Xi'an Jiaotong-Liverpool University
西交利物浦大学

# EEE109: Semiconductor and Diodes
## Chapter 1

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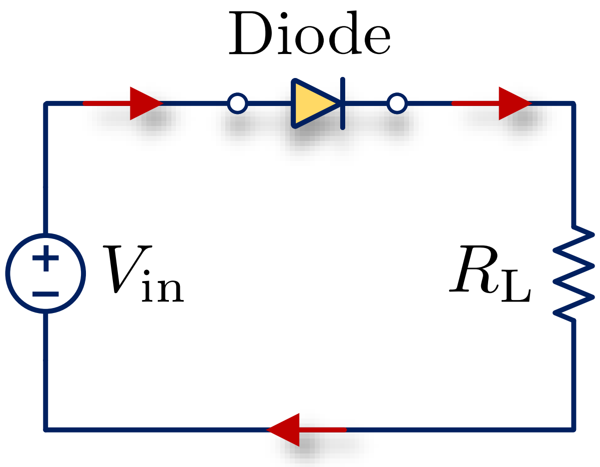
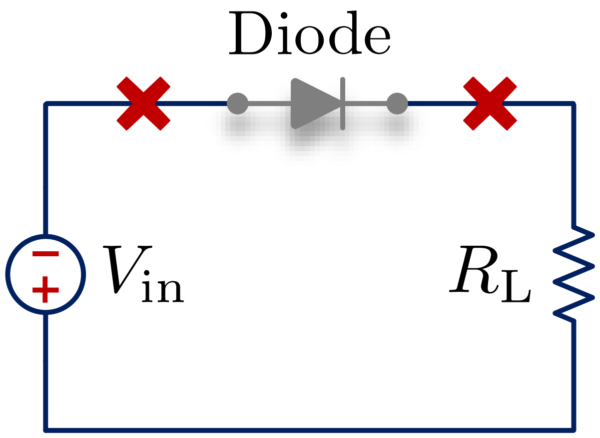
- Diode Circuit: **AC** Equivalent Circuit
  - Apply an equivalent circuit for a diode that is used when a small, time varying signal is applied to a diode circuit

# Diode

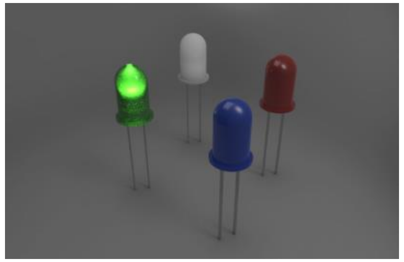
- A diode is a two-terminal electronic component that conducts current in one direction, and **limit** the current from flowing in the opposite direction (二极管具有单向导通性)

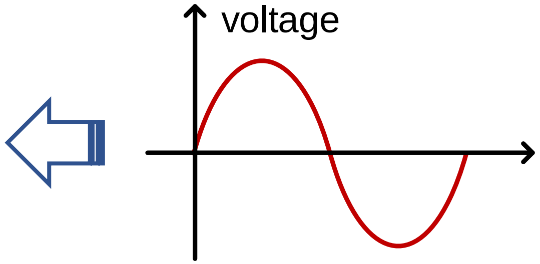



Conduction




Cut-off






What is the working theory of the diode? We should start with the story of semiconductor

# Semiconductor Material and Properties

Gain a basic understanding of a few semiconductor material properties including the two types of carriers (载流子) that exist in a semiconductor and the two motions that generate currents in a semiconductor.

# Semiconductor



- A semiconductor is the material with a conductivity (导电率) between conductor and insulator.

| Insulator | Semiconductor | conductor |
| --- | --- | --- |
| $10^{-20} \sim 10^{-10} \mathrm{ohm}^{-1}\mathrm{m}^{-1}$ | $10^{-6} \sim 10^{4} \mathrm{ohm}^{-1}\mathrm{m}^{-1}$ | $10^{4} \sim 10^{7} \mathrm{ohm}^{-1}\mathrm{m}^{-1}$ |

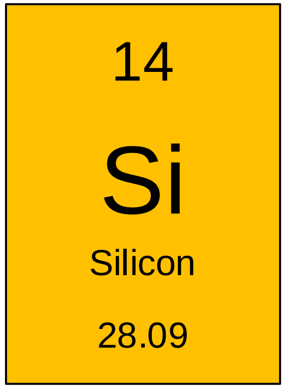
Conductivity →

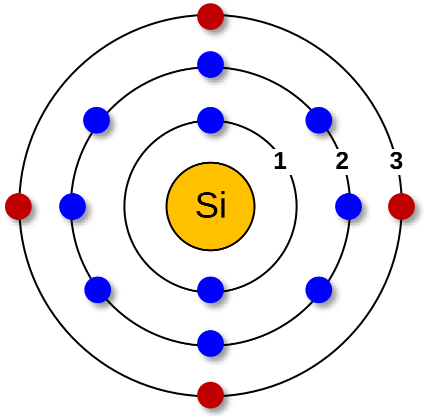
- Semiconductor can be pure element: intrinsic semiconductor (本征半导体)
- If we add some impurities (掺杂物) into the intrinsic semiconductor, it becomes extrinsic semiconductor (非本征半导体)

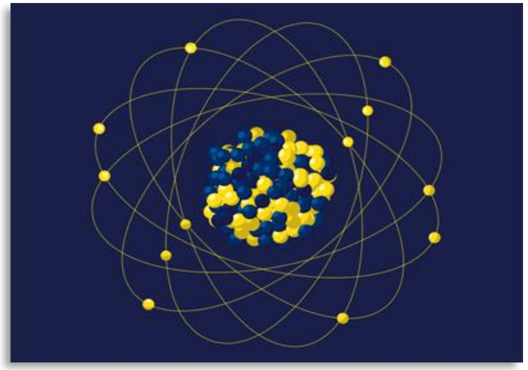
# Atom



- An atom is the smallest unit of ordinary matter that forms a chemical element. The electrical property of atom is 「Neutral」 (电中性).



| | |
|---|---|
| **Proton (质子)** | **Positive** |
| **Electron** | **Negative** |
| **Neutron (中子)** | **Neutral** |

- Electrons in the outermost (最外层) shell are called valence electrons (价电子). It will determine the chemical activity of the atom (最外层电子数决定该原子的化学特性).

# Intrinsic semiconductor



- An intrinsic semiconductor is a pure semiconductor without any significant doping impurities. So, ideally 100% pure material.

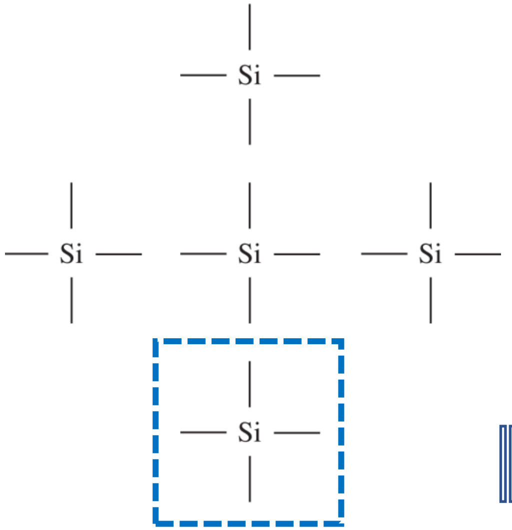
- Silicon（硅）is by far the most common semiconductor material used for semiconductor devices and integrated circuit.

| III | IV | V |
|---|---|---|
| 5 **B** Boron | 6 **C** Carbon | |
| 13 **Al** Aluminum | 14 **Si** Silicon 😁 | 15 **P** Phosphorus |
| 31 **Ga** Gallium | 32 **Ge** Germanium | 33 **As** Arsenic |
| 49 **In** Indium | | 51 **Sb** Antimony |

A portion of the periodic table
元素周期表

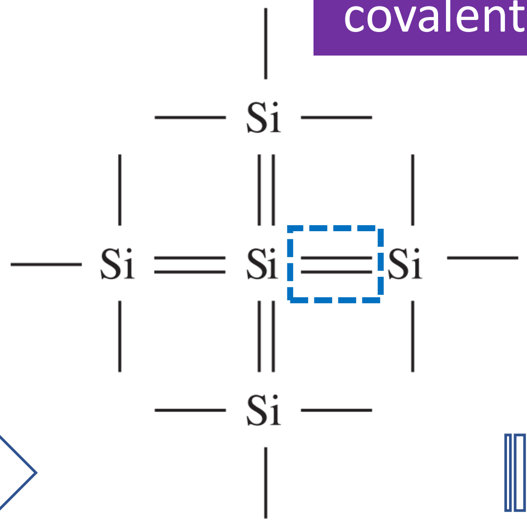
# From Atom to Crystal (晶体)

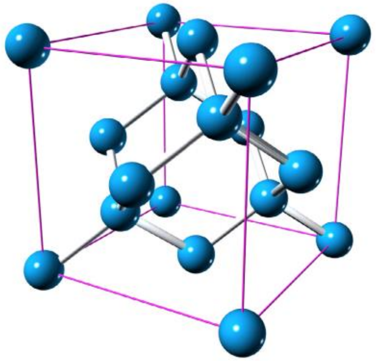
- Silicon atom can attach to one or more other atoms by covalent bonds (共价键) to form a silicon crystal. Normally, crystal like this made of covalent bonds is stable enough that electrons will not move around. But…




one Si atom with four valence electrons

covalent bonds



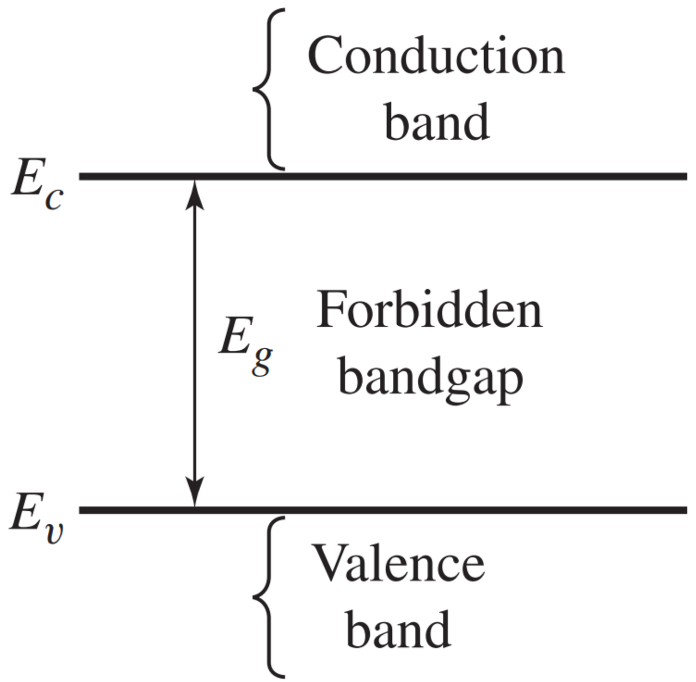



Silicon crystal

# Electron Transition (跃迁)



- At T = 0K, each electron is in its lowest possible energy state, so the covalent bond is stable. Silicon is an insulator at this temperature (absolute zero)




$$C = K - 273 \quad K = Kelvin \quad C = Celsius, {}^{o}C$$

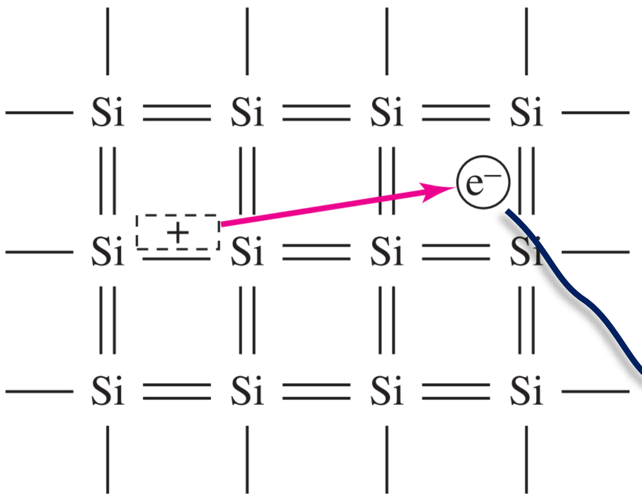
| | |
|---|---|
| $E_{\mathrm{c}}$ | **Lowest value of conduction band** |
| $E_{\mathrm{v}}$ | **Highest value of valence band** |
| $E_{\mathrm{g}}$ | $E_g = E_c - E_v$ |

- Electron can not exist within the forbidden bandgap
- Electron get energy to jumps from valence to conduction band is called 「TRANSITION」

# Electron Transition



- However, if we increase the temperature to break the covalent bond, valence electron will get this thermal energy and jump to conduction band to become the free electron. This process is called 「ELECTRON TRANSITION」




- When an electron leaps into the conductions band, it leaves behind a 「HOLE」 in the valence band (当电子逃走的时候，会在原地留下一个“空穴”。且为了继续保持原子电中性，调节阴阳平衡，此空穴带正电)

Dobby is FREE!

# How to Understand Hole?

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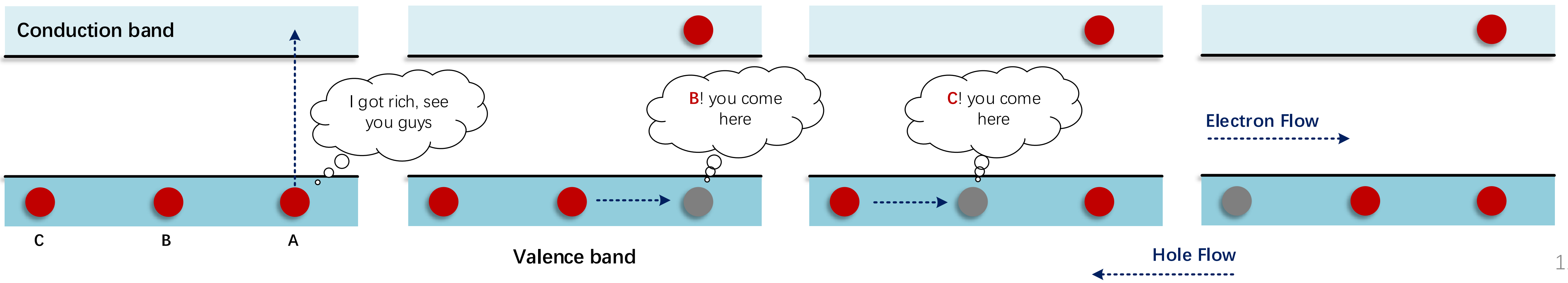
- If electron is negative, what is this "positive particle" that flow in a circuit (电路中真的存在带正电的物理形态的粒子在运动吗)?
- Hole is not a physical particle. Rather than, "positive charge" is really a lack of negative-charge - an empty space with higher electric-potential, and the electrons are necessarily attracted towards.

| | |
|---|---|
| **Electron** | **contribute electron current** |
| **Hole** | **contribute hole current** |



# Intrinsic Carrier Concentration



- The concentration (浓度) of electrons and holes is a important parameter that will influence the magnitude (强度) of current in a semiconductor.

- The symbol of $n_i\ (cm^{-3})$ is the 「intrinsic carrier concentration」

5.23*$10^{15}$ for silicon

$$n_i = BT^{\frac{3}{2}} e^{\frac{-E_g}{2KT}}$$

1.1 (eV) for silicon

300K for room temperature

$B$ coefficient related to specific semiconductor

$T$ temperature in Kelvin (K)

$E_g$ semiconductor bandgap energy (eV)

$K$ Boltzmann's constant (8.6*$10^{-5}$ eV/K)

# Reinforce Your Learning 🤖

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- Calculate the intrinsic carrier concentration in silicon (si) at temperature T = 300K

- **Solution**

$$n_i = BT^{\frac{3}{2}} e^{\frac{-E_g}{2KT}} = \left(5.23 \times 10^{15}\right) (300)^{\frac{3}{2}} e^{\left(\frac{-1.1}{2\left(86\times10^{-6}\right)(300)}\right)}$$

$$= \boxed{1.5 \times 10^{10} cm^{-3}}$$

**Table 1.3** Semiconductor constants

| Material | $Eg$ (eV) | $B$ ($cm^{-3}\,K^{-3/2}$) |
|---|---|---|
| Silicon (Si) | 1.1 | $5.23 \times 10^{15}$ |
| Gallium arsenide (GaAs) | 1.4 | $2.10 \times 10^{14}$ |
| Germanium (Ge) | 0.66 | $1.66 \times 10^{15}$ |

# Extrinsic Semiconductor

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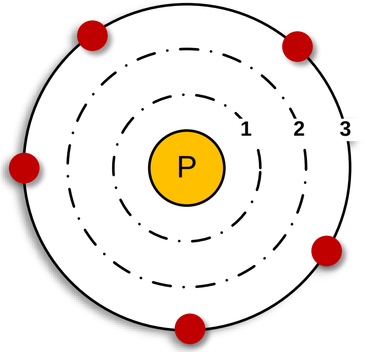
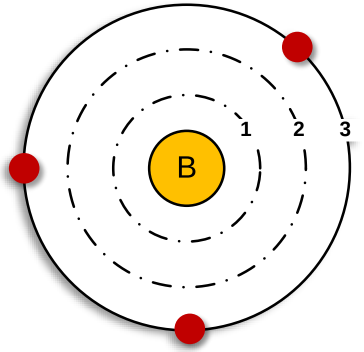
- Why do we need to reform the intrinsic semiconductor? → Since the carrier concentration in the intrinsic semiconductor is 「Small」 and the conductivity is 「Weak」

- If we can add a controlled amounts of certain impurities into the intrinsic semi, the concentrations of holes and electrons can be greatly increased!

| | |
|---|---|
| **Donor Impurity** | **It contributes the electron concentration, such as the Phosphorus in Group V** |
| **Acceptor Impurity** | **It contributes the hole concentration, such as the Boron in Group III** |

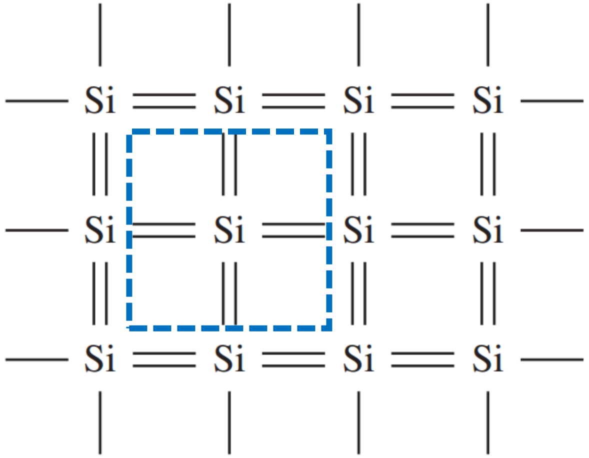


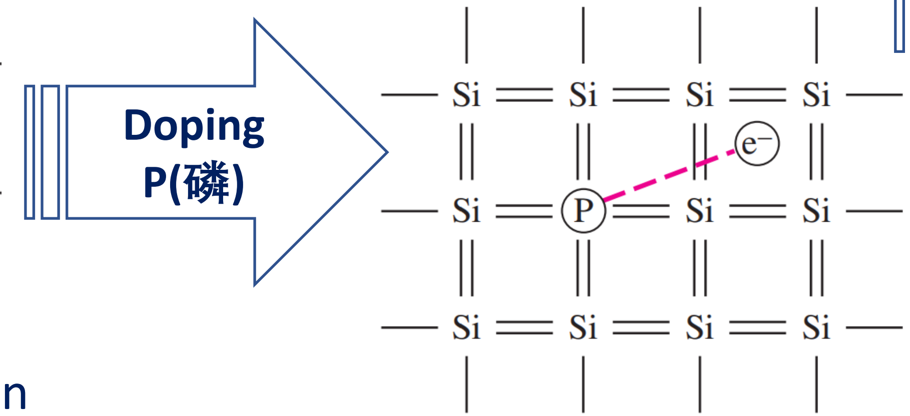
# Donor Impurity



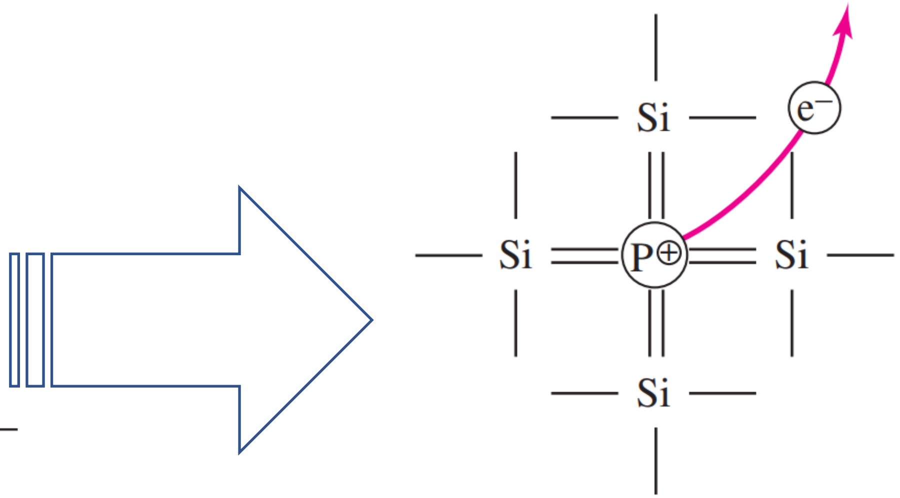
- We use silicon atoms as a target to analyze




Silicon Crystal, each silicon atom is linked together by covalent bonds



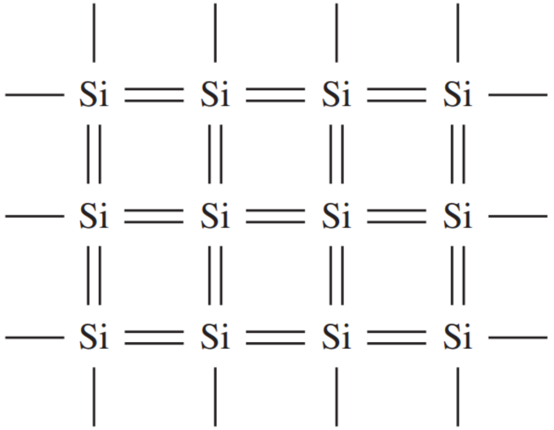

**P** is in Group V, four of its valence electrons are used to satisfy the covalent bond requirement



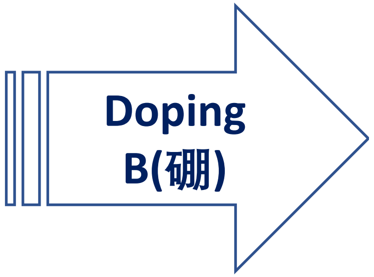

The **fifth** valence electrons is easily to run away at room temperature to be the **free electron**

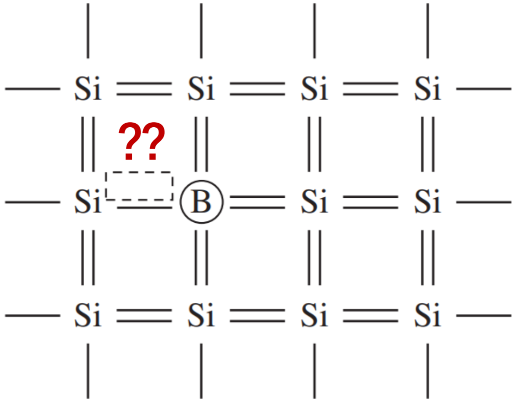
# Acceptor Impurity

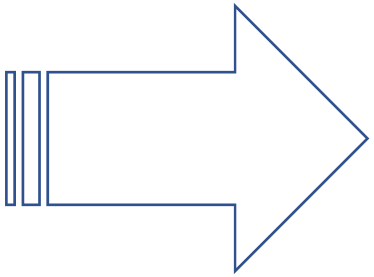
**B** is in Group III, three of its valence electrons are used to satisfy the covalent bond

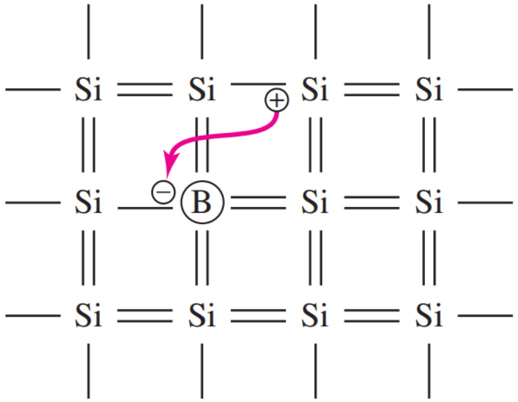


Silicon Crystal, each silicon atom is linked together by covalent bonds





It leaves one bond position open. At room temperature, adjacent silicon valence electrons have sufficient thermal energy to move into this position, thereby creating a **hole**.

# Donor & Acceptor Impurity



- A semiconductor that contains「Donor」impurity atoms is called ***N***-type semiconductor (for the negatively charged electrons)

- A semiconductor that contains「Acceptor」impurity atoms is called ***P***-type semiconductor (for the positively charged holes)

| | | | | | | |
|---|---|---|---|---|---|---|
| **N type** | **---->** | **Donor impurity to make it** | **---->** | **High concentration of electron** | **---->** | **N for negative** |
| **P type** | **---->** | **Acceptor impurity to make it** | **---->** | **High concentration of hole** | **---->** | **P for positive** |

# Donor & Acceptor Impurity

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- A fundamental relationship between the electron and hole concentration in the thermal equilibrium (热平衡) is

$$n_o p_o = n_i^2$$

$n_o$ is the thermal equilibrium concentration of free electrons

$p_o$ is the thermal equilibrium concentration of holes

$n_i$ is the intrinsic carrier concentration

**N-type**

- ***N*$_d$** is the Donor concentration

$$N_d \gg n_i \Rightarrow n_o \cong N_d$$

- Hole concentration is: $\boxed{p_o = \dfrac{n_i^2}{N_d}}$

**P-type**

- ***N*$_a$** is the Acceptor concentration

$$N_a \gg n_i \Rightarrow p_o \cong N_a$$

- Electron concentration is: $\boxed{n_o = \dfrac{n_i^2}{N_a}}$

# Reinforce Your Learning 🤖



- Consider silicon at T=300**K** doped with phosphorus at a concentration of $N_d = 10^{16}\text{cm}^{-3}$, and $n_i = 1.5*10^{10}\text{cm}^{-3}$ calculate the thermal equilibrium electron and hole concentrations.

- **Solution**

# Drift & Diffusion

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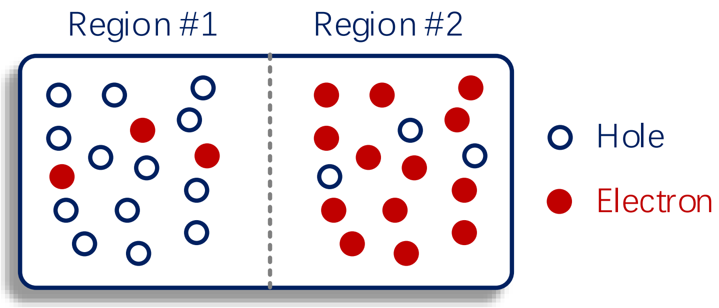
- In the semiconductor, we have two carriers that are ready to contribute the current. However, If they were just sitting there, we would not be able to have any current. Therefore, they have to「Move」

| Two basic Motions | | |
|---|---|---|
| | **Drift** | **This movement is caused by electric fields** |
| | **Diffusion** | **This movement is caused by concentration differences (浓度差值)** |



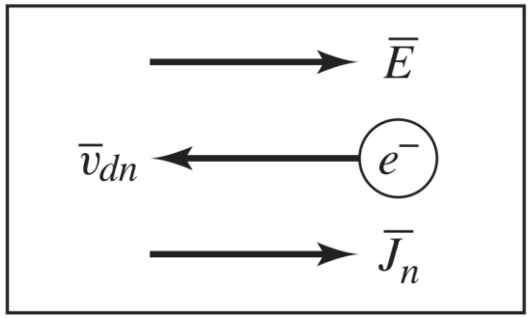

| | |
|---|---|
| **Hole concentration** | **Region #1 > Region #2** |
| **Electron concentration** | **Region #1 < Region #2** |

# Drift Current



- The drift current is caused by the 「**Applied Electric Field**」

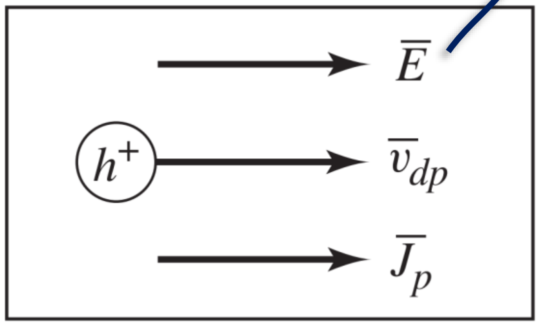
$n$-type




- Since the majority carriers in N-type is electrons with negative charge, the movement direction is opposite to the electric filed direction.

APPLIED ELECTRIC FIELD

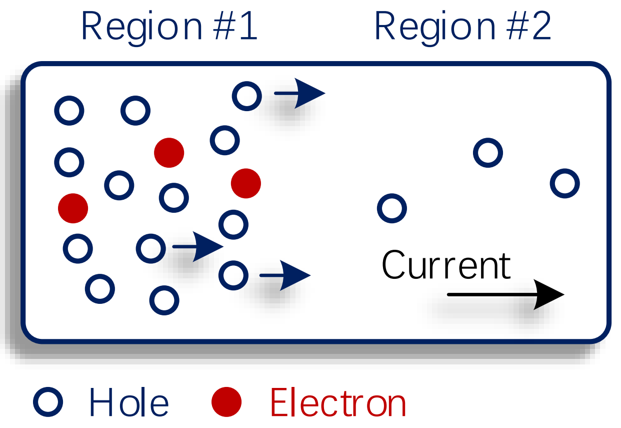
$p$-type




- Since the majority carriers in P-type is Holes with positive charge, the movement direction is the same to the electric filed direction.

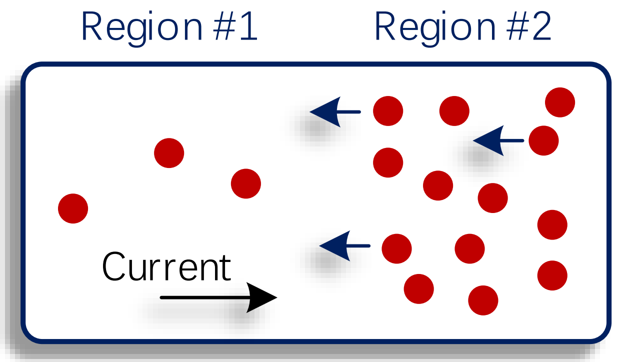
# Diffusion Current

- Diffusion(扩散):Carriers flow from regions of 「**High**」 concentration to regions of 「**Low**」 concentration (从高浓度扩散至低浓度)




- **P-type semiconductor**: Hole diffusion current is the same with the hole diffusion movement.

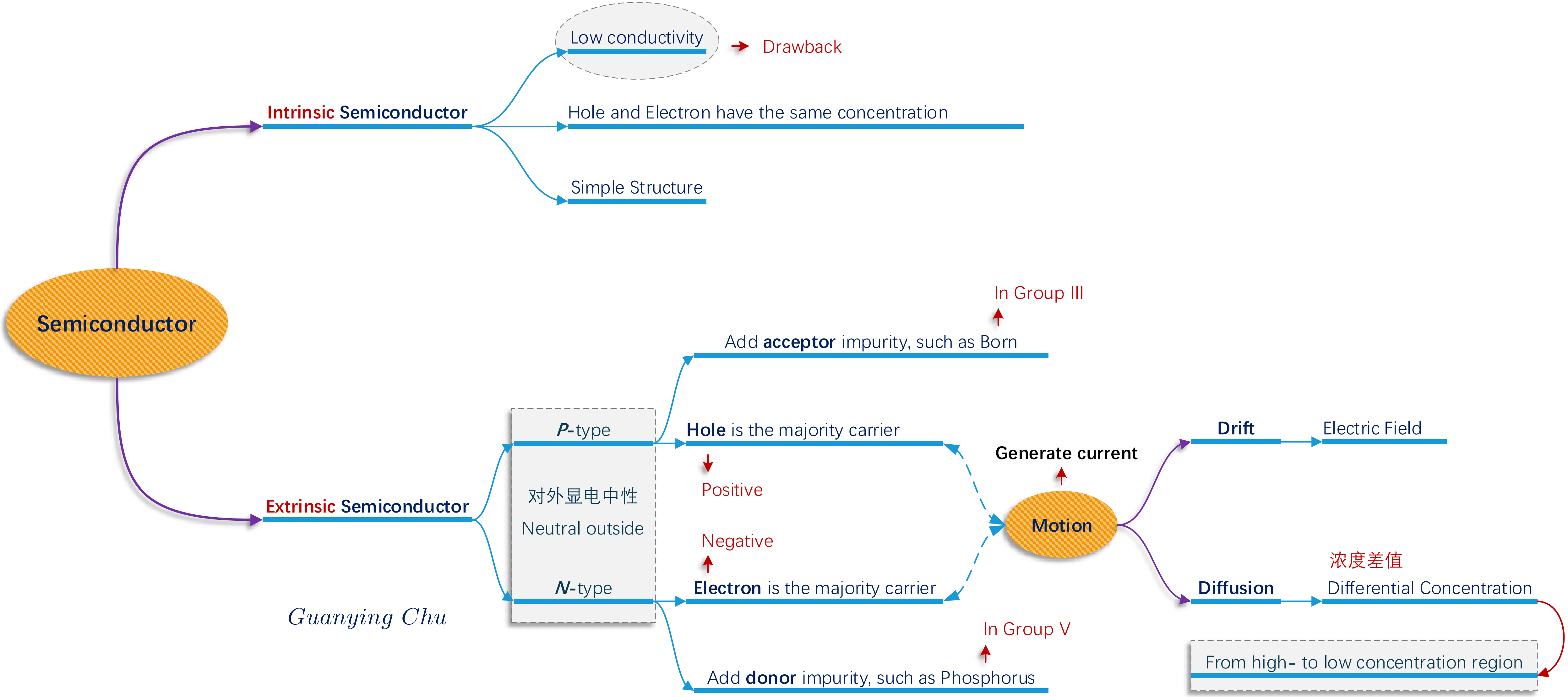
- **N-type semiconductor**: Electron diffusion current is opposite to the electrons diffusion movement




But they the same current direction, interesting

# Mind Map—Semiconductor



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# The P-N Junction

The real power of semiconductor electronics occurs when p- and n-regions are directly adjacent to each other, forming a pn junction. Determine the properties of a pn junction including the ideal current-voltage characteristics of the pn junction diode.

# PN Junction

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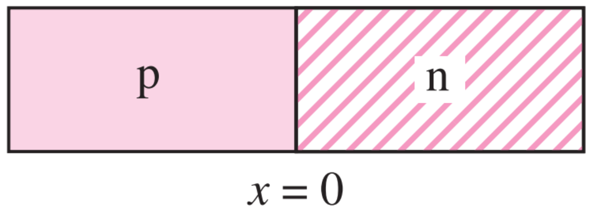
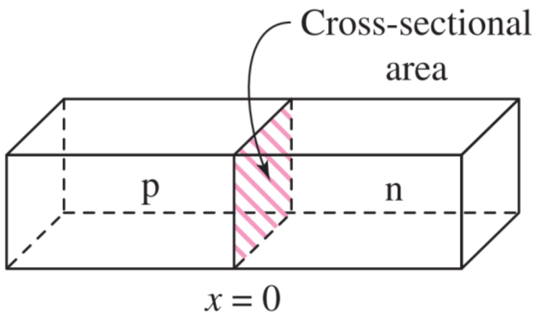
- In most integrated circuit application, the entire semiconductor material is a single crystal, which one region doped to be p-type and the adjacent region doped n-type.

- If we put a p-type and n-type directly adjacent together, we can have a pn junction. Due to the difference in concentration, the diffusion of the pn junction occurs first.




(a)

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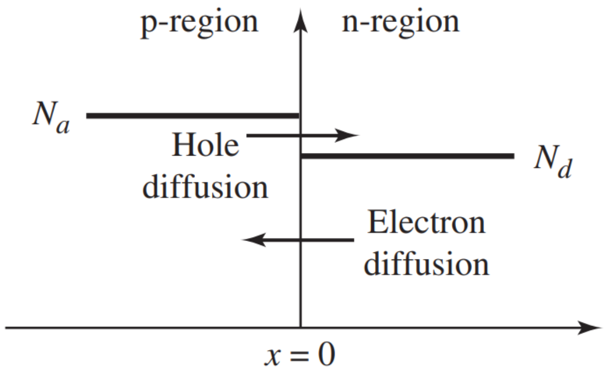
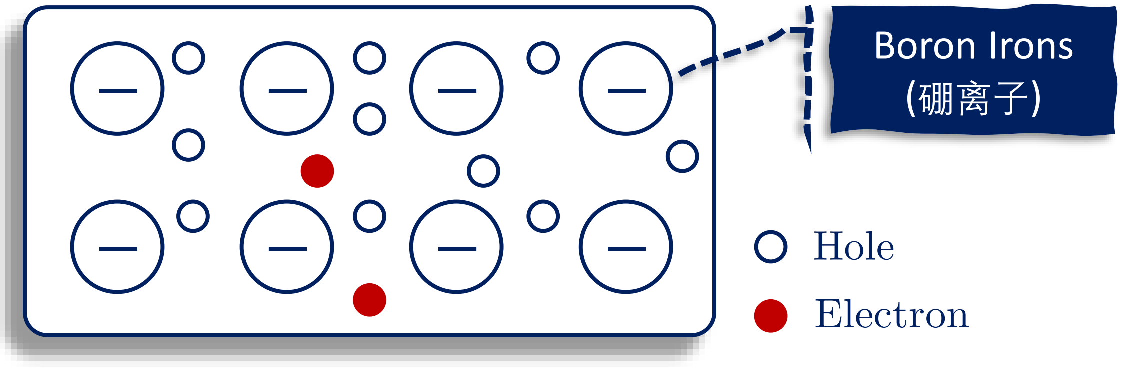



(c)

# PN Junction

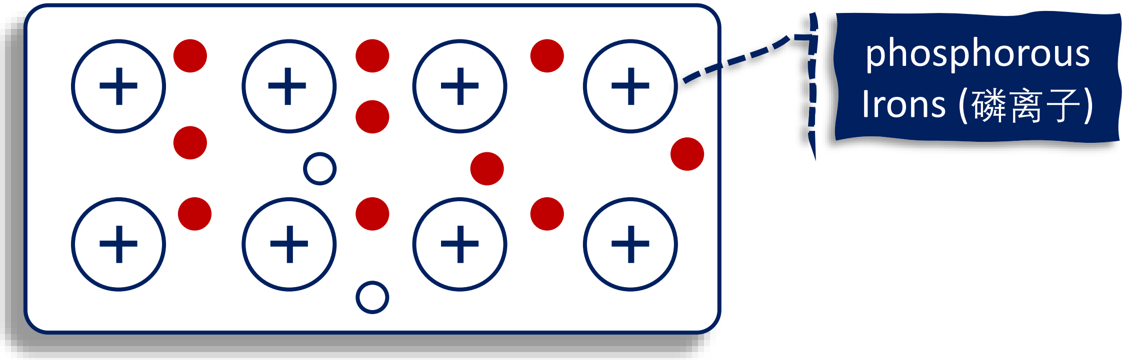
## P-Type Semiconductor




Charges Distribution (电荷分布)

- Hole (10), with positively charge
- B ion (8) and electron (2), with negatively charge
- 10 = 8+2 and P-Type is Neutral

## N-Type Semiconductor

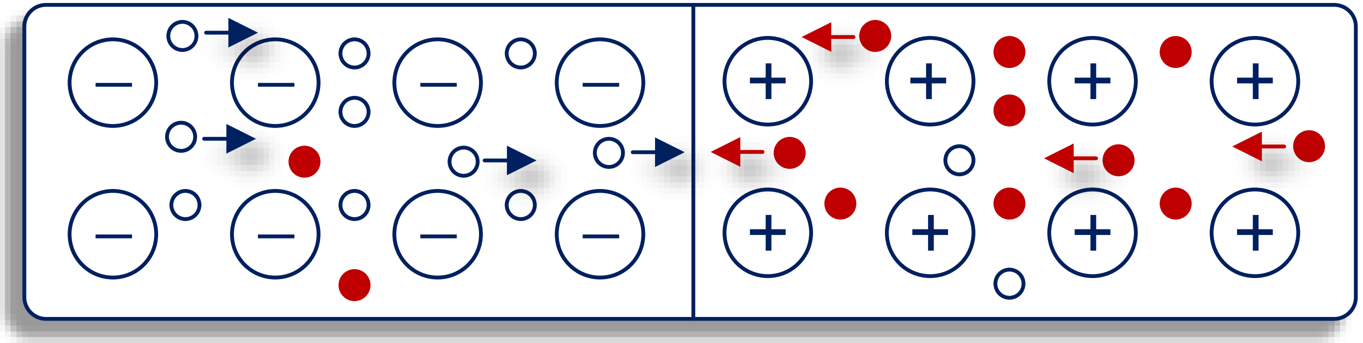



Charges Distribution

- Electron (10), with negatively charge
- P ion (8) and Hole (2), with positively charge
- 10 = 8+2 and N-Type is Neutral

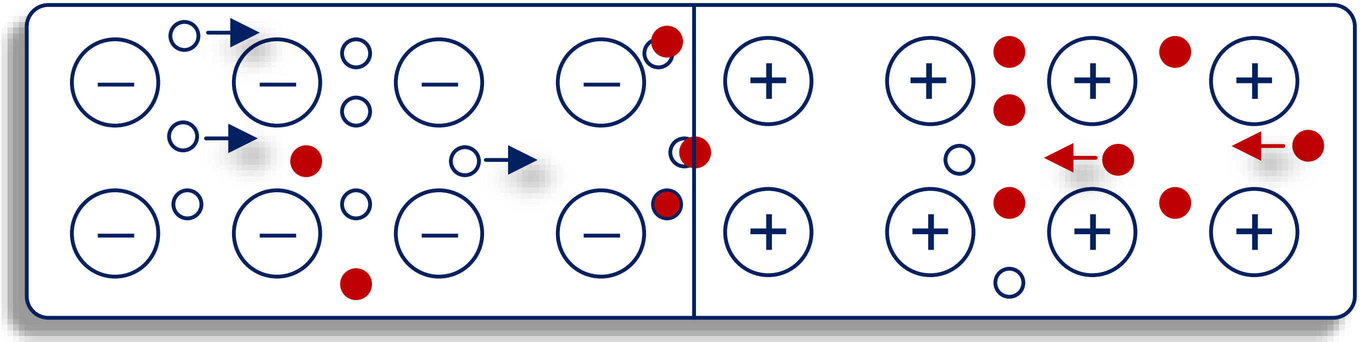
# PN Junction



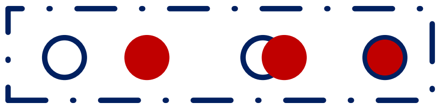


- Stage I: 「**Diffusion Movement**」

- Holes from P type are moving toward to N type. And Electron from N type are moving toward to P type. They will meet near the interface.



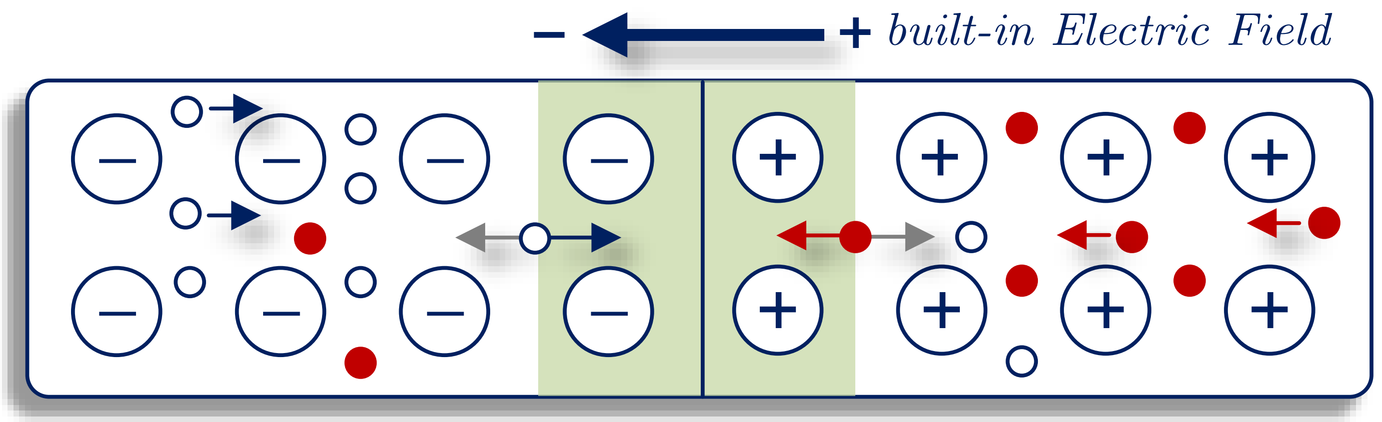
- Stage II: 「**Recombination**」



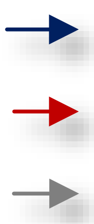
- With this action, the electron and hole disappear. This is called electron-hole pair recombination or simple recombination in semiconductors.

# PN Junction

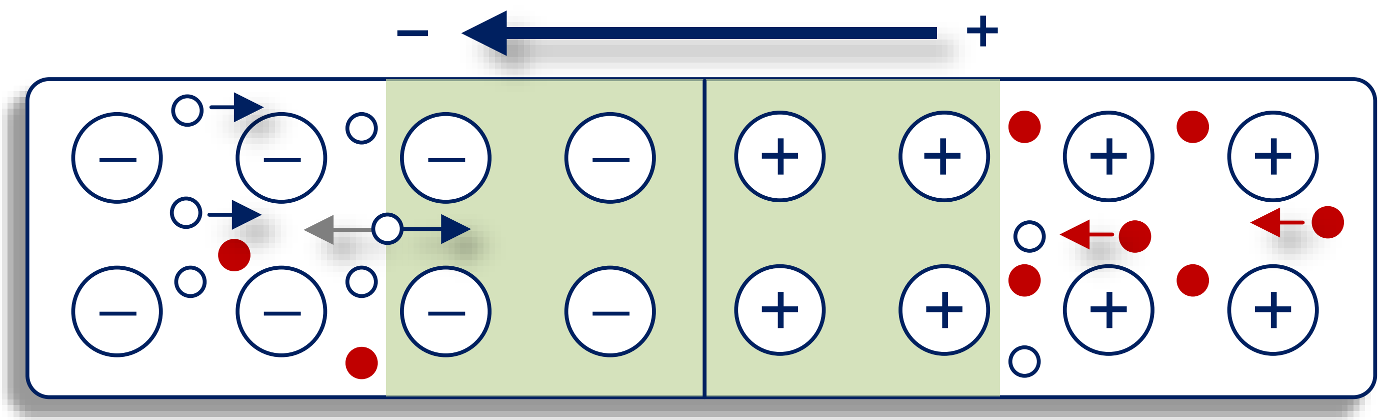





- Stage III: 「Drift Movement」




- The internal balance is broken. The ions at the interface exhibit electrical properties and create a built-in electric field. It cause drift movement. However, drift and diffusion will fight each other.




space charge region

- Stage IV: 「Equilibrium」
- The two forces reach an equilibrium point where the motion is almost cease

# Built-in Voltage

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- When both the Diffusion and Drift motions finally reach the Equilibrium, we get a built-in potential voltage or built-in barrier voltage

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

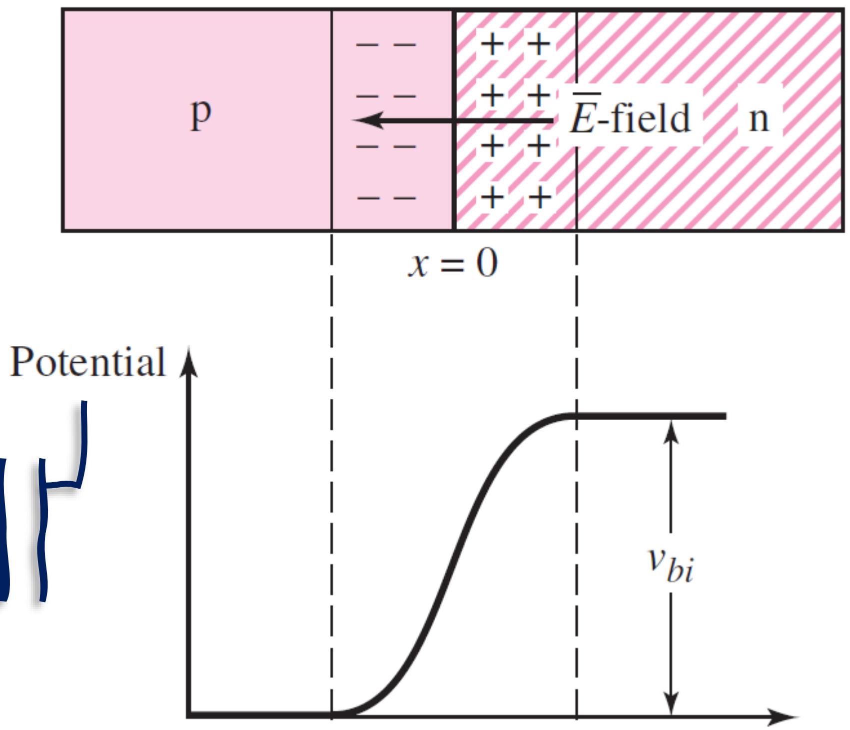
$e$ is the magnitude of the electronic charge

$k$ Boltzmann's constant

$T$ absolute temperature

$V_T$ the thermal voltage

Constant, for a known pn junction

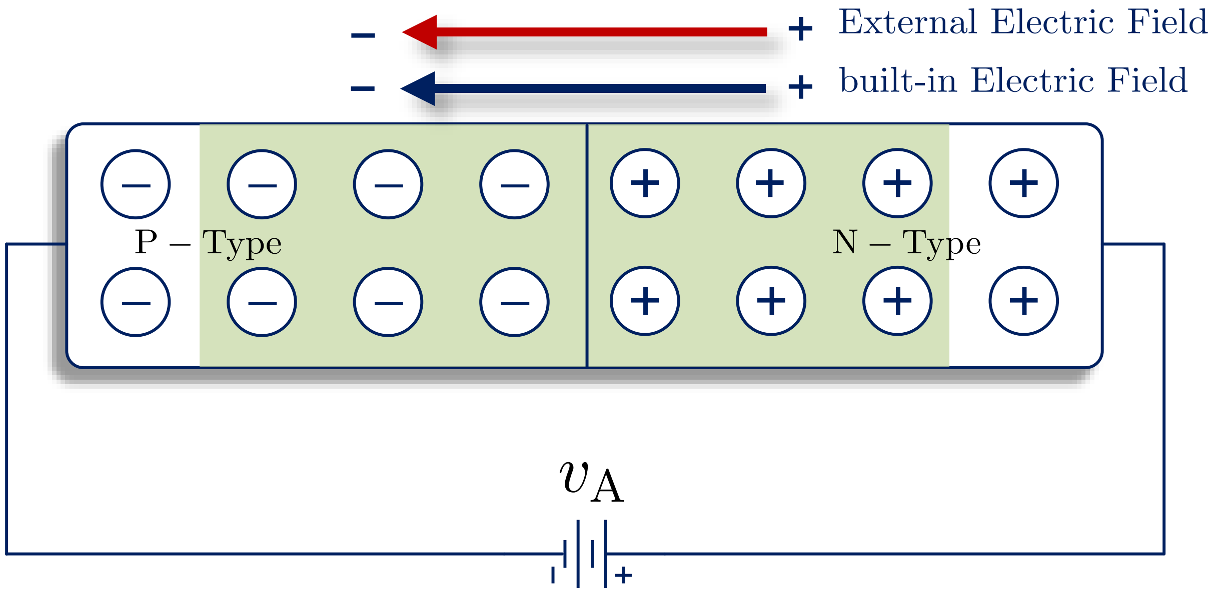



$V_T = 0.026V$ at room temperature $T = 300K$

# Reversed-biased of pn junction



- Consider an external voltage is applied on the pn junction. If the n-region with positive and p-region with negative, it is called 「**Reversed-Biased**」



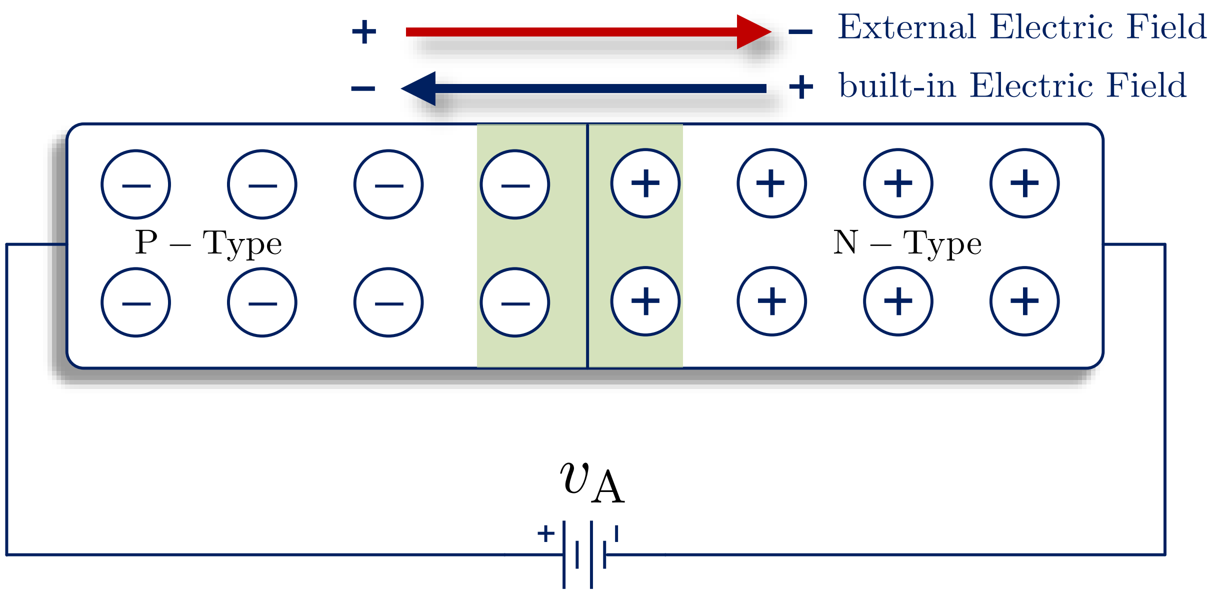

- The two fields are in the same directions, it will boost up the final electric field

- A bigger net electric field and a bigger barrier between the p- and n-regions. If we increase the external voltage, the space-charge width will be increased.

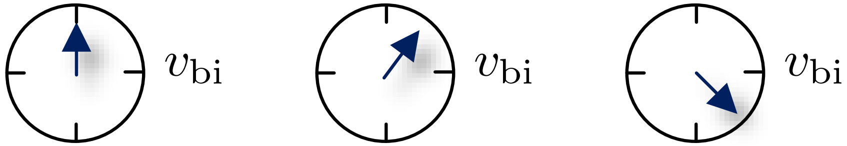
# Forward-biased of pn junction



- Consider an external voltage is applied on the pn junction. If the n-region with negative and p-region with positive, it is called 「**Forward-biased**」



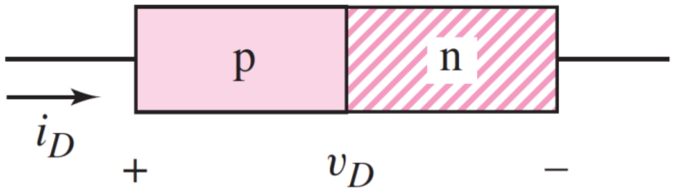

- The two fields are in the opposite directions, they will weaken each other.



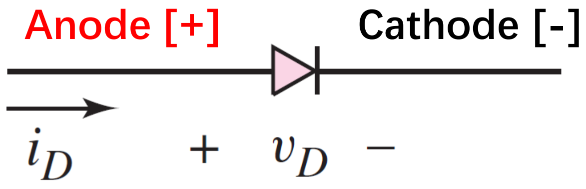

- A smaller net electric field and a smaller barrier between the p- and n-regions. If we increase the external voltage, the space-charge width will be <u>decreased</u>.

# Diode

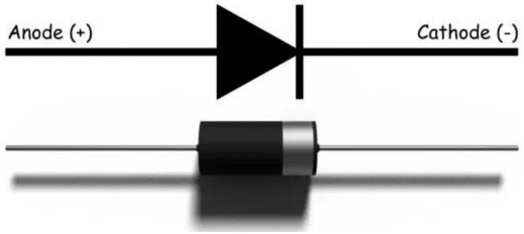
- Diode, a two-terminal electronic component that allows the flow the current in only one direction
- The diode is "OFF" for a reverse-bias external voltage
  - **High** inside resistance, and a very **small** current is created (nearly equal to 0)
- The diode is "ON" for a forward-bias external voltage
  - **Low** inside resistance, and a relatively **large** current is created




Diode in pn junction




Diode symbol




Diode in real world

# Model of diodes



- We have known the basic function of the diode, next we should know the model the diode and then we can put it in a specific circuit to analyze.

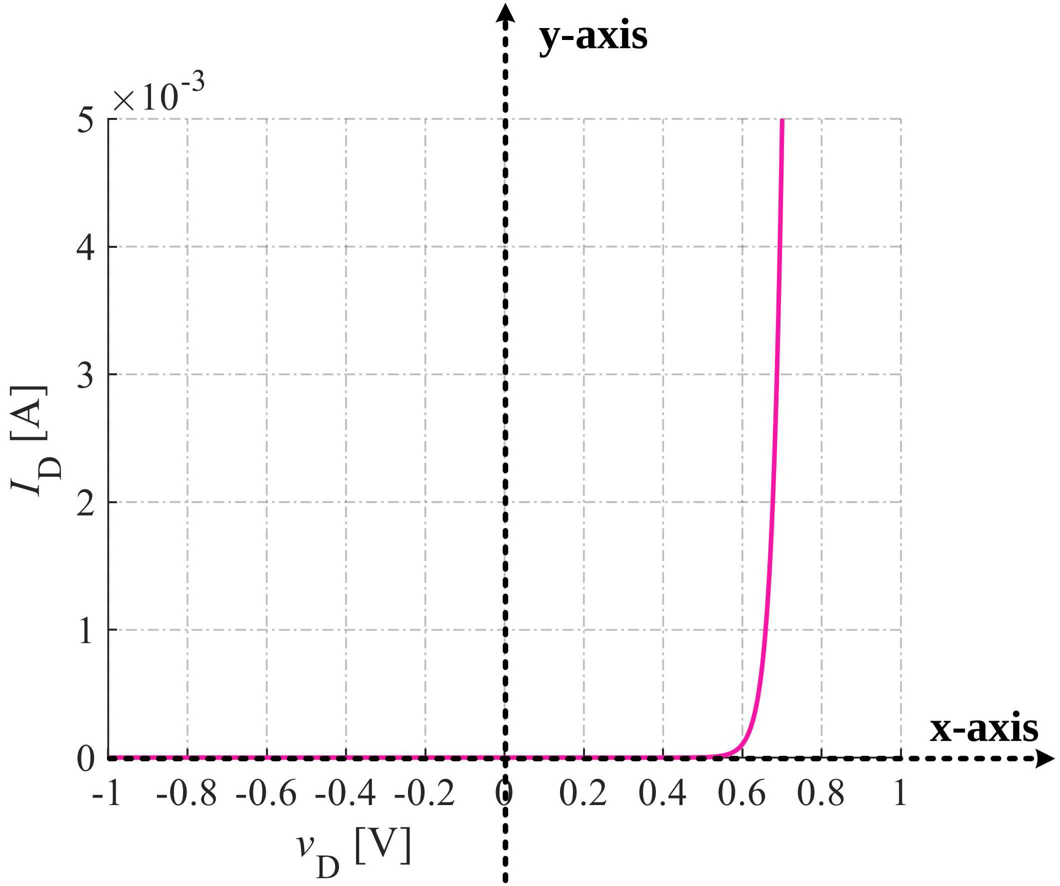
- There are three models of the Diode
  - Mathematical model
  - Ideal Model
  - **Piecewise linear model (分段线性模型)**

# Mathematical model



- The first type is mathematical model, and this model is based on the following equation. Most accurate, but non-linear and complex.

$$I_D = I_S \left[ e^{\left(\frac{v_D}{nV_T}\right)} - 1 \right]$$




$I_D$ is diode current

$I_S$ is the reverse-bias saturation current (constant)

$n$ is emission coefficient (constant, assume **n=1**)

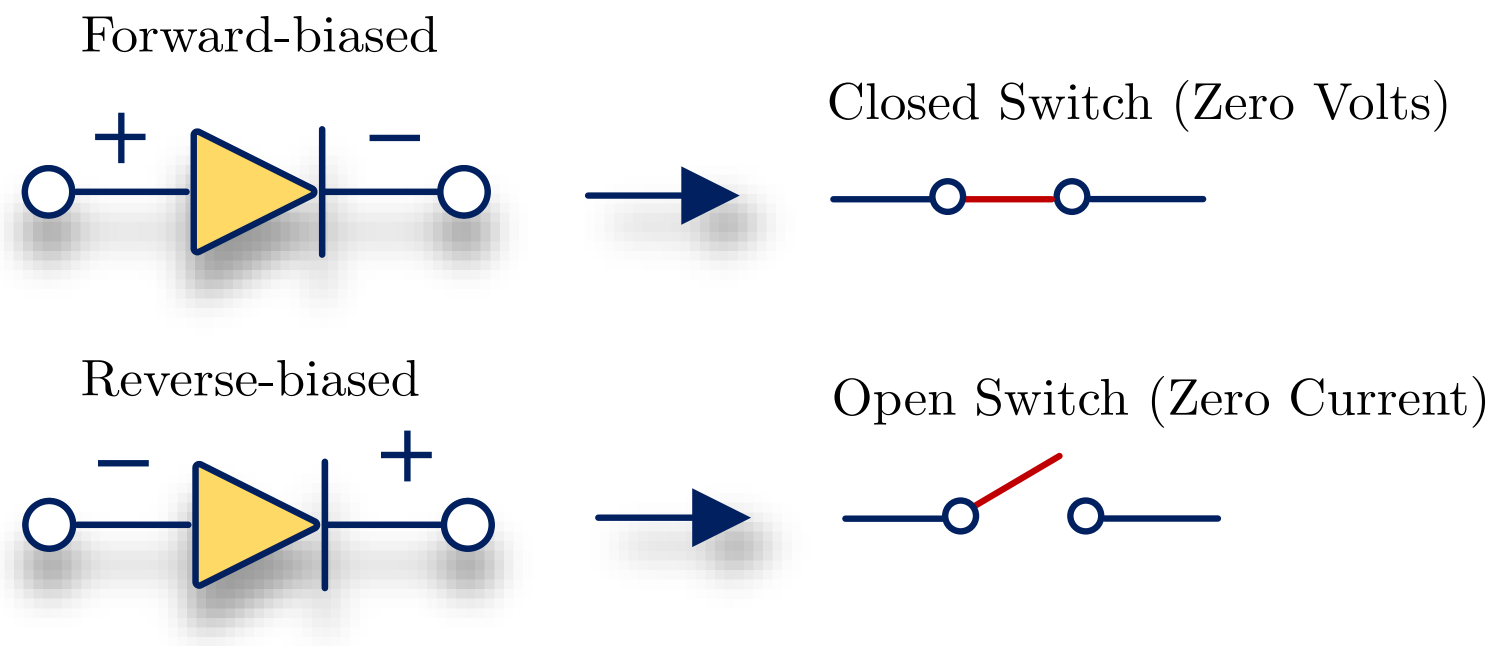
$V_T$ the thermal voltage

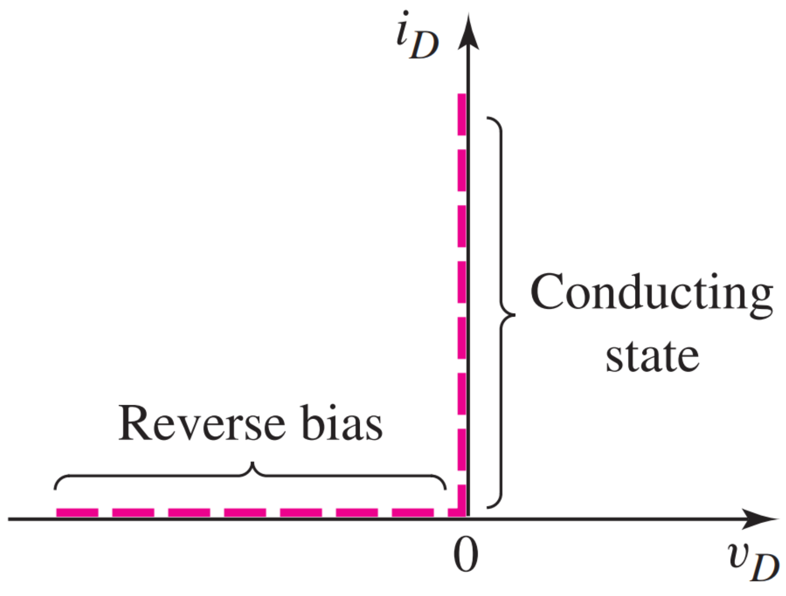
$V_T = 0.026V$ at room temperature $T = 300K$

# Ideal Model



- In the ideal, the diode is considered as a forward-biased ideal switch with zero voltage drop (没压降，没能量损失). It is not able to use in real-life circumstances but used only for general approximations where accuracy is not required.



# Piecewise Linear—without resistor

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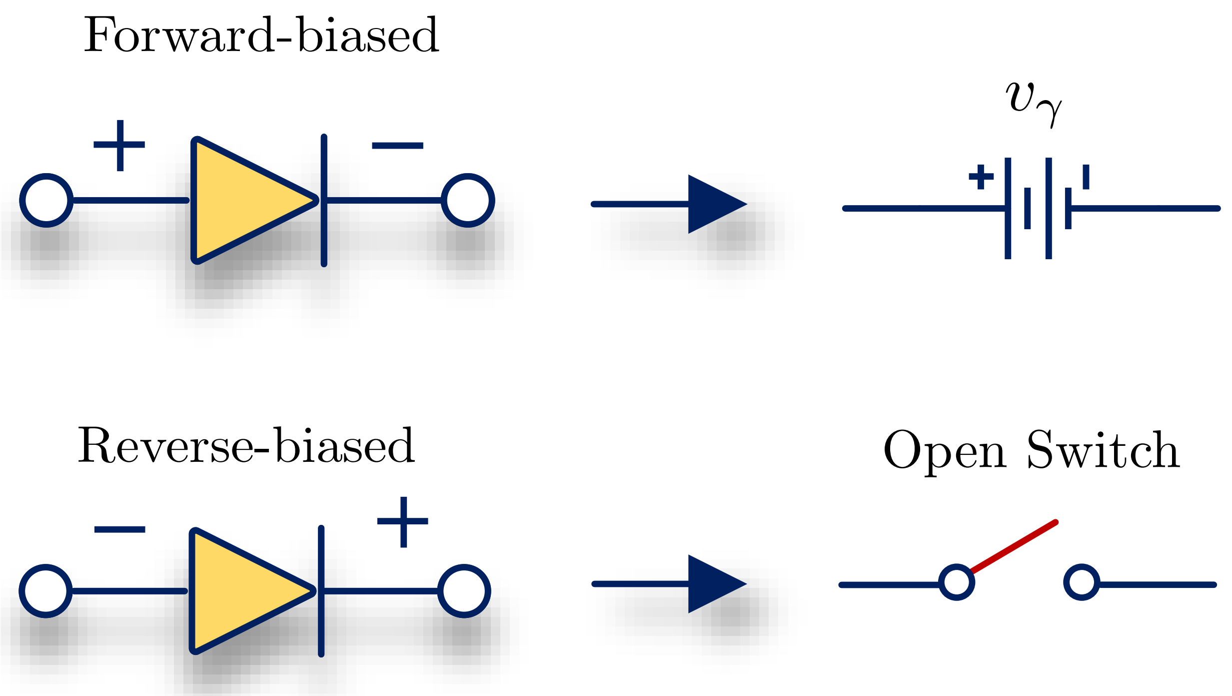
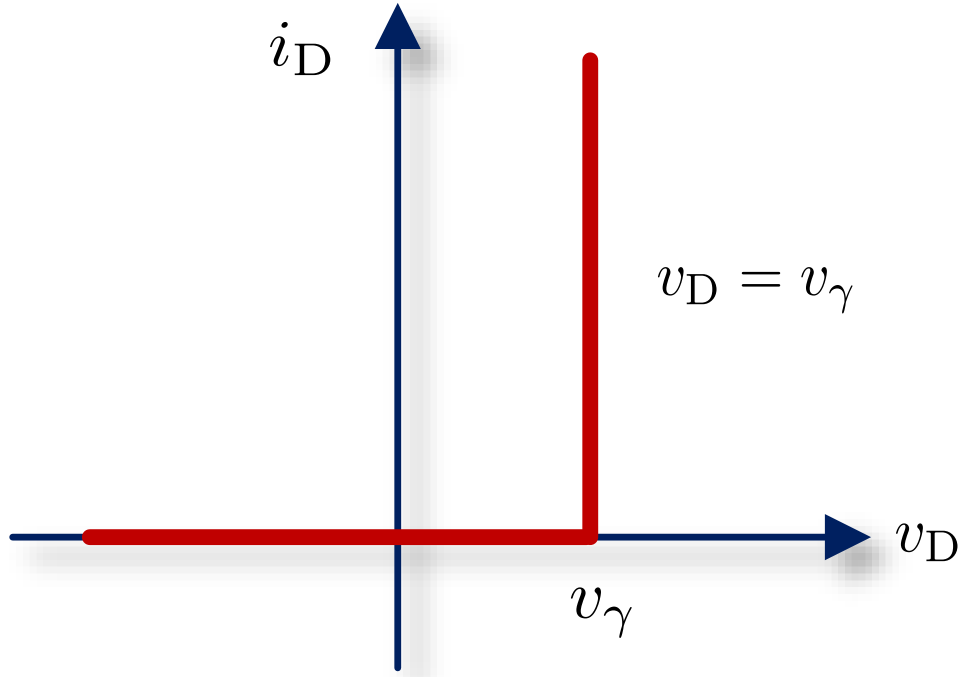
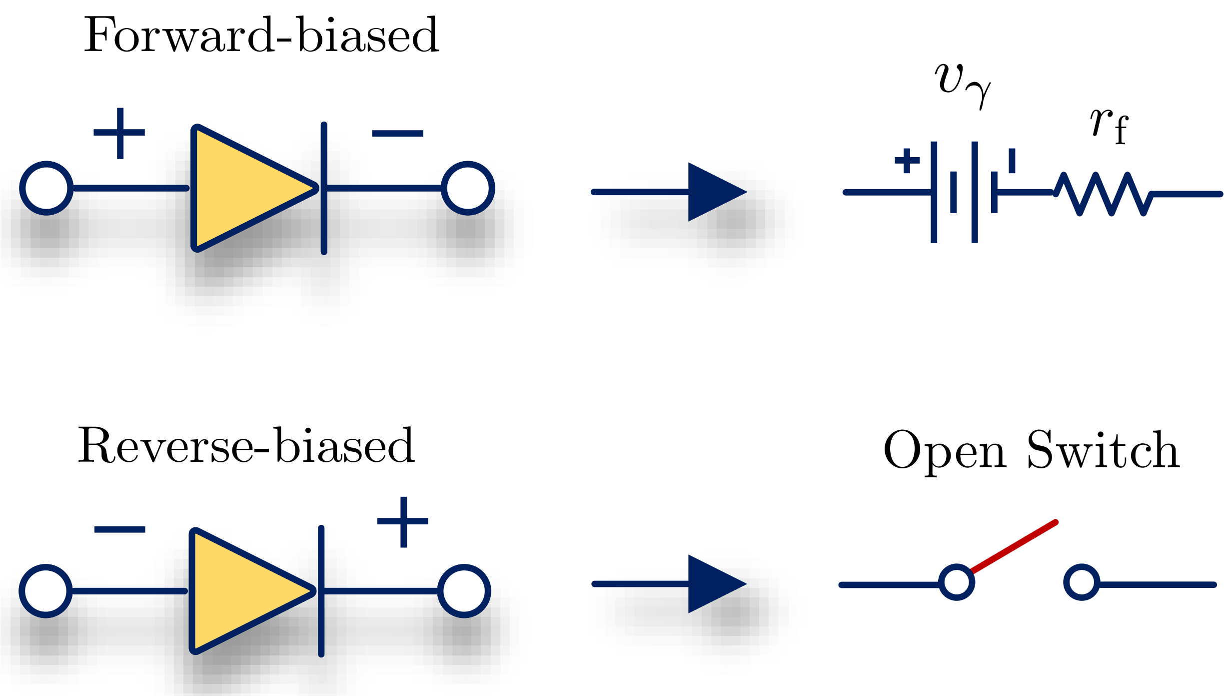
- In the piecewise linear model, the diode is considered as a forward-biased diode in series with a battery ($V_\gamma$) to turn on the device. For a silicon diode to turn on, it needs 0.7V. The diode turns off if the voltage is less than 0.7V.



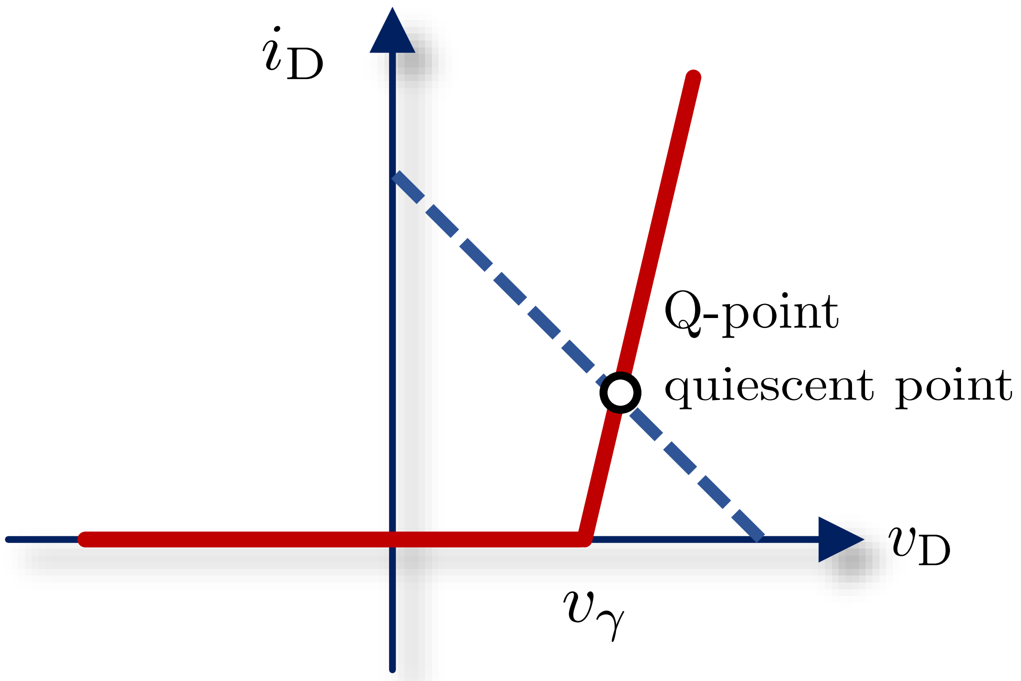



# Piecewise Linear—with resistor

- In the piecewise linear model, the diode is considered as a forward-biased diode in series with a battery ($V_\gamma$) and a small resistor ($r_f$)



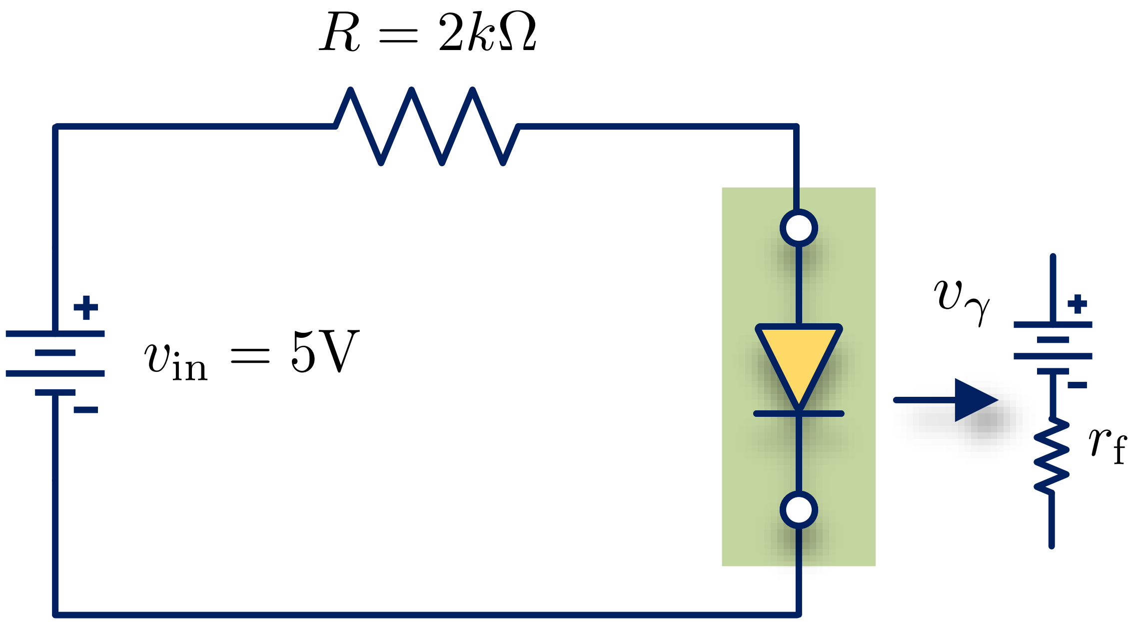

$$v_\mathrm{D} = v_\gamma + i_\mathrm{D} r_\mathrm{f}$$



# Reinforce Your Learning

- Determine the diode voltage $v_D$ and current $i_D$ in the circuit shown below, using a piecewise linear model. Also determine the power dissipated in the diode. Assume the piecewise linear diode parameters of $V_\gamma$ = 0.7V and inside resistor is $r_f$ = 10Ω

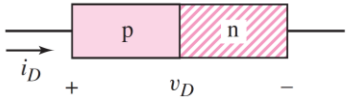
- **Solution**



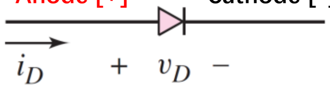
# Mind Map—Diode

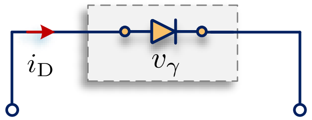


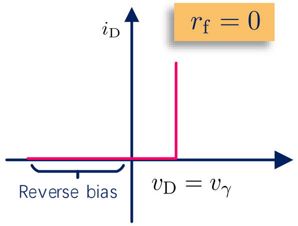
- **Diode**
  - 正向偏置 **Forward bias**
    - Diode is "ON" state
    - Low inside resistance, a very High current is created
    - Three models
      - Mathematical model
      - Ideal model
      - Piecewise linear model
        - without inside resistance → $v_D = v_\gamma$
        - with inside resistance → $i_D = \frac{v_{in} - v_\gamma}{R + r_f}$, $v_D = v_\gamma + i_D r_f$
  - 反向偏置 **Reversed bias**
    - High inside resistance, a very small current is created
    - Diode is "OFF" state

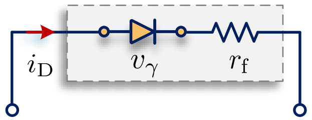


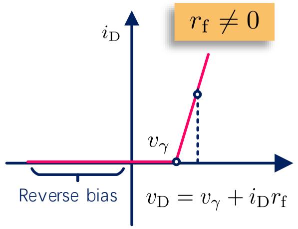

Anode [+] Cathode [-]

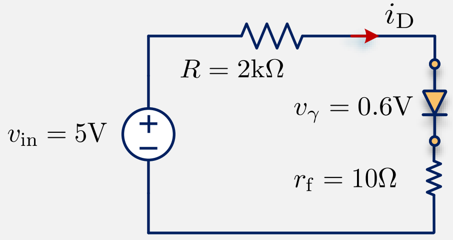



$$I_D = \frac{V_{in} - V_\gamma}{R + r_f} = \frac{5 - 0.6}{2 \times 10^3 + 10} = 2.19mA$$

$$V_D = V_\gamma + I_D r_f = 0.6 + \left(2.19 \times 10^{-3}\right)(10) = 0.622V$$

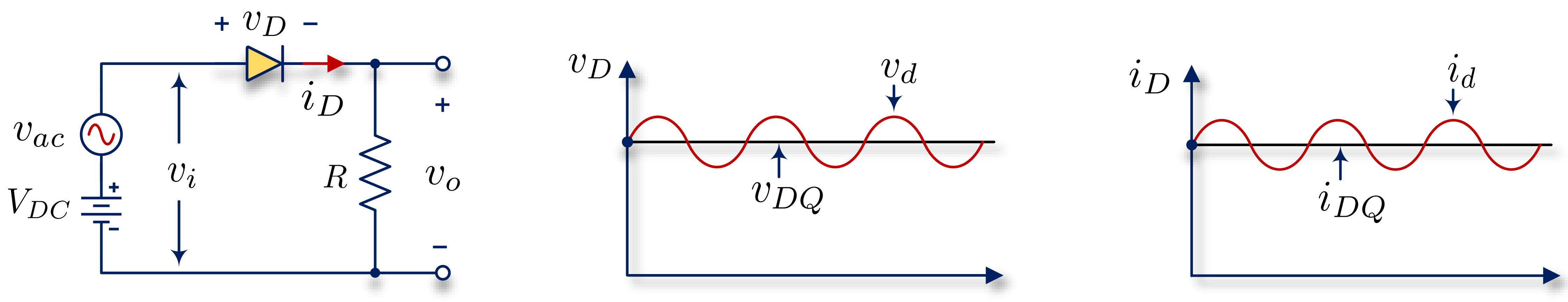
$$P_D = V_D I_D = 2.19 \times 0.622 = 1.36mW$$

*Guanying Chu*

# AC Analysis in diode circuit



- A complex circuit, we cannot have only DC sources, there is a high probability that AC sources will be added. Therefore we also have to do the **AC analysis** of the diode.




- The voltage source $v_{ac}$ is assume to be a AC sine signal. The total input voltage $v_{in}$ is composed of a **DC** component $V_{DC}$ and an **AC** component $v_{ac}$ ($v_{ac} << V_{DC}$)

# Derivation

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$$\boxed{v_D = V_{DQ} + v_d}$$

$$\Uparrow$$

$$I_D = I_S\left[e^{\left(\frac{v_D}{nV_T}\right)} - 1\right] \Rightarrow I_D = I_S e^{\left(\frac{v_D}{V_T}\right)} \Rightarrow I_D = I_S e^{\left(\frac{V_{DQ}+v_d}{V_T}\right)} = I_S e^{\left(\frac{V_{DQ}}{V_T}\right)} e^{\left(\frac{v_d}{V_T}\right)}$$

- We assume that the ac signal is very "**Small**", $v_d << V_T$

$$e^{\left(\frac{v_d}{V_T}\right)} \cong 1 + \frac{v_d}{V_T}$$

Linear Expansion by using equivalent infinitesimals
等价无穷小展开

$$\Downarrow$$

$$i_D = I_S e^{\left(\frac{v_{DQ}}{V_T}\right)}\left(1 + \frac{v_d}{V_T}\right) = I_{DQ}\left(1 + {}^{v_d}/_{V_T}\right) \triangleq I_{DQ} + i_d$$

$$\Downarrow$$

$$i_d = I_{DQ}\frac{v_d}{V_T} \Rightarrow v_d = \boxed{\left(\frac{V_T}{I_{DQ}}\right)} i_d \Rightarrow v_d \triangleq r_d i_d \Rightarrow \boxed{r_d = \frac{V_T}{I_{DQ}}}$$

$r_d$ is the **small-signal incremental resistance** or diffusion resistance

# Derivation

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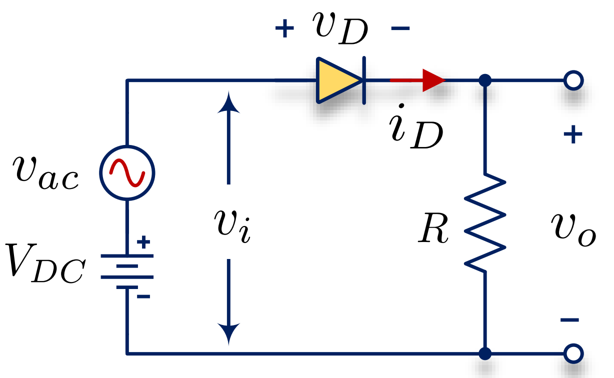
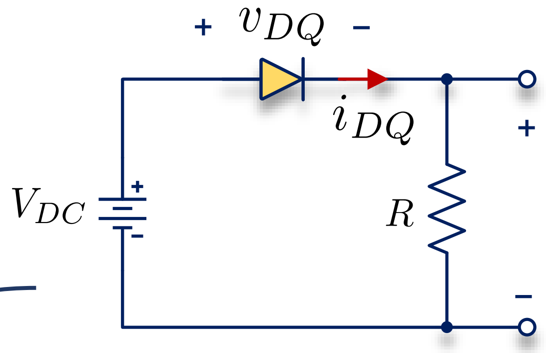


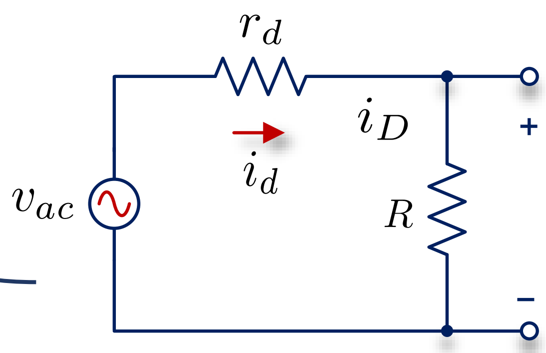

Original Circuit




DC part

- **DC** equivalent circuit
  - Forward-bias
  - Piecewise linear turn-on voltage

The objective is to calculate the Q-point diode current $I_{DQ}$ and voltage $V_{DQ}$




AC part

- **AC** equivalent circuit
  - Diffusion resistance $r_d$
  - All small-signal time-varying parameter

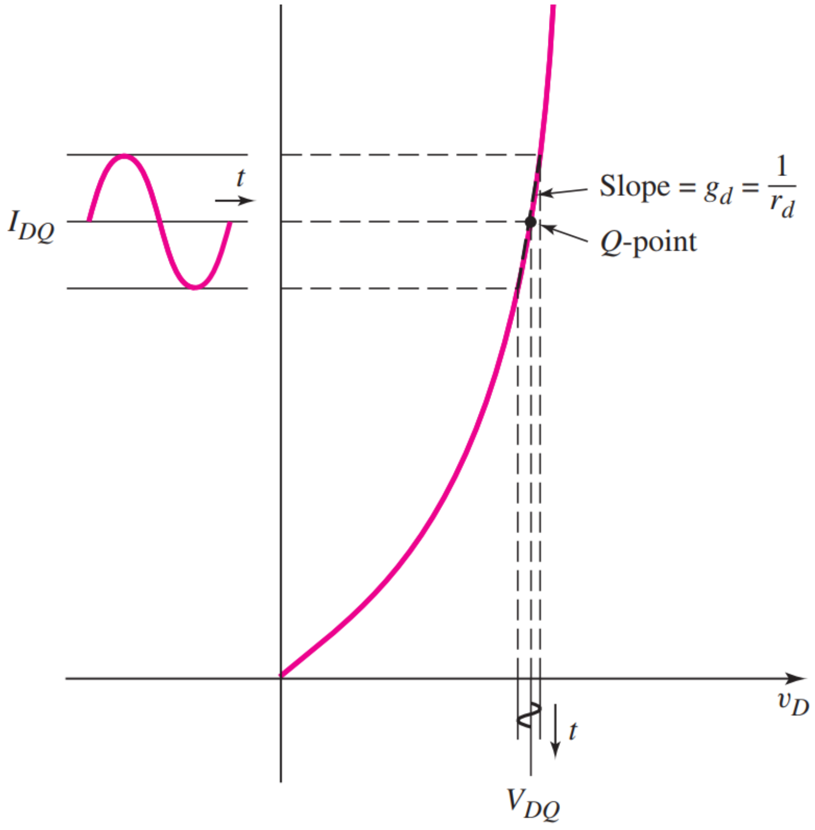
$$r_d = \frac{V_T}{I_{DQ}}$$

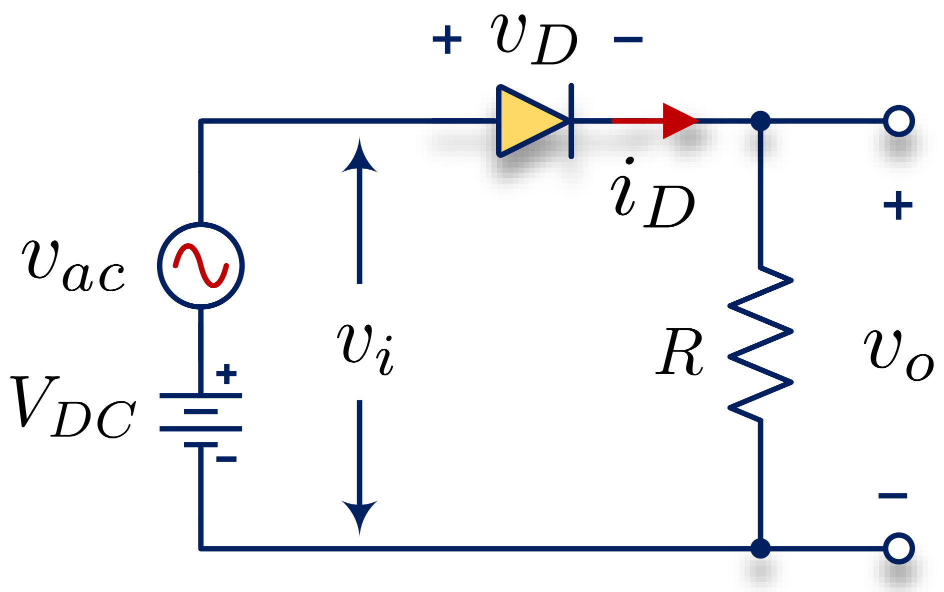
Then, $r_d$ can be derived

# Reinforce Your Learning



- Analyze the circuit shown in below. Assume circuit and diode parameter of $V_{DC}$ = 5V, R = 5kΩ, $V_\gamma$=0.6V, $r_f$=0Ω, and $v_{ac} = 0.1 \sin \omega t$



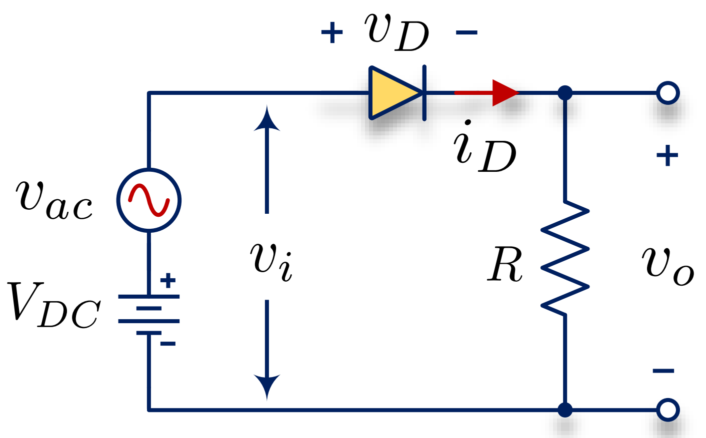
# Reinforce Your Learning 🤖



- The circuit and diode parameter of $V_{DC}$ = 5V, R = 5kΩ, $V_\gamma$=0.6V, $r_f$=0Ω, and $v_{ac} = 0.1\sin\omega t$
- Please calculate the output voltage for DC  and ac component, respectively.

- **Solution** Divide the analysis into two parts: the DC analysis and AC analysis

For the DC analysis, we set $v_{ac} = 0$ and determine the DC quiescent current



# Reinforce Your Learning 🤖



- For the AC analysis, we consider only the AC signal and parameter in the circuit as shown below. In other words, we set $V_{DC} = 0$ The AC Kirchhoff voltage law (KVL)