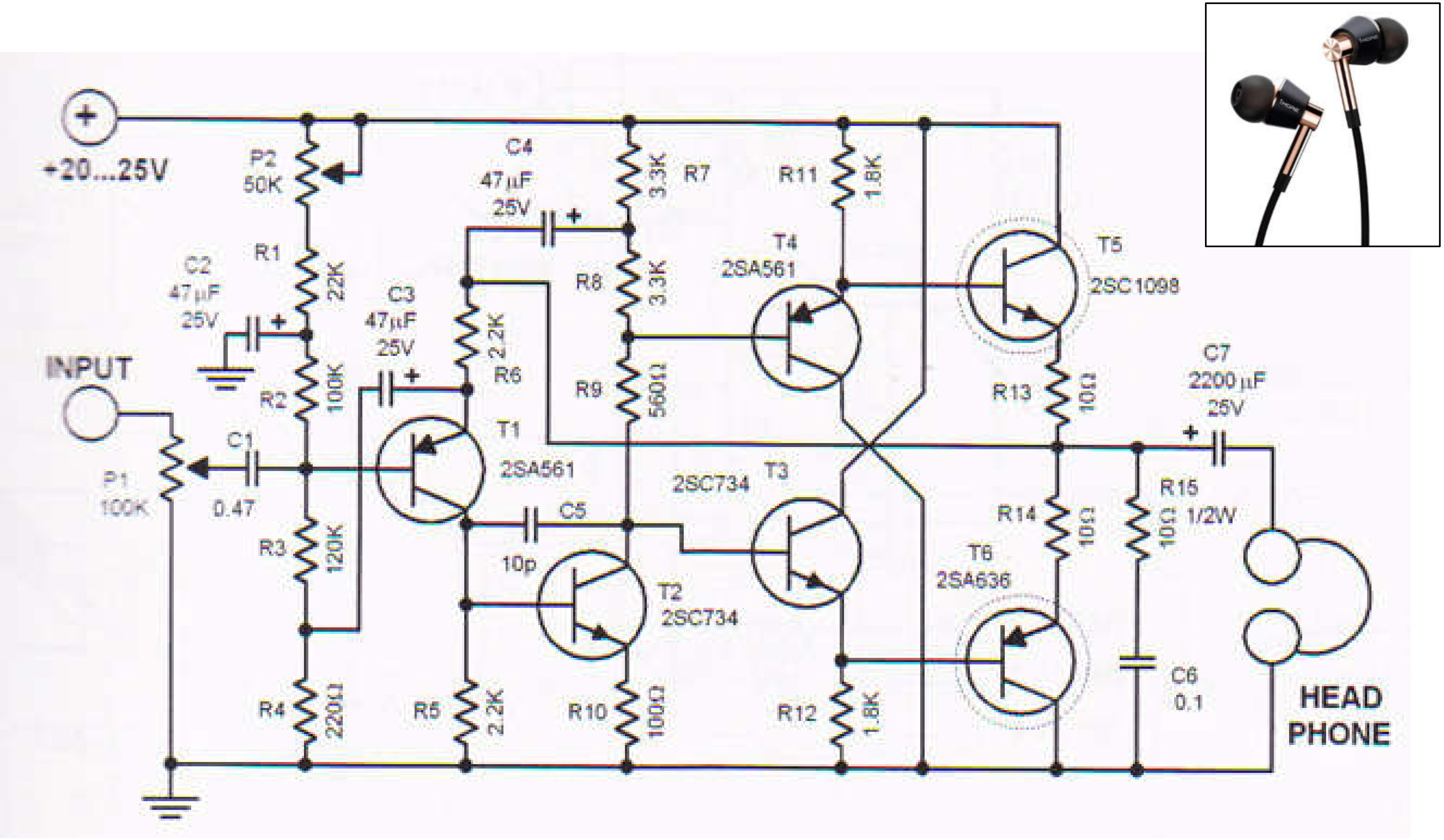
CMOS AND



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

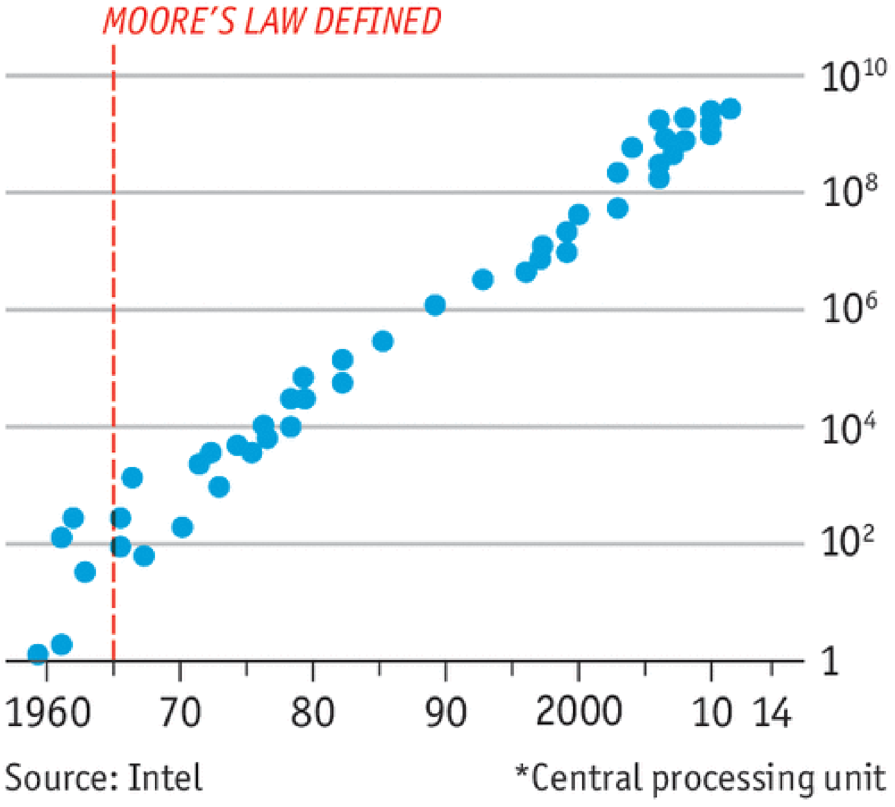
CMOS OR

CMOS Circuits



Integrated Circuits

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

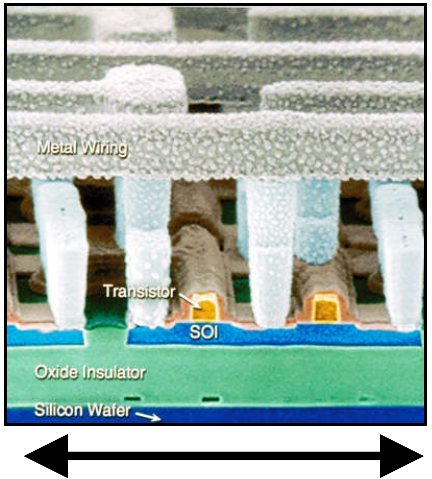


Source: Intel

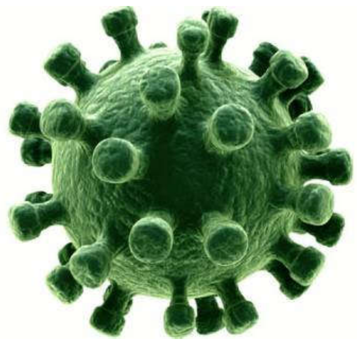
*Central processing unit

Economist.com

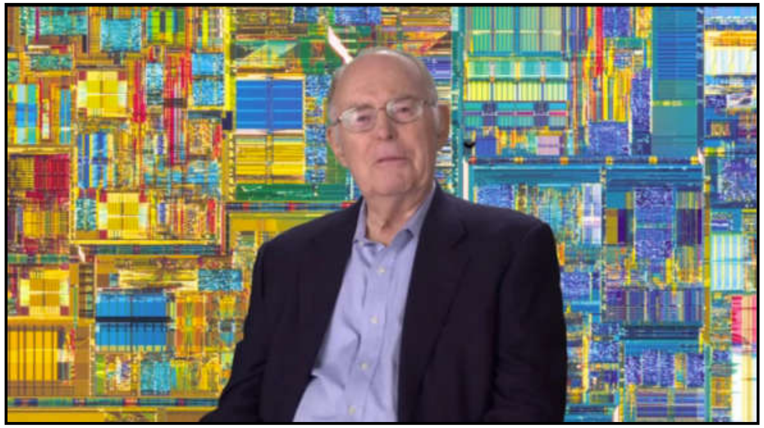
Modern Electronics is a real Nanotechnology



< 100 nm



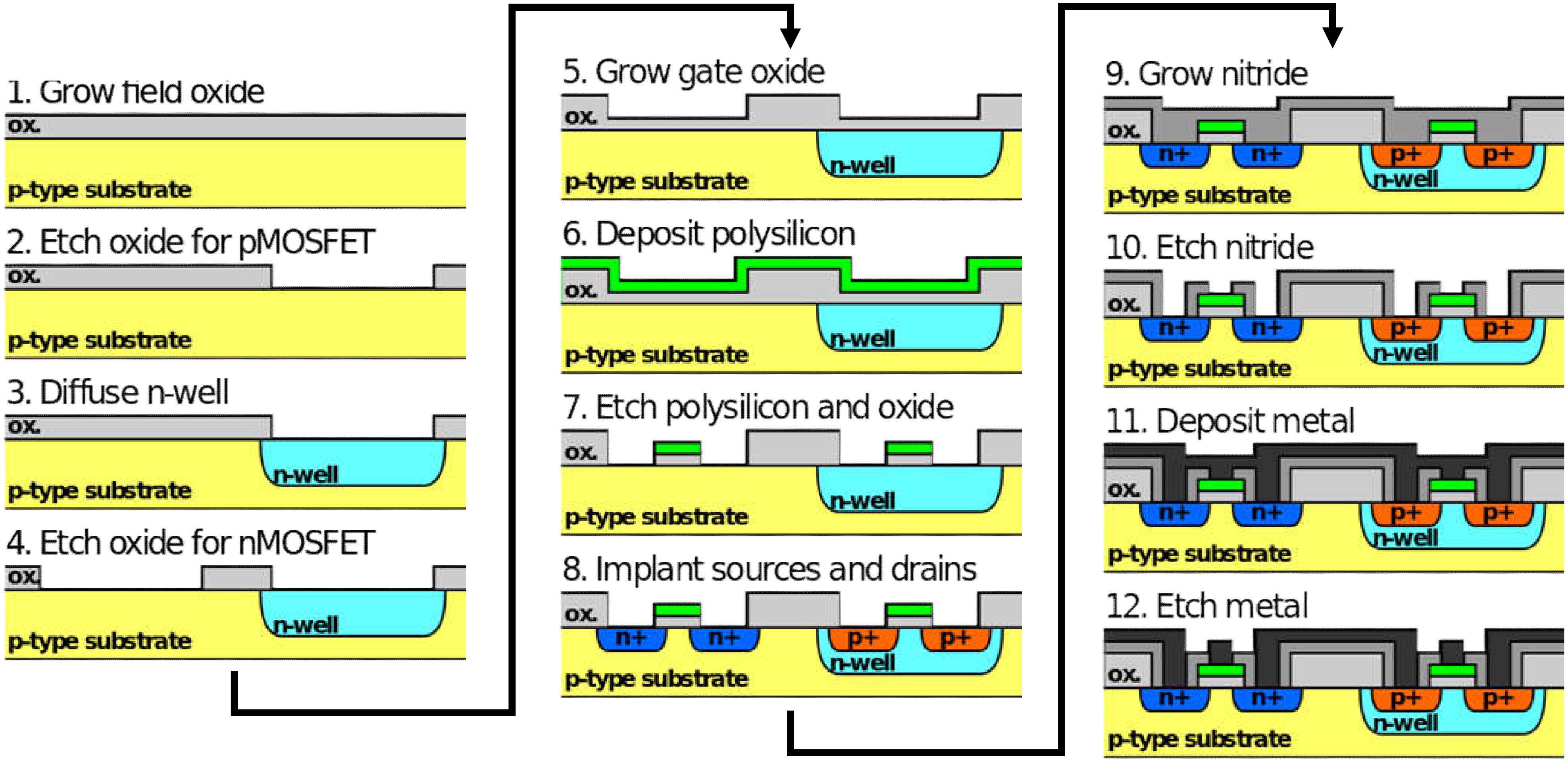
coronavirus



Gordon Moore

Intel i7 CPU, ~ 10^9 transistors

CMOS Process



1. Grow field oxide
2. Etch oxide for pMOSFET
3. Diffuse n-well
4. Etch oxide for nMOSFET
5. Grow gate oxide
6. Deposit polysilicon
7. Etch polysilicon and oxide
8. Implant sources and drains
9. Grow nitride
10. Etch nitride
11. Deposit metal
12. Etch metal

Video Intel

Video TSMC

Thank you for your attention