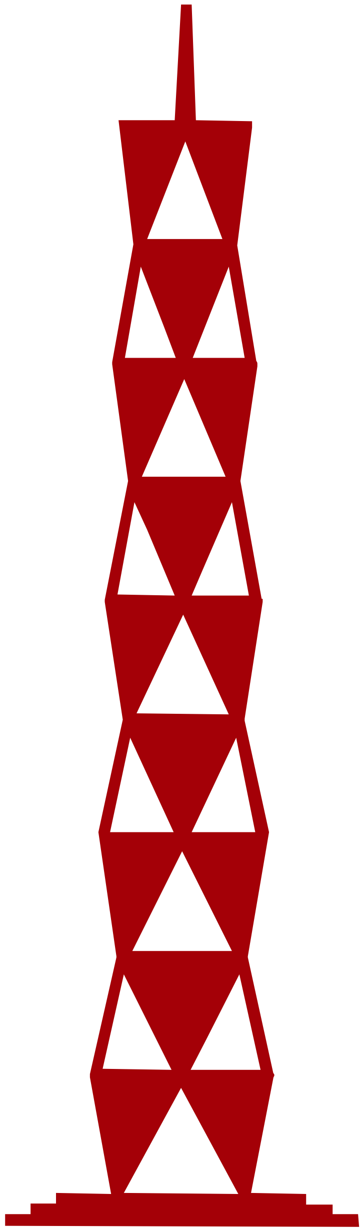


SI100B
Introduction to Information Science and Technology (Part 3: Electrical Engineering)

Lecture #2 Semiconductor & Electronic Devices

Instructor: Junrui Liang (梁俊睿)

Nov. 11th, 2020

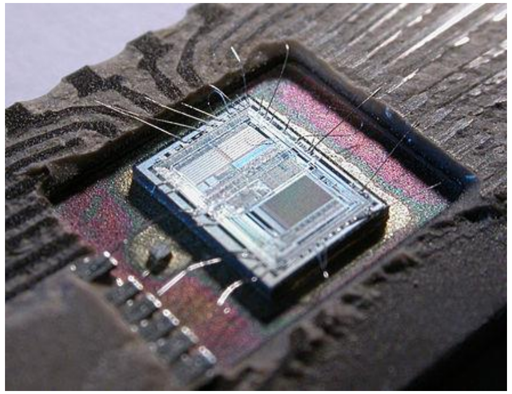
Independent Study

- High-school style
  - Specific space (固定教室)
  - A few subjects (科目少)
  - Repeating contents (反复复习)
  - Monotonous media (媒介单一)
  - Learning for exams (在考中学)
  - Single purpose (高考独木桥)
  - 知识改变命运
- University style
  - Open environment (开放式环境)
  - Many subjects (许多科目)
  - Few recitation (极少重复)
  - Multi-media (多种媒介)
  - Learning by doing (尝试在做中学)
  - Diversity (出路差异化)
  - 见识决定宽度，能力决定高度

(Pictures are from the Internet)

The Theme Story

Devices (1)



Circuits (4)

Systems (2)

(Pictures are from the Internet)

Study Purpose of Lecture #2

- 哲学（bao'an）三问
  - Who are you?
  - Where are you from?
  - Where are you going?

To answer those questions throughout your life

- In this lecture, we ask
  - Why semiconductor 半导体 can be used to process information?
  - What are the fundamental semiconductor devices 器件?
  - How an integrated circuit (IC) 集成电路 is build?

Lecture Outline

1. The historical ways of information processing
2. Fundamental circuit components and their dynamics *
3. Semiconductor
4. PN junction
5. Diode

---------------- (break) ----------------

6. Transistor
7. Switch and logic gate (digital application)
8. Linear amplification (analog application)
9. Integrated circuit manufacturing and the Moore's Law

The history of information processing (calculation)

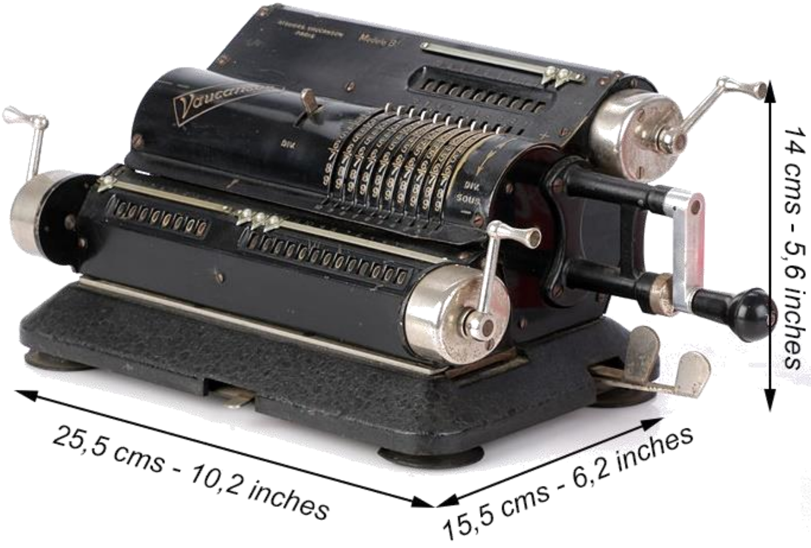
Digits 手指

Counting rods 算筹

Abacus 算盘

Slide rule 计算尺

（可计算加、减、乘、除、指数、对数等）

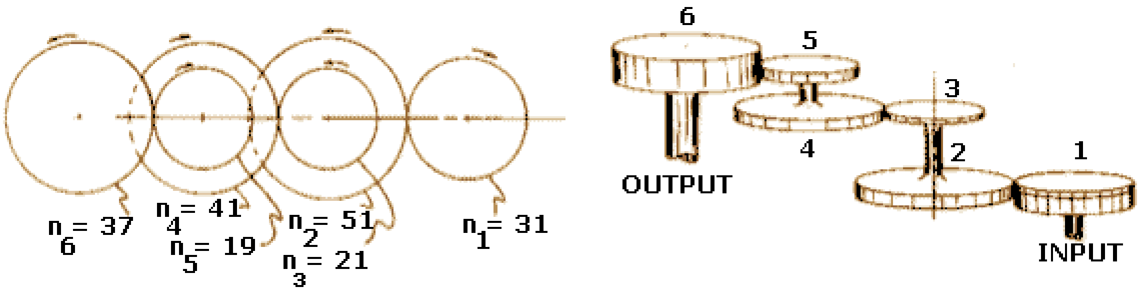


Mechanical calculator (computer?) 机械计算器

(Pictures are from the Internet)

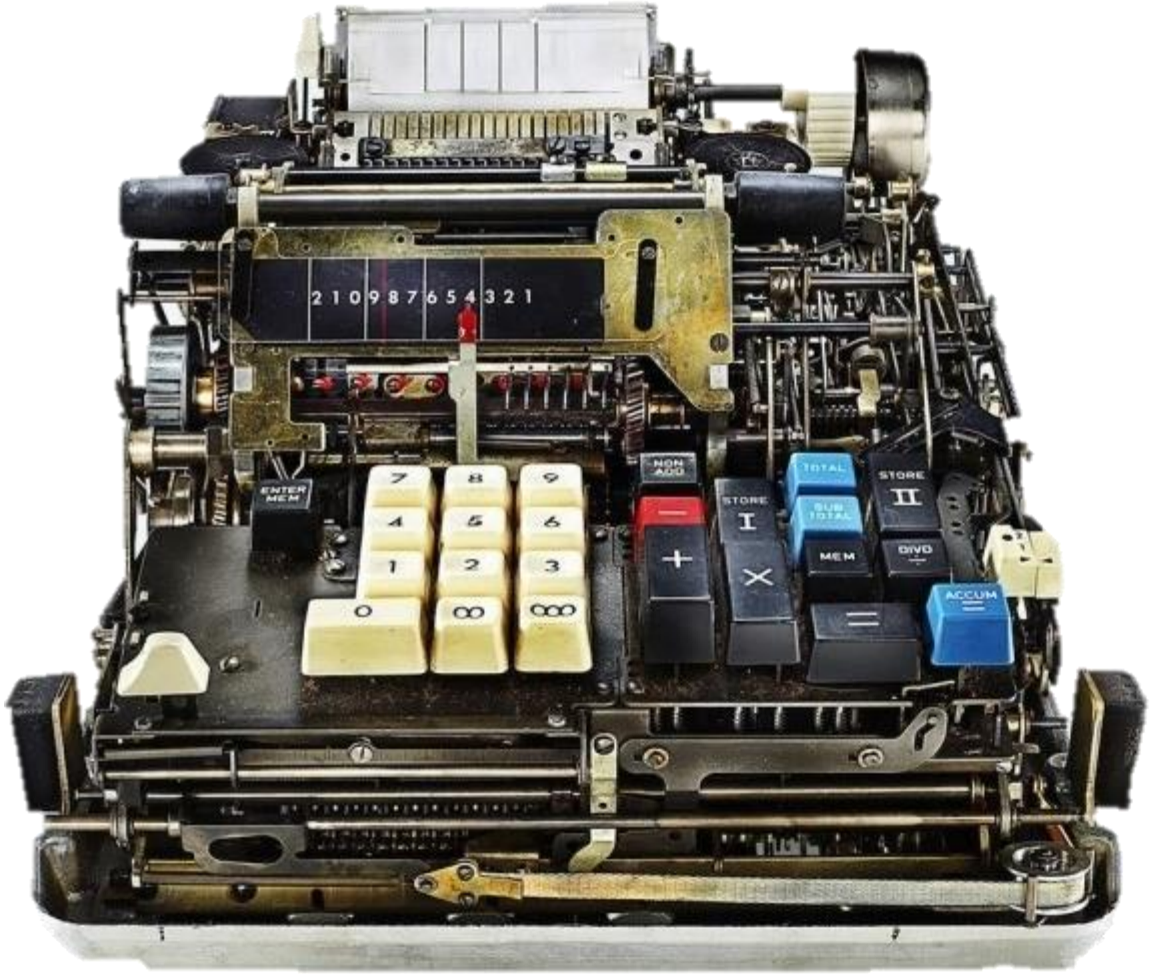
Why no longer mechanical calculator?

- Gears 齿轮 are the kernel of many mechanical calculator



(Pictures are from the Internet)

- Difficulty in scaling down



ENIAC - the first electronic computer

calculator

computer

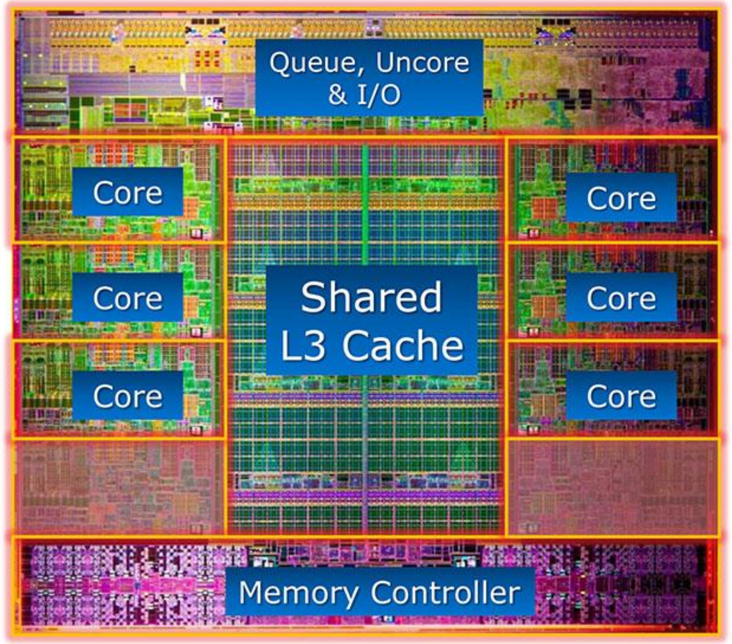
- The first programmable, electronic, general purpose digital computer
- Able to solve "a large class of numerical problems" through reprogramming
- It was Turing-complete 图灵完备性
- By the end of its operation in 1956, ENIAC contained
  - 18,000 vacuum tubes 真空管
  - 7,200 crystal diodes 二极管
  - 1,500 relays 继电器
  - 70,000 resistors 电阻
  - 10,000 capacitors 电容
  - about 5,000,000 hand-soldered joints
  - weighed 27 tons
  - roughly 2.4 m × 0.9 m × 30 m in size
  - occupied 167 m^2
  - consumed 150 kW of electricity
  - one ENIAC hour ≈ 2,400 human hours

(Pictures are from the Internet)

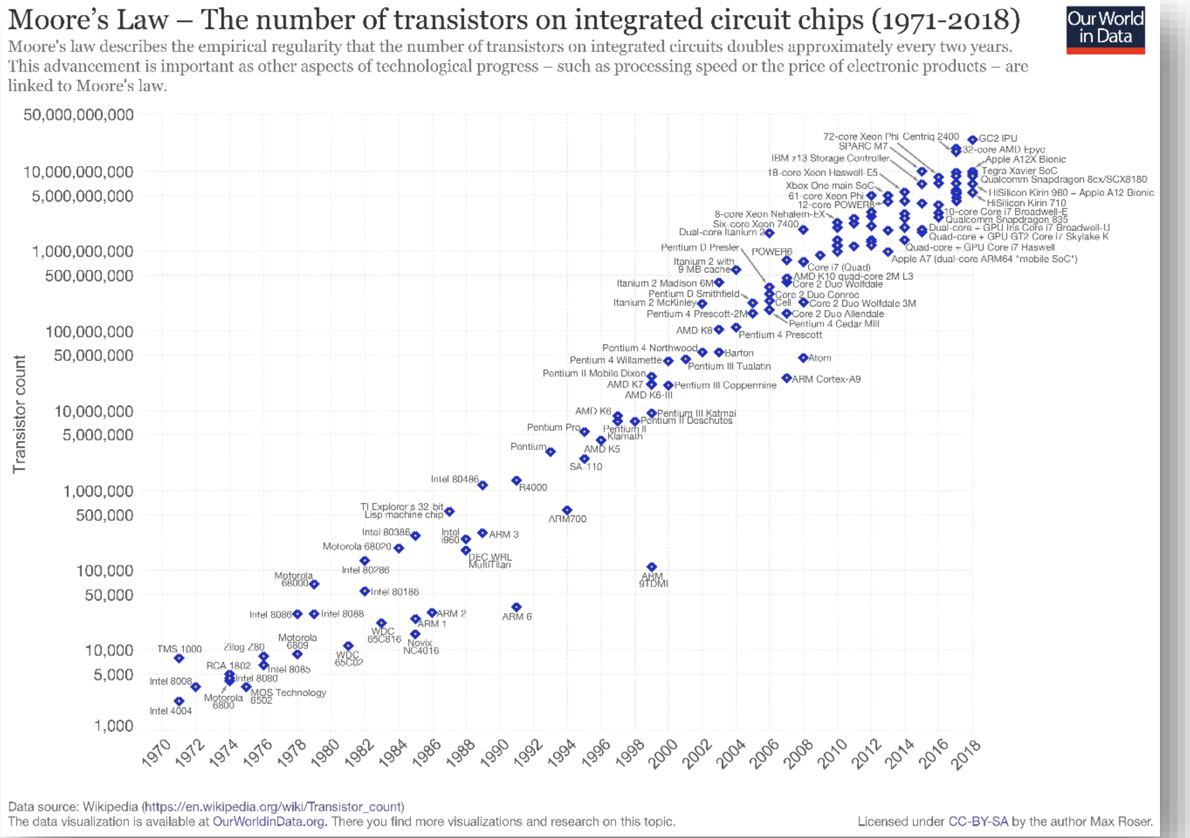
The magic of integrated circuit (IC)

晶粒
(裸芯片)

Intel® Core™ i7-3960X Processor Die Detail



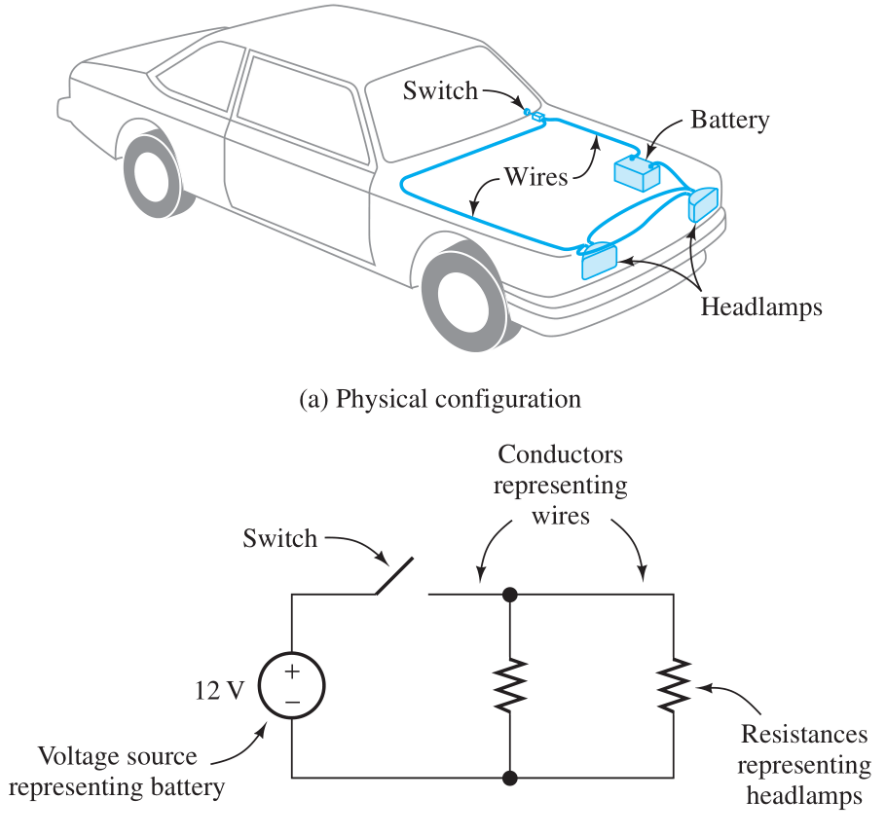
- Core i7 3rd Generation (Nov. 2011)
- 32 nm process 制程工艺 technology
- 2.27 billion (2,270,000,000) transistors 晶体管



(Pictures are from the Internet)

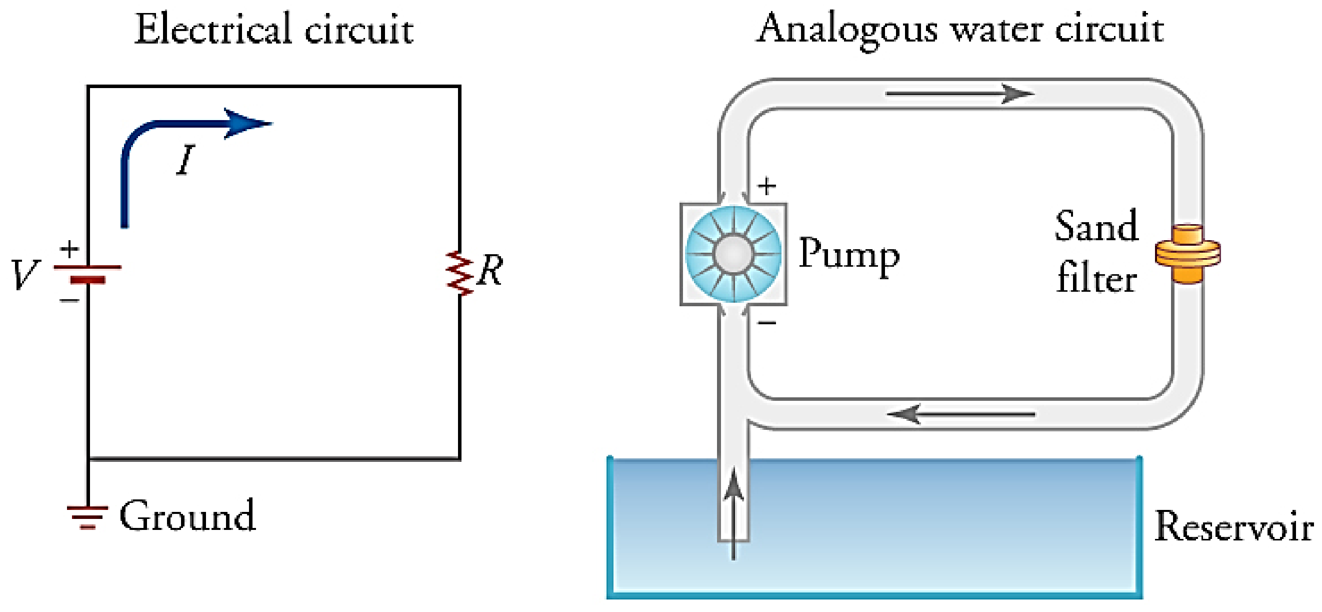
Electrical circuit

- An electrical circuit consists of various types of circuit elements connected in closed paths by conductors.
- The fluid-flow analogy can be very helpful initially in understanding electrical circuits.



(a) Physical configuration

(b) Circuit diagram



(a)

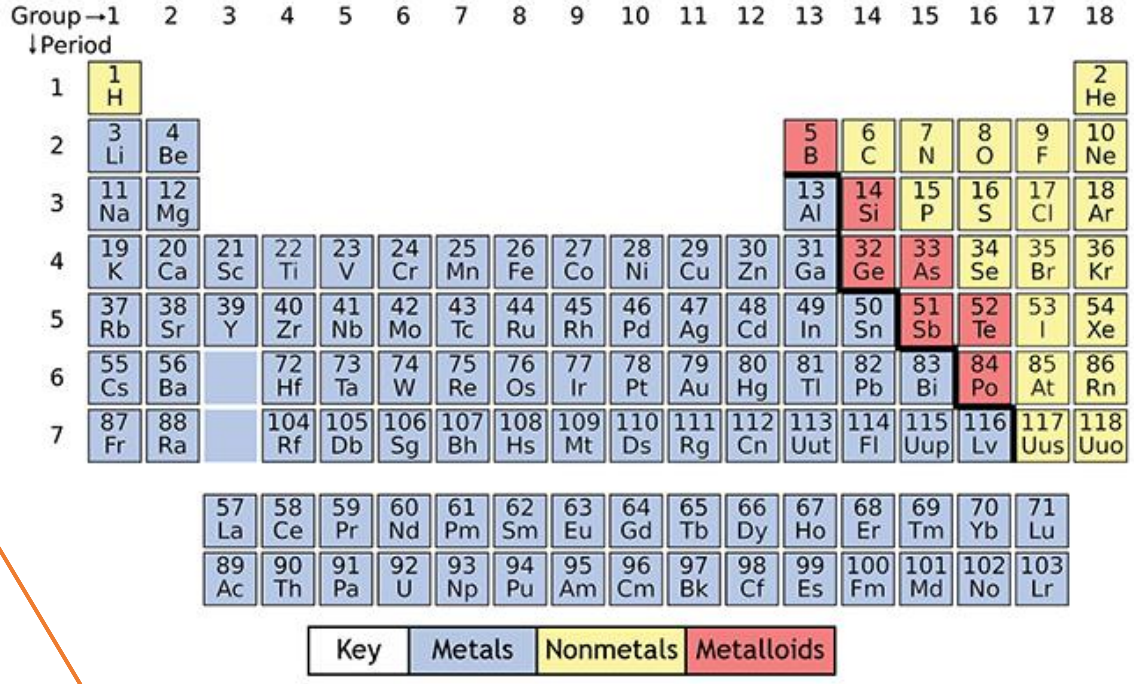
(b)

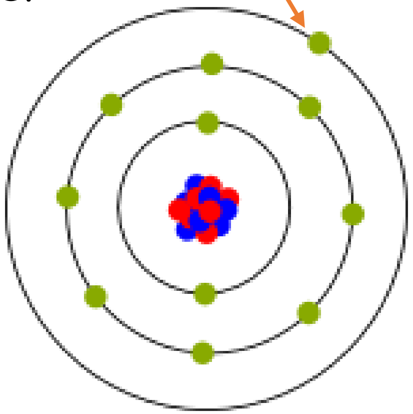
(EE Section 1.2)

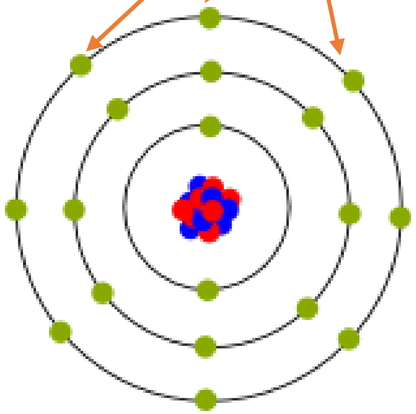
Conductor and insulator

Conductor 导体

- The atoms have single (or few) electrons in the outer orbit called valence electrons （价电子）
- They might become free electrodes （自由电子） and can be moved from one atom to another easily and enhance the movement of electrons.







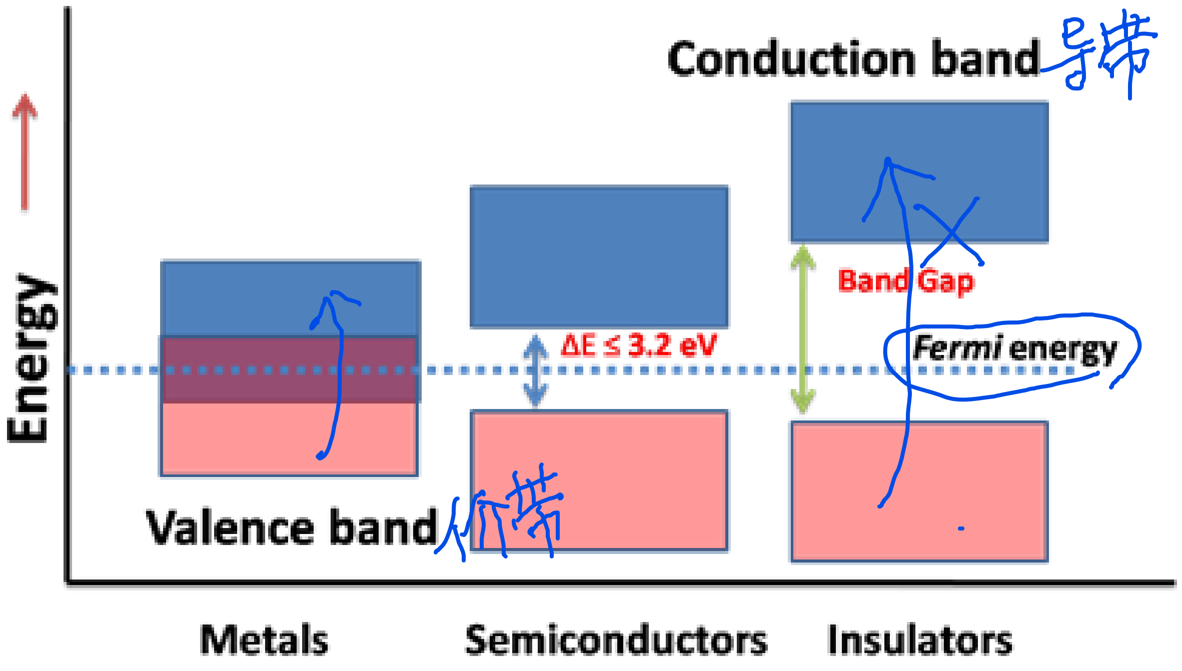
Insulator 绝缘体

- has many (7-8) electrons in the outer orbit.
- these electrons are very difficult to move from one atom to the other and resist the movement of electrons.

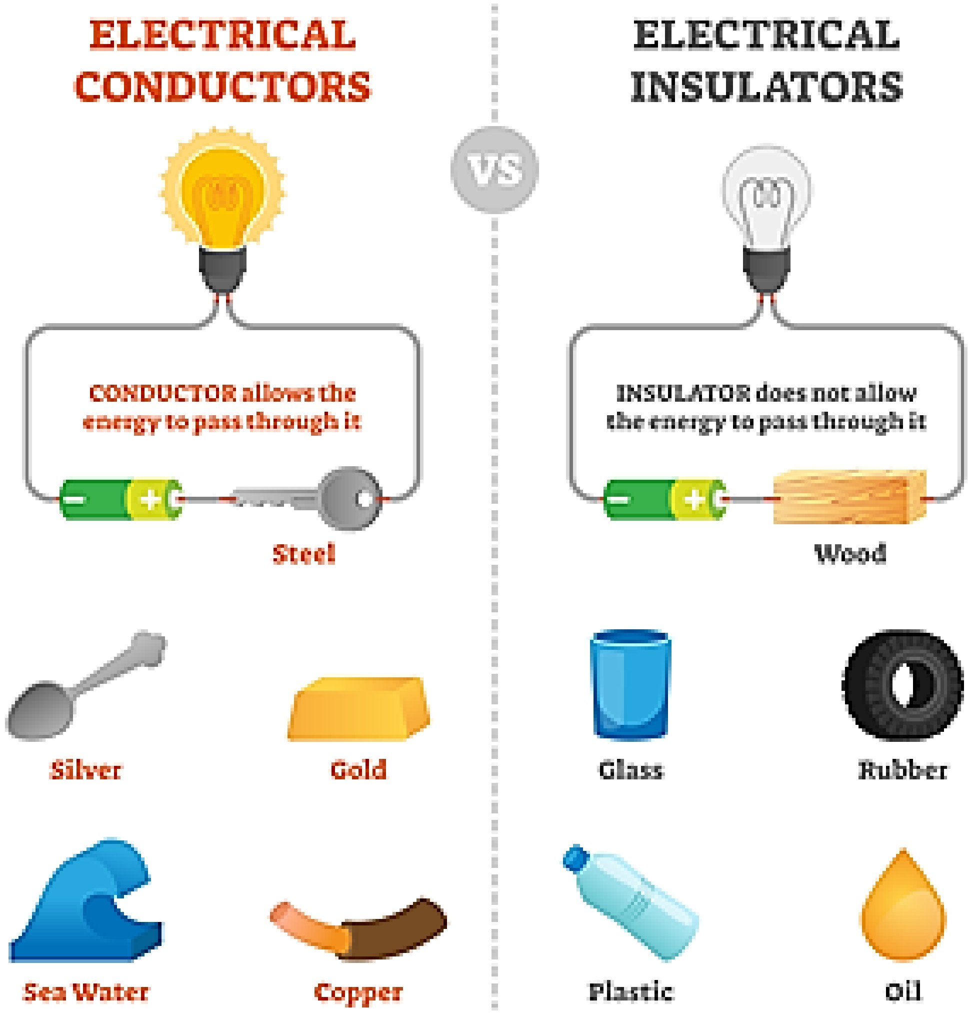
(Pictures are from the Internet)

Conductor and insulator

- Physical insight



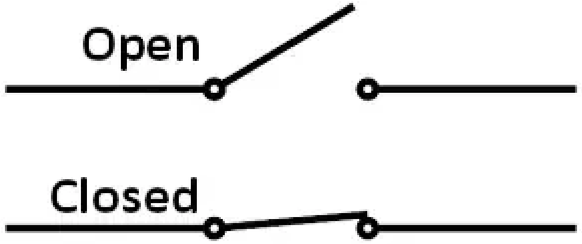
- Everyday life experience



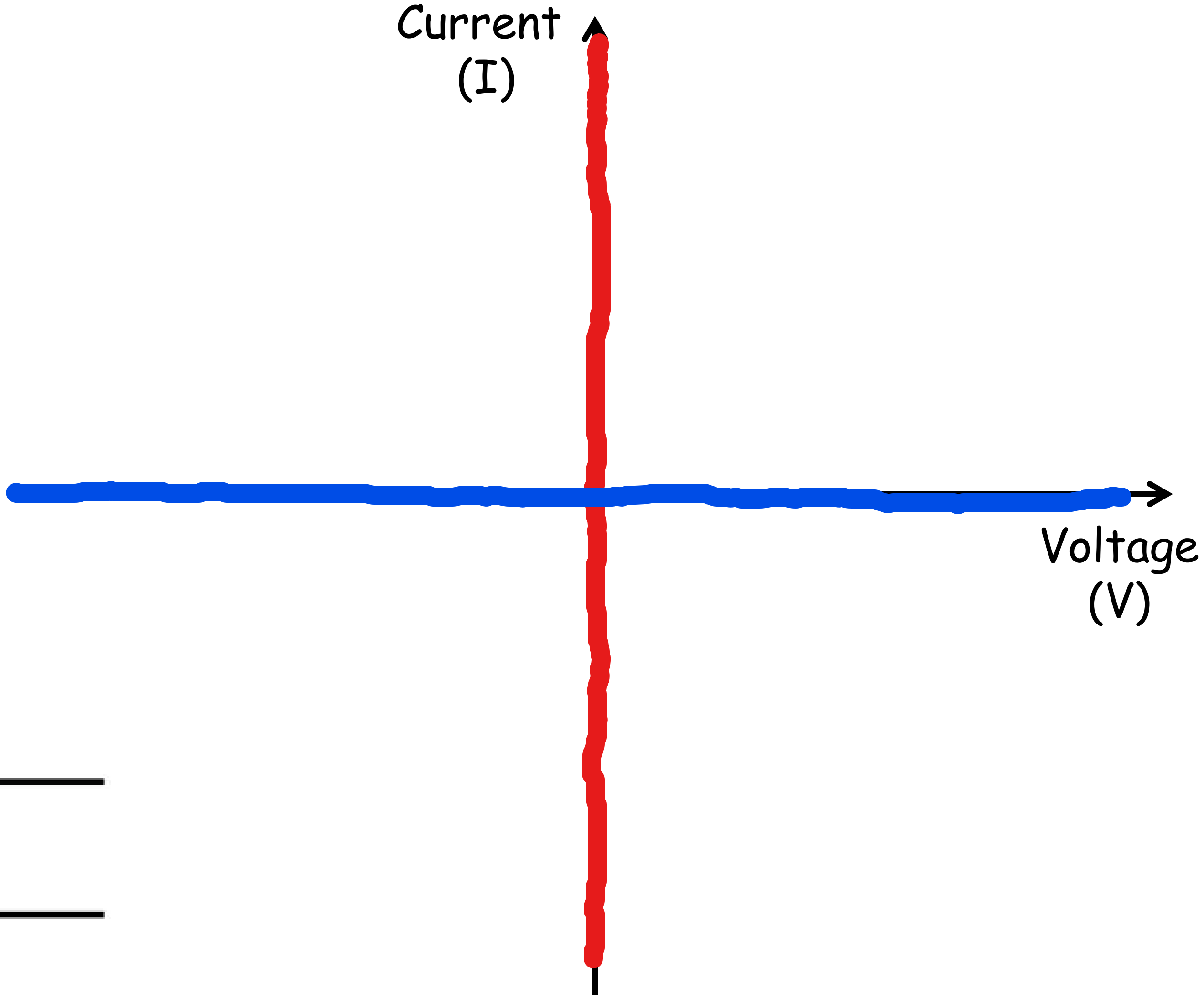
(Pictures are from the Internet)

The electrical characteristic of a switch

- OFF (an insulator)
- ON (a conductor)



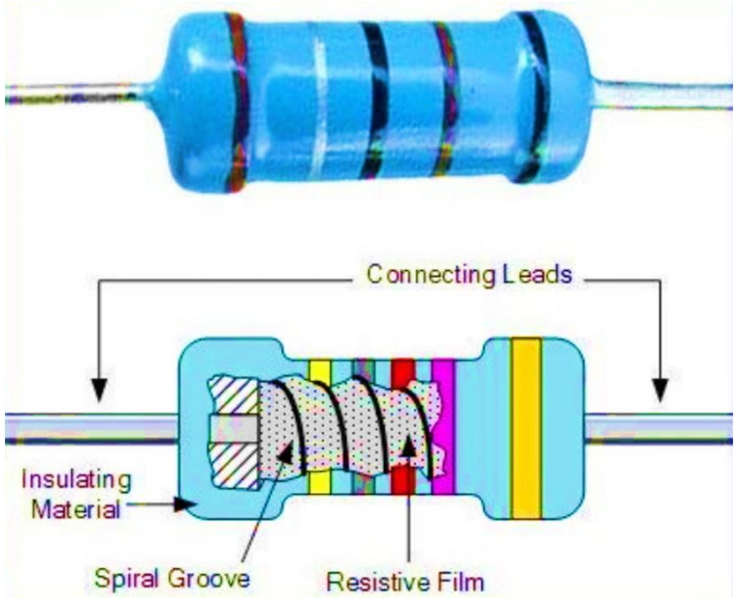
- The I-V characteristics?

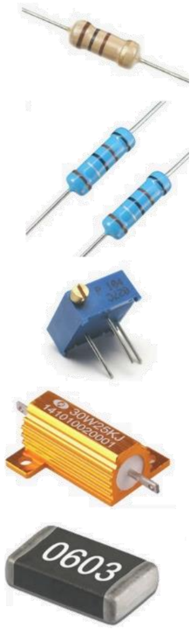


(Pictures are from the Internet)

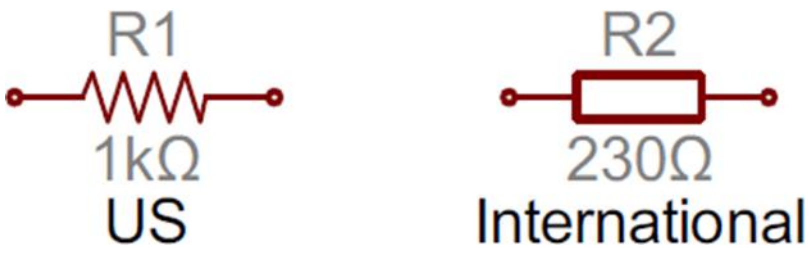
The electrical characteristic of a resistor

- Practical resistors

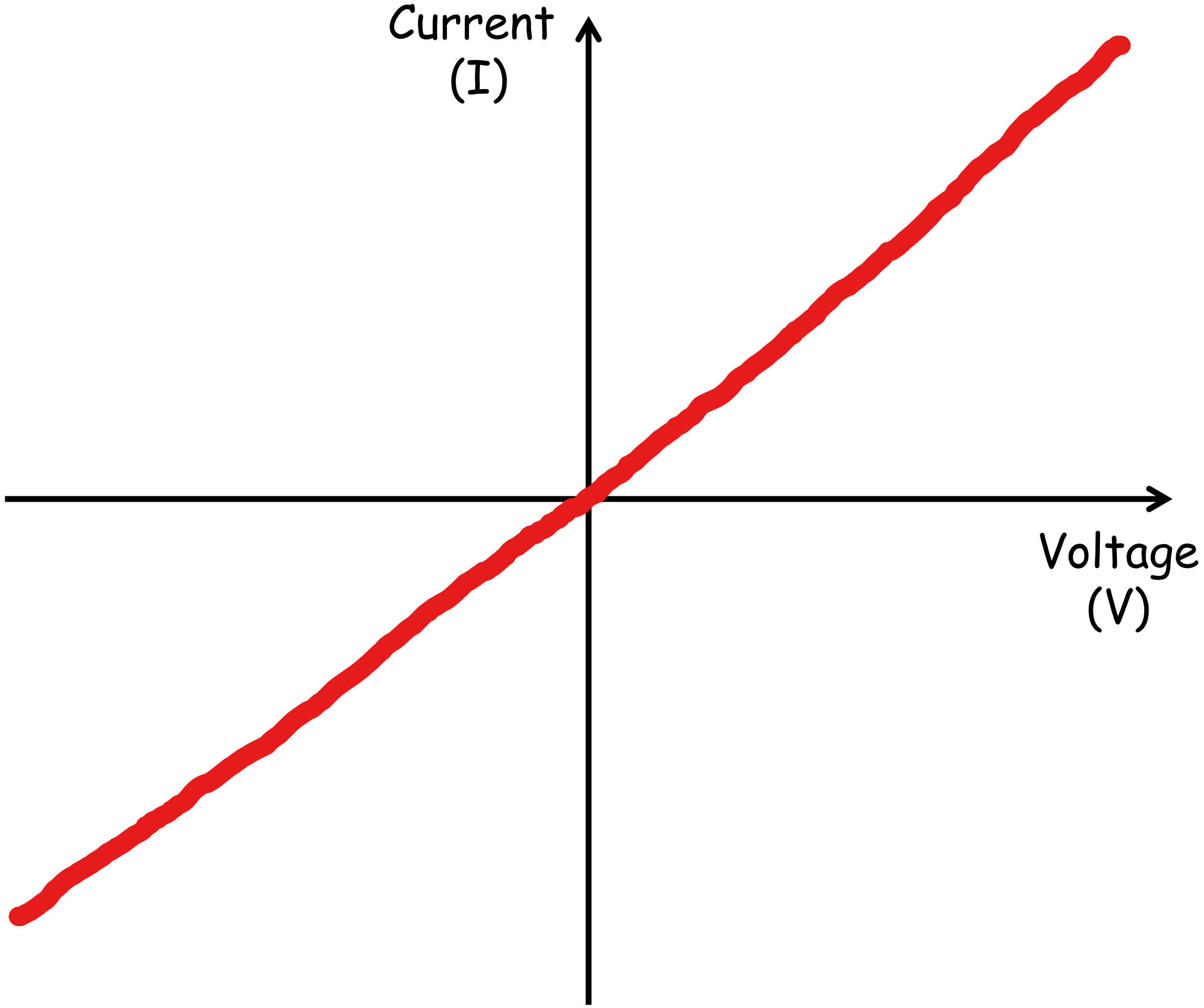




- Symbol



- The I-V characteristics?

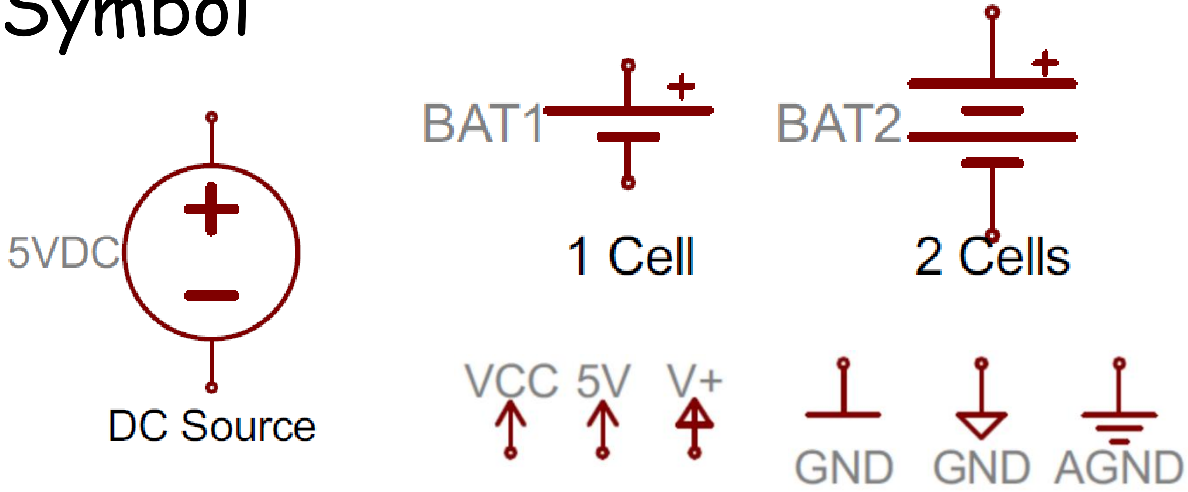


(Pictures are from the Internet)

The electrical characteristic of a dc voltage source

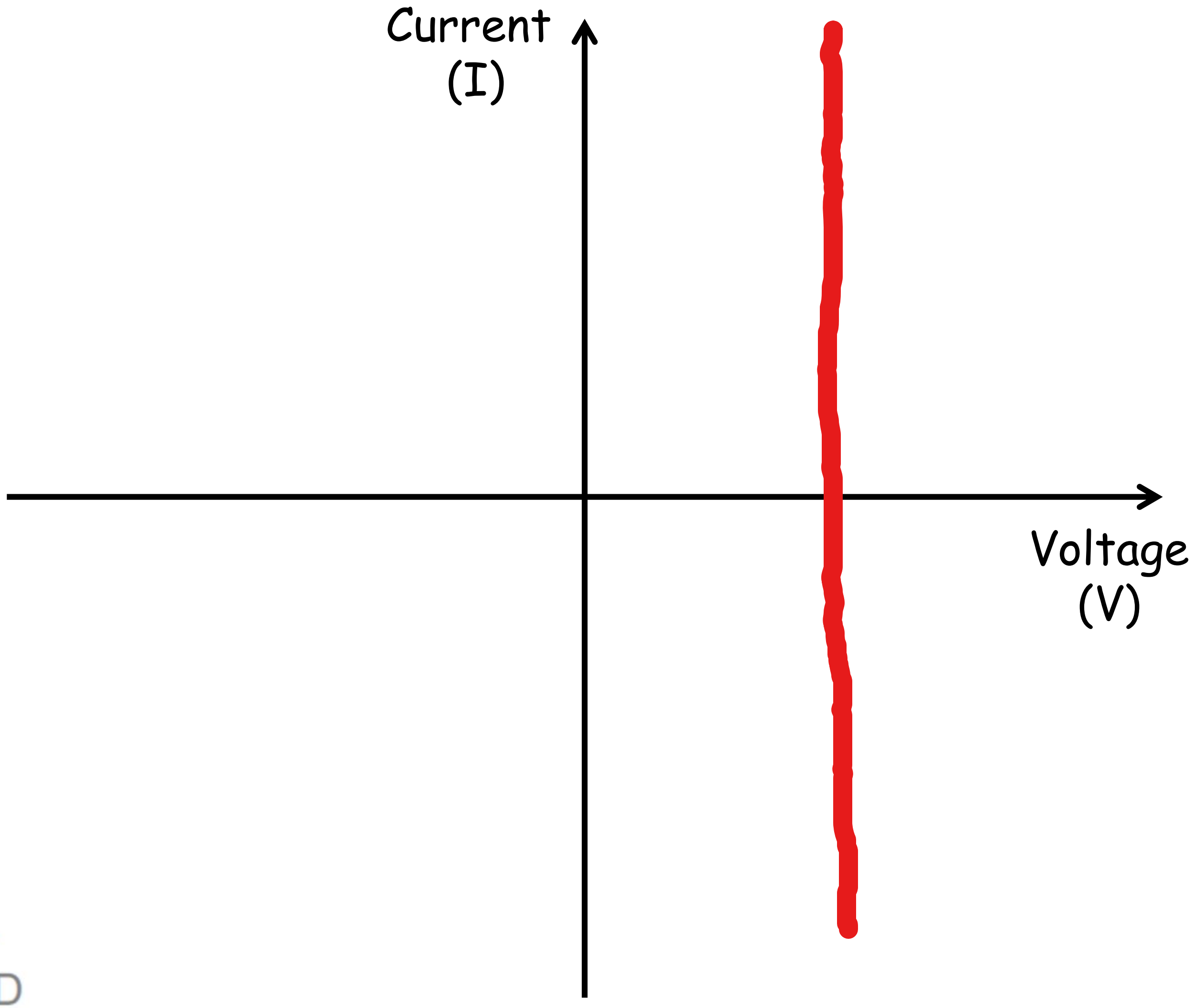
- Practical voltage (power) supply

- Symbol



(Pictures are from the Internet)

- The I-V characteristics?



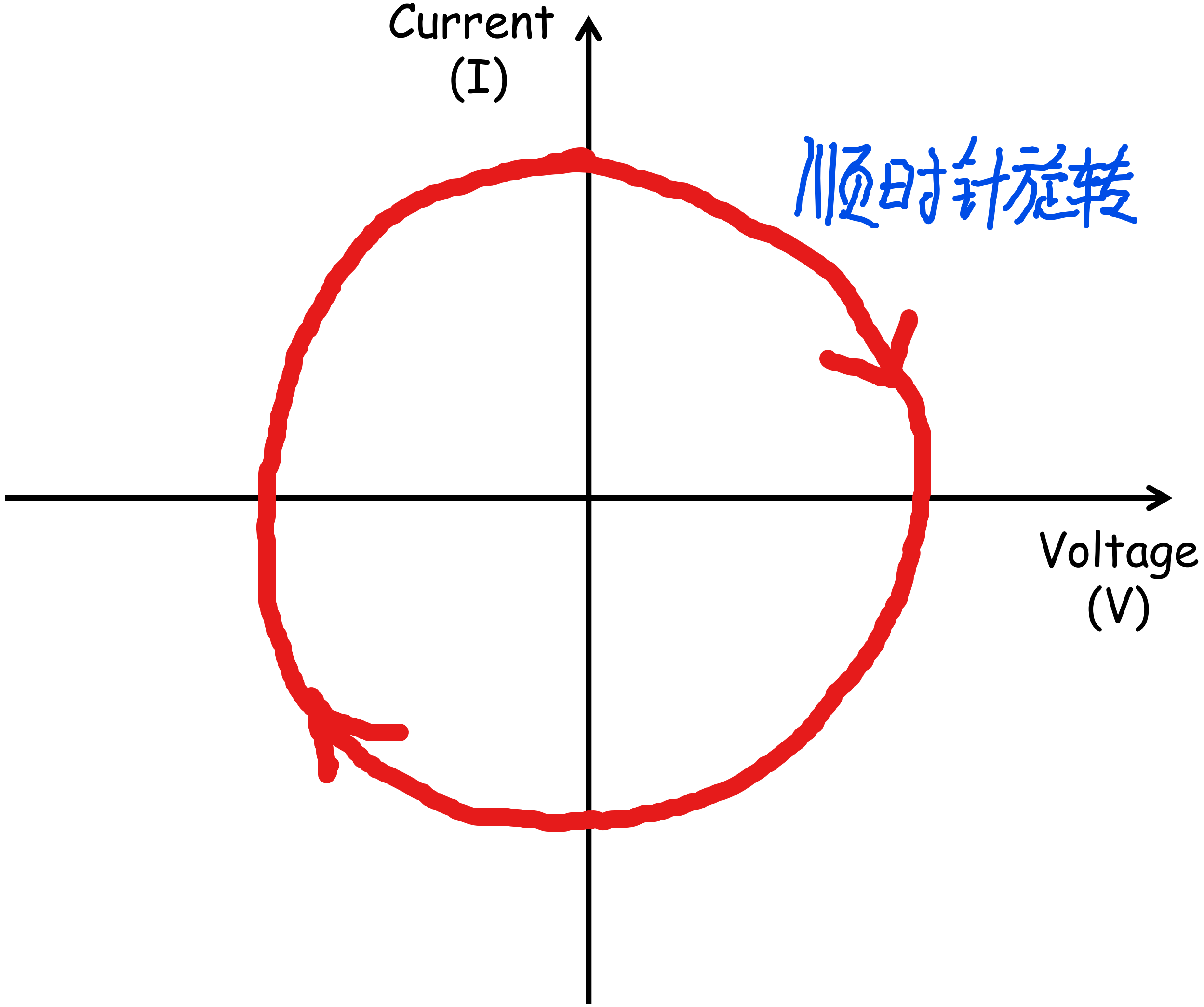
The electrical characteristic of a capacitor

- Practical capacitors $v = \frac{1}{C}\int i\,dt$

- Symbol

Non-polarized Polarized

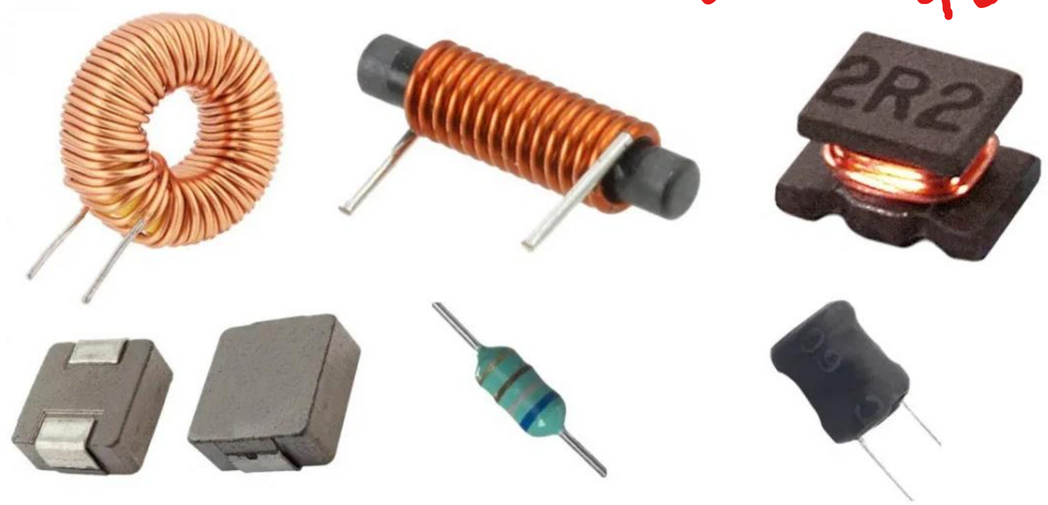
- The I-V characteristics?



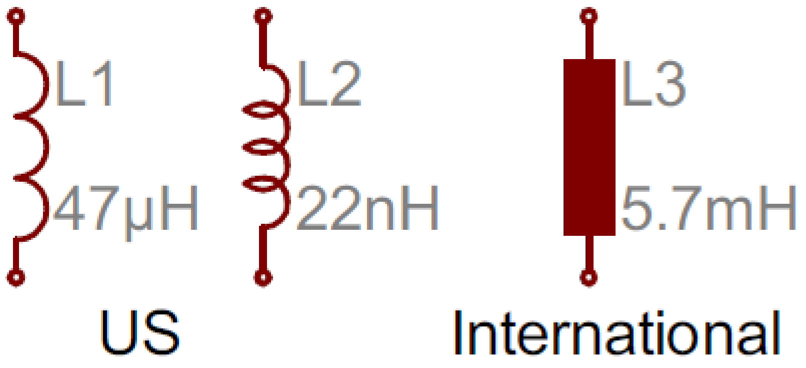
(Pictures are from the Internet)

The electrical characteristic of a inductor

- Practical inductors $V = L\frac{di}{dt}$

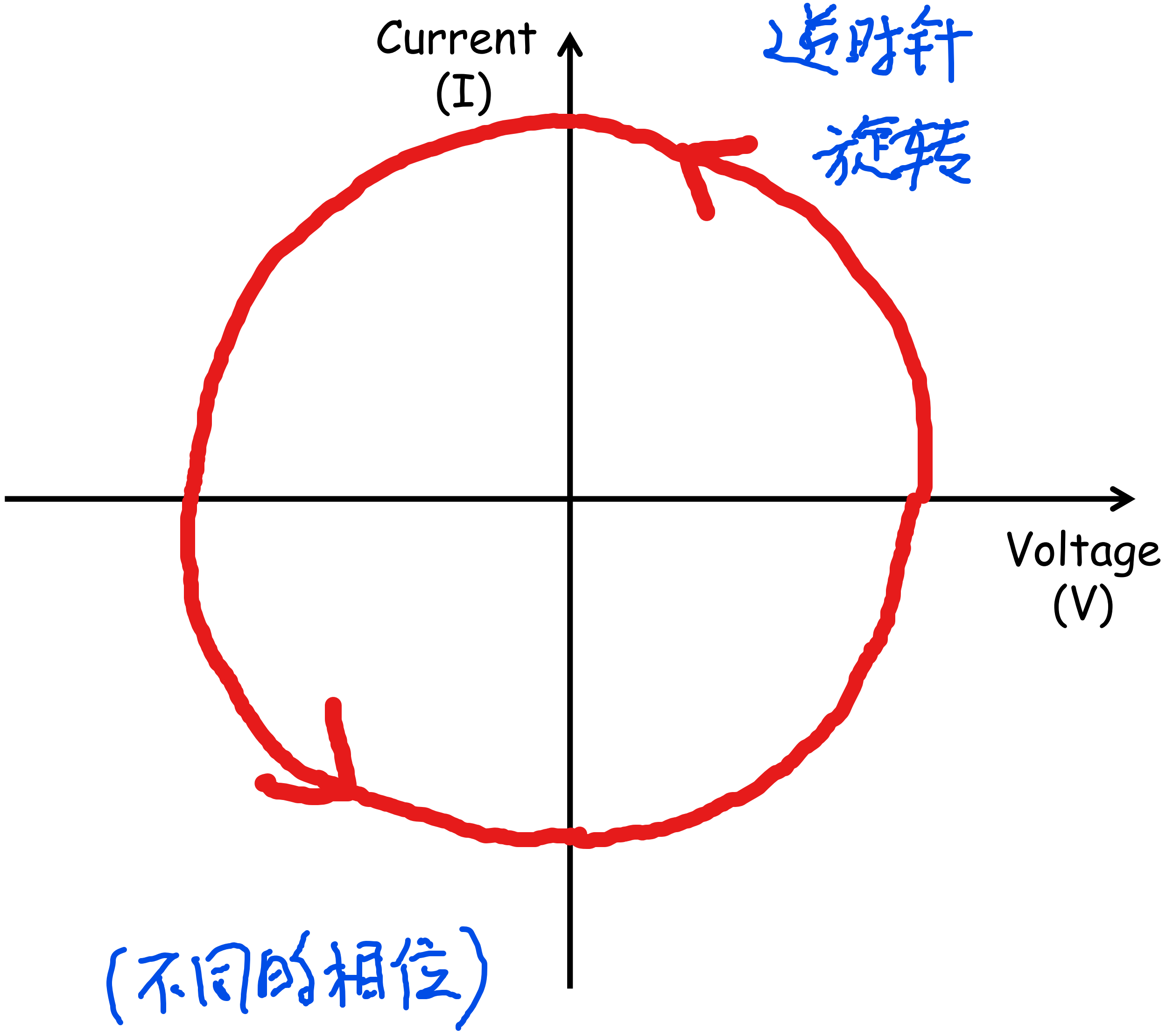


- Symbol

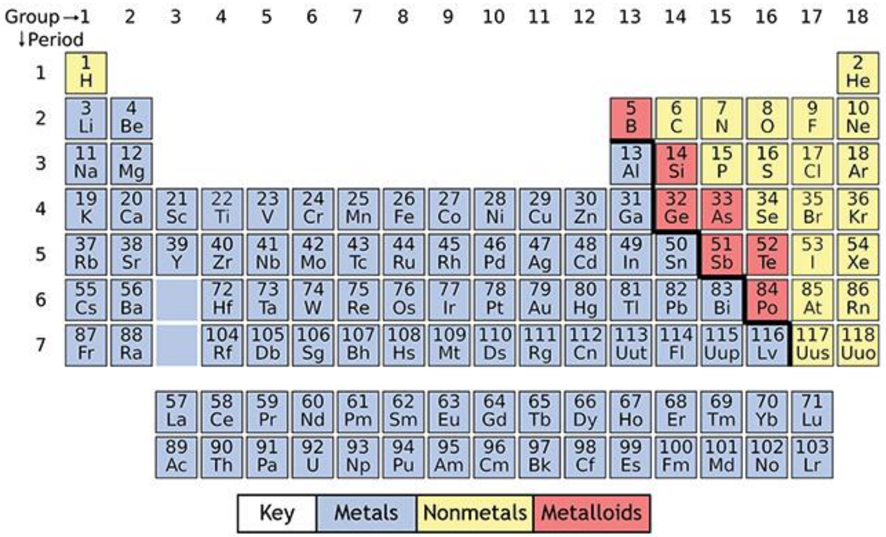


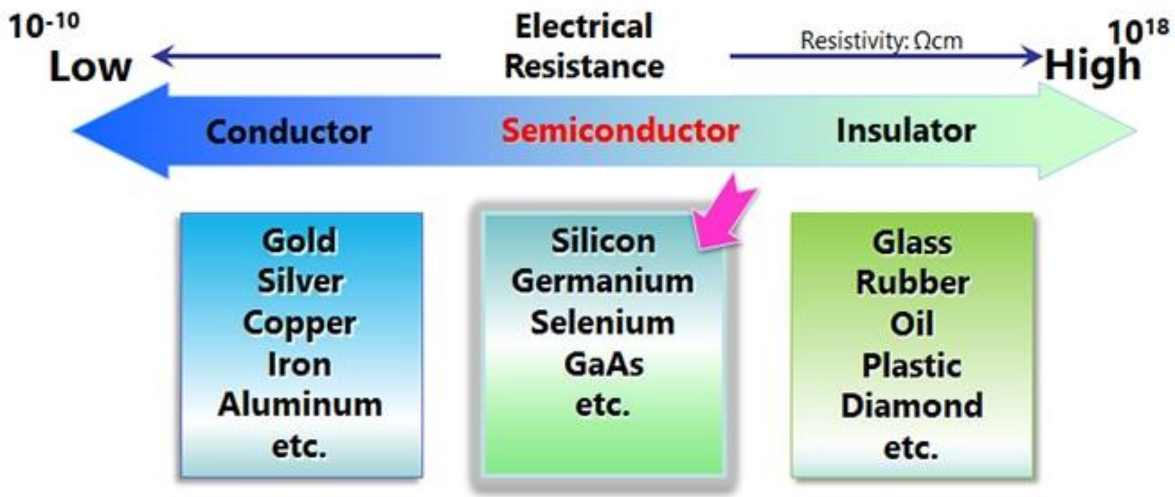
(Pictures are from the Internet)

- The I-V characteristics?

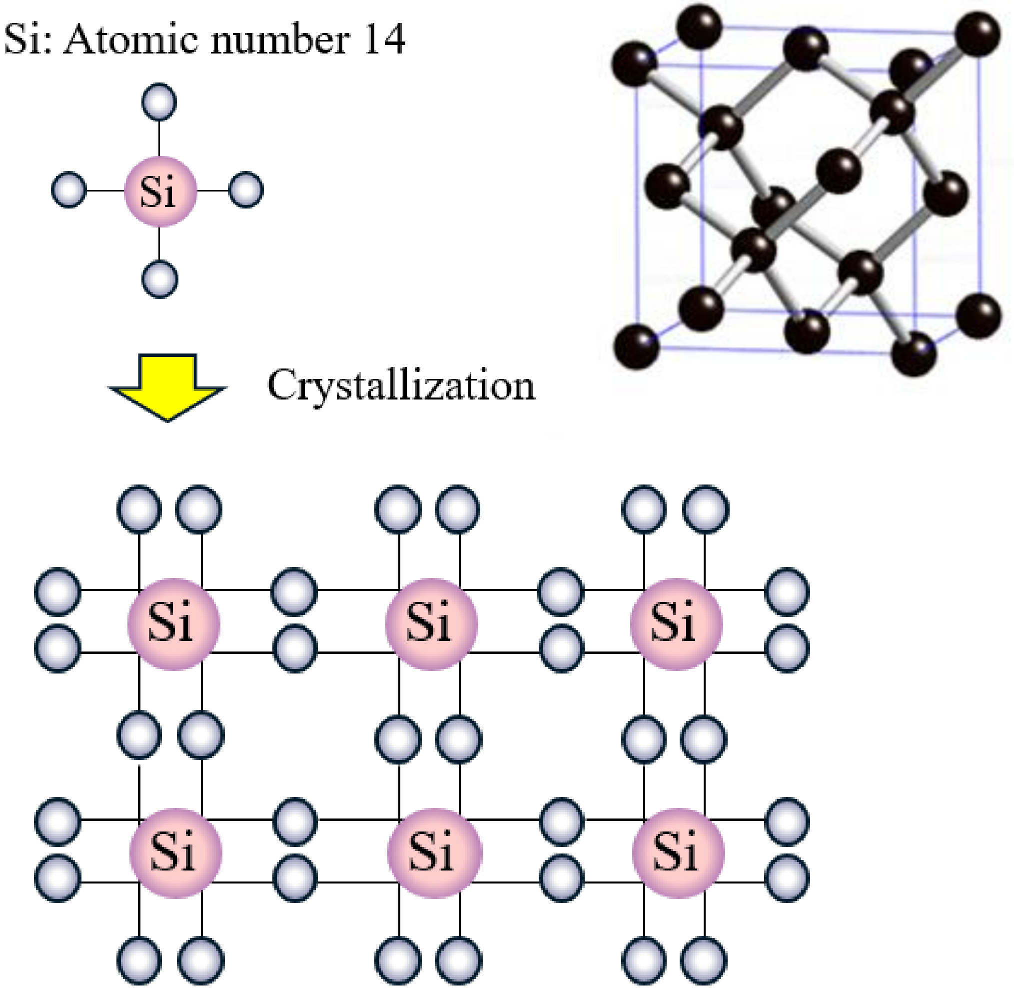


Semiconductor





- Silicon crystal 硅晶体



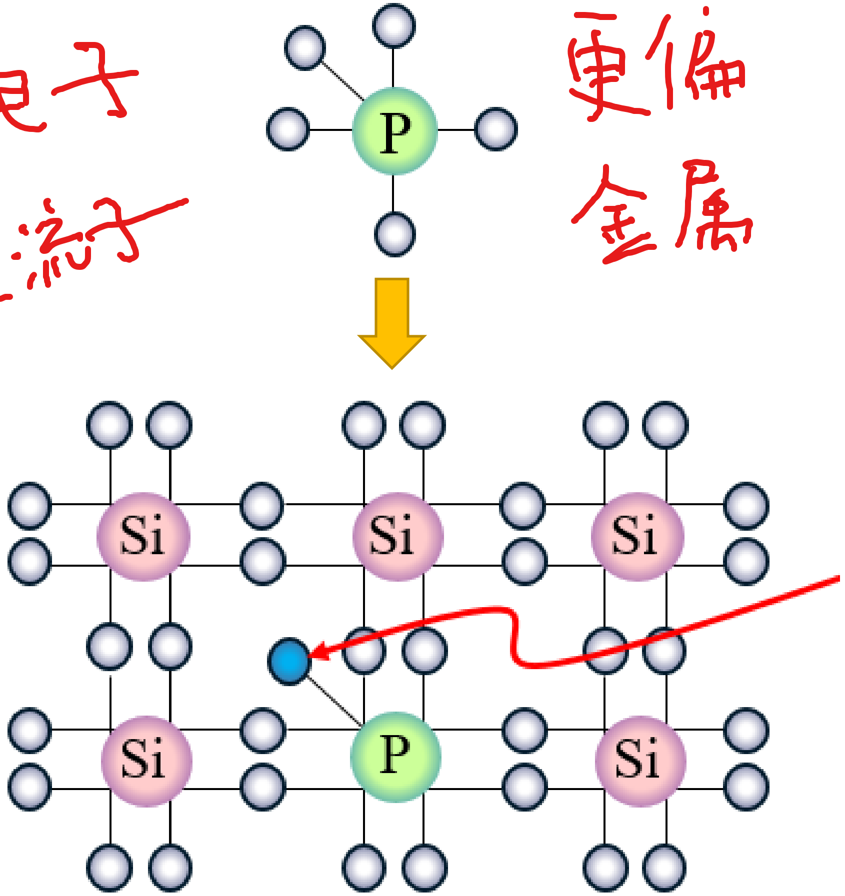
(Pictures are from the Internet)

After doping 掺杂

- N-type semiconductor Negative (e^-)
  - Some of the silicon atoms are replaced with P (phosphorus) 磷

自由电子为载流子

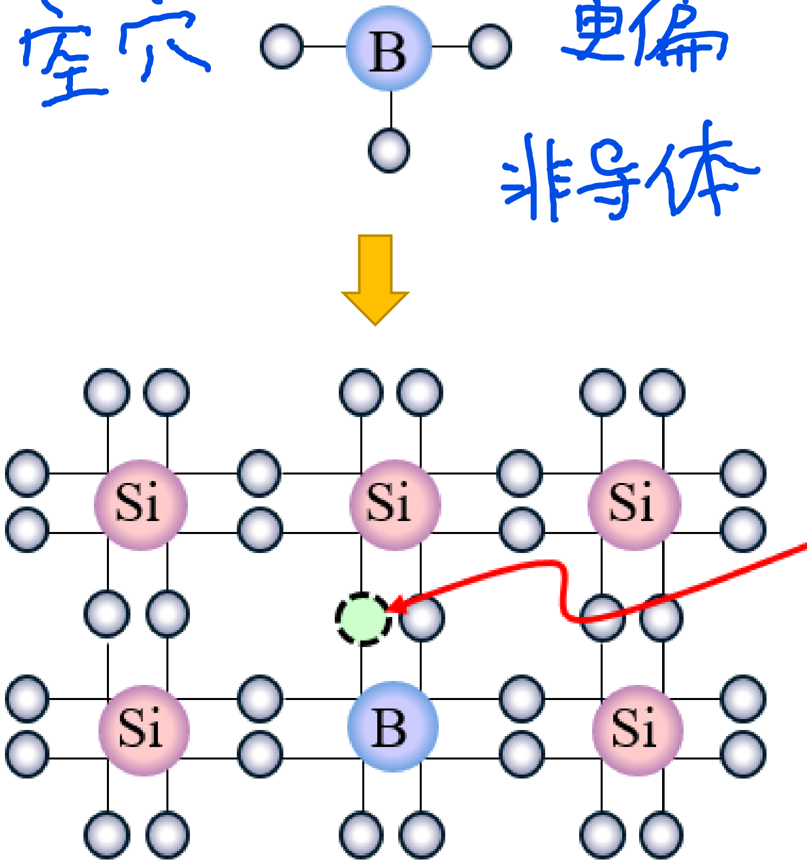
更偏金属



- P-type semiconductor Positive
  - Some of the silicon atoms are replaced with B (boron) 硼

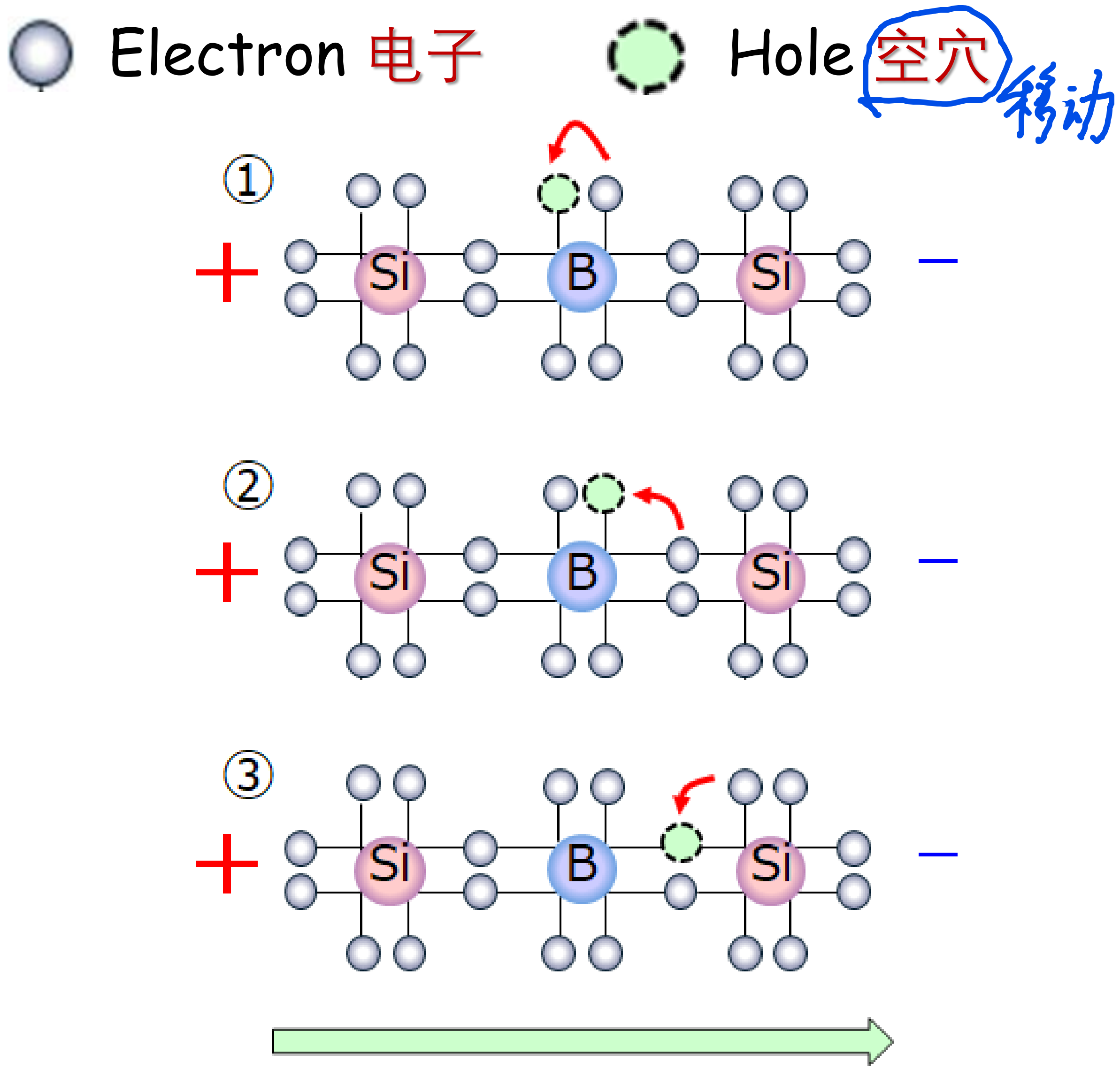
空穴

更偏非导体



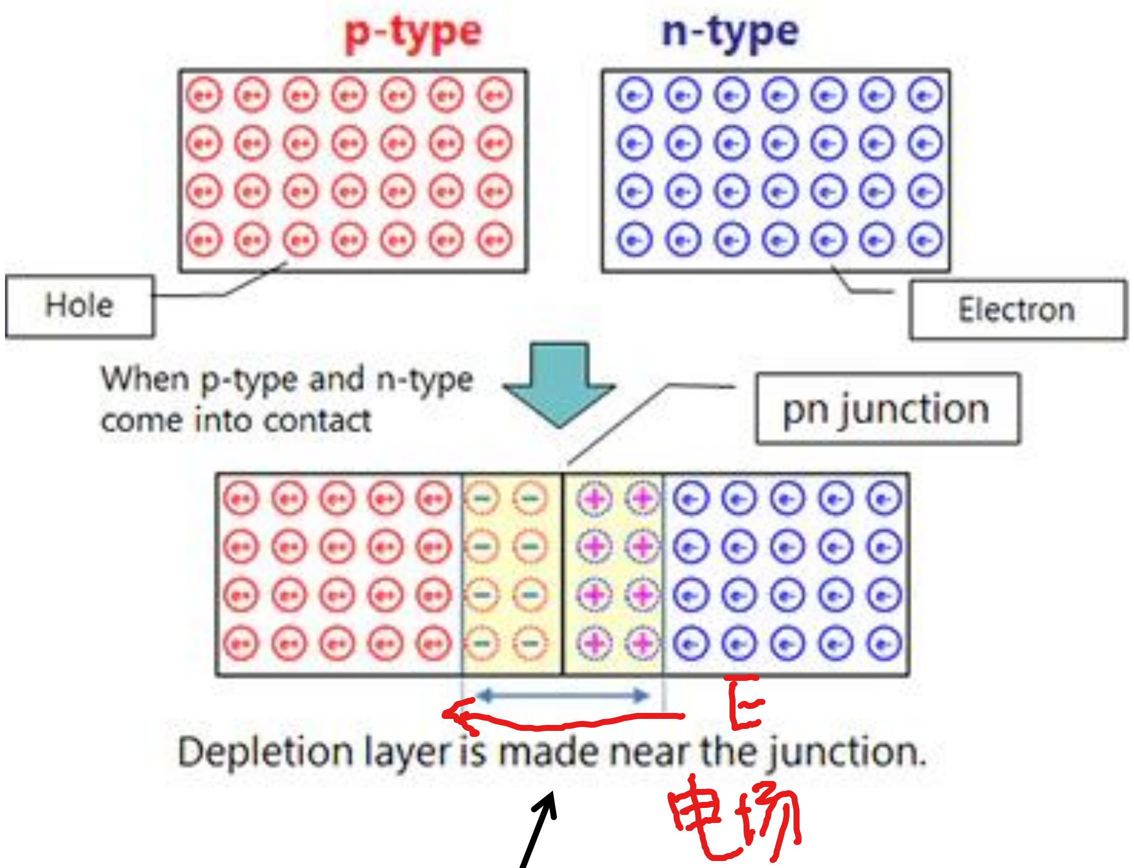
(Pictures are from the Internet)

How current flows in p-type semiconductors



1. Electrons are drawn to the positive (+) pole 正极 and move to close holes.
2. Then, as the electrons move to vacant holes, new holes are created and then the adjacent electrons move to the new vacant holes again.
3. As this process is repeated, electrons move toward the positive (+) pole, and at the same time, the holes appear to move toward the negative (-) pole 负极.
4. Only electrons are actually moving, but the holes can be considered as having positively charged particles.

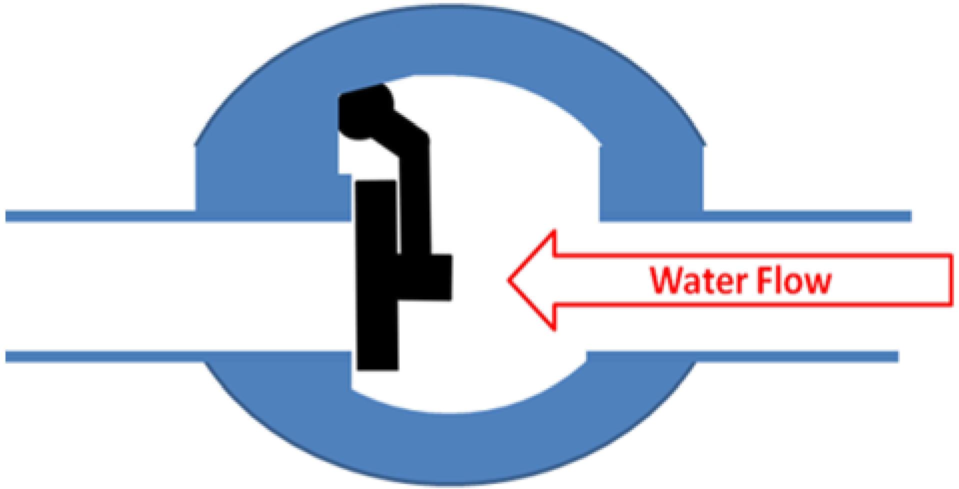
When p-type meets n-type

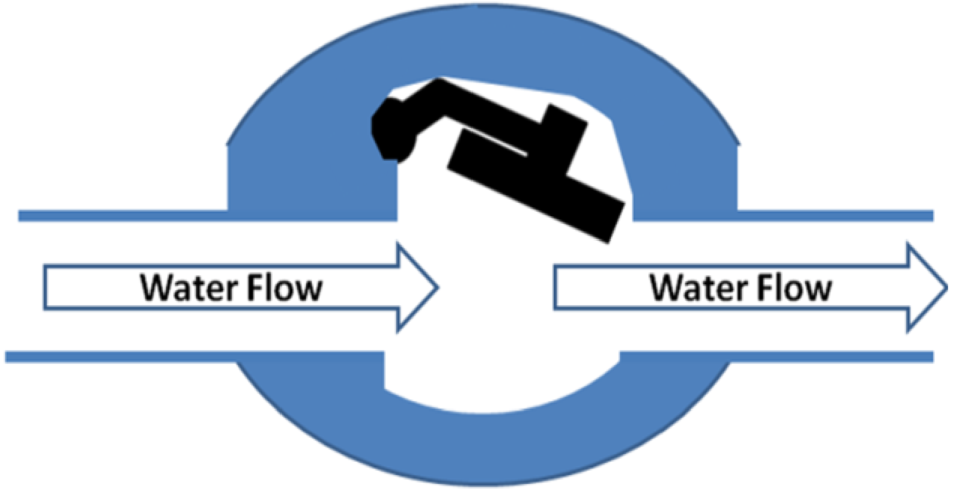


Depletion region 耗尽层（扩散形成）

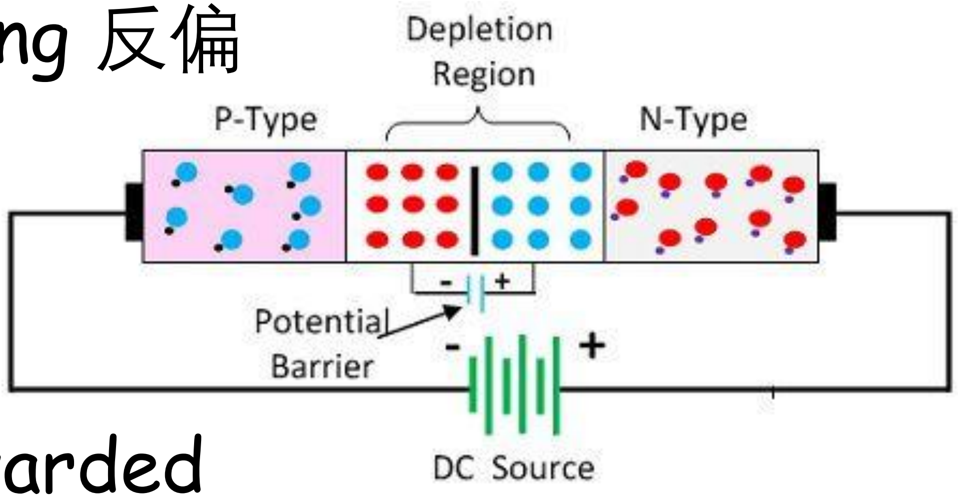
Uni-directional flow

- Flapper valve

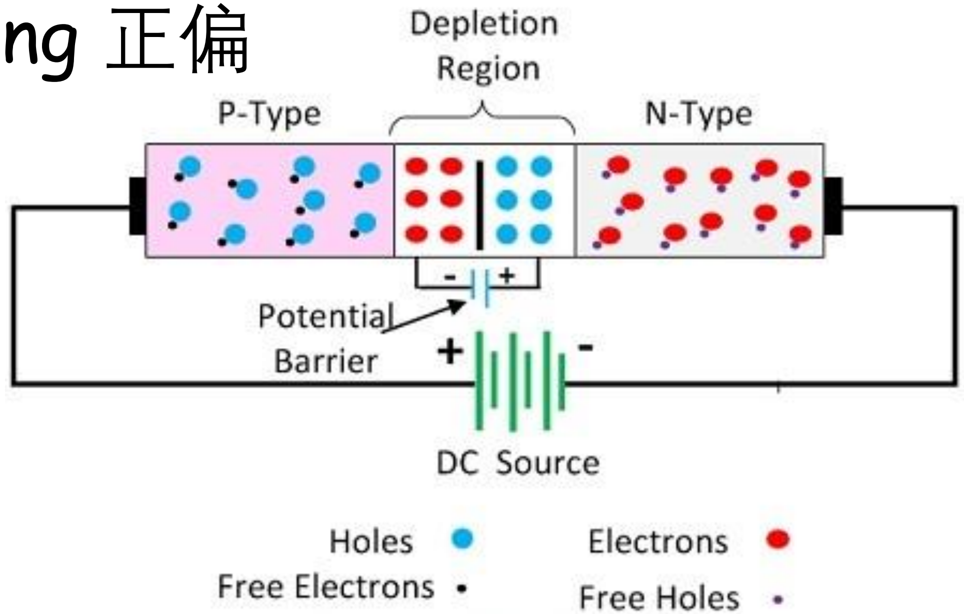




- Reversed biasing 反偏

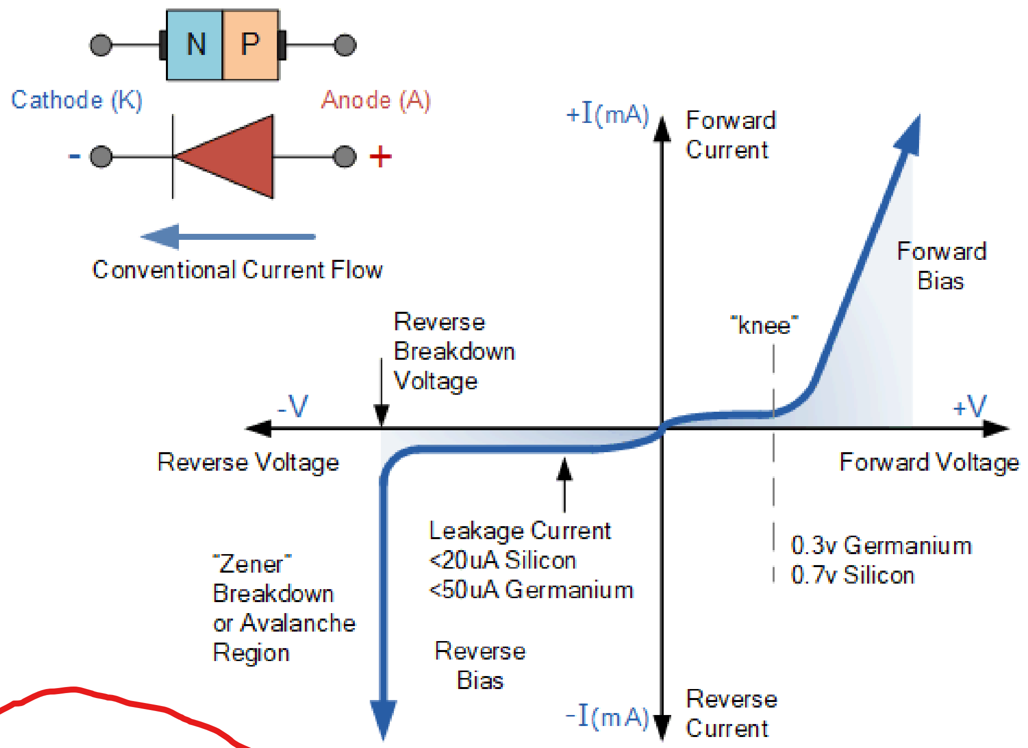


- Forwarded biasing 正偏



Diode characteristic

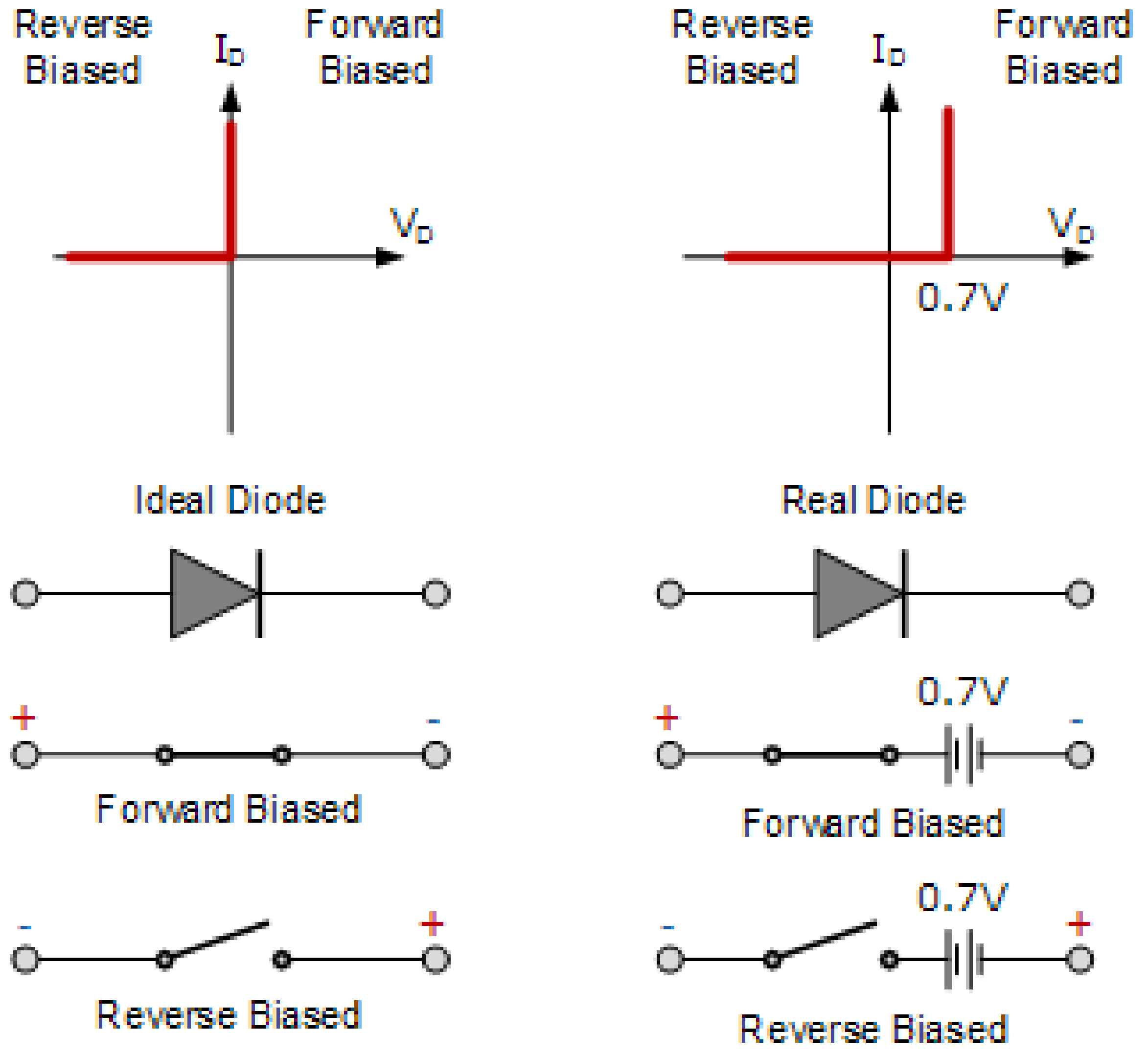
- Solid-state devices 固态器件



- Shockley diode equation

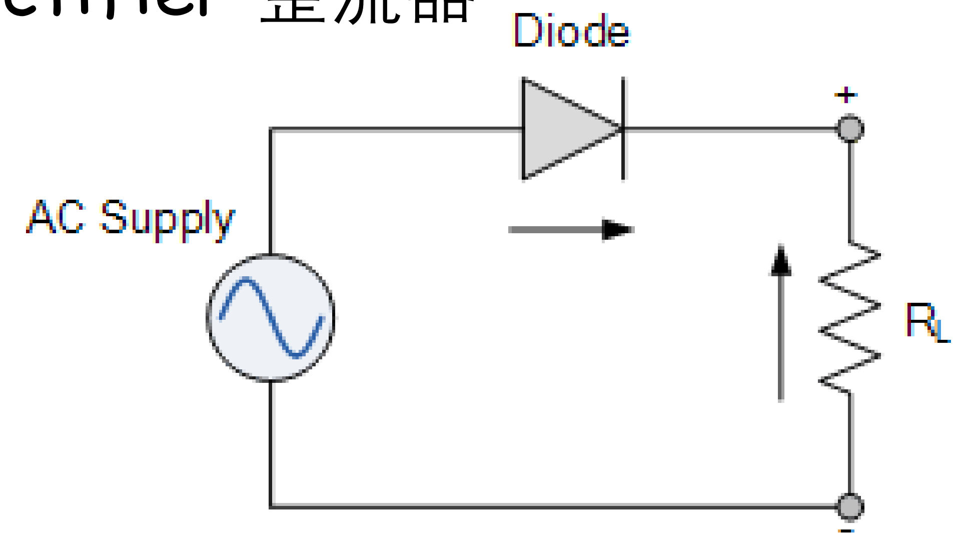
$$I = I_s\left[e^{\left(\frac{V_d}{nV_T}\right)} - 1\right]$$

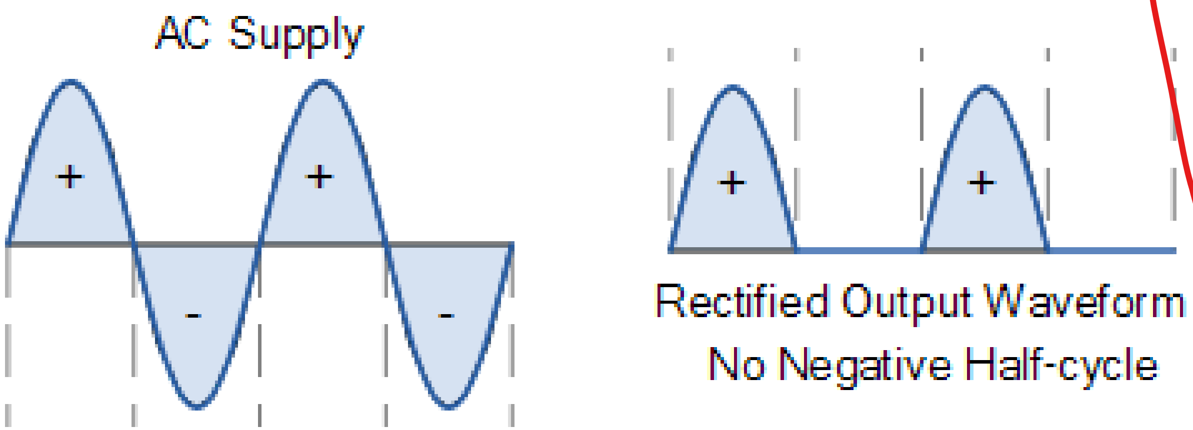
- Simplified models



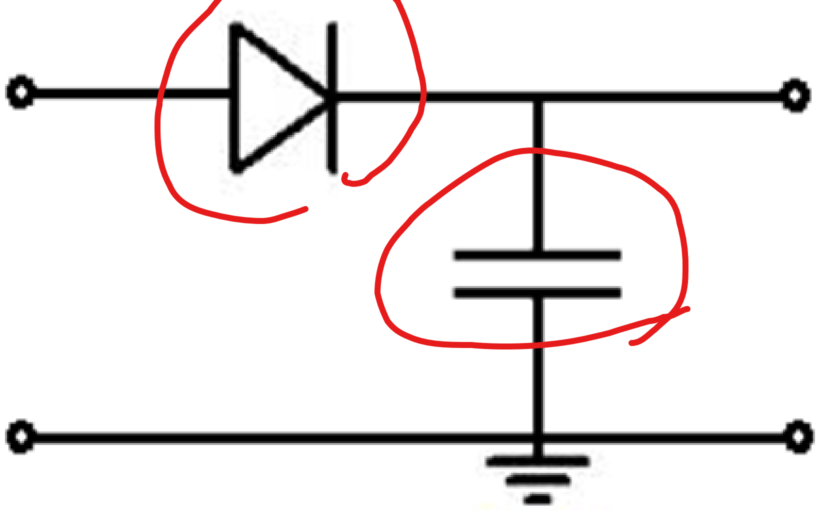
Diode circuits

- Rectifier 整流器



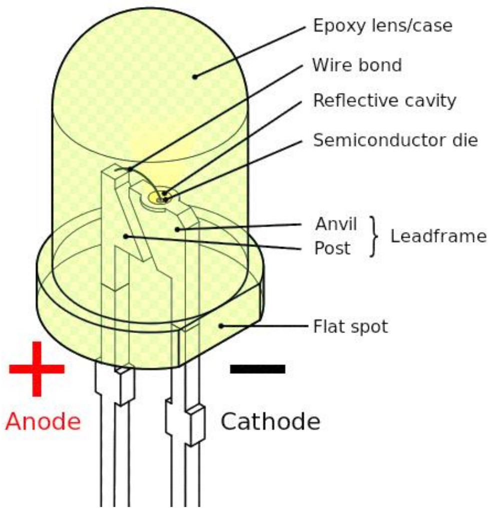


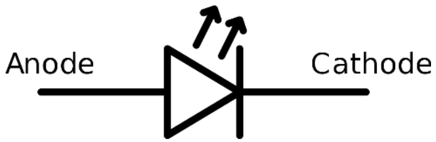
- Peak detector 峰值检测



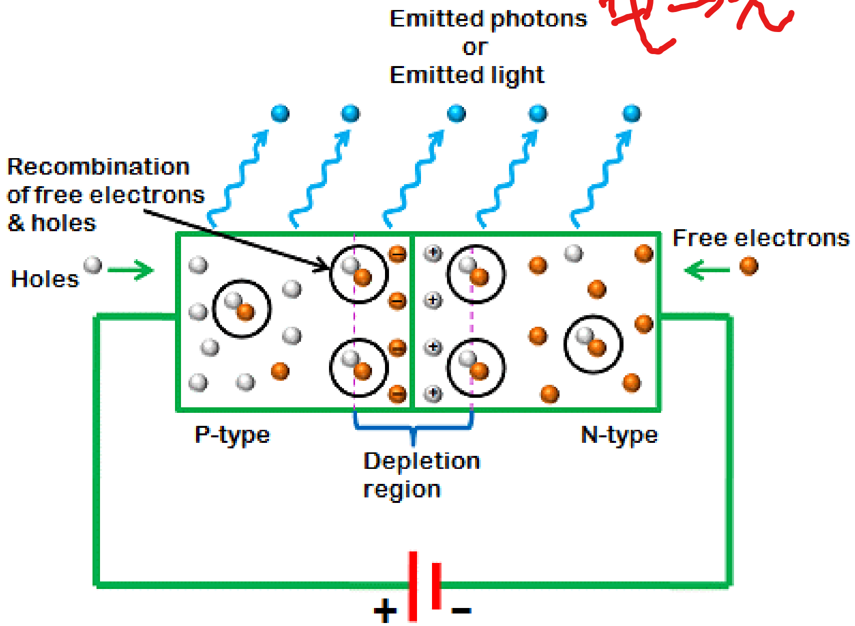
Other applications of PN junction

- LED (light emitting diode) ⇌
- Solar PV (photovoltaics)

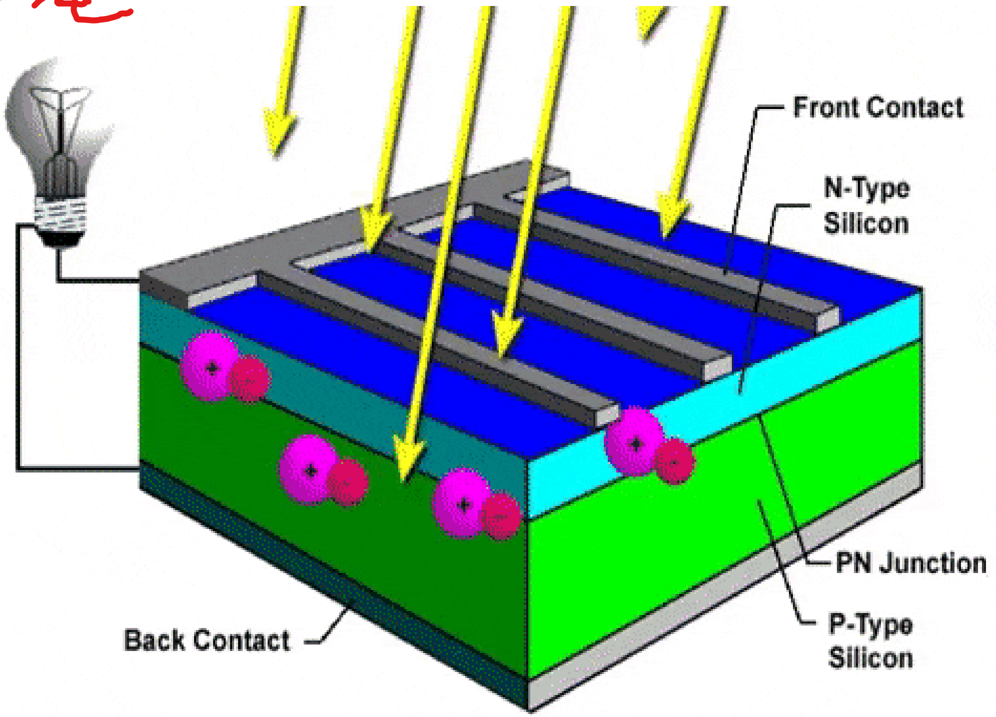




电→光

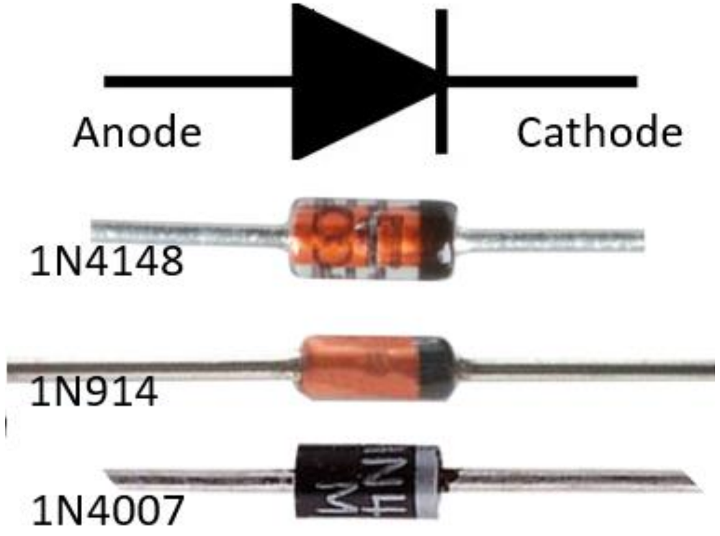


光→电



Passive and active switches

- Passive
  被动

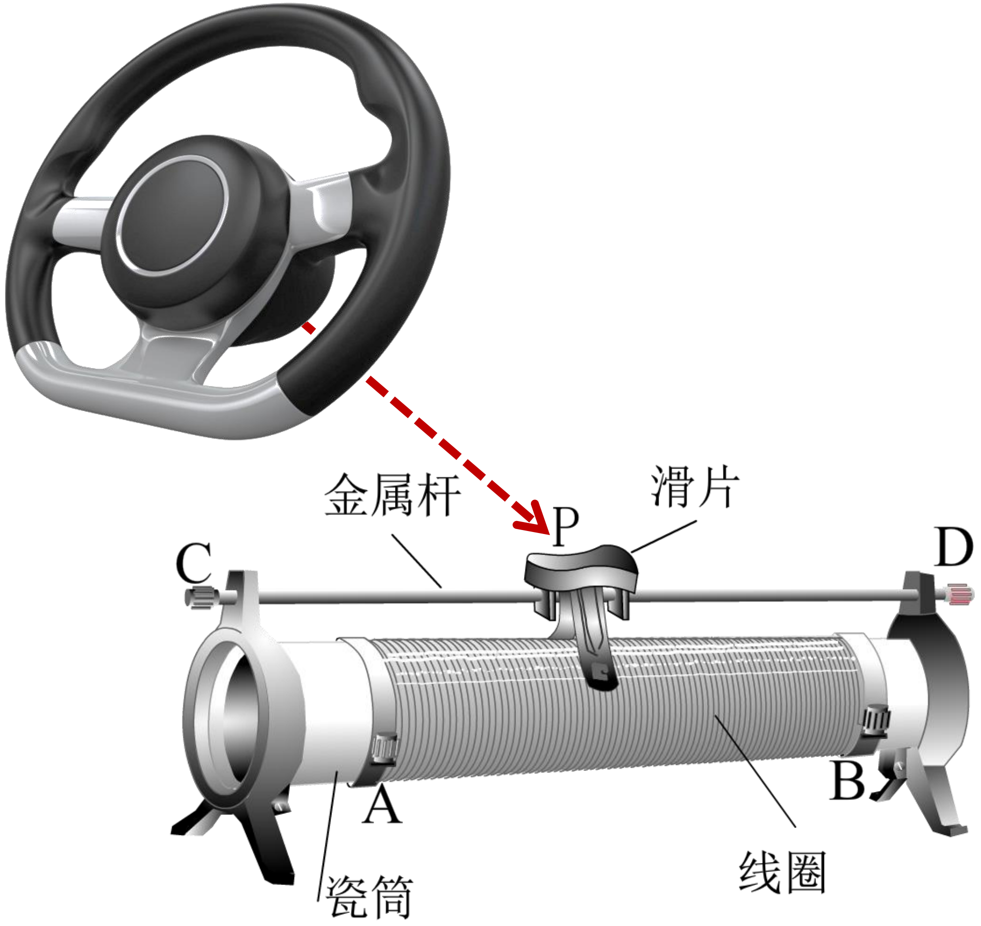


- Active
  主动

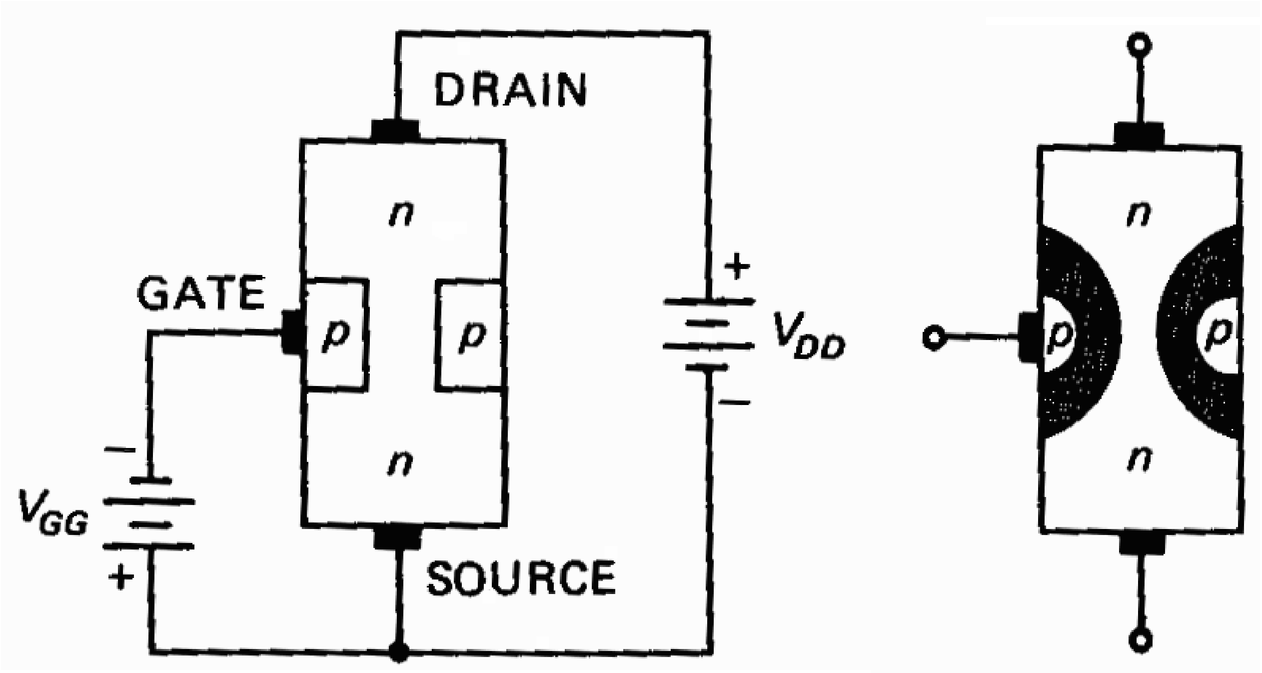
Electronic counterpart?

History of transistors

- Transistor（晶体管）
  "transfer" 转换 + "resistor" 电阻

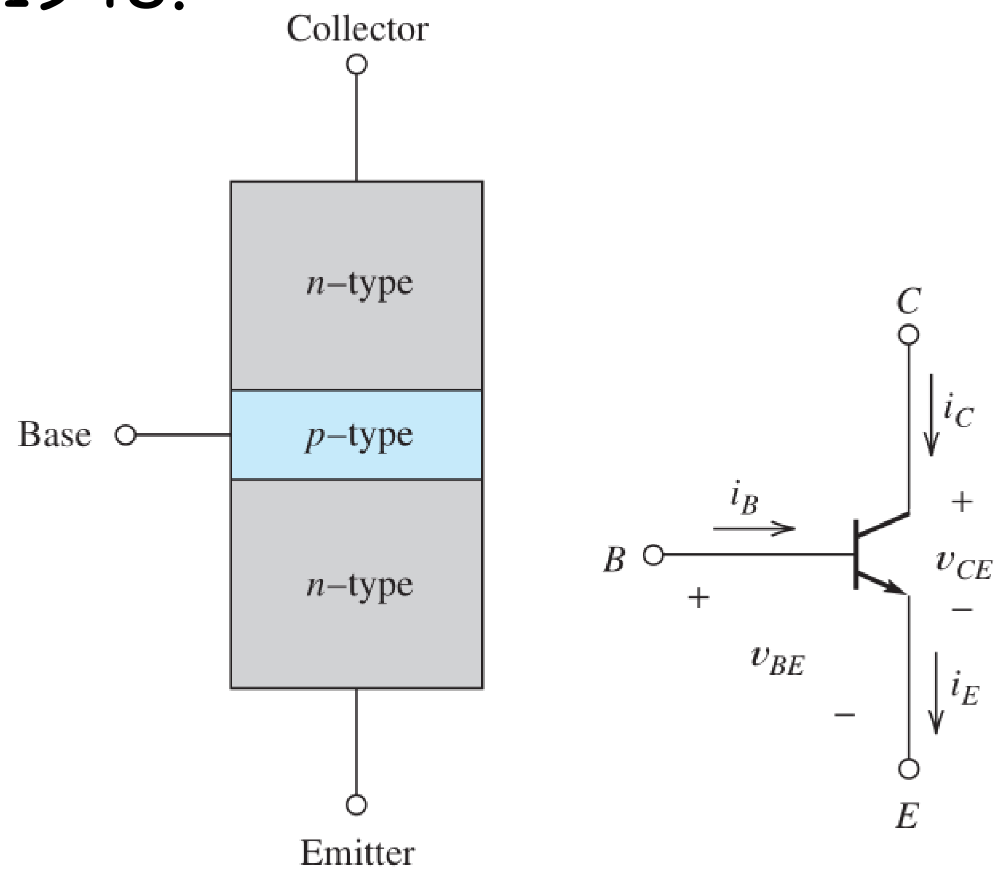


- Junction field-effect
  1 transistor (JFET) 结型场效应晶体管, was first patented by [Heinrich Welker]() in 1945



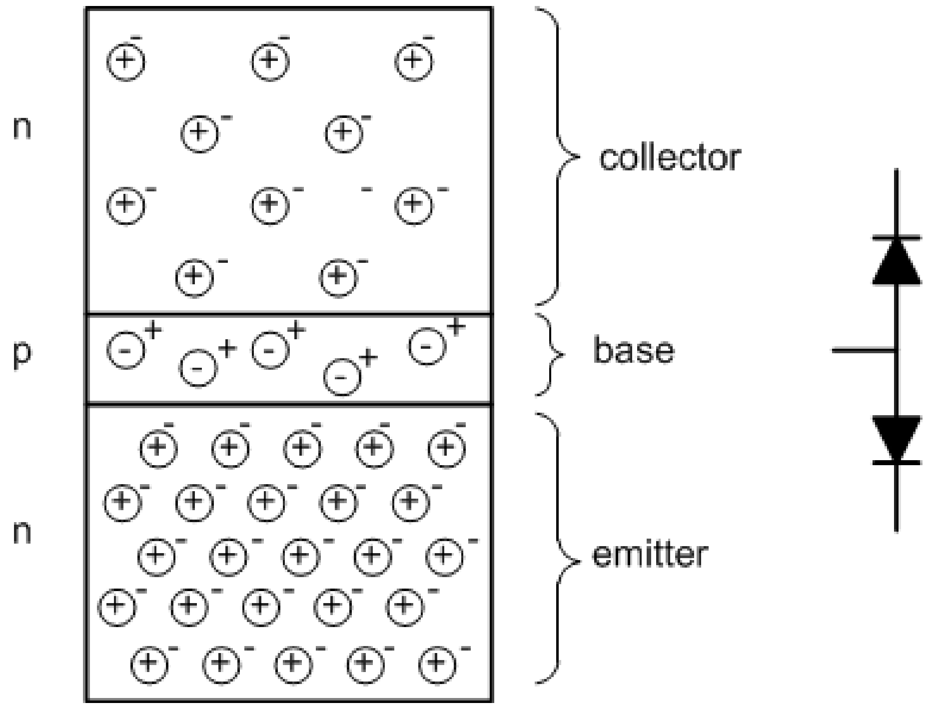
History of transistors

- Shockley's **bipolar junction transistor** (**BJT**) 双极型晶体管 in 1948.



(a) Physical structure (b) Circuit symbol

- By the mid-1950s, researchers had largely given up on the FET concept, and instead focused on bipolar junction transistor (BJT) technology

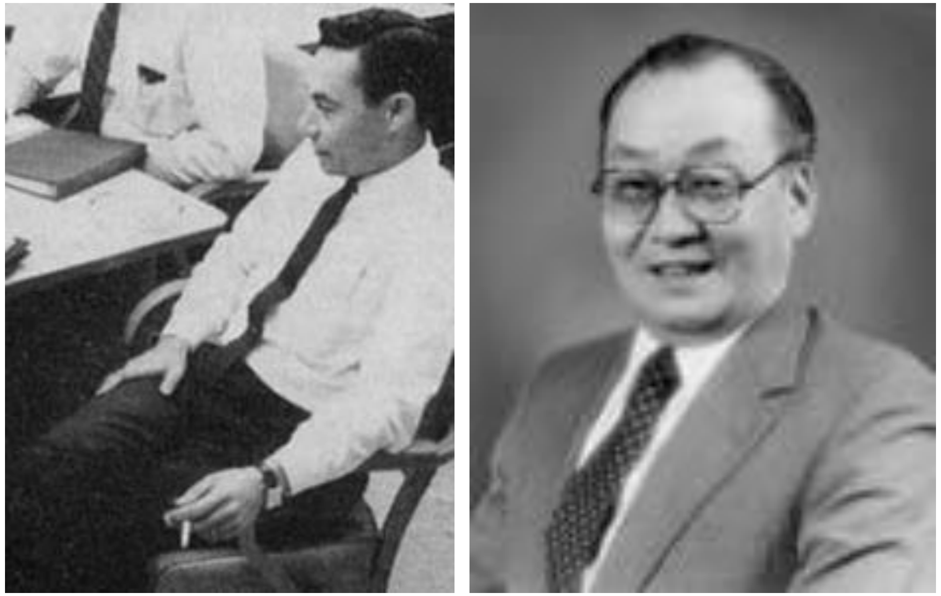


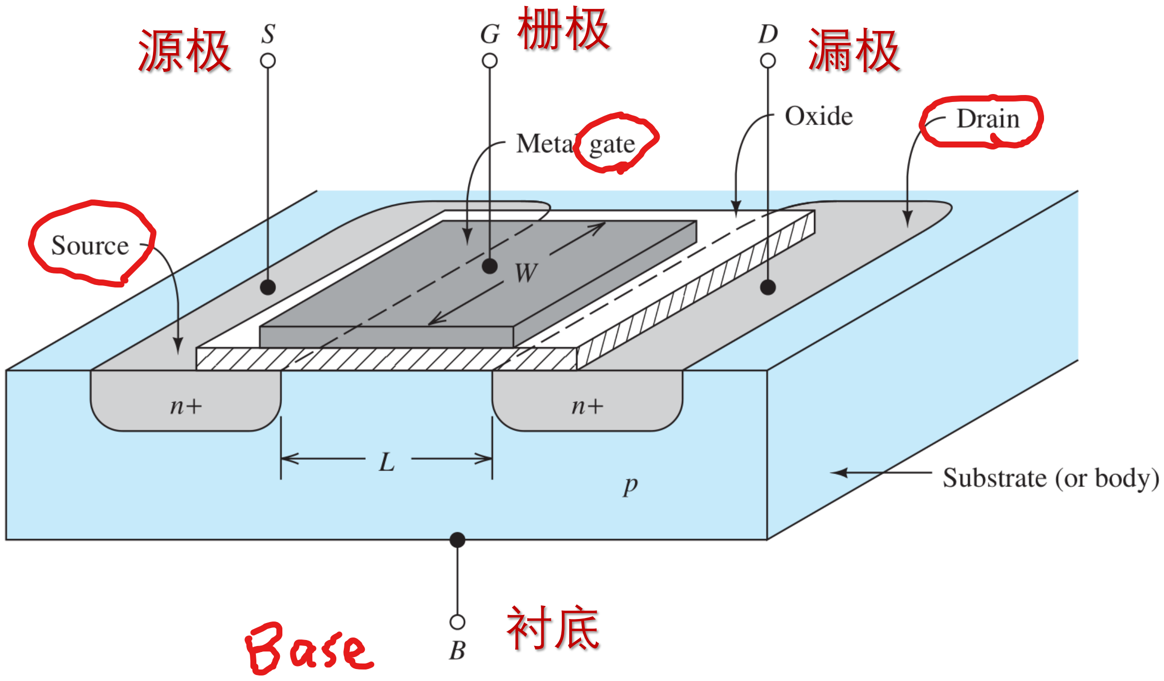
History of transistors

(不经过 PN 结)

- The metal-oxide-semiconductor field-effect transistor (MOSFET) 金属氧化物半导体场效应晶体管 was invented by Mohamed Atalla and Dawon Kahng at Bell Lab in 1959.

- high scalability 小体积
- much lower power consumption 低功耗
- higher density than BJT
- possible to build high-density integrated circuits (ICs)

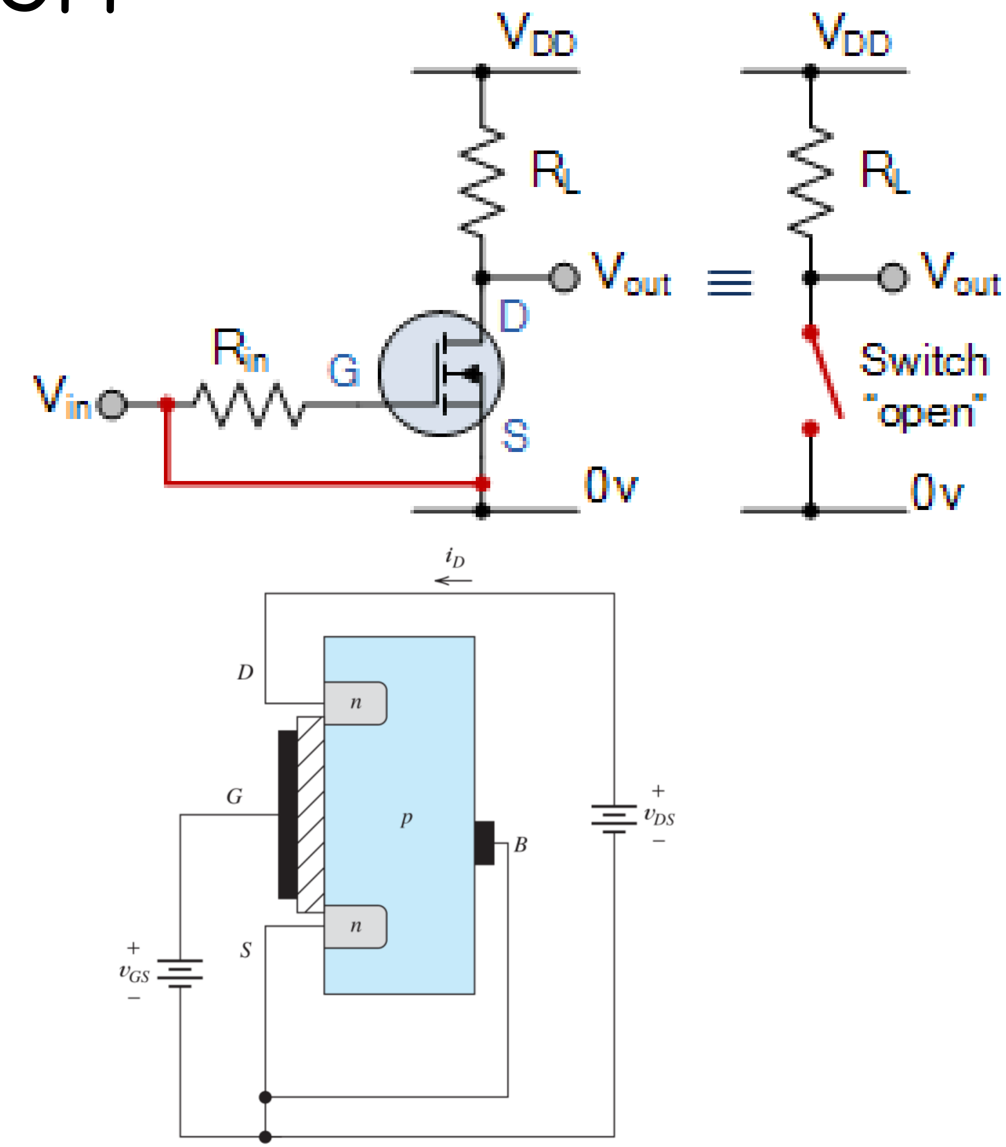




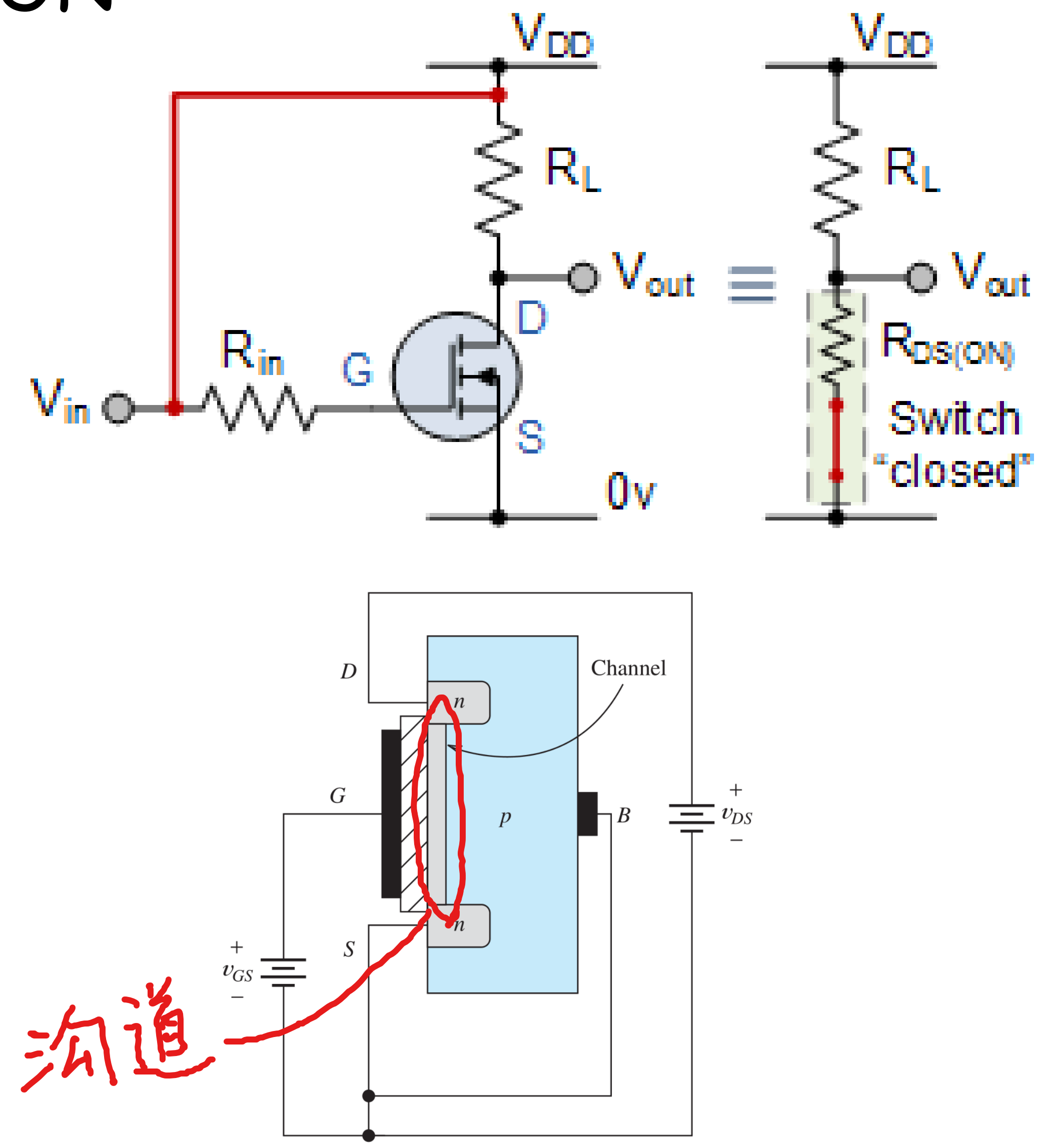
(https://en.wikipedia.org/wiki/History_of_the_transistor)

MOSFET operation

- OFF

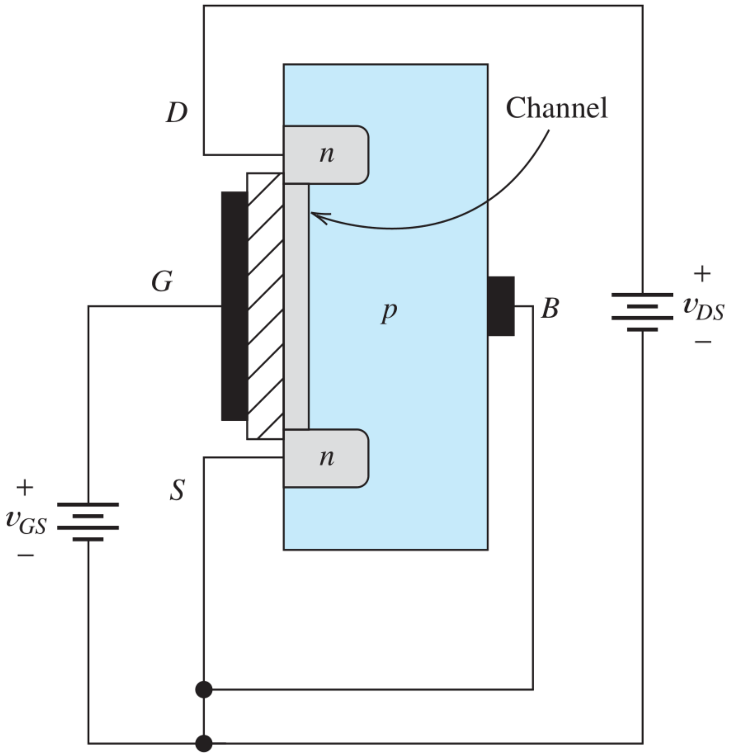


- ON

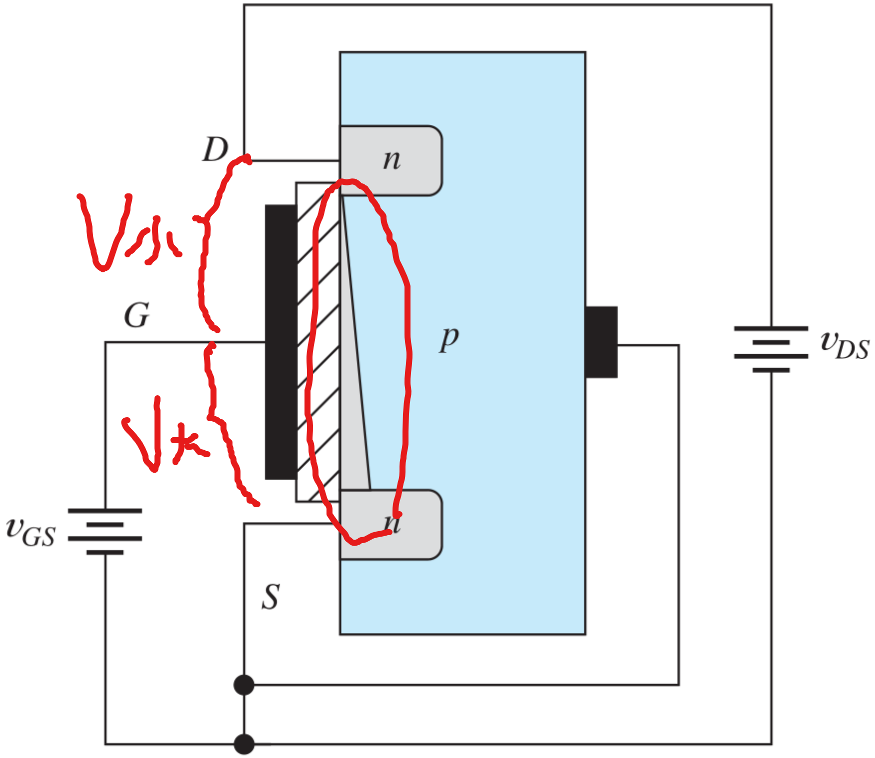


MOSFET operation

- Ideal channel

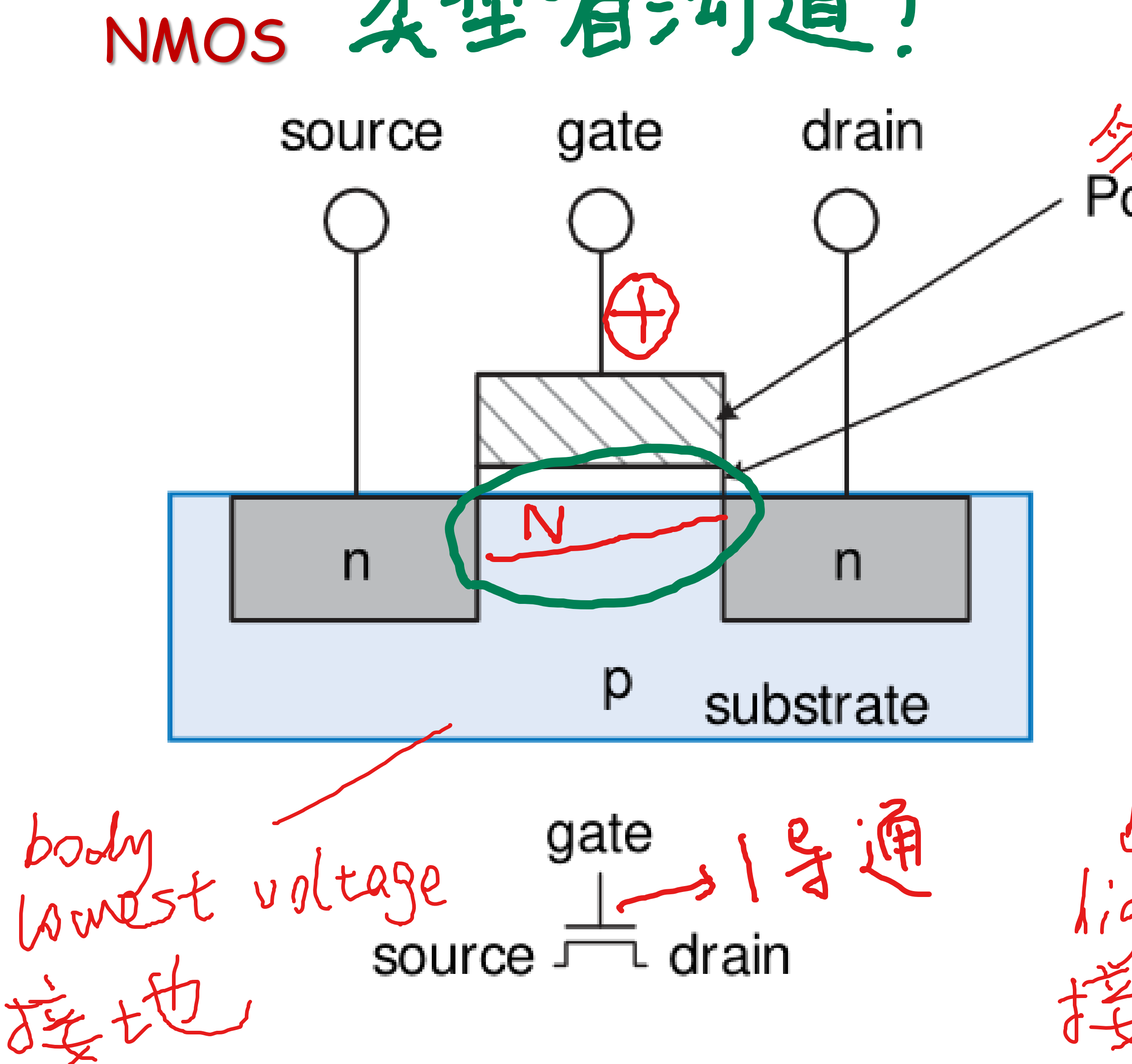


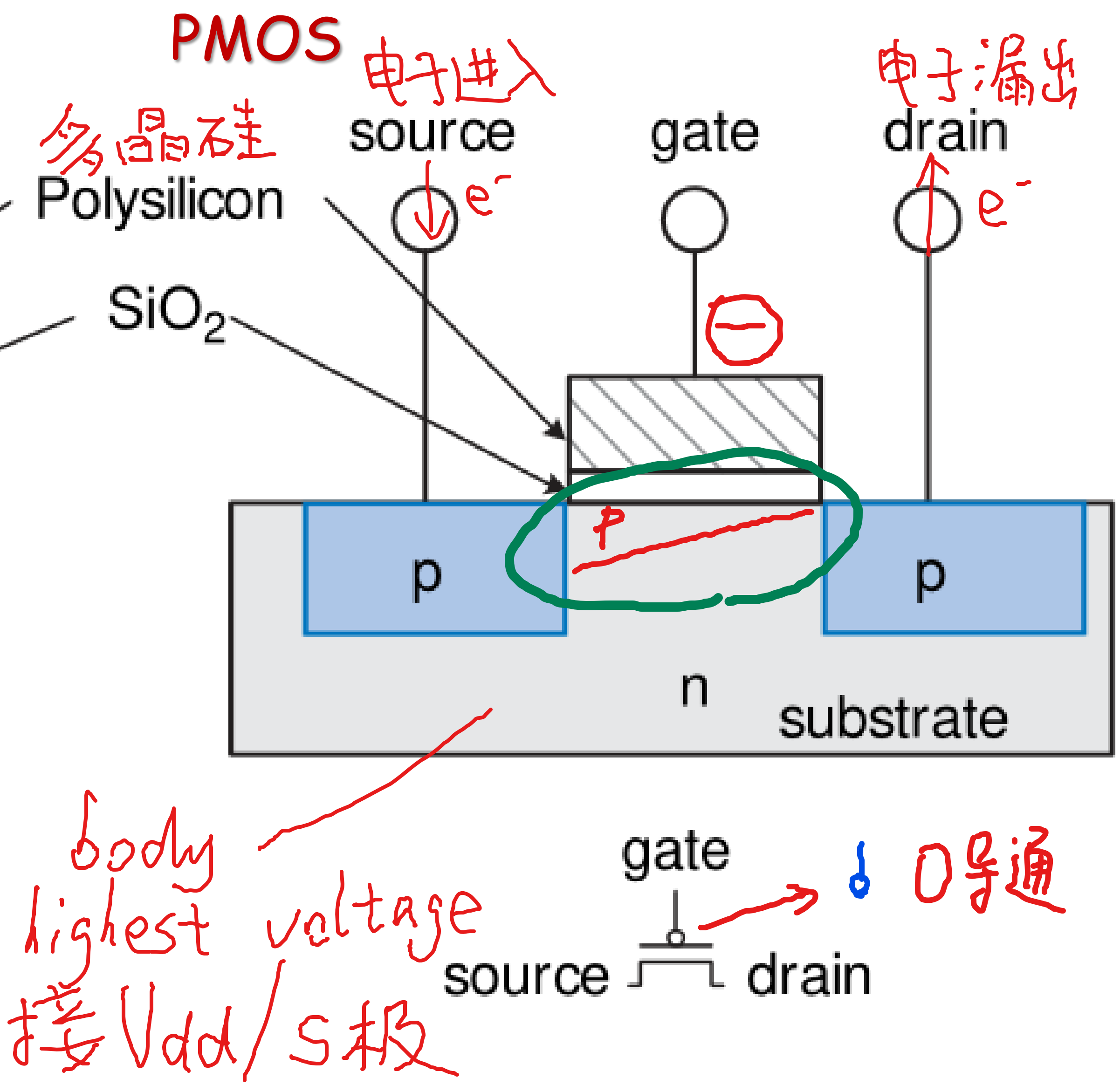
- Actual channel



NMOS & PMOS

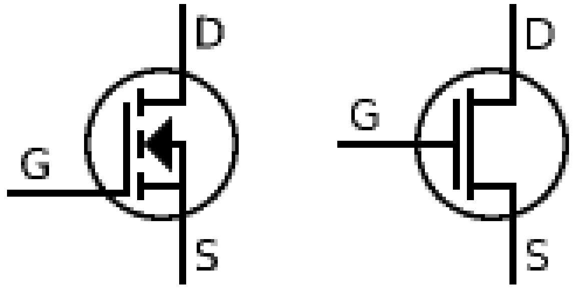
类型看沟道!



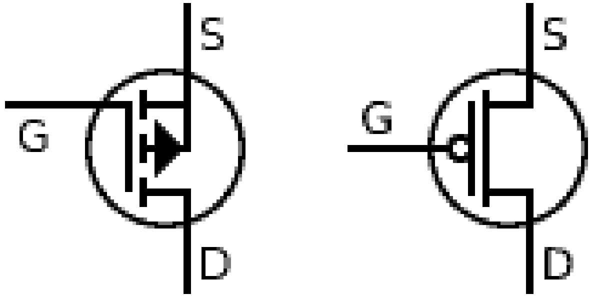


Symbols

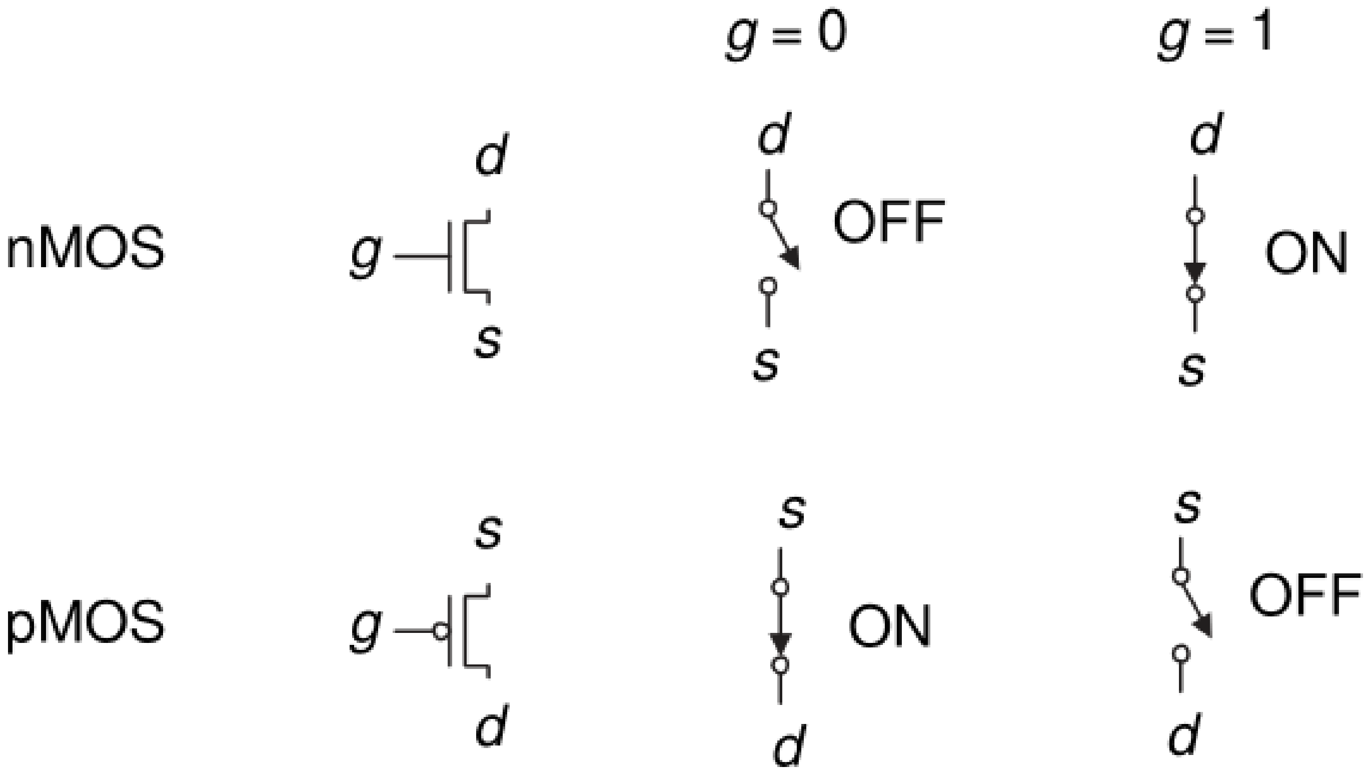
- Symbol
  - NMOS



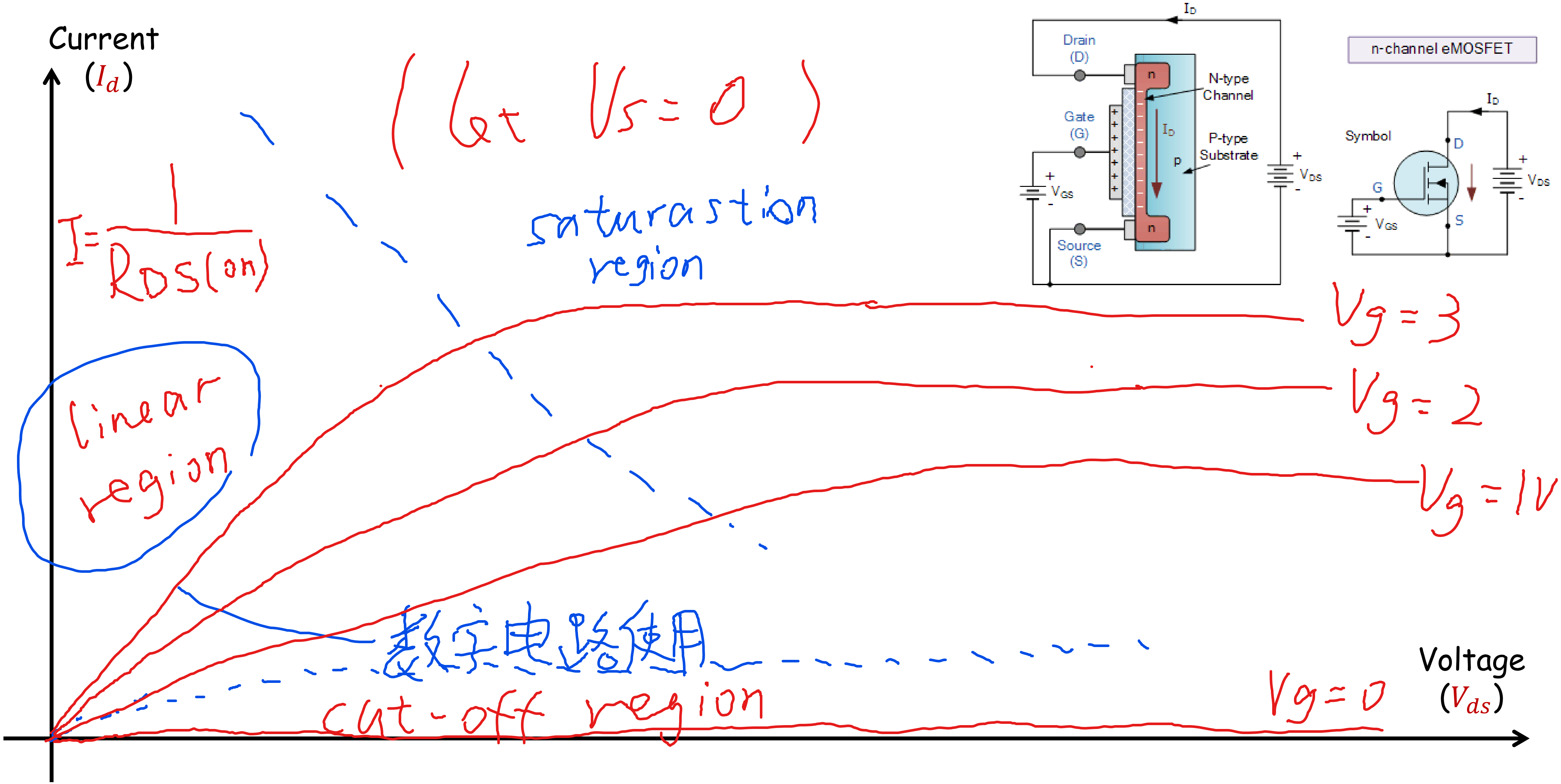
  - PMOS



- ON / OFF



The I-V characteristic of a MOSFET



Computation

- Arithmetic

$5.5 - 3.4 = 2.1$

$15 / 3 = 5$

$2 + 15 = 17$

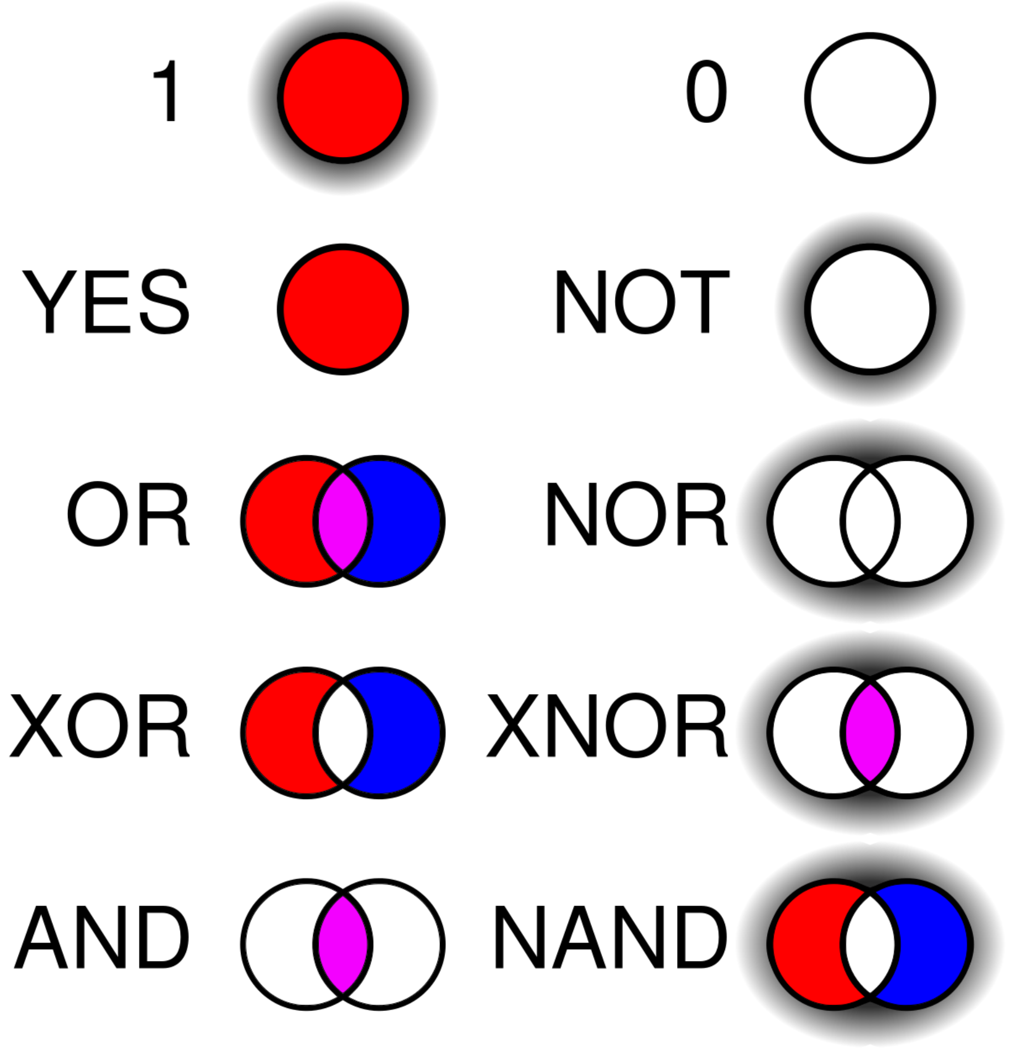
$3 \times (4+2) = 18$

25% of 12 is 3

$\sqrt{9} = 3$

$\frac{3}{4} \times 16 = 12$

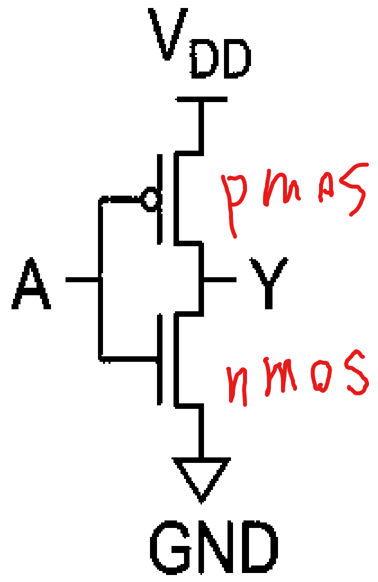
- Boolean logic

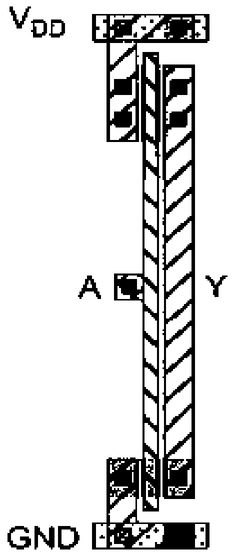


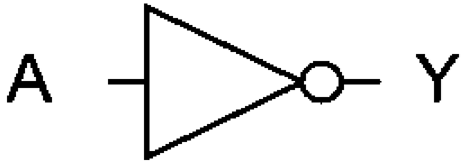
CMOS & not gate

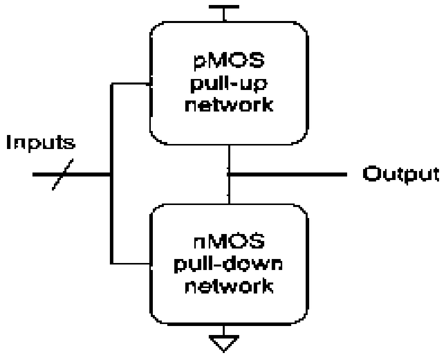
- CMOS technology (Complementary Metal-Oxide-Semiconductor Transistor, 互补金属氧化物半导体)

BASICS OF CMOS TECHNOLOGY





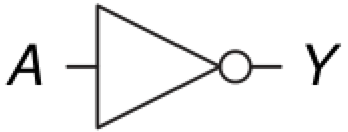




- Not gate 非门

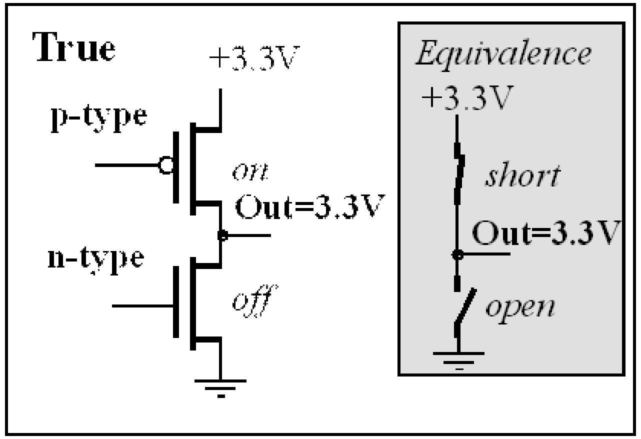
反相器

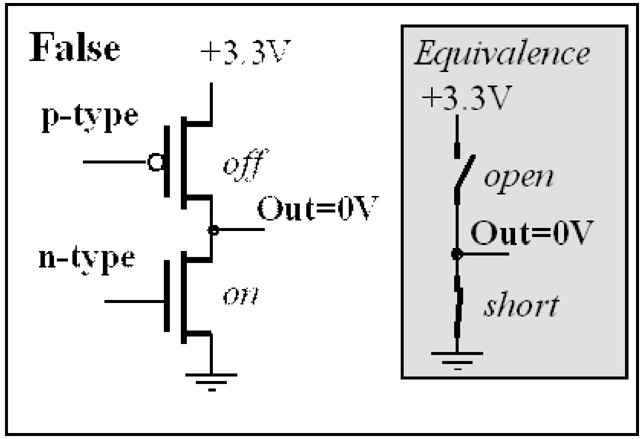
NOT



$Y = \overline{A}$

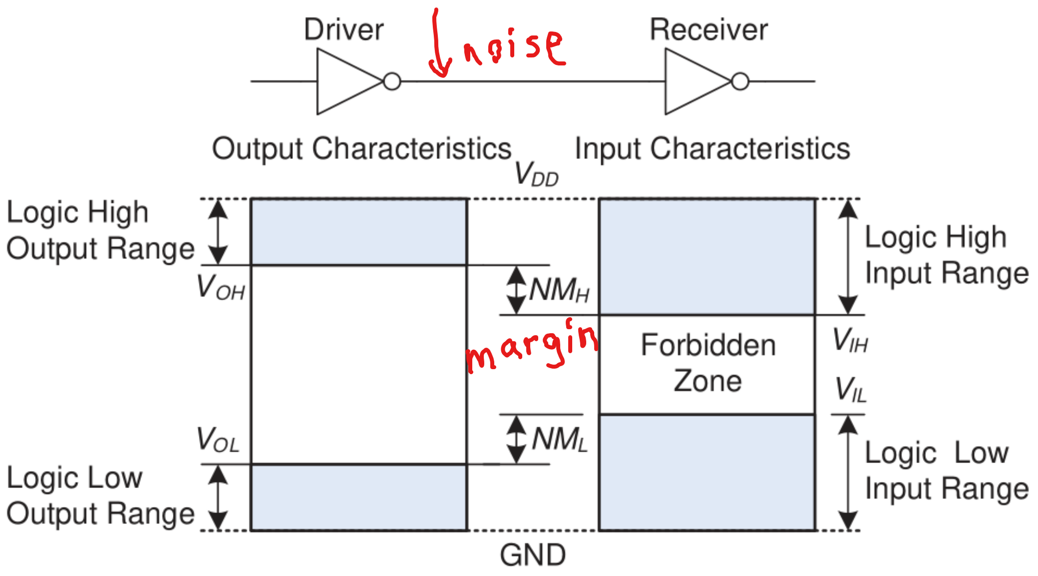
A	Y
0	1
1	0



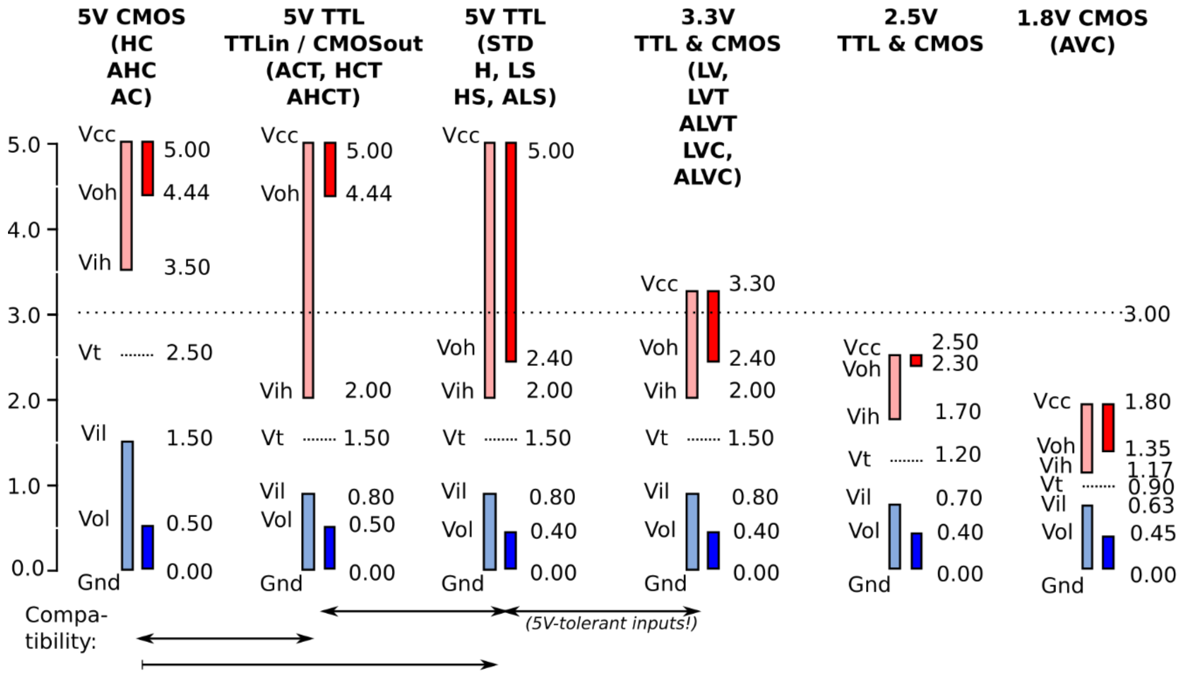


Logic voltage levels

- How to physically express the virtual concept of logic?



- Logic families

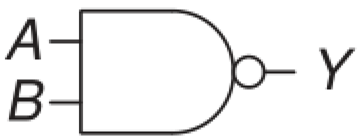


Data source: EETimes, A brief recap of popular logic standards (Mark Pearson, Maxim).

Other logic gates

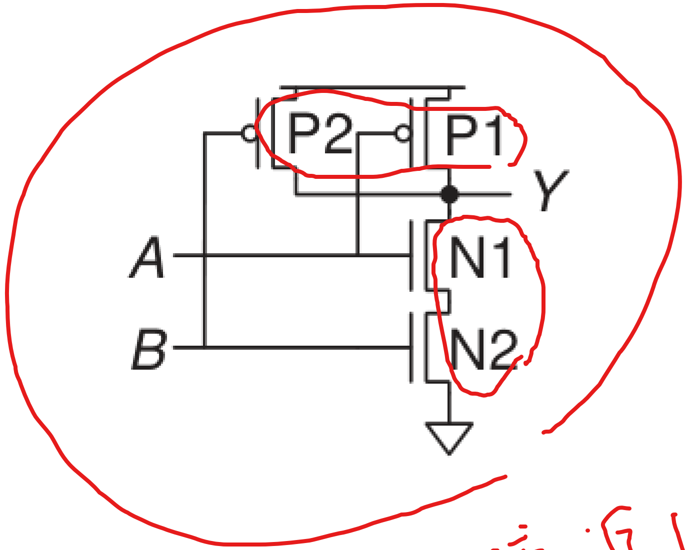
- NAND gate 与非门

NAND



$$Y = \overline{AB}$$

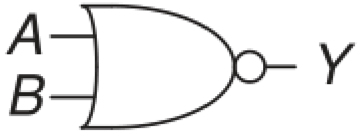
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0



特点：PMOS接近Vdd
NMOS接近地

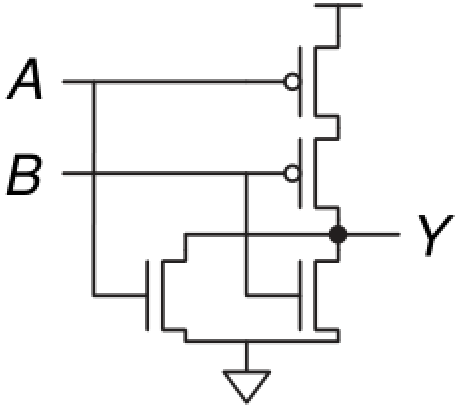
- NOR gate 或非门

NOR



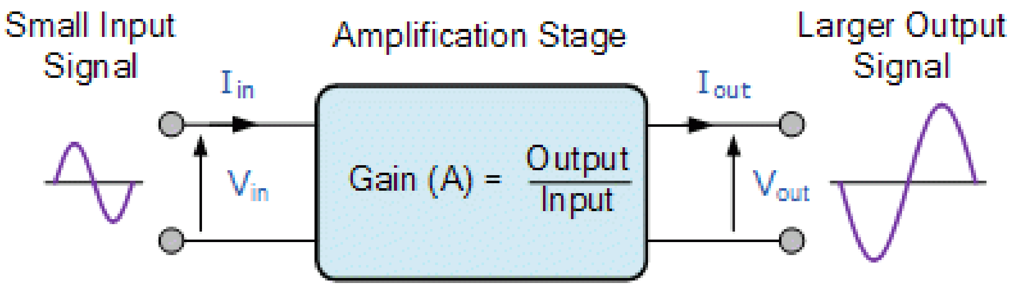
$$Y = \overline{A + B}$$

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

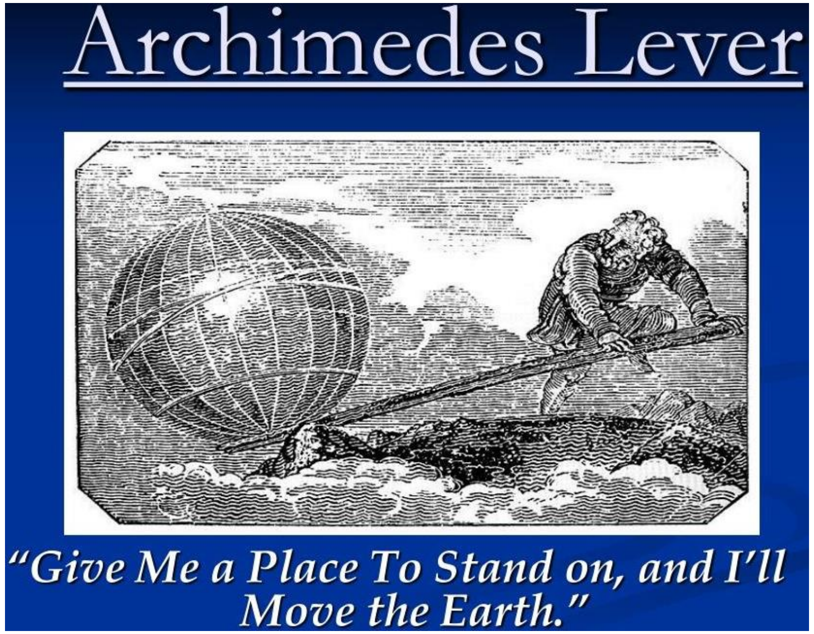


Amplification and CMOS amplifier

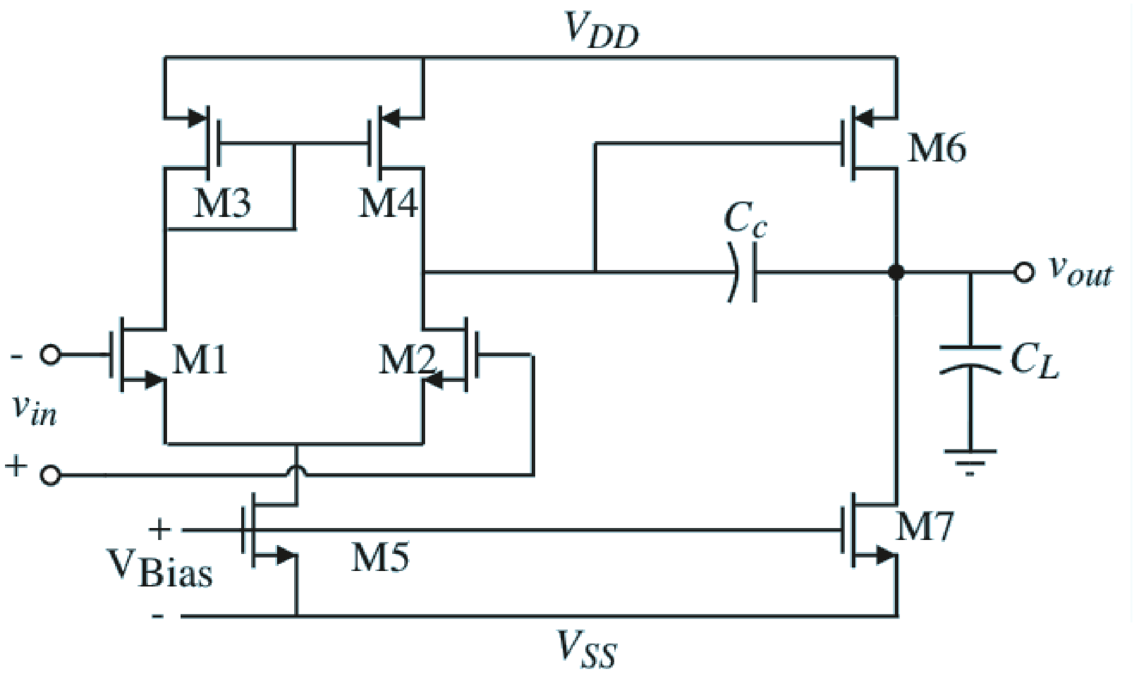
- What is an amplifier



- Why we need amplifier



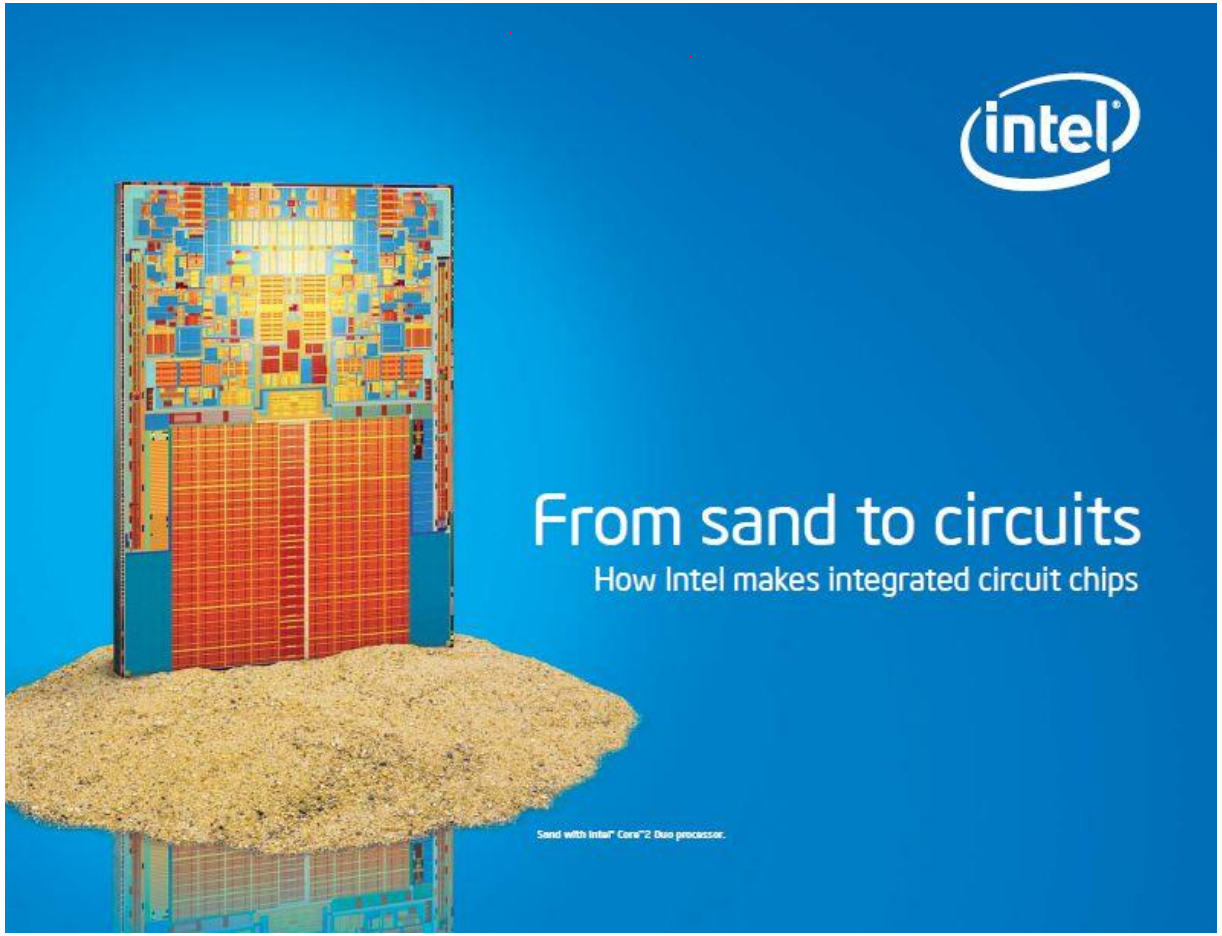
- CMOS amplifier 放大



(will be further elaborated in the 6th lecture)

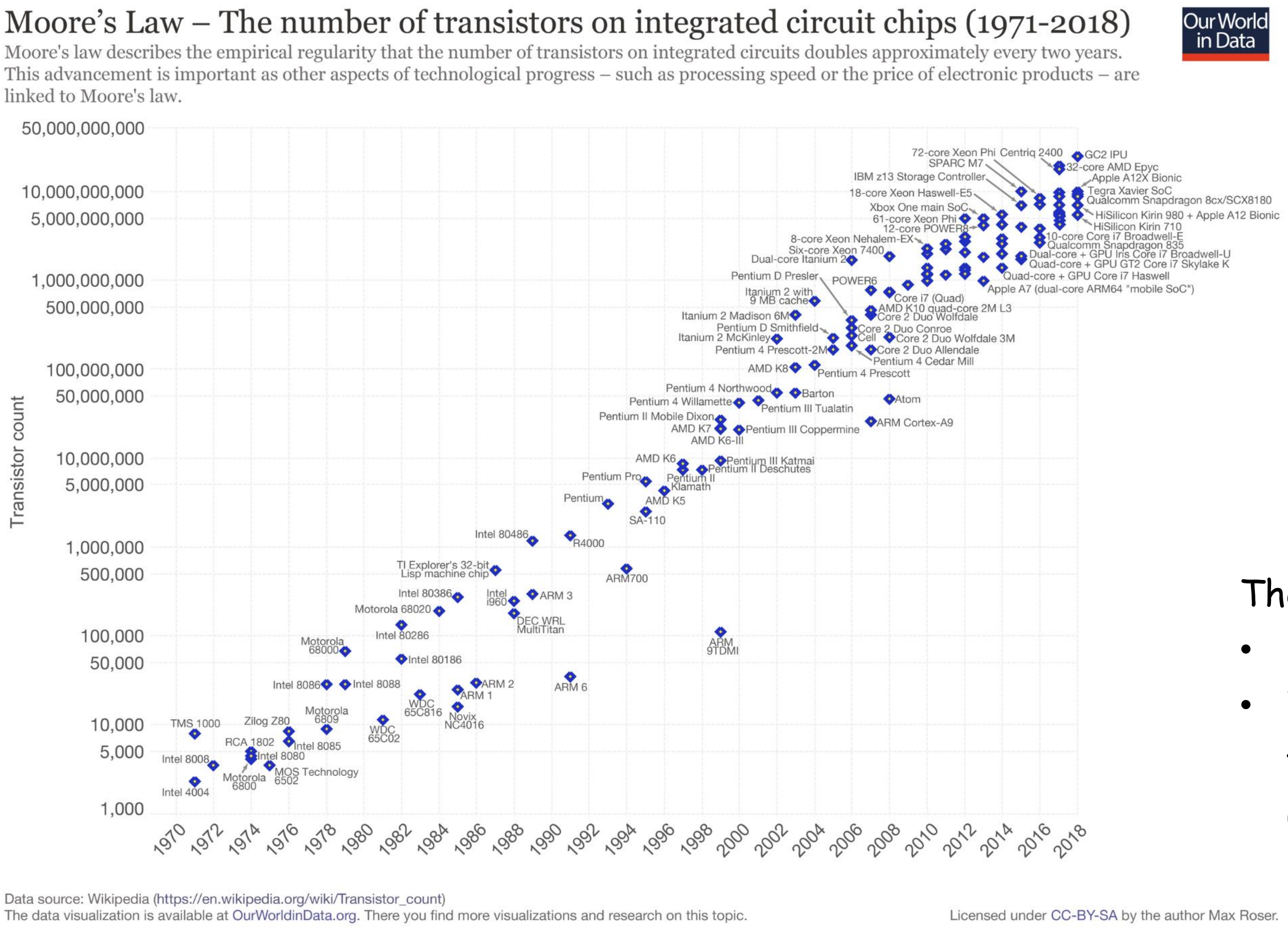
From sand to valuable integrated circuits (ICs)

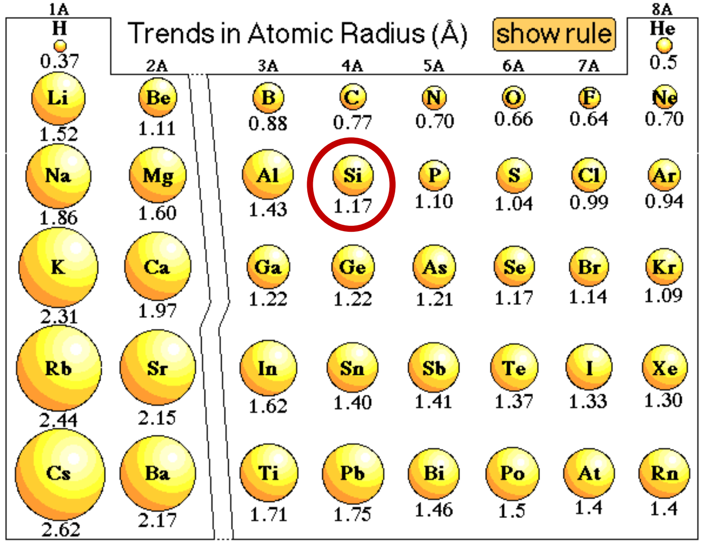
schemetic → layout → simulate
photo mask 光掩膜



- Three recommended video for self-study
  - 从沙子到芯片的完整流程（Intel）
    https://www.bilibili.com/video/BV1Rt411A7bV
  - CPU制造过程（格罗方德GlobalFoundries，前身AMD半导体)
    https://www.bilibili.com/video/BV1TW411q7Eq
  - 芯片制造介绍和光刻技术（英飞凌Infineon）
    https://www.bilibili.com/video/BV1Jt4y1X783

The Moore's Law





The physical limit:

- Silicon atom diameter ≈ 0.23 nm
- The most advanced smallest transistor feature is 7 nm (less than 35 silicon atoms wide)