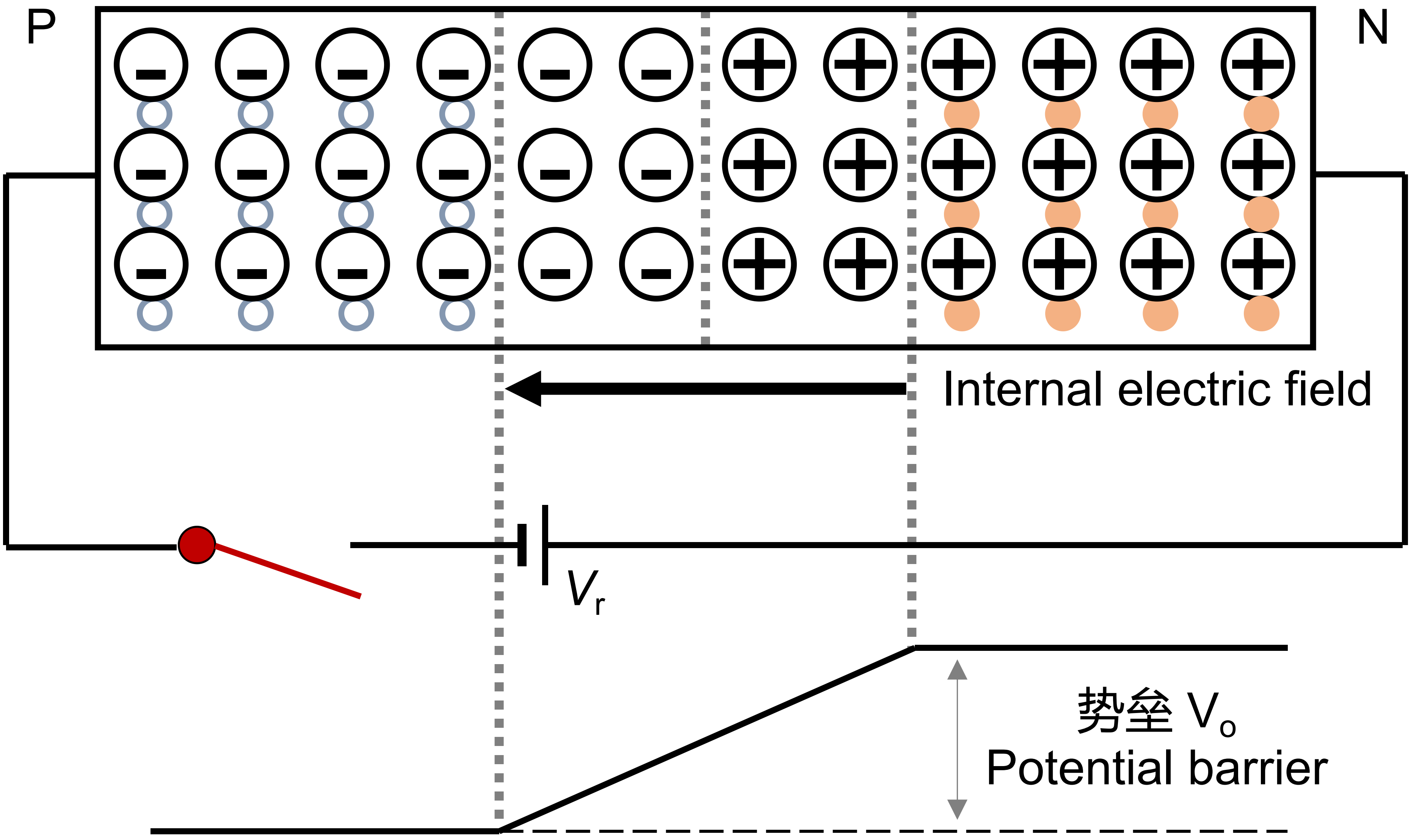
Electronic Materials and Devices

5 Semiconductor

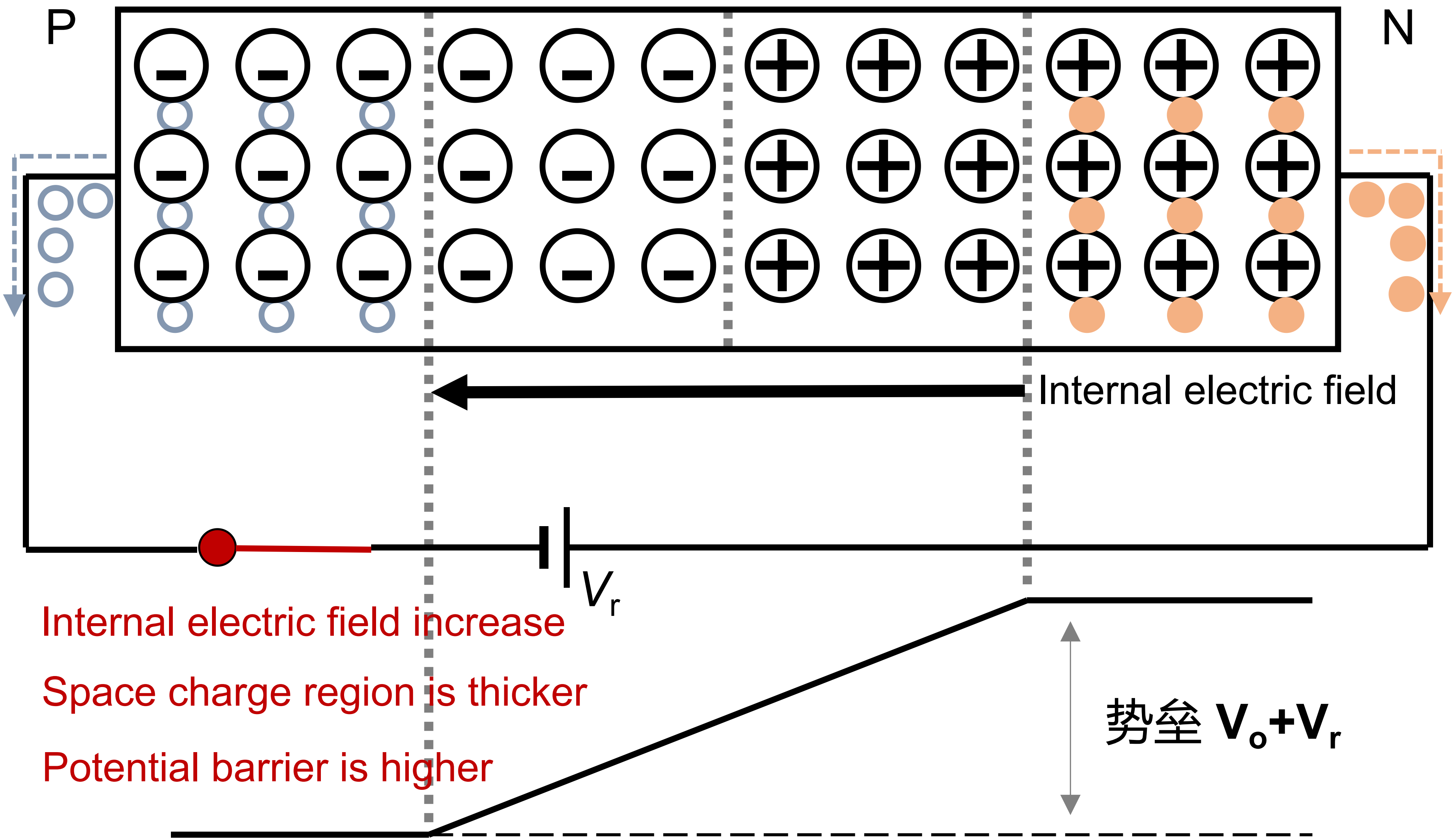
陈晓龙 Chen, Xiaolong

电子与电气工程系

Reverse bias 反向偏置电压

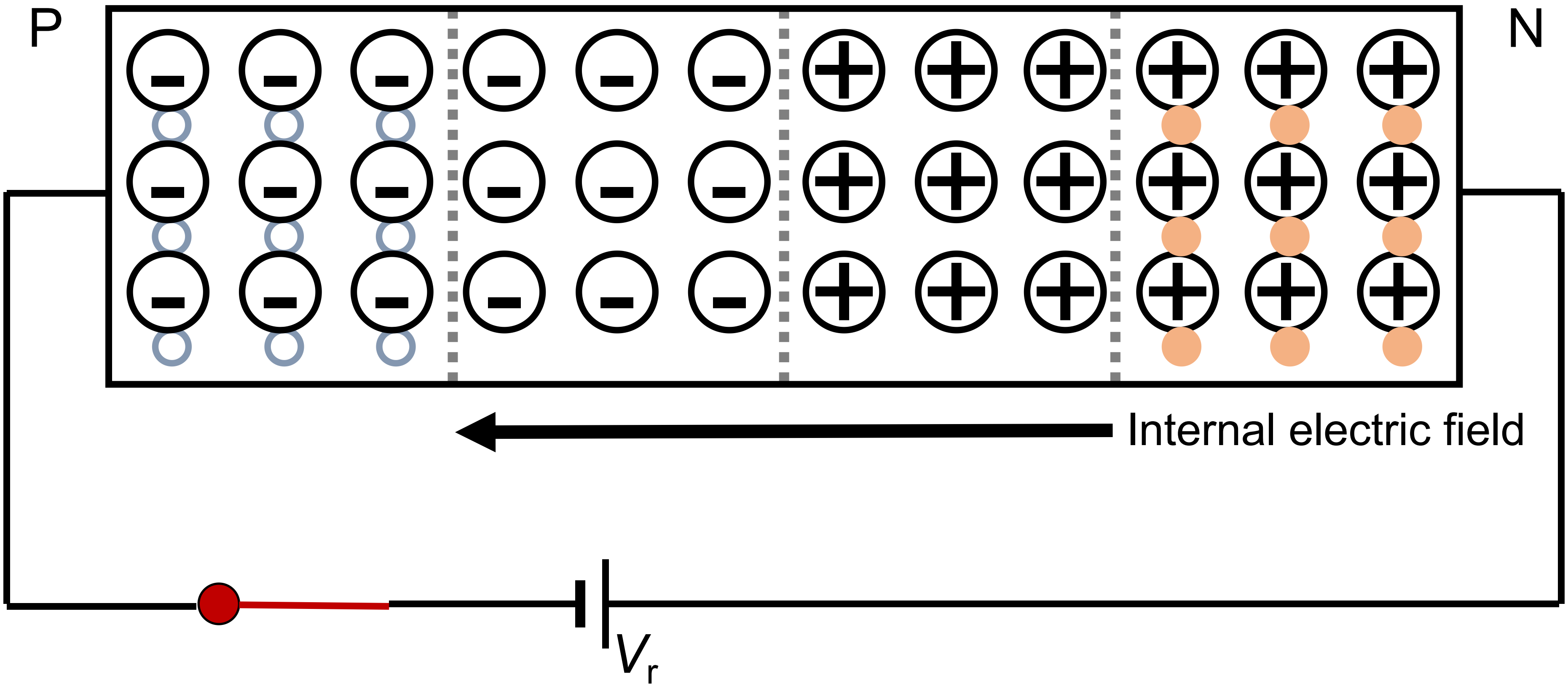


Reverse bias



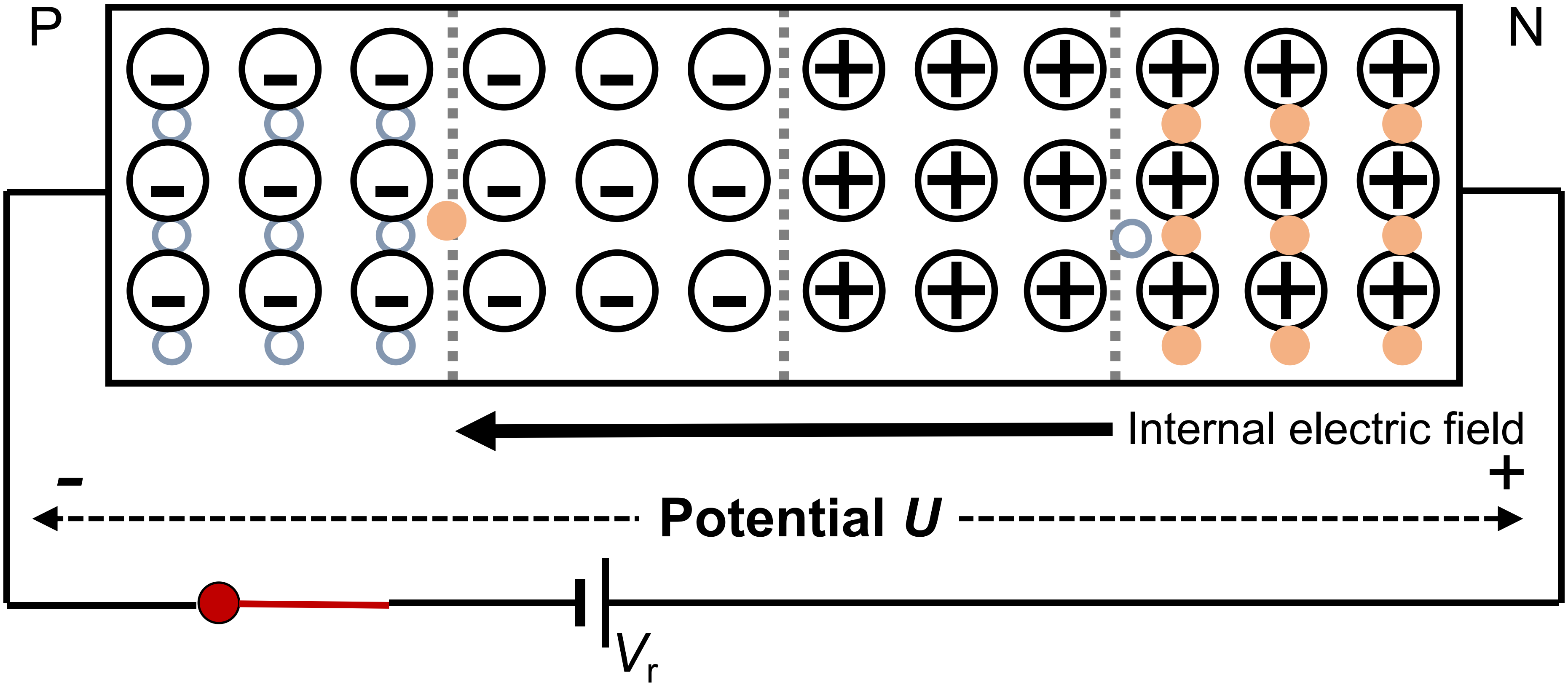
PN-junction is off with high resistance

Reverse bias



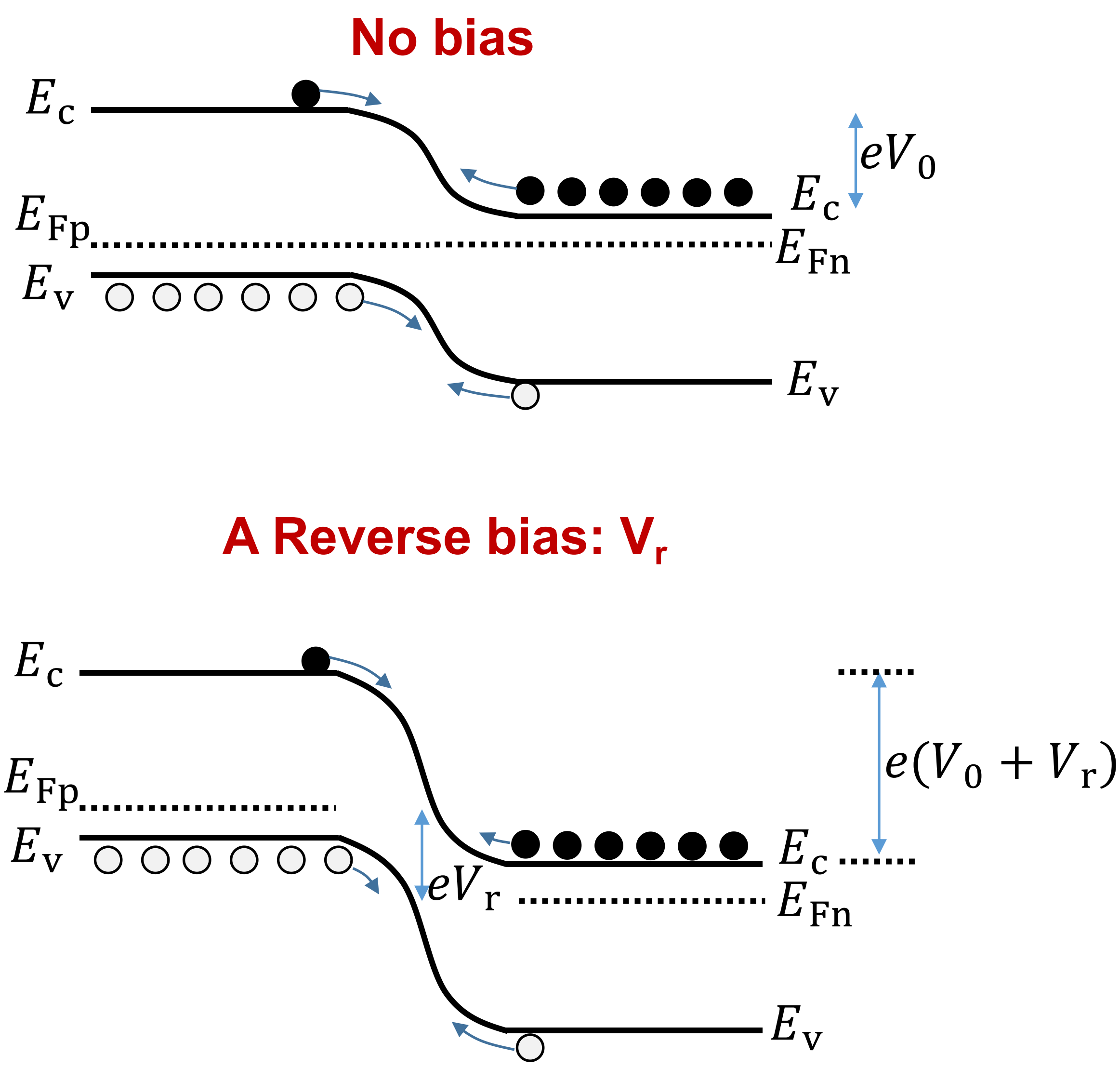
Q: Will there still be current in reverse bias?

Reverse bias



◆ There will be a small current originated from the **drift of minor carriers** and **diffusion of major carriers**, which is called the **reverse saturation current**.

Band diagram at reverse bias

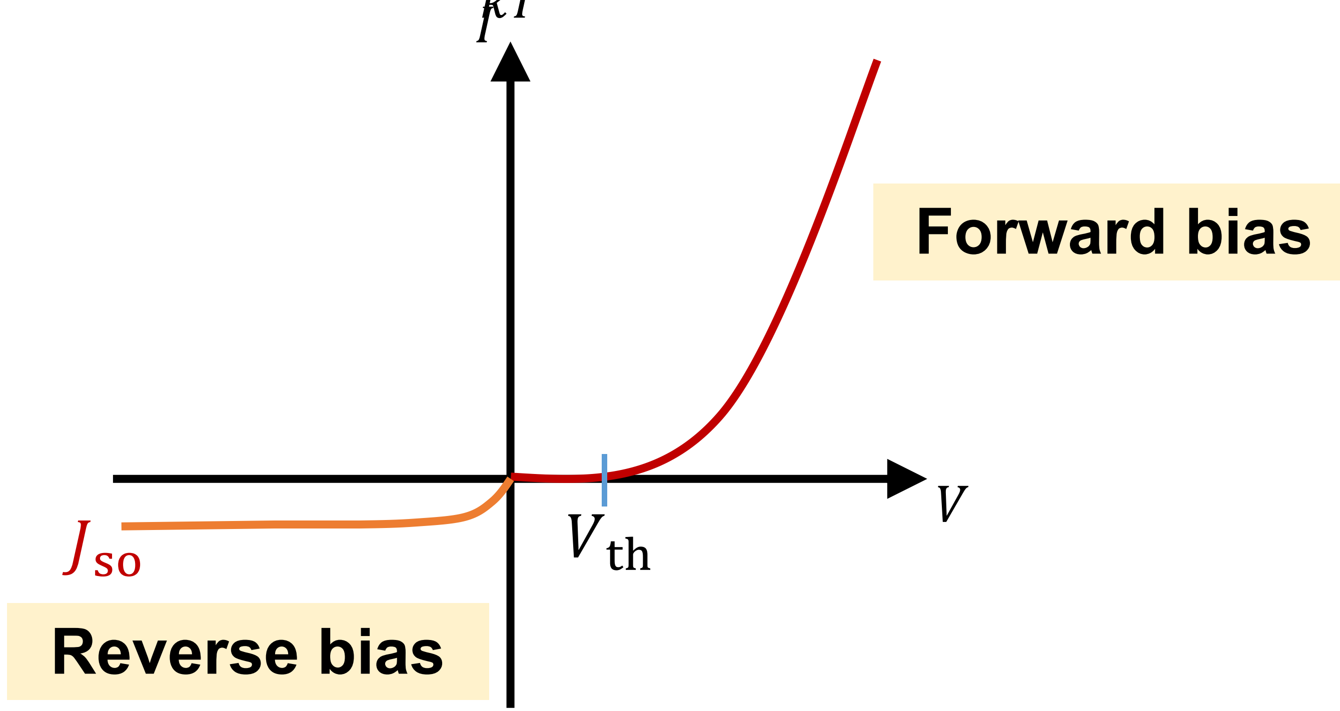


Reverse saturation current density

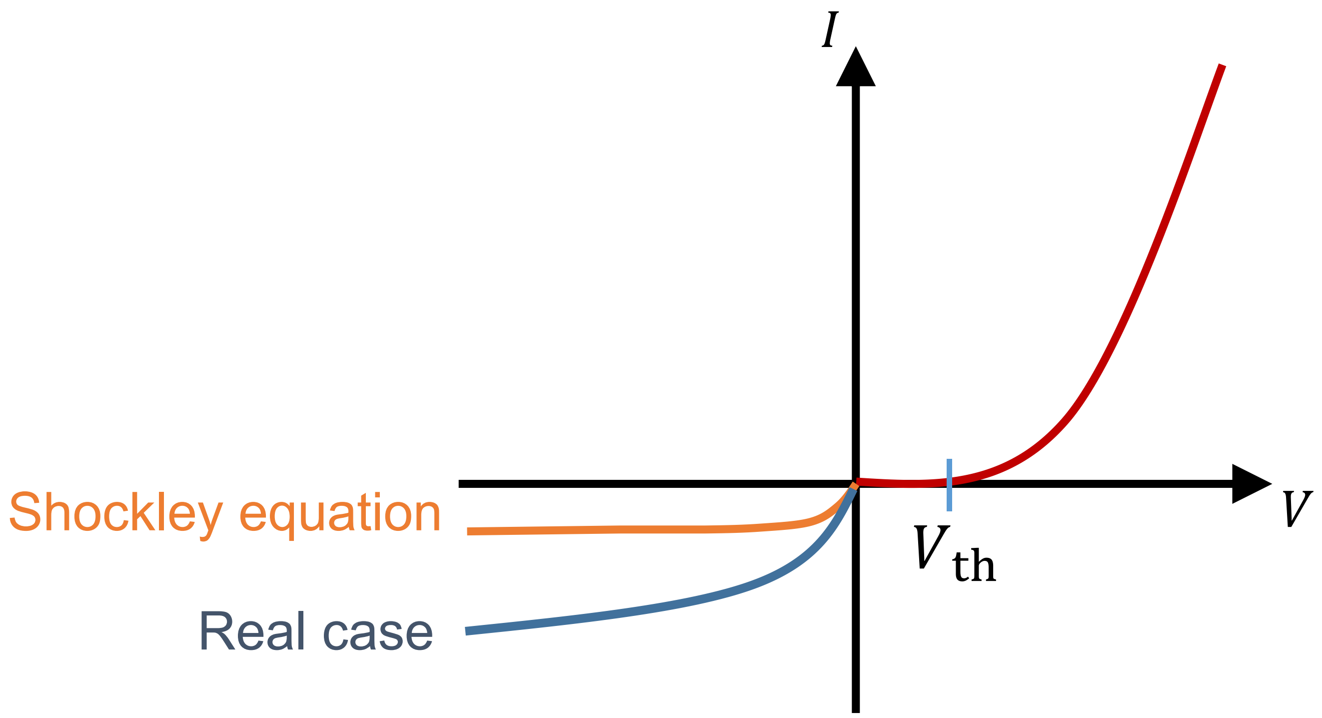
$$J = \left(\frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a}\right) n_i^2 \left[\exp\left(\frac{eV}{kT}\right) - 1\right] \quad = J_{so}\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

For reverse bias: $V = -V_r$

$J \approx -J_{so}$, when $V_r \gg kT$

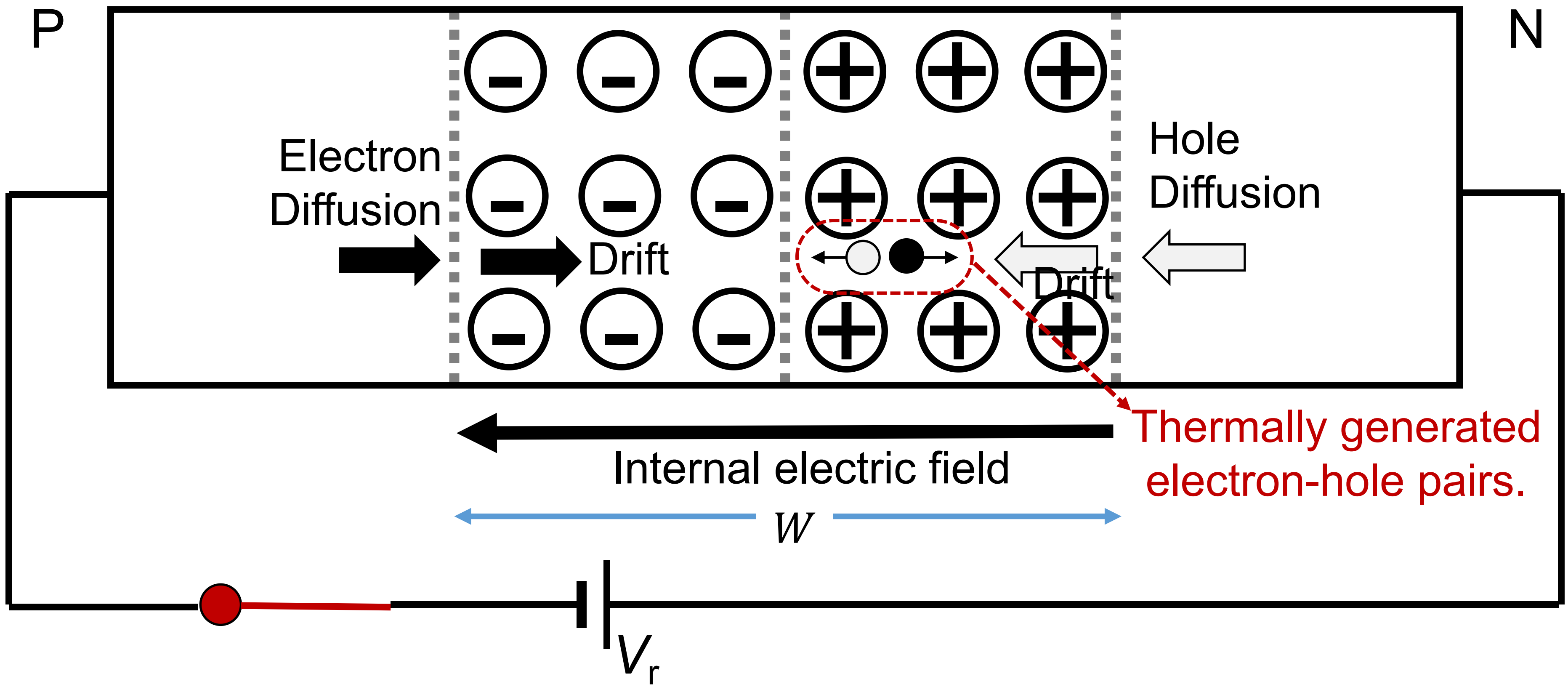


Reverse saturation current density



Reverse current: the sum of diffusion and generation components.

$$J_{\mathrm{rev}} = J_{\mathrm{D}} + J_{\mathrm{gen}}$$

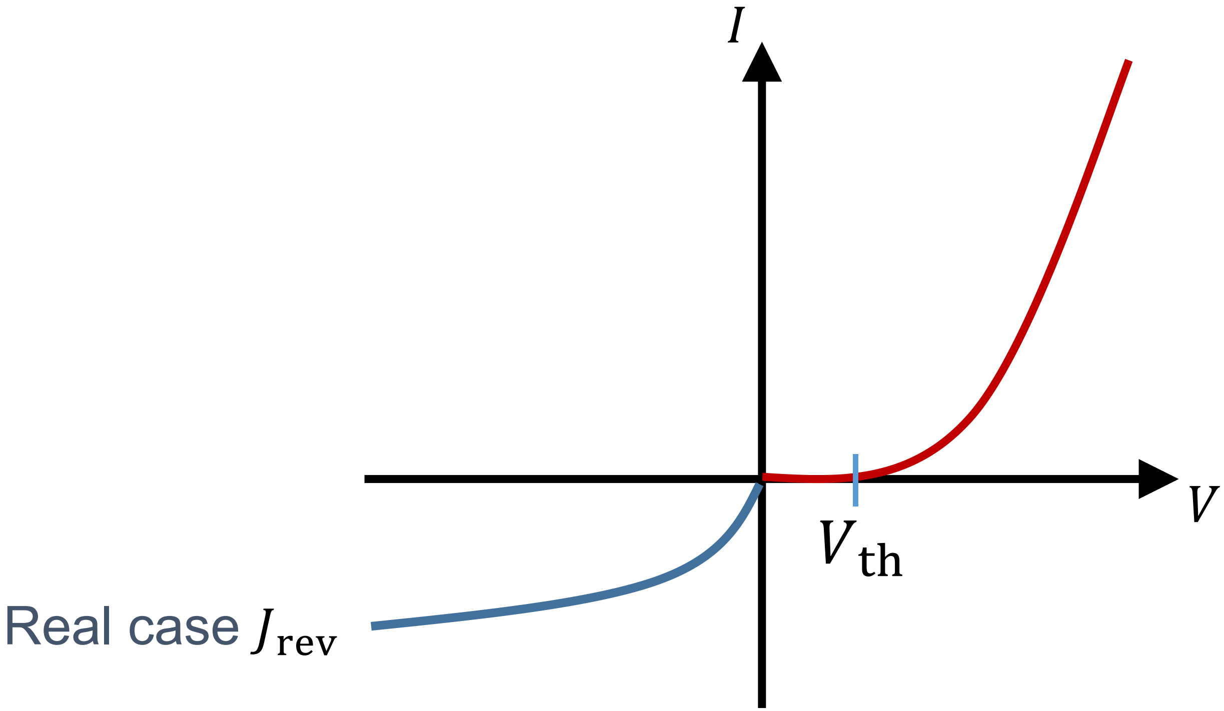


Mean time to generate n_i electron-hole pair per volume: τ_g

Current due to the drift of thermally generated electron-hole pairs J_{gen}:

$$J_{gen} = \frac{eWn_i}{\tau_g}$$

Reverse saturation current density



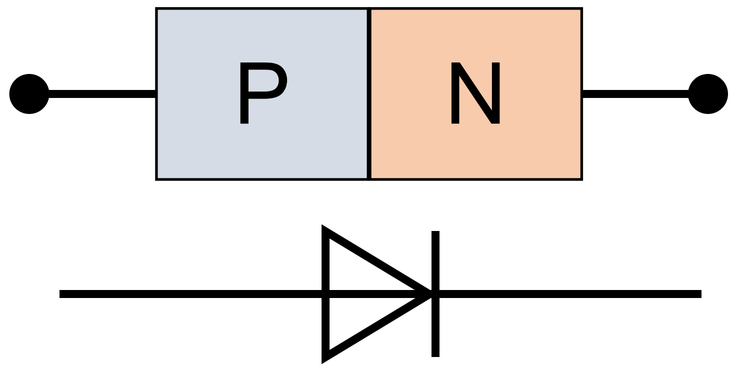
$$J_{\mathrm{rev}} = -\left(\frac{eD_{\mathrm{h}}}{L_{\mathrm{h}}N_{\mathrm{d}}} + \frac{eD_{\mathrm{e}}}{L_{\mathrm{e}}N_{\mathrm{a}}}\right)n_{\mathrm{i}}^2 - \frac{eWn_{\mathrm{i}}}{\tau_{\mathrm{g}}}$$

The width of depletion region *W* depends on *V*.

Diode 二极管

Diode: connect PN junction or Schottky junction with wires and seal with shell.

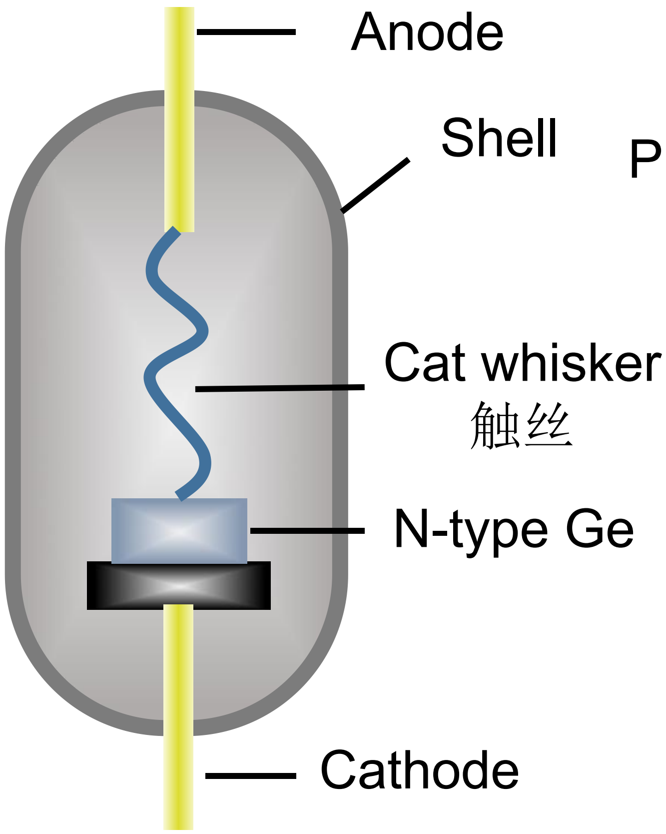
Anode
阳极



Cathode
阴极

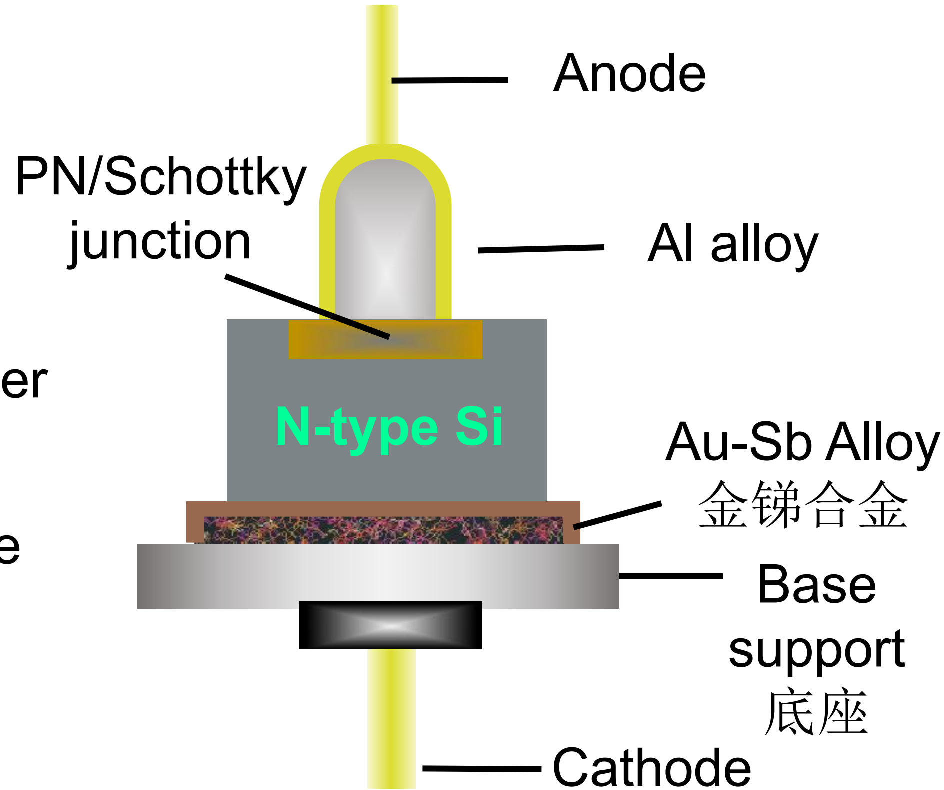
Types of diode

Point contact diode
点接触型



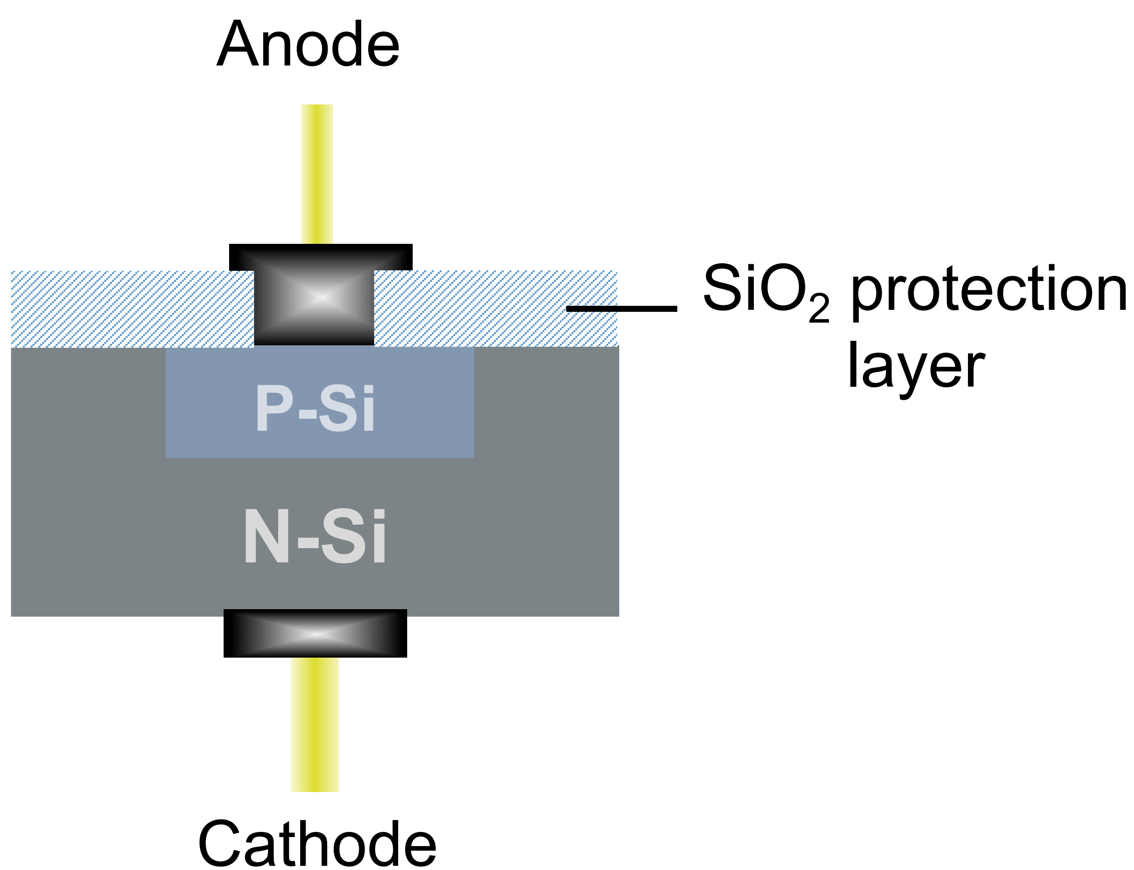
Small contact area: high frequency

Surface contact diode
面接触型

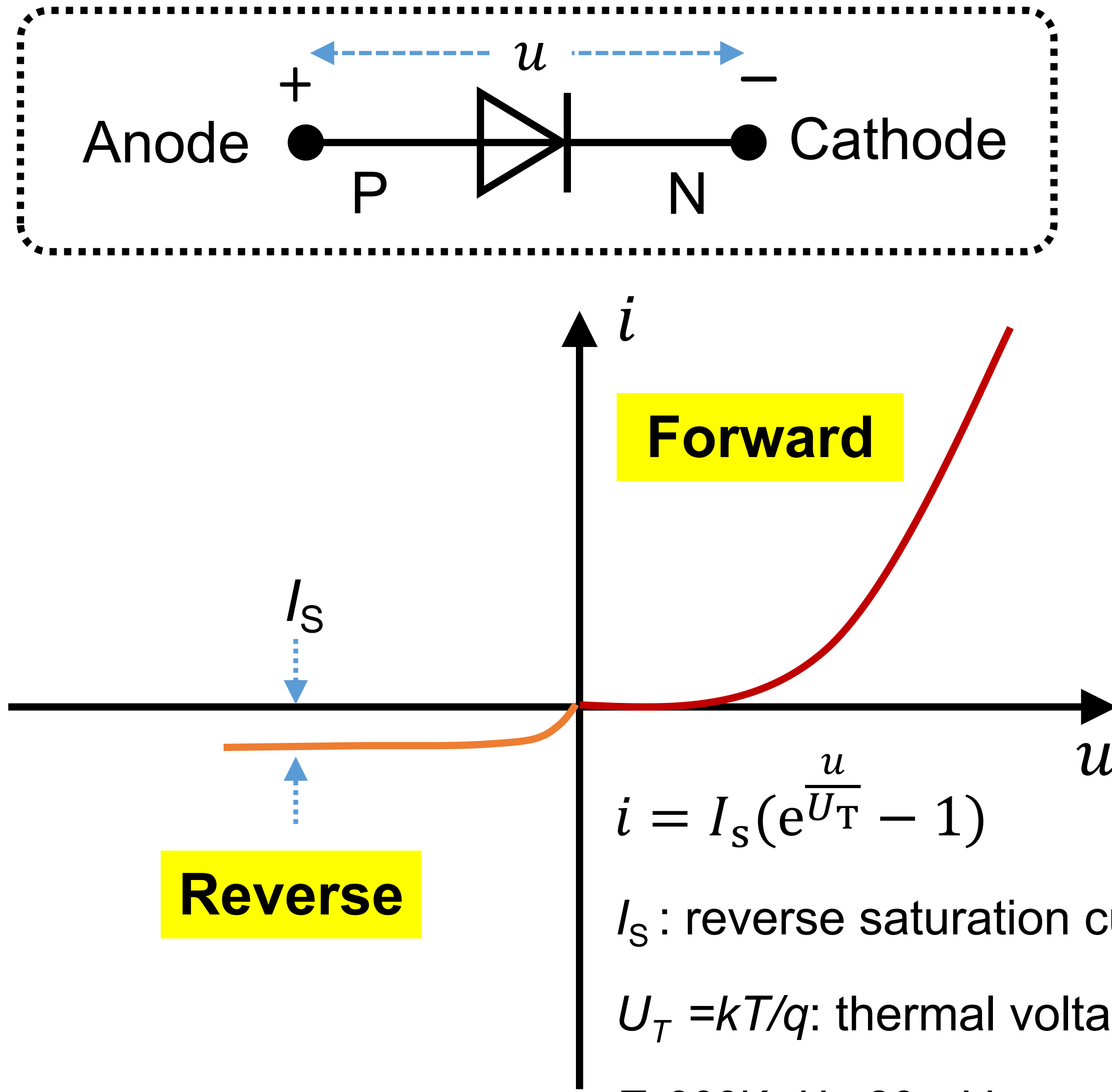


Large contact area: high current applications

Planar diode平面型



Good for integrated circuit!



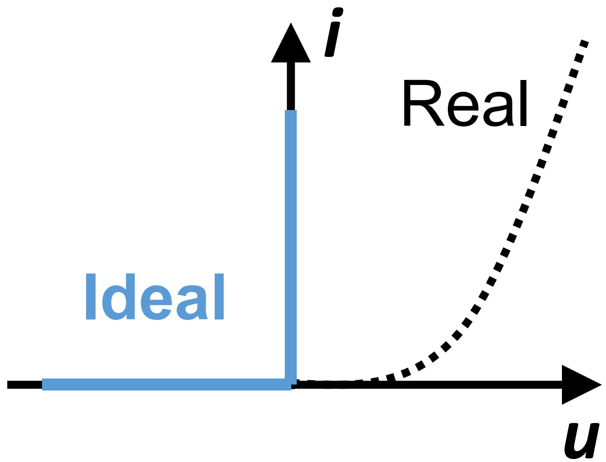
$$i = I_s\left(e^{\frac{u}{U_T}} - 1\right)$$

I_S : reverse saturation current

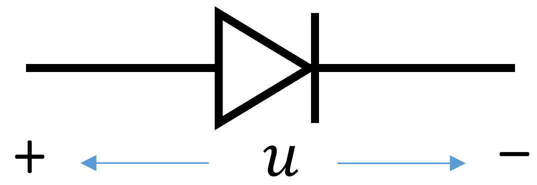
$U_T = kT/q$: thermal voltage

T=300K, U_T=26 mV

Ideal diode 理想二极管

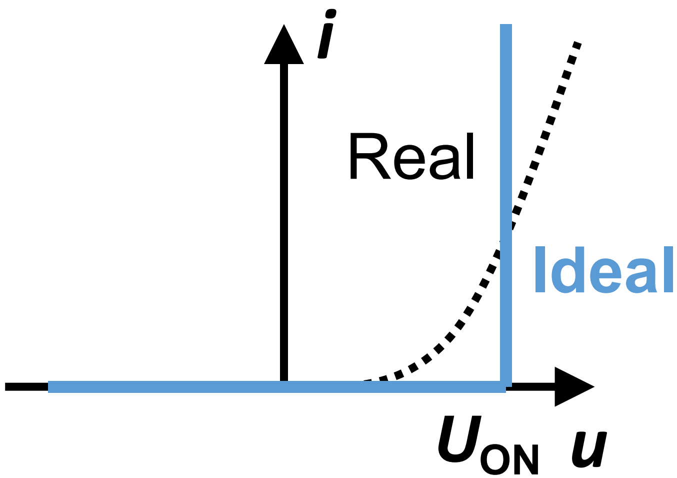


The symbol for ideal diode



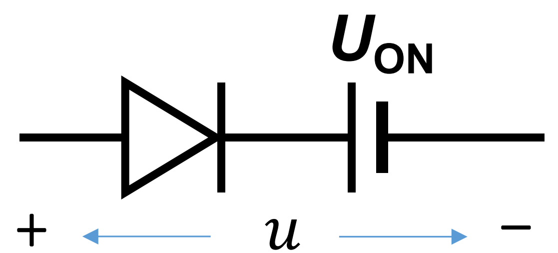
$$\begin{cases} u > 0:\ r = 0 \\ u \le 0:\ r \to \infty \end{cases}$$

Constant-volt model 恒压模型

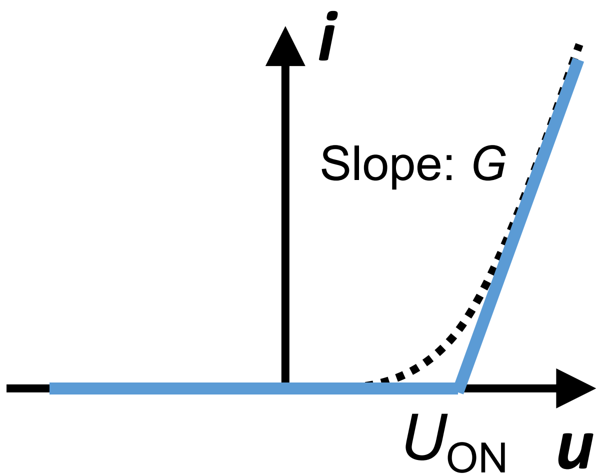


Q: The symbol?

$$\begin{cases} u > U_{\mathrm{ON}}:\ r = 0 \\ u \le U_{\mathrm{ON}}:\ r \to \infty \end{cases}$$



Broken-line model 折线模型



Q: What's the symbol?

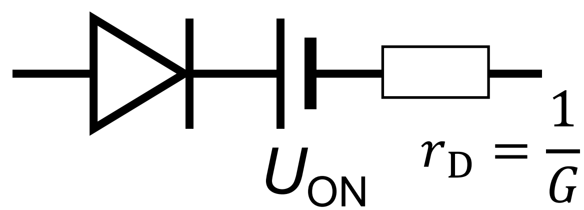
$$u \le U_{\mathrm{ON}}:$$

$$r \to \infty$$

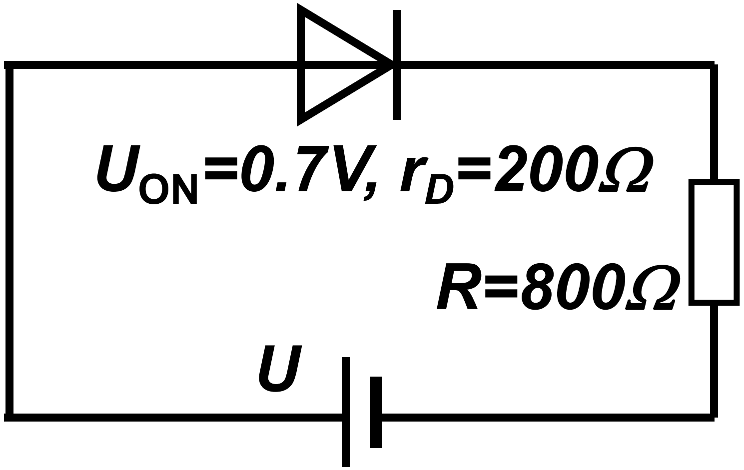
$$u > U_{\mathrm{ON}}:$$

$$i = G(u - U_{\mathrm{ON}})$$

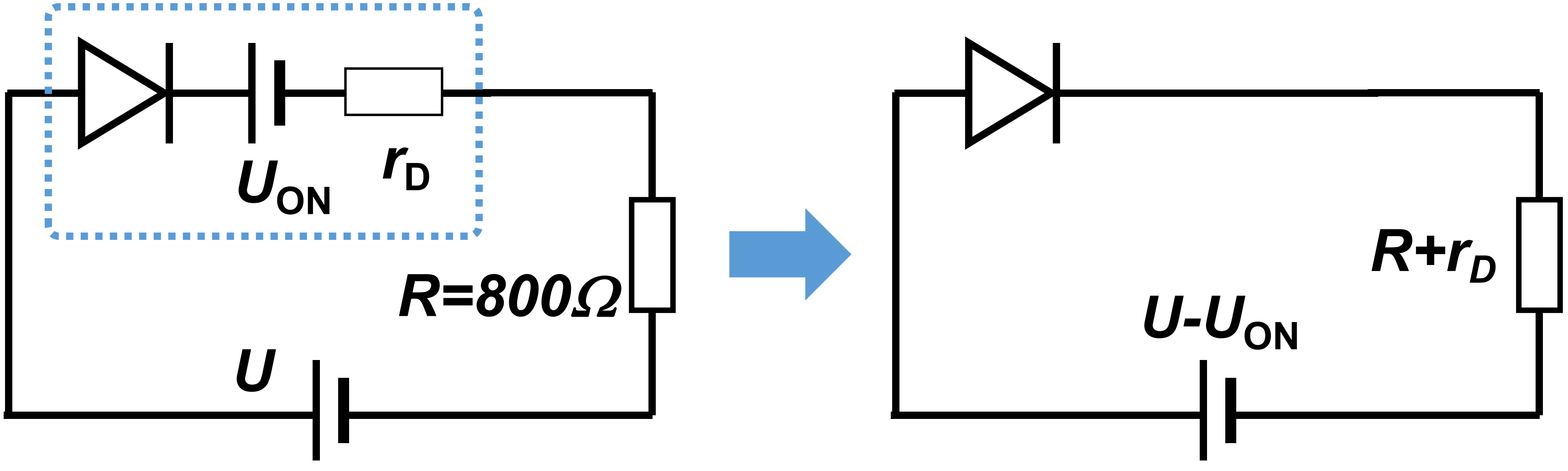
$$u = U_{\mathrm{ON}} + i/G$$

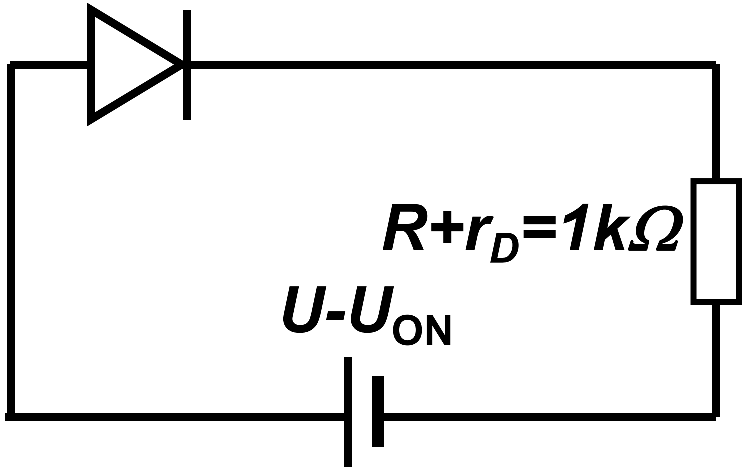


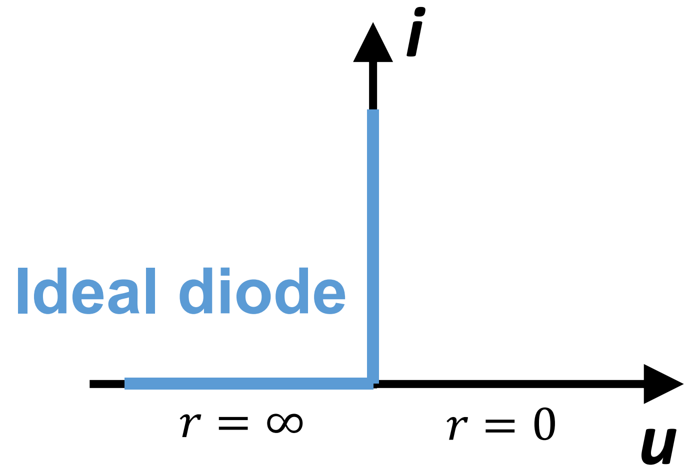
Example 1:

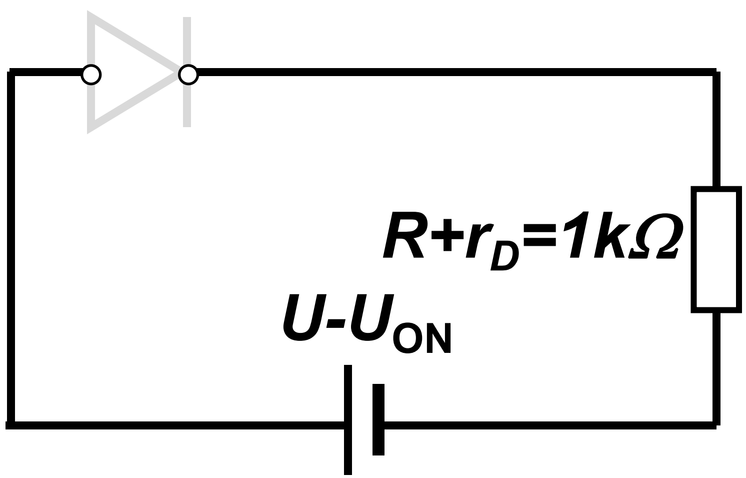


[Q1] Using the broken-line mode, ask: when U= 0.5V, 1.7V, and -1.3V， the current in the circuit?







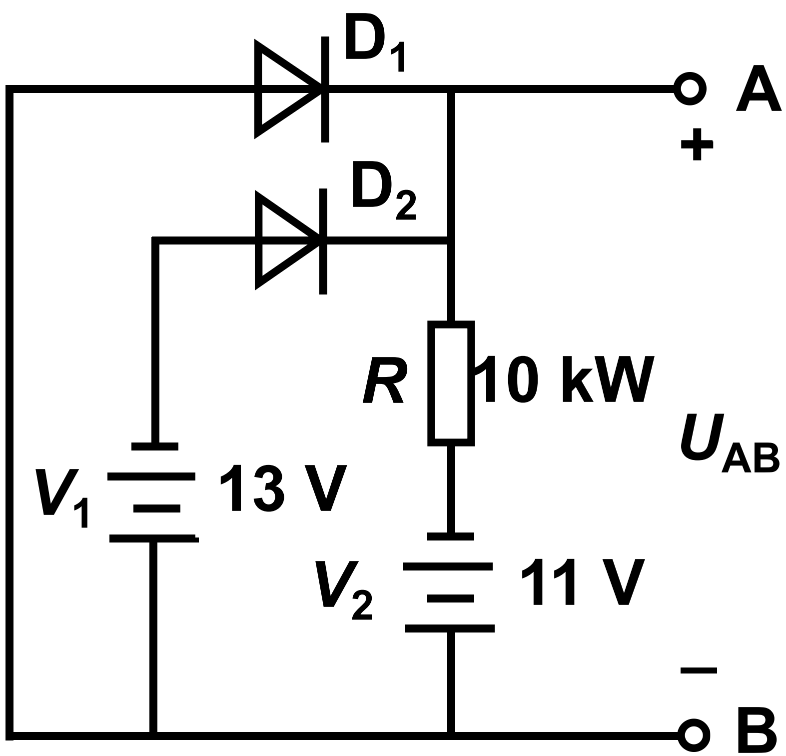


Assume diode is off

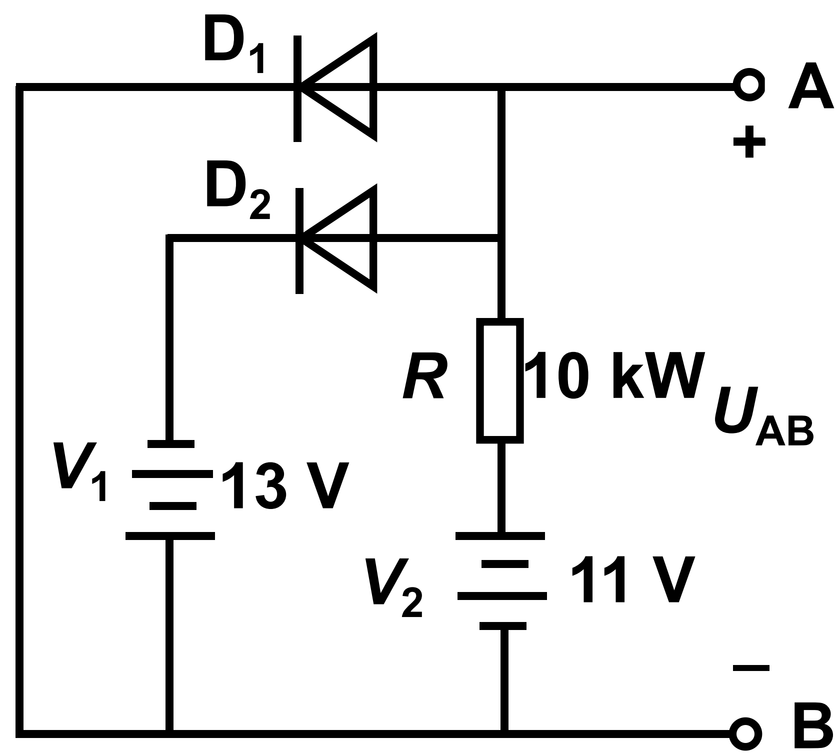
1. U=-1.3V， U-U_{ON}=-2V， i=0;
2. U=0.5V， U-U_{ON}=-0.2V， i=0;
3. U=1.7V， U-U_{ON}=1V，

Assumption is wrong, and diode is on: i=(U-U_{ON})/(R+r_D)=1mA;

[Example2] All the diode is ideal. Ask: (1) the diode D_1 and D_2 is on or off. (2) The value of U_{AB}.



(a)



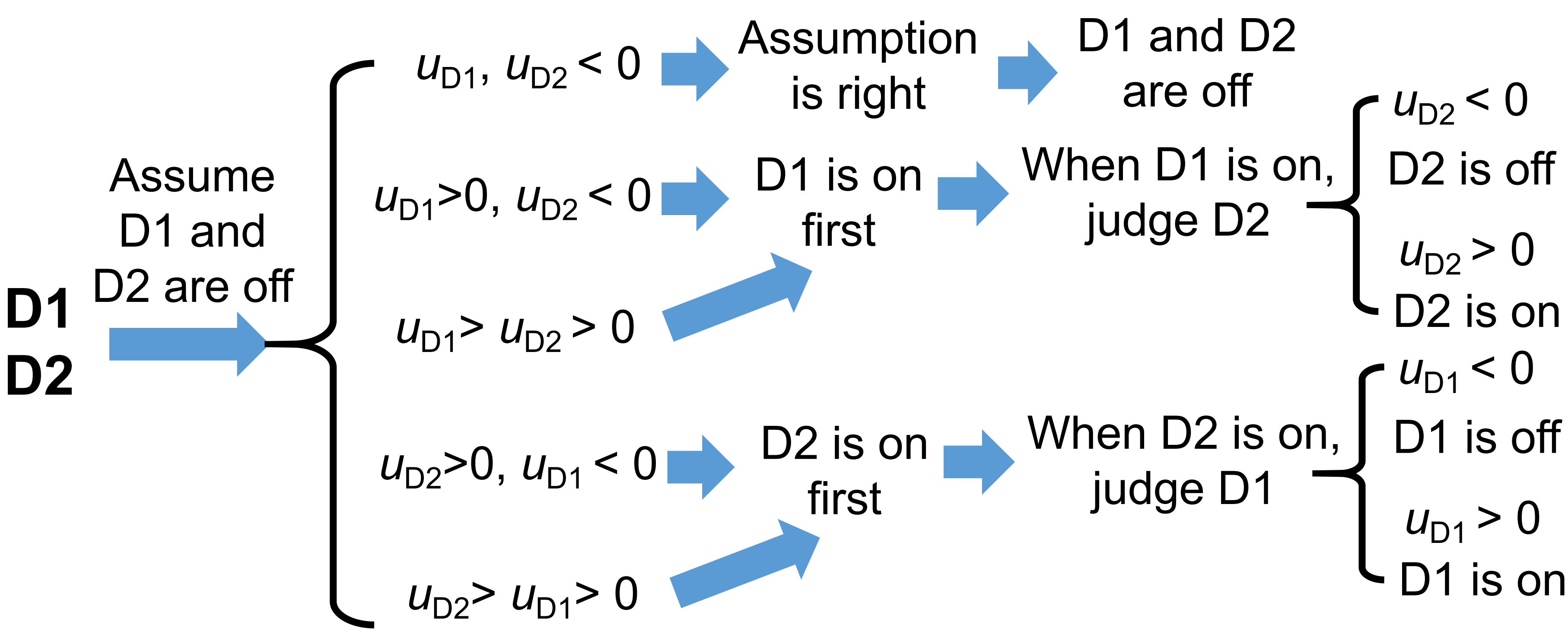
(b)

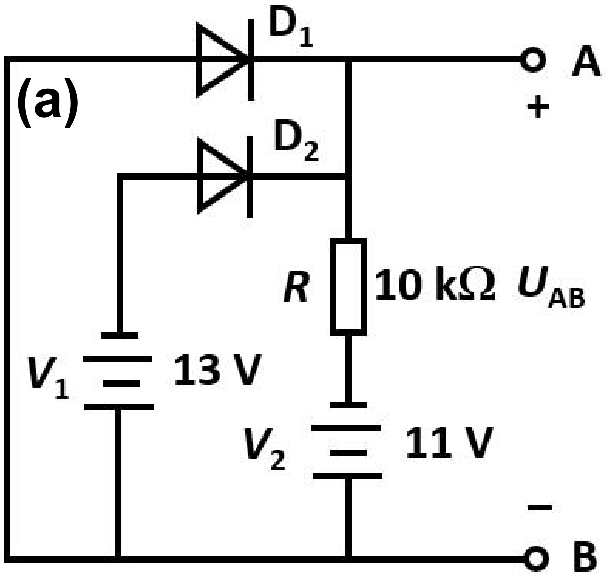
[Answer] How to judge diode on or off.

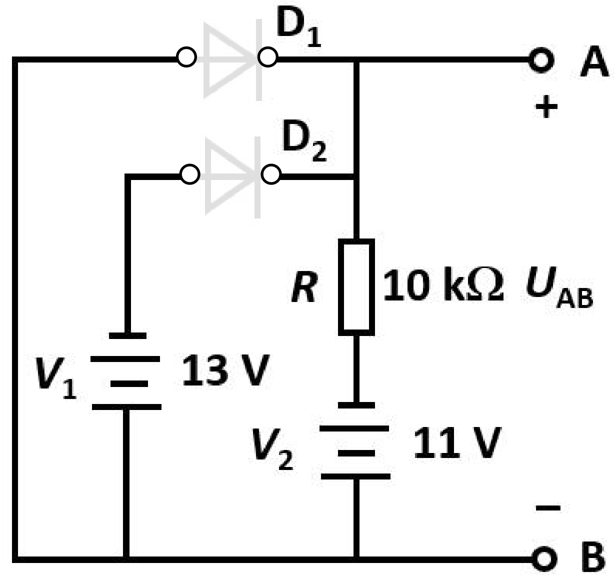
1. One diode: assume diode is off, and analyze the circuit. If the $u_{\text{Diode}} > U_{\text{ON}}$, diode is on. If the $u_{\text{Diode}} < U_{\text{ON}}$, diode is off.

2. If there are two identical diodes D_1 and D_2 in the circuit, assume both diodes are off, and analyze the circuit. Compare u_{Diode1} with u_{Diode2}. The diode with higher u_{Diode} is on first. With one diode on, then judge the other diode.

[Answer] How to judge diode on or off.







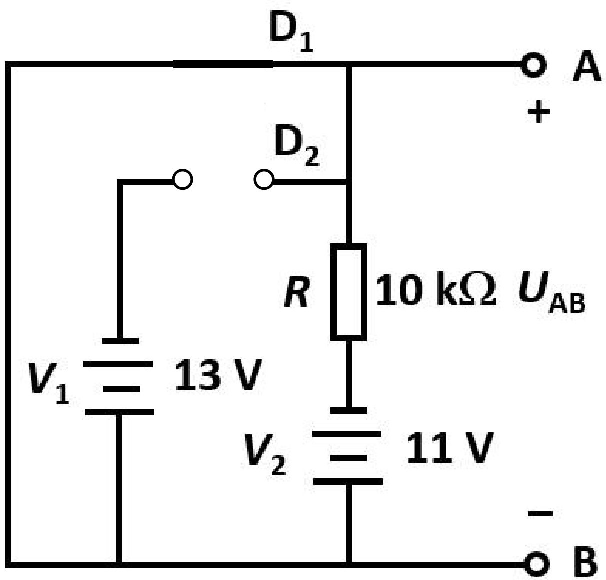


Fig.(a): voltage of D_1, D_2 is:

11 V, –2 V

D_1 on, assume D_2 off

Voltage of D_2 is: -13 V

D_2 off

U_{AB} = 0 V

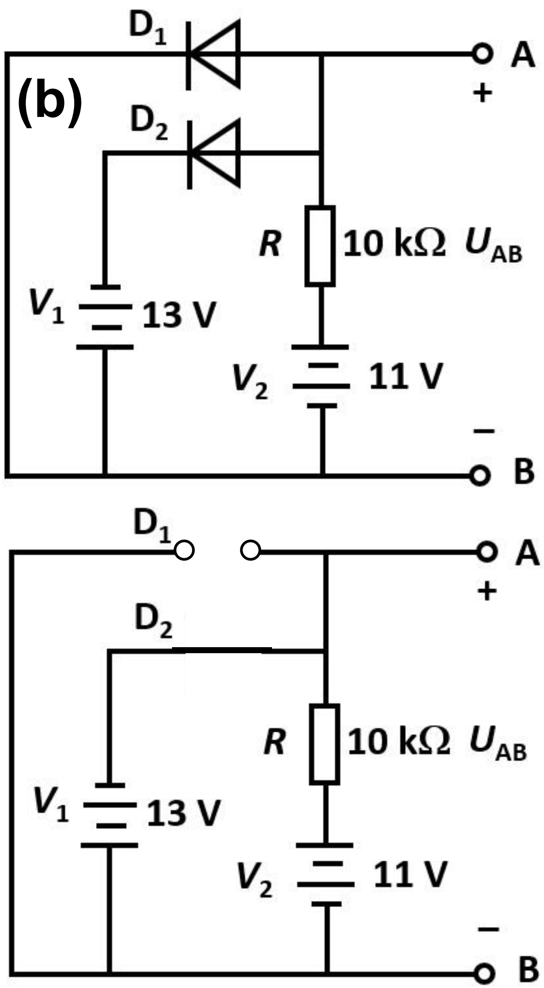


Fig.(b): voltage of D_1, D_2 is:

11 V, 24 V

D_2 is on first

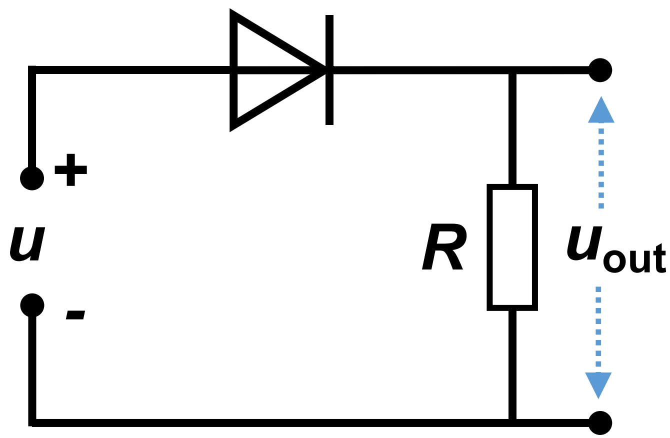
Assume D_1 is off

Voltage of D_1 is -13 V

D_1 off $U_{AB} = -13$ V

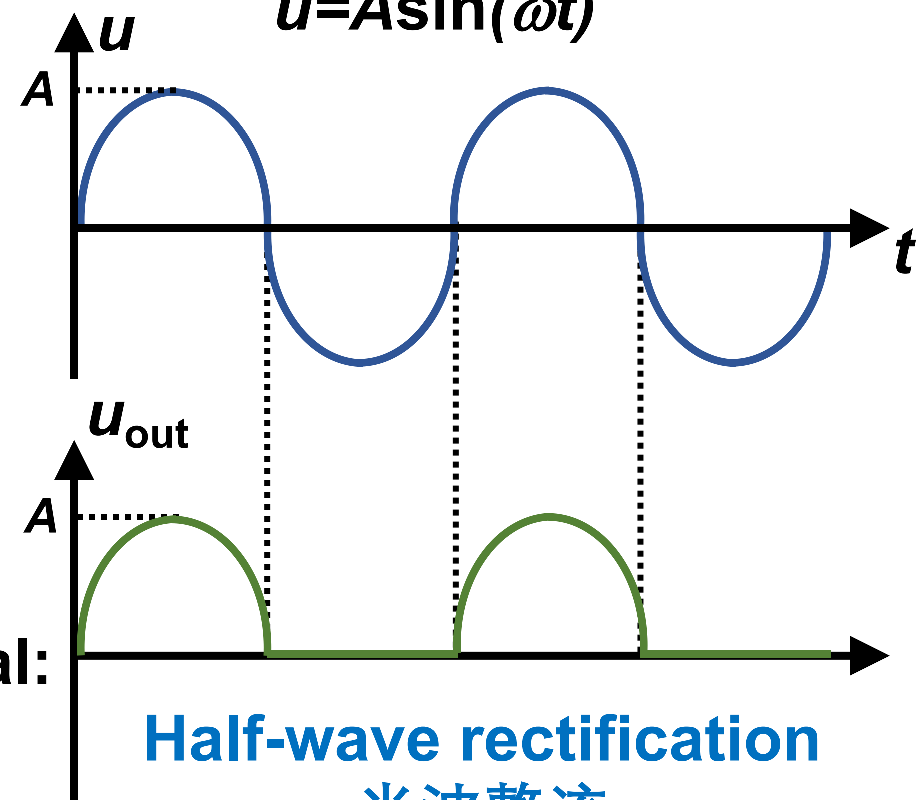
Application of diodes as rectifier

二极管在整流电路的应用



Input AC voltage signal:

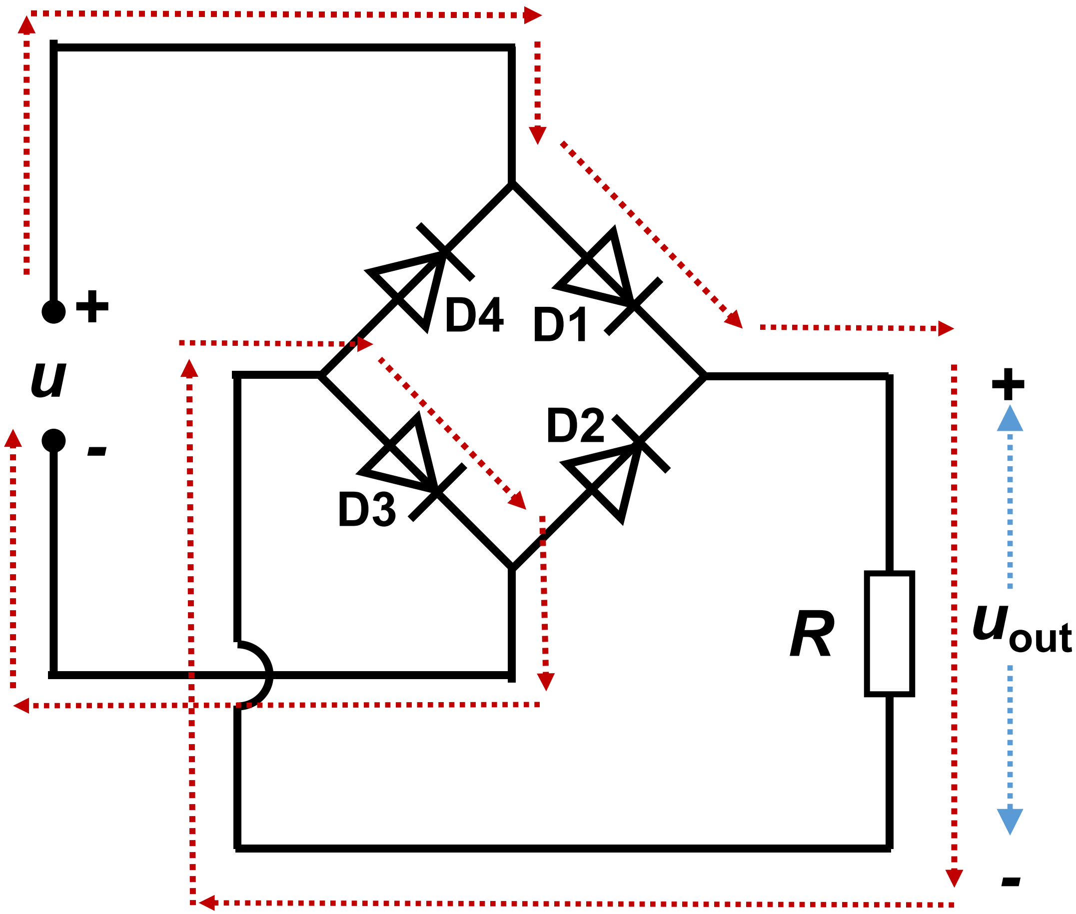
$u = A\sin(\omega t)$



Output AC voltage signal:

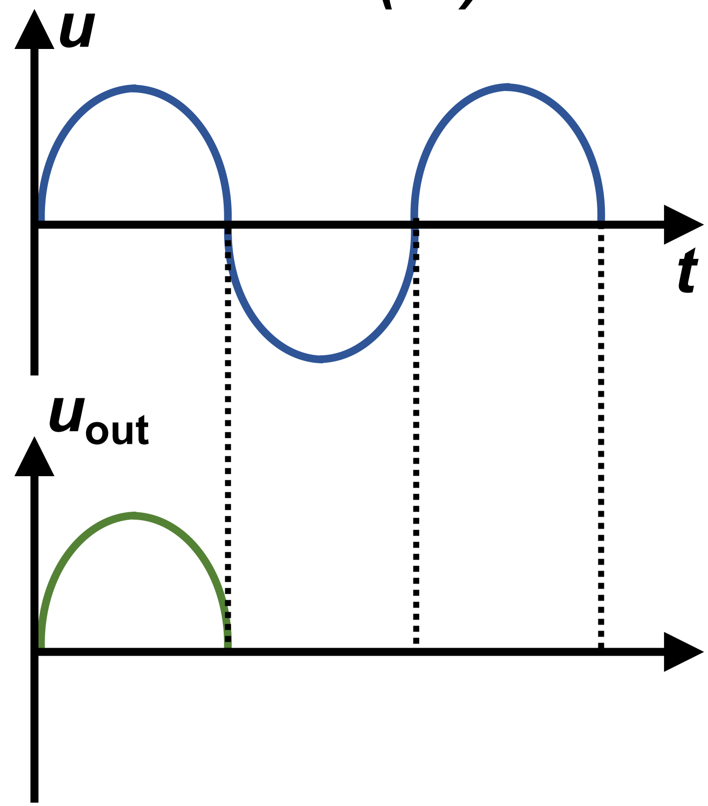
Half-wave rectification
半波整流

Full-wave rectification全波整流

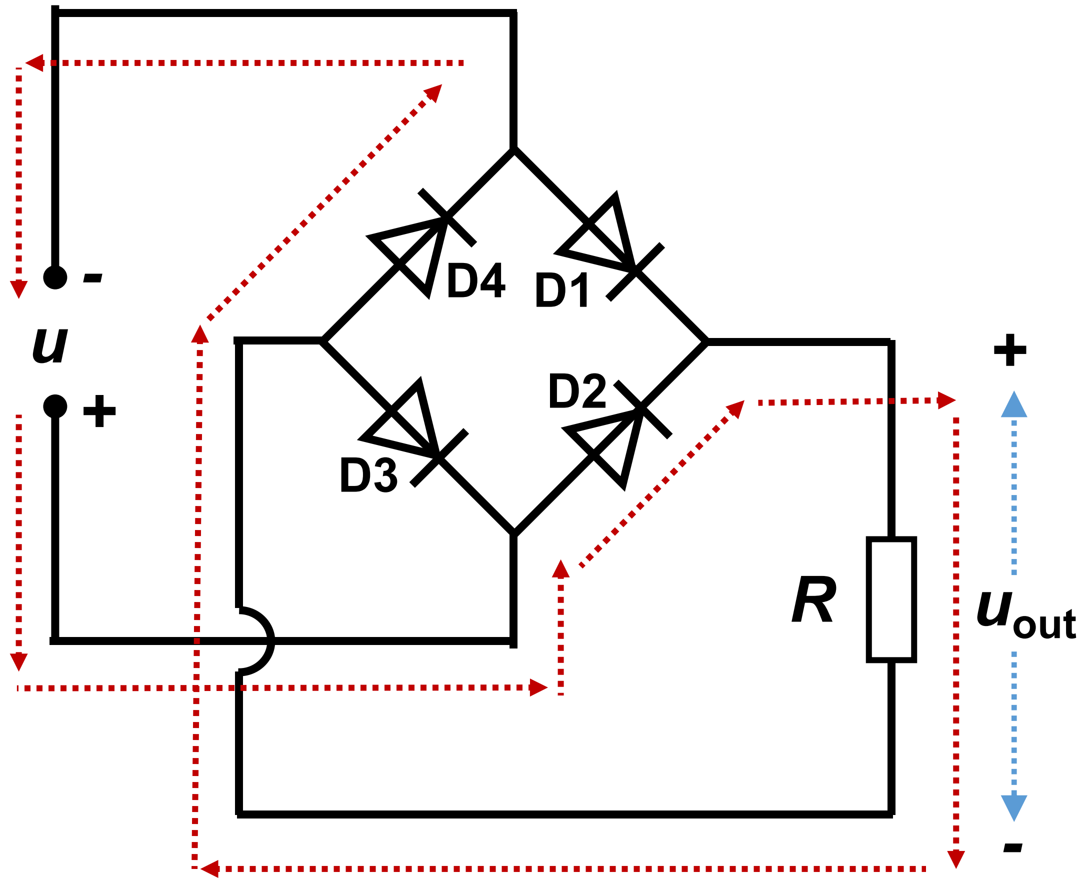


Input AC voltage signal:

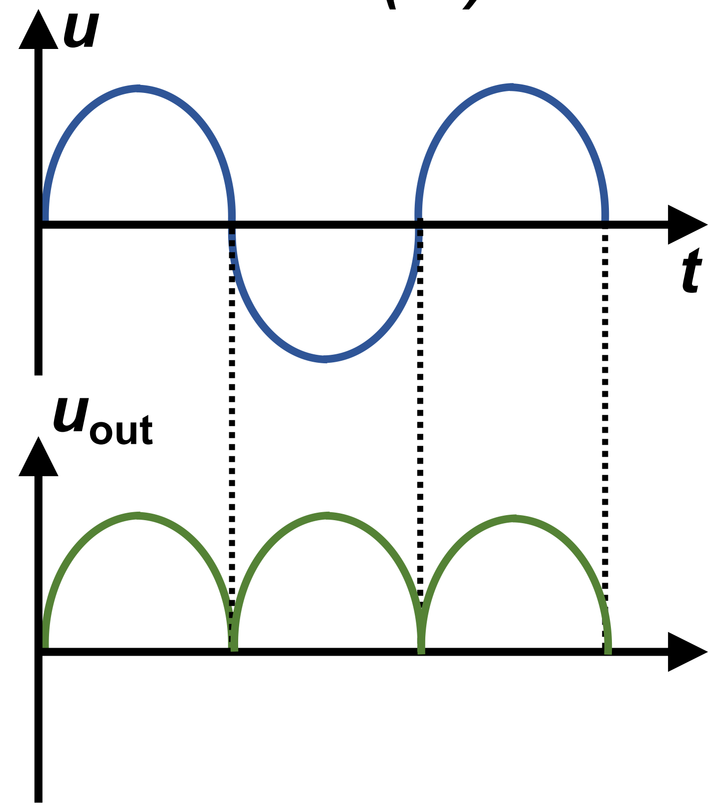
$u = A\sin(\omega t)$



Full-wave rectification全波整流



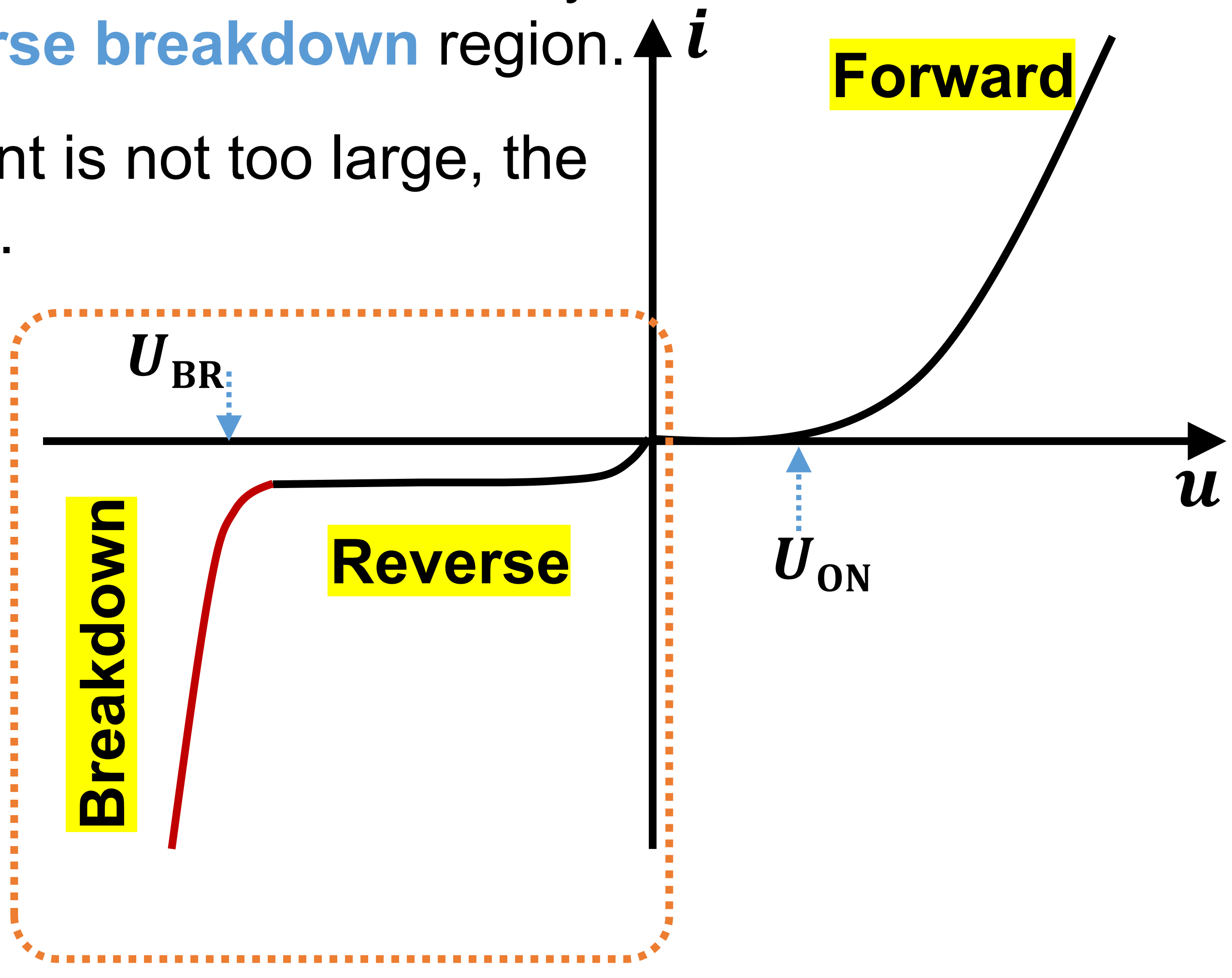
Input AC voltage signal:
$u=A\sin(\omega t)$



5.5 Revers breakdown in PN junction

$|u| > |U_{BR}|$， current increases dramatically and enter the **reverse breakdown** region.

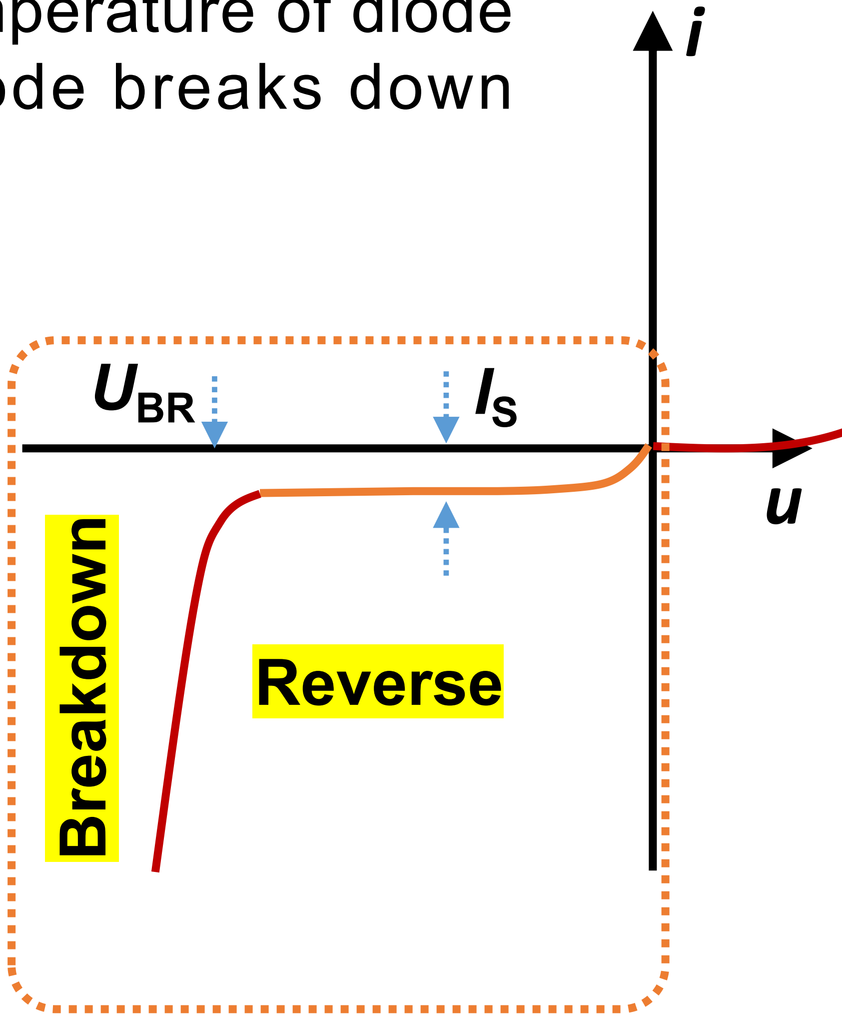
If the reverse current is not too large, the diode can still work.



Reverse breakdown

If the current is too large, the temperature of diode increases significantly, and diode breaks down permanently.

Diode	Breakdown temperature
Si	150~200 °C
Ge	75~100 °C

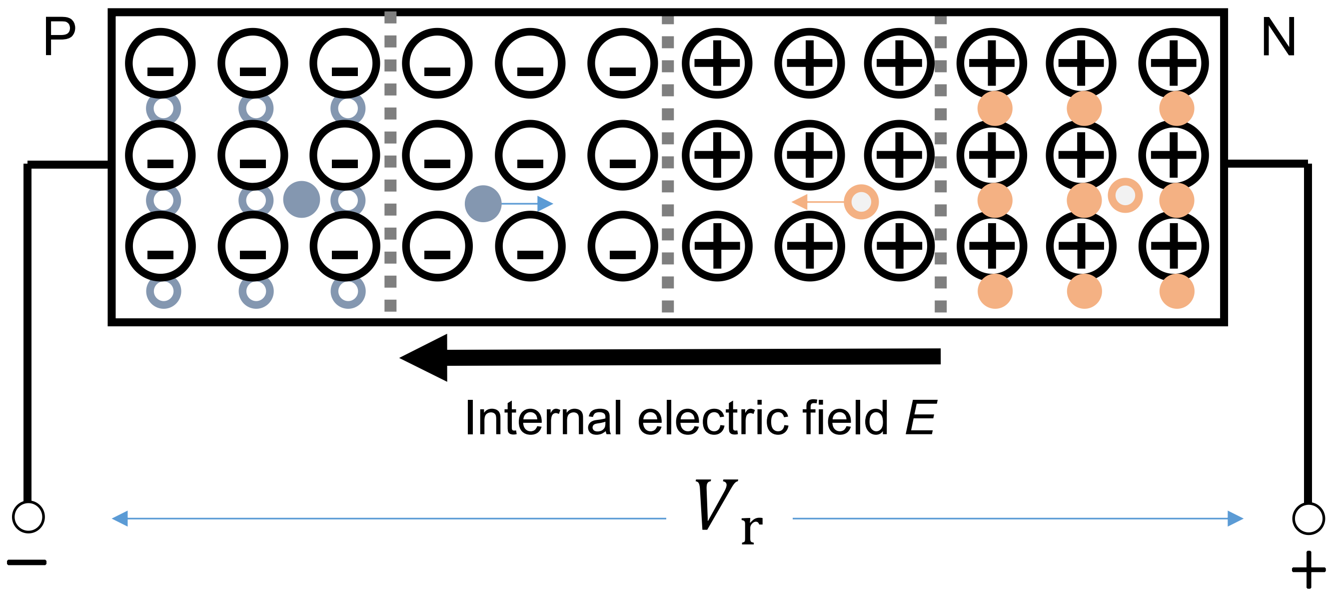


Breakdown mechanism:

Avalanche breakdown雪崩击穿

Zener breakdown齐纳击穿

Avalanche breakdown雪崩击穿



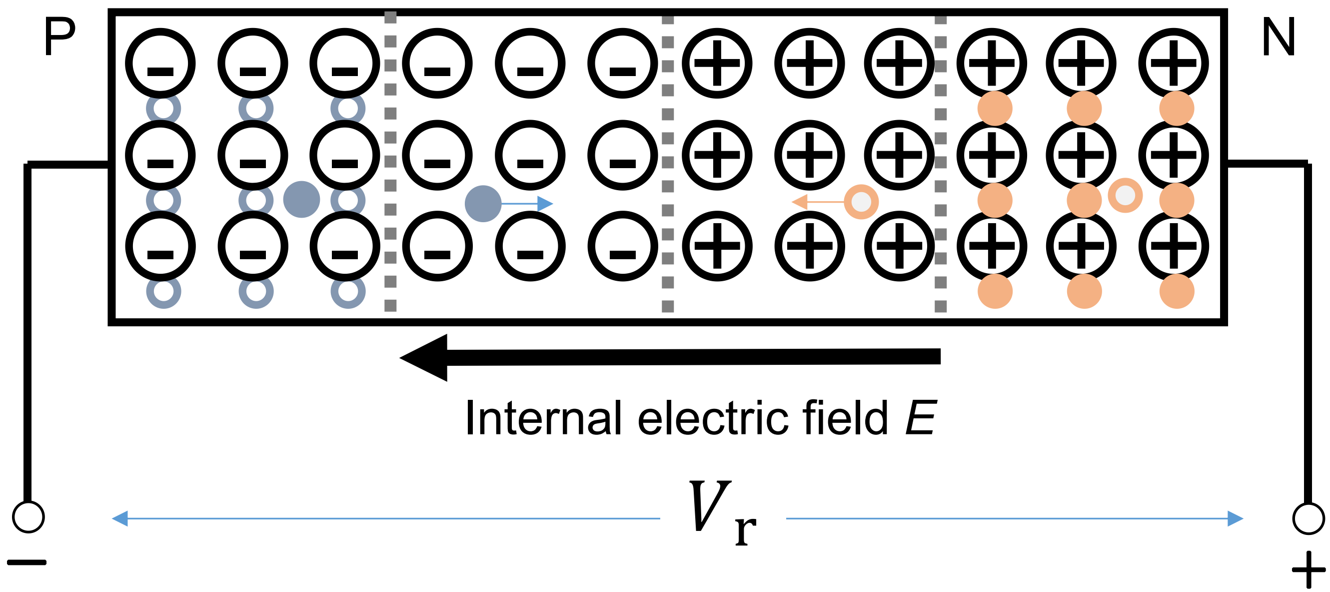
When $|u| > |U_{BR}|$, *E* is large.

Minor carriers are accelerated to a very high speed and energy.

Accelerated electrons will collide with bonded electrons and kick them out.

More and more carriers are generated and current increases dramatically!

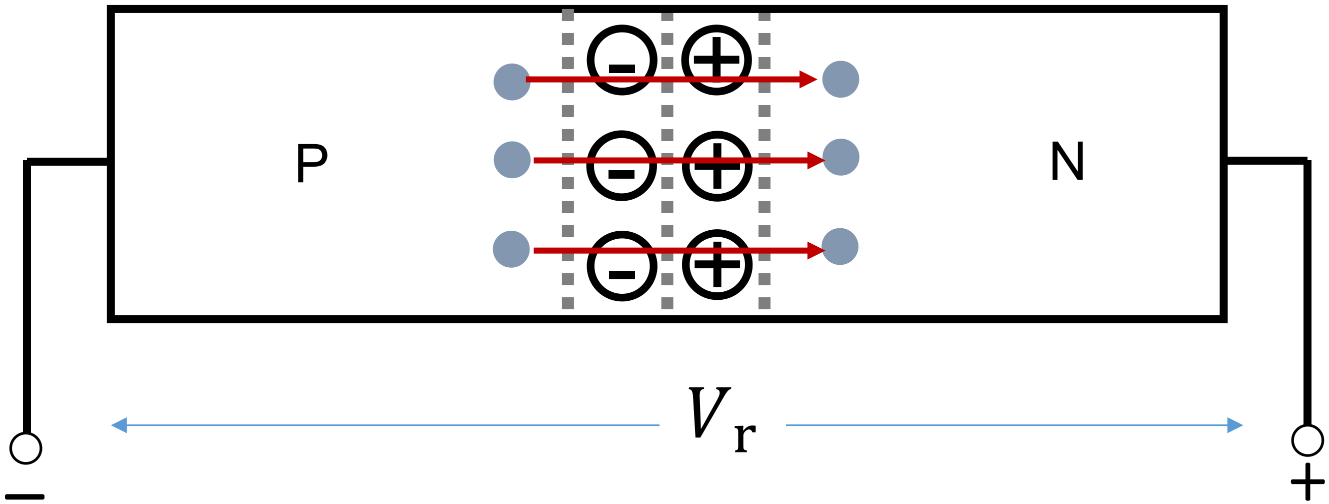
Avalanche breakdown雪崩击穿



The condition for observing the avalanche breakdown:

- Depletion region is wide
- Low doping concentration

Zener breakdown 齐纳击穿

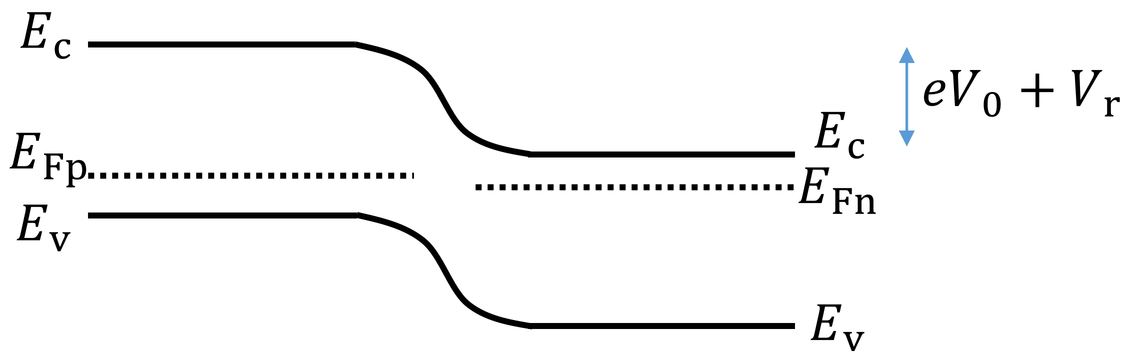


Electrons directly tunnels from P to N region.

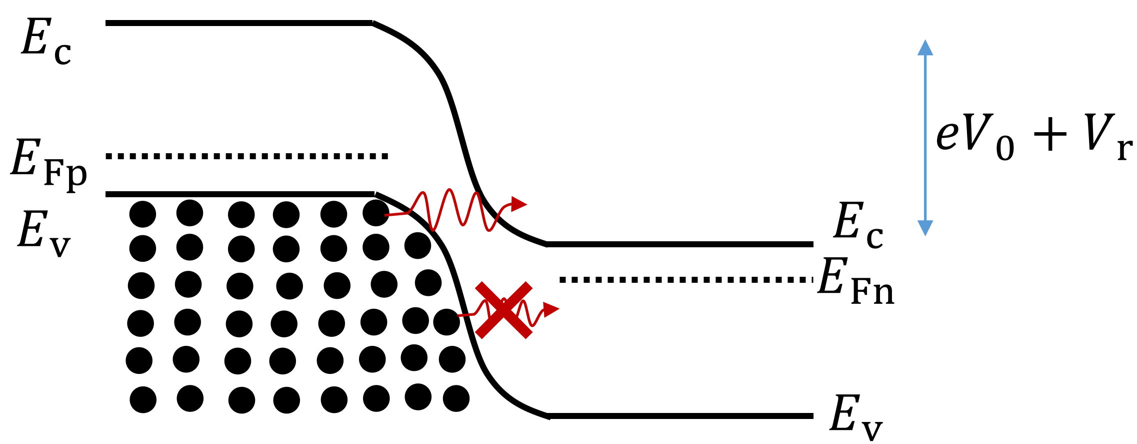
- Depletion region is thin
- High doping concentration

Zener breakdown 齐纳击穿

V_r is small

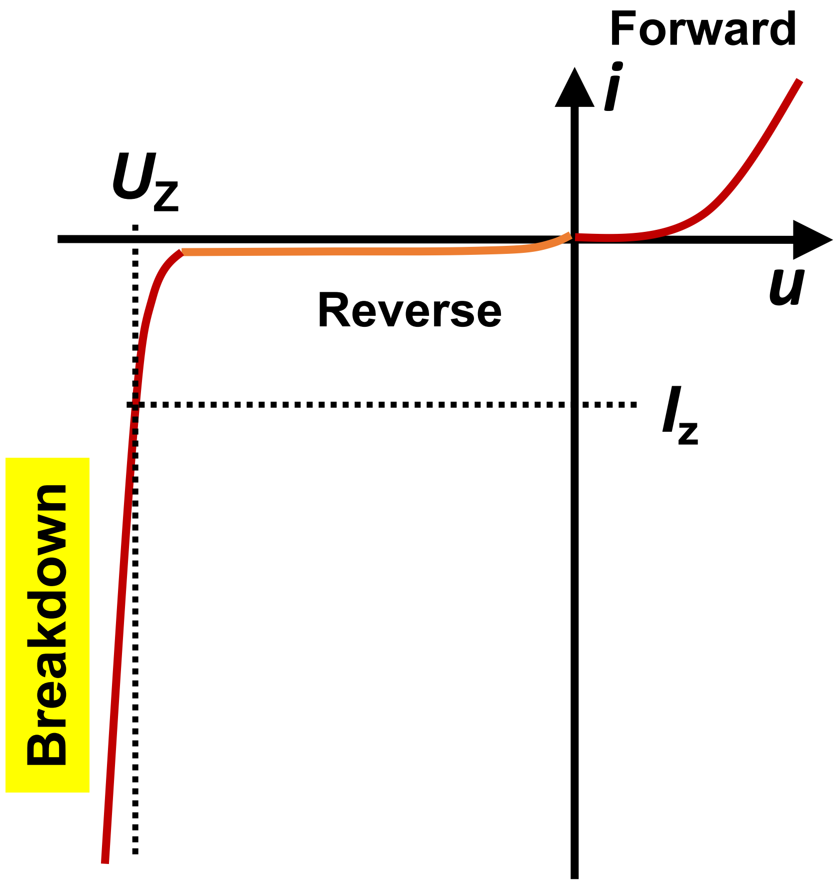


V_r is large enough



Electrons in valence band of P-type semiconductor can directly tunnel into the conduction band of N-type semiconductor.

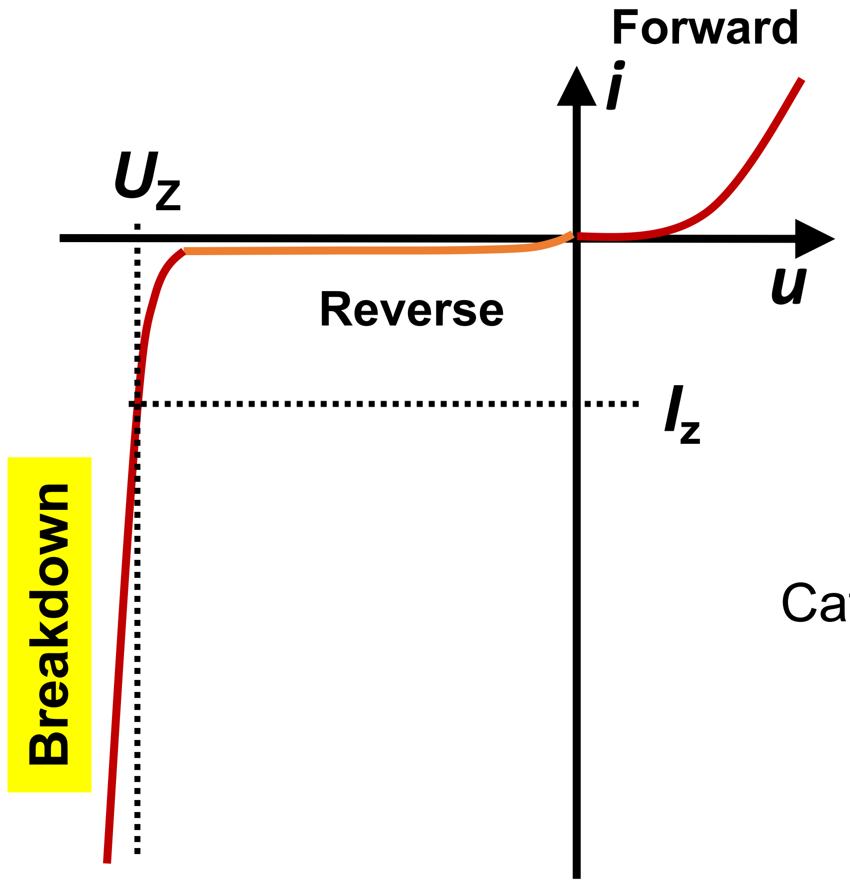
Voltage regulator diode 稳压二极管



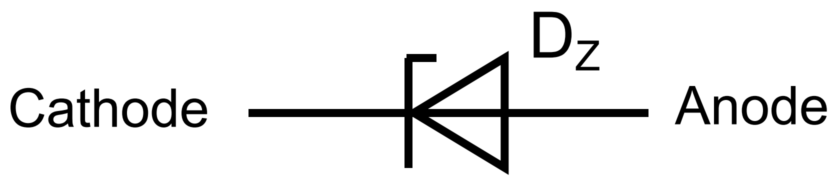
Working principle：

I-V curve in **breakdown** region is very steep, which is almost parallel to y-axis.

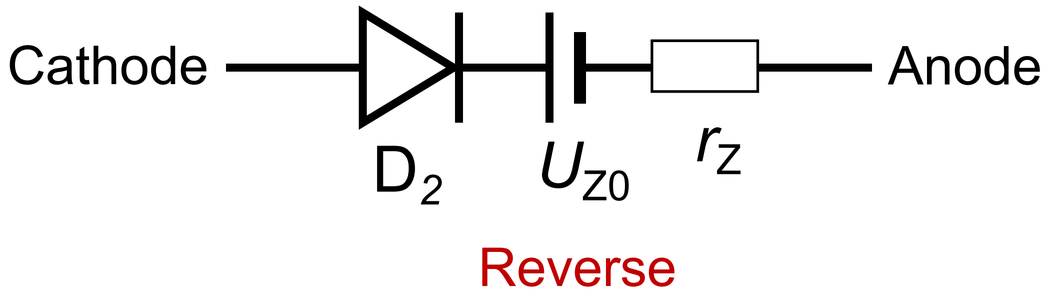
The reverse current change significantly, while the voltage is almost a constant. Hence it can stabilize the voltage.



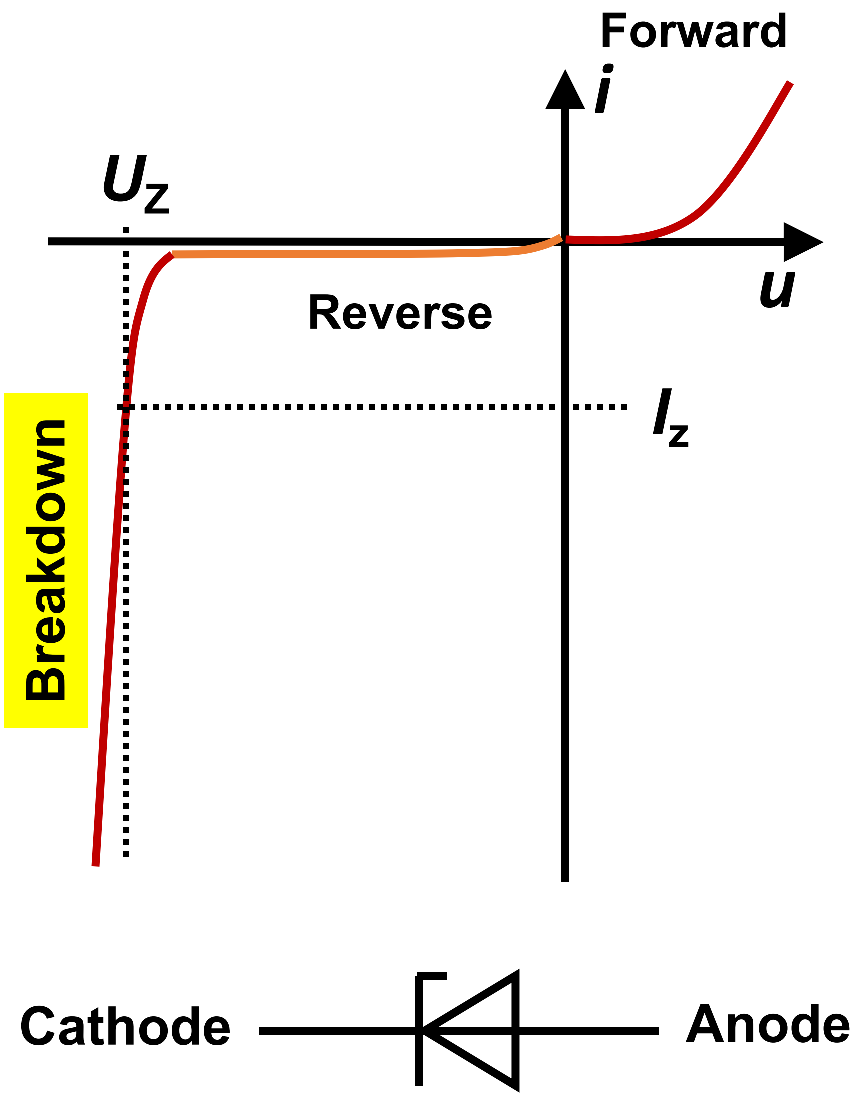
Symbol of voltage regulator diode:



Equivalent circuit



For ideal regulator diode: r_Z=0



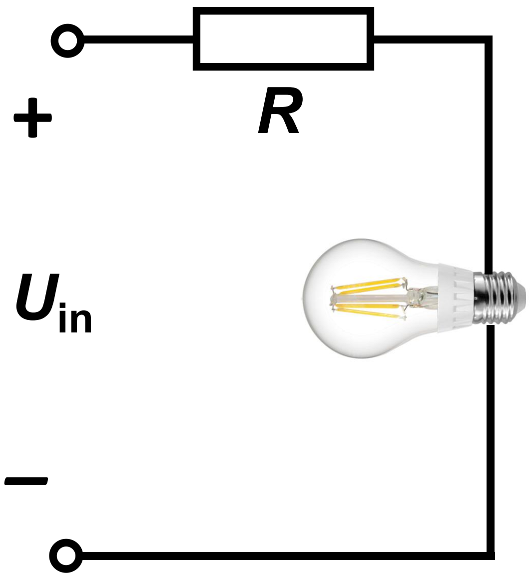
Key parameters:

1. Working current I_Z: $I_{zmax} > I_Z > I_{zmin}$. Larger than I_{zmax}: device breakdown permanently. Smaller than I_{zmin}, the voltage stabilization effect becomes worse.

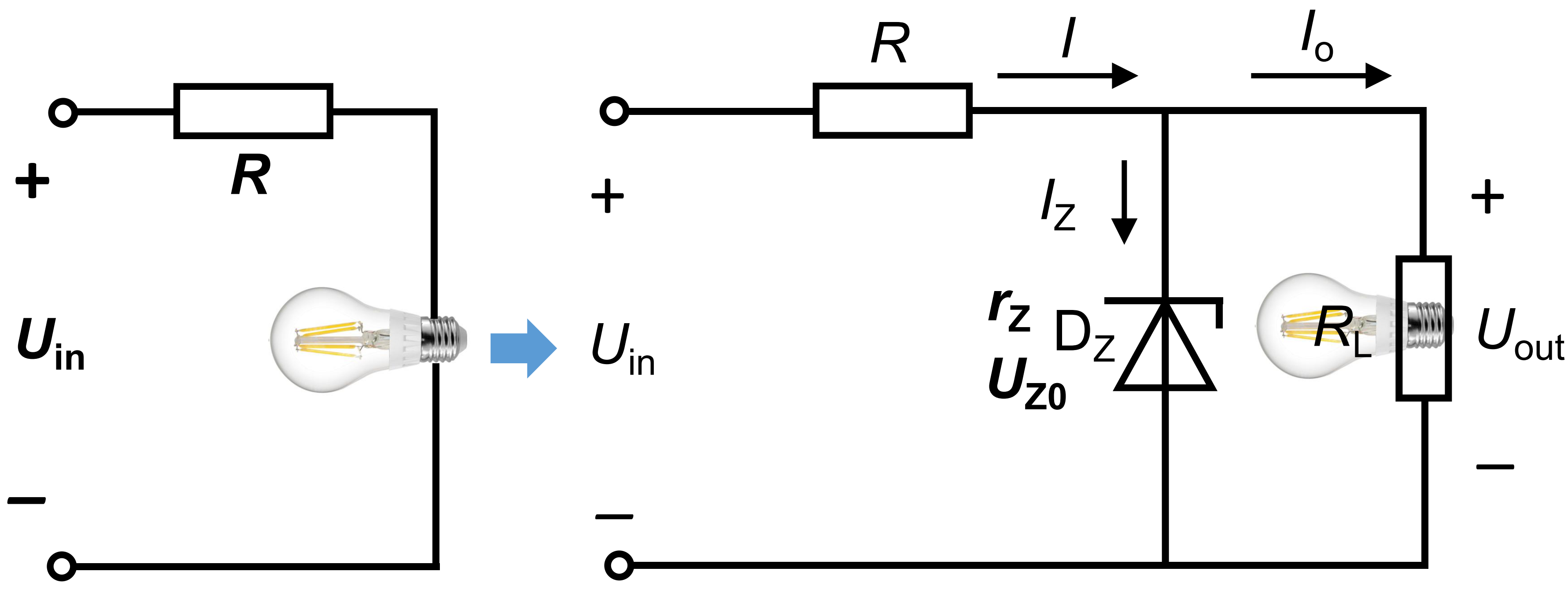
2. Working voltage U_Z: almost a constant

3. Dynamic resistance r_Z: Smaller r_z, better performance

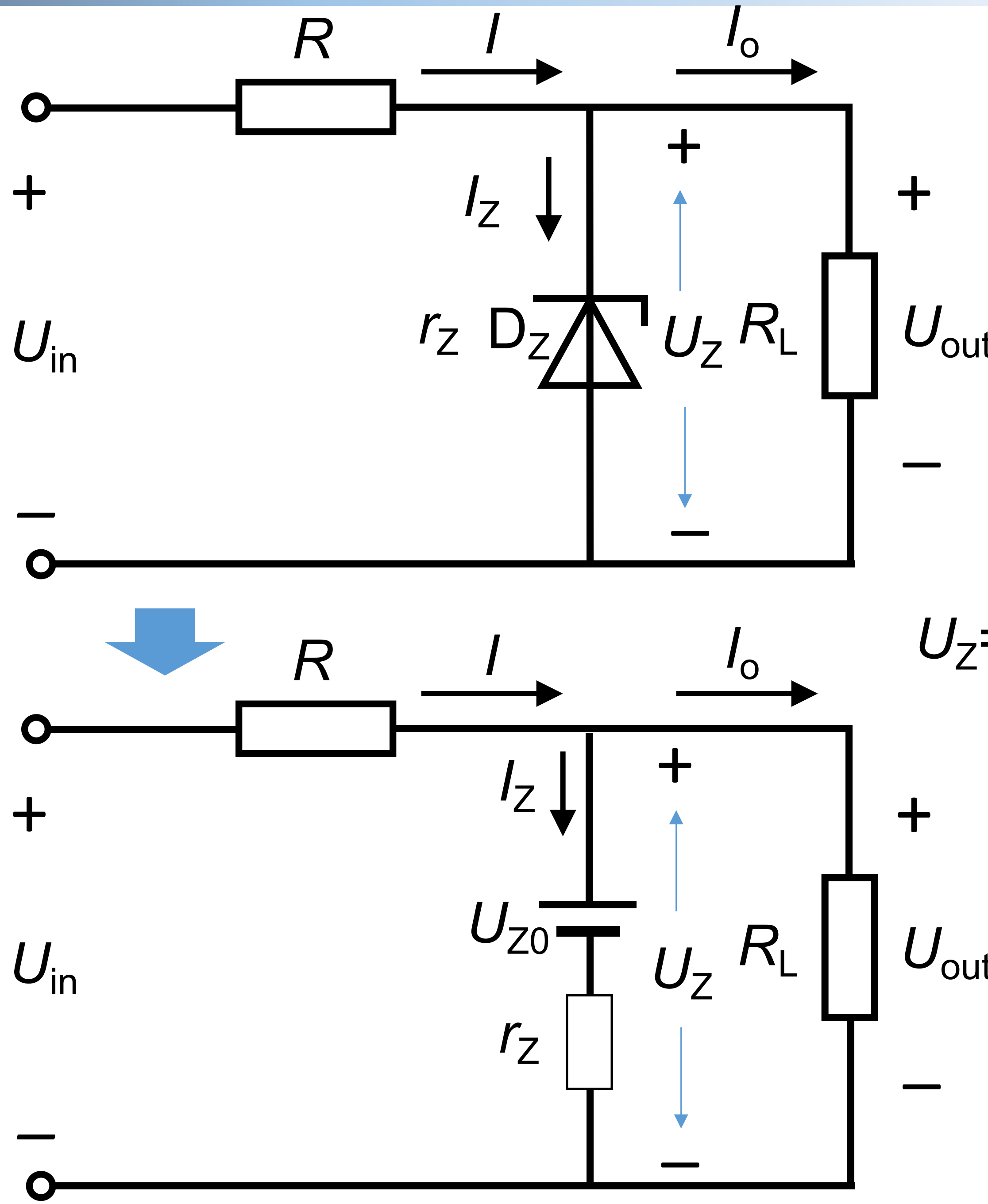
Working principle



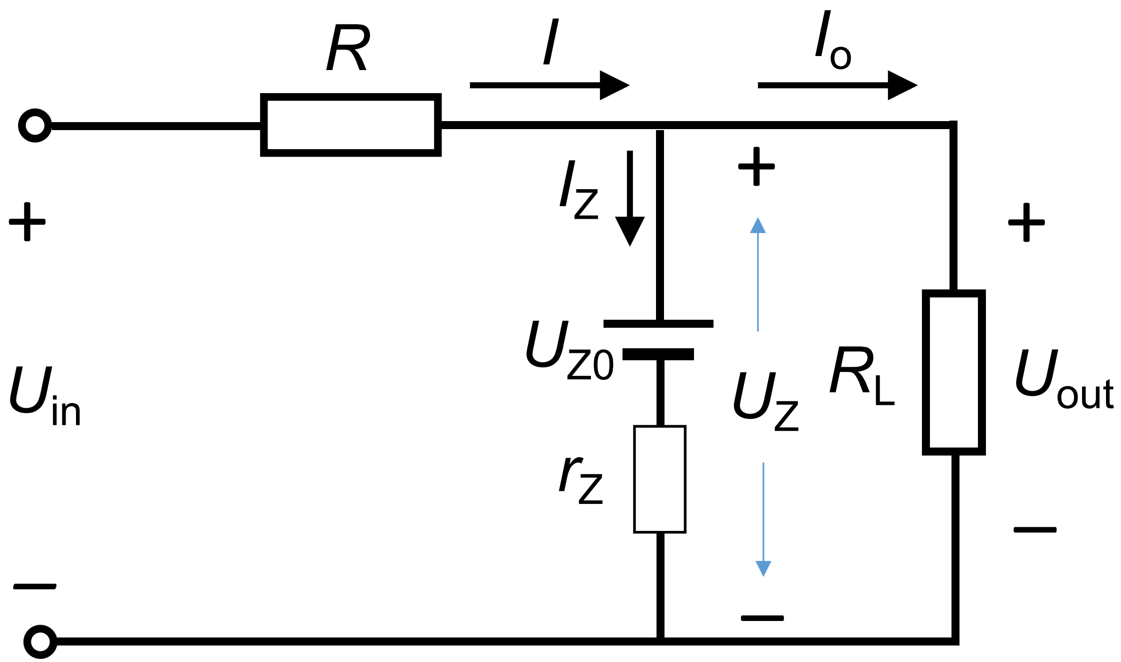
Q: Input voltage U_{in} is unstable, and the bulb is flickering. How to resolve the problem？



R
+
U_{in}
−
R
I
I_o
+
I_Z
r_Z
D_Z
U_{Z0}
U_{in}
R_L
U_{out}
+
−
−



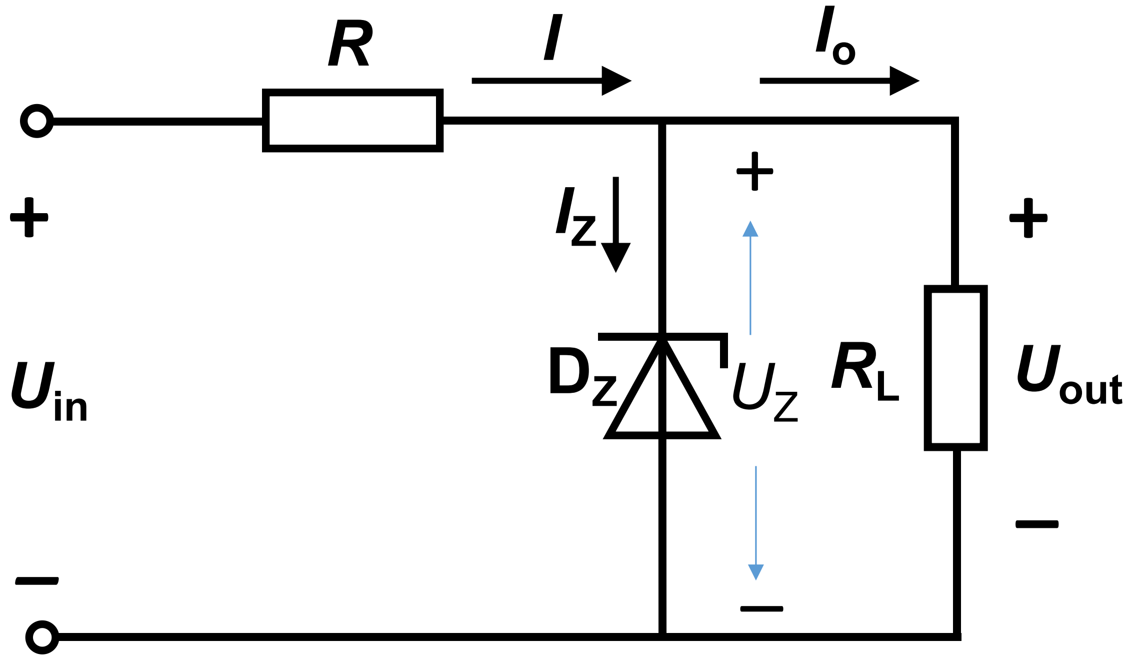
$$U_Z = U_{Z0} + I_Z r_Z$$



For ideal regulator diode, r_Z=0

$$U_{out}=U_{Z0}$$

U_{in} unstable



$U_{in}\uparrow \Rightarrow U_{out}\uparrow \Rightarrow U_Z\uparrow \Rightarrow I_Z\uparrow\uparrow\uparrow \Rightarrow I\uparrow\uparrow\uparrow$

$\Downarrow$

$U_{out}= U_{in}-IR\downarrow \Leftarrow I\,R\uparrow\uparrow\uparrow$