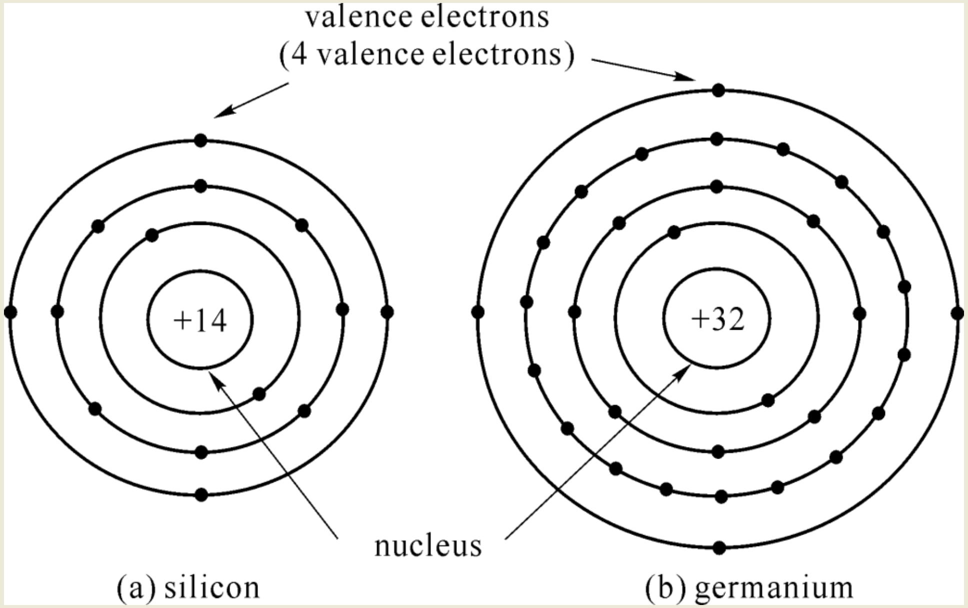
Chapter 1:
Semiconductor Basis and Diodes

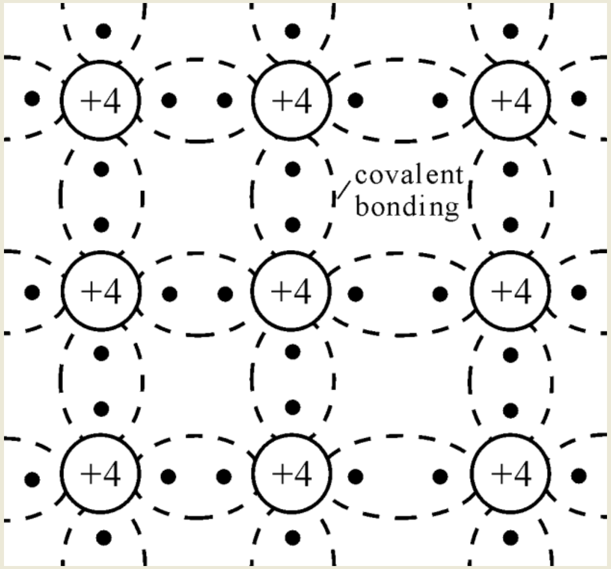
1.1 Principles of Semiconductors

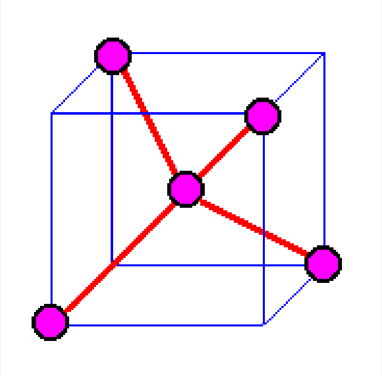
Common materials used in the development of semiconductor devices:

- ***Silicon (Si)***
- ***Germanium (Ge)***
- ***GaAs***
- ***GaN, SiC …***



Covalent bonding of the silicon atom.

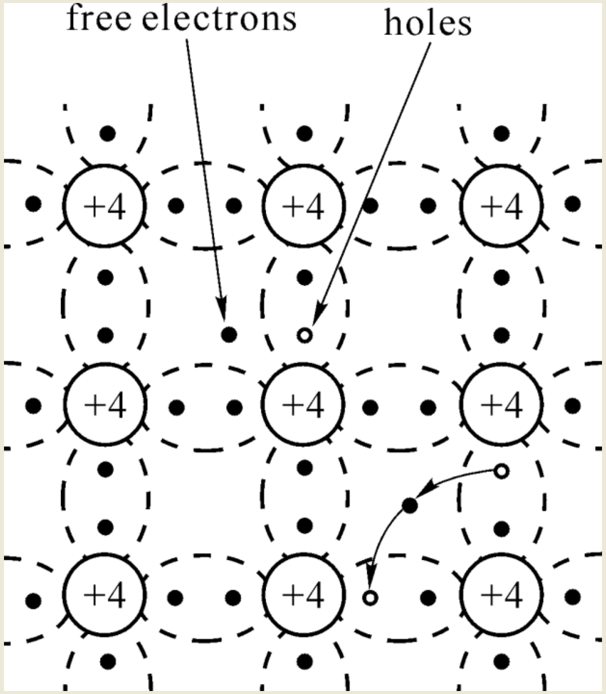




1.1.1 Intrinsic Semiconductors

- **Intrinsic semiconductor**: The single-crystal formed by pure semiconductor materials
- **Holes**: Vacancies in the covalent bond
- **Electron-hole pairs**: a free electron and a hole is generated from the covalent bond by thermal energy
- The free electrons and holes in a material only due to external causes are referred to as **intrinsic carriers**
- Two types of **charged particles (Intrinsic carriers) in a semiconductor**
  - **Free electrons** n_i
  - **Holes** p_i

$$n_i = p_i$$



Semiconductor	Intrinsic Carriers (/cm³) @ room T.
GaAs	1.7×10^{6}
Si	1.5×10^{10}
Ge	1.7×10^{13}

$$T \uparrow \Rightarrow n_i \uparrow \; p_i \uparrow$$

Semiconductor materials have a Negative Temperature Coefficient

1.1.1 Intrinsic Semiconductors

- **Movement of Free electrons**: move by itself
- **Movement of Holes**: by movement of covalent electrons from adjacent covalent bonds
- **Electrical conductivity** of intrinsic semiconductors is determined by the concentration of free electrons and holes

空穴的运动：空穴的运动是通过相邻共价键中的共价电子的移动来实现的。

本征半导体的电导率：本征半导体的电导率由自由电子和空穴的浓度决定。当一个电子从价带跃迁到导带时，它在价带中留下一个空穴。空穴的移动实际上是相邻的共价电子通过跃迁来填补这些空穴，从而表现为空穴的运动。电导率因此取决于电子和空穴的浓度，且随着温度的升高，载流子的数量会增加，电导率也随之增大。

1.1.2 Extrinsic Semiconductors: N type and P type

The electrical characteristics of intrinsic semiconductors are improved by adding ***impurity materials*** in a process called ***doping***.

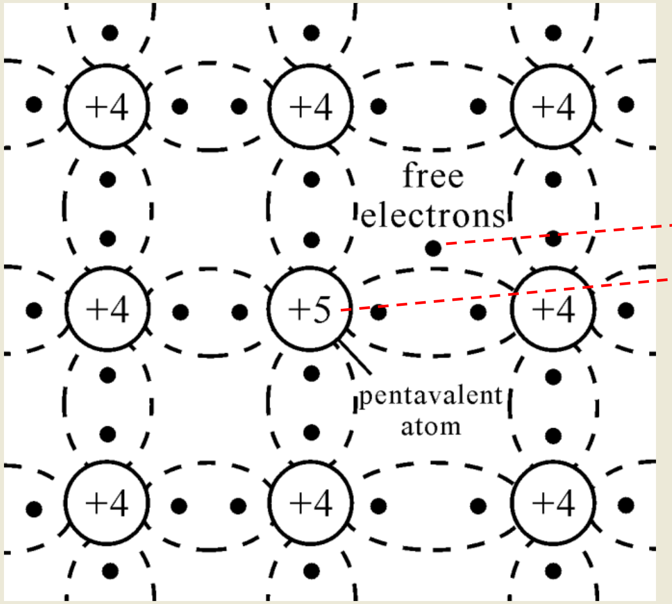
The materials containing ***impurity atoms*** are called ***extrinsic semiconductors***, or ***doped semiconductors***.

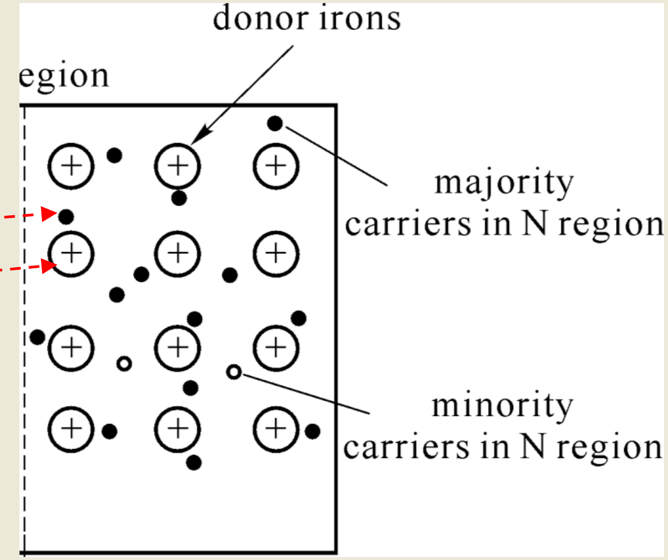
There are just two types of doped semiconductor materials:

- **N type:** impurities are from group **V** elements, e.x. *Phosphorus*
- **P type:** impurities are from group **III** elements, e.x. *Boron*

(1) N type Semiconductors and Carriers

- A semiconductor that contains donor impurity atoms is called a ***N type*** semiconductor.
- Impurities in *N type* materials act as **Donor.** N_D
- The **minority carriers** in N type materials are holes. $p = p_i$
- The **majority carriers** in N type materials are free electrons. $n = n_i + N_D = p + N_D$



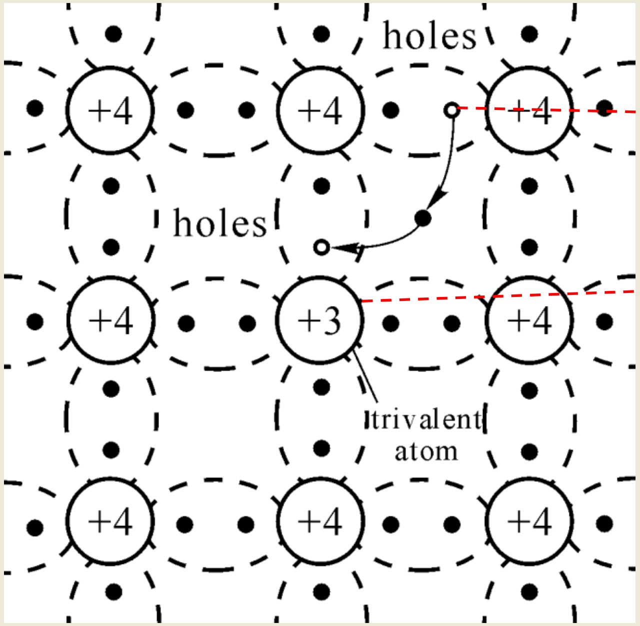


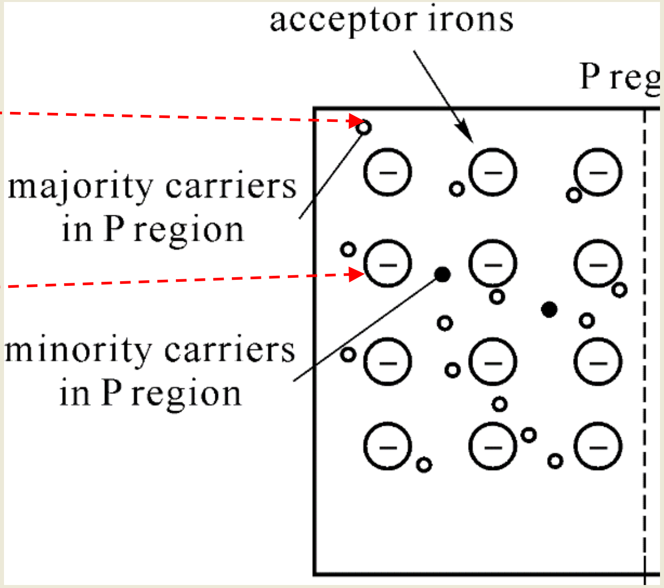
N typte Semiconductor

(2) P type Semiconductors and Carriers

- A semiconductor that contains acceptor impurity atoms is called a ***P type*** semiconductor.
- Impurities in P type materials act as **Acceptor.** N_A
- The **minority carriers** in P type materials are free electrons. $n = n_i$
- The **majority carriers** in P type materials are holes.

$$p = p_i + N_A = n + N_A$$

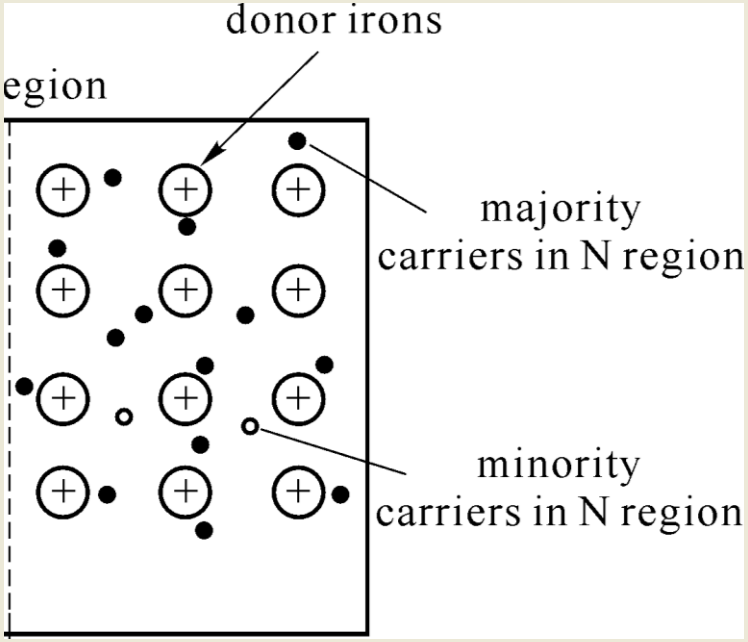


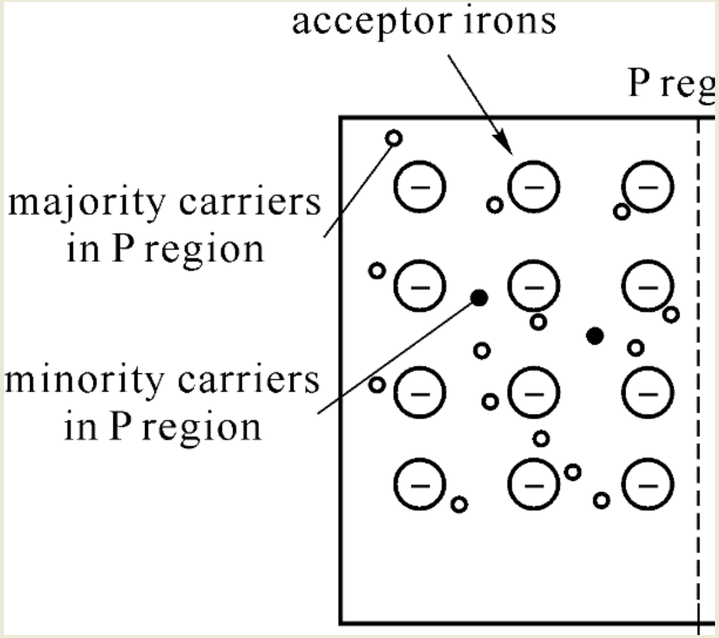


P-type Semiconductor

intrinsic semiconductor ⟶ **doping**

N type ⟵ **extrinsic semiconductor** ⟶ **P type**





$$n = p + N_D \qquad\qquad p = n + N_A$$

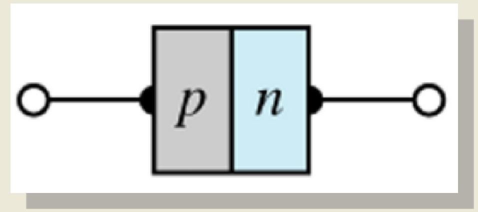
mass-action law: $np = n_i p_i$ **or** $np = n_i^2$

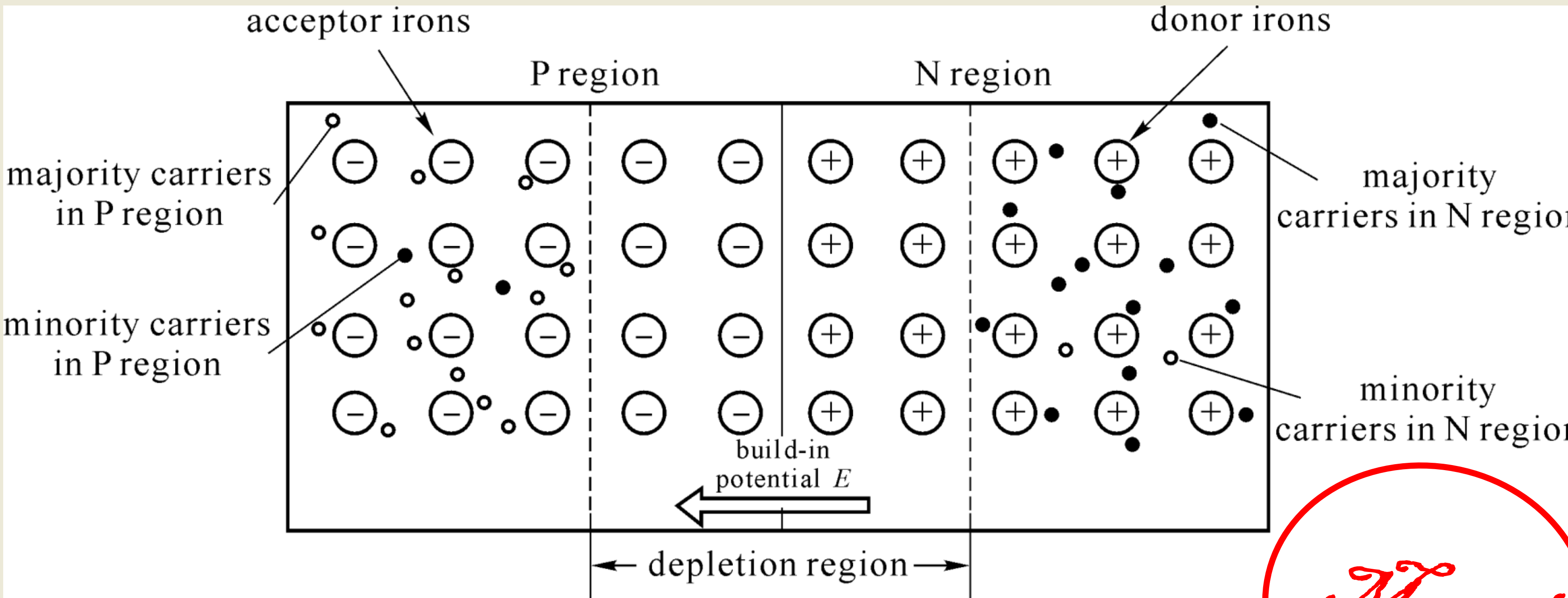
	N type semiconductor	P type semiconductor
Majority carriers:	***Free electrons***	***Holes***
Minority carriers:	***Holes***	***Free electrons***

1.2 PN Junction

One end of a silicon or germanium crystal can be doped as a P type material and the other end as an N type material.

The result is a *PN Junction*.





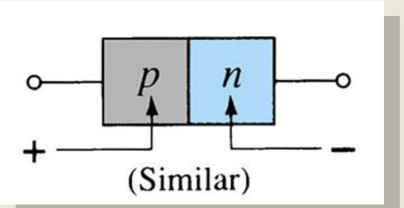
Key Point: **the formation process of the depletion region around the junction.**

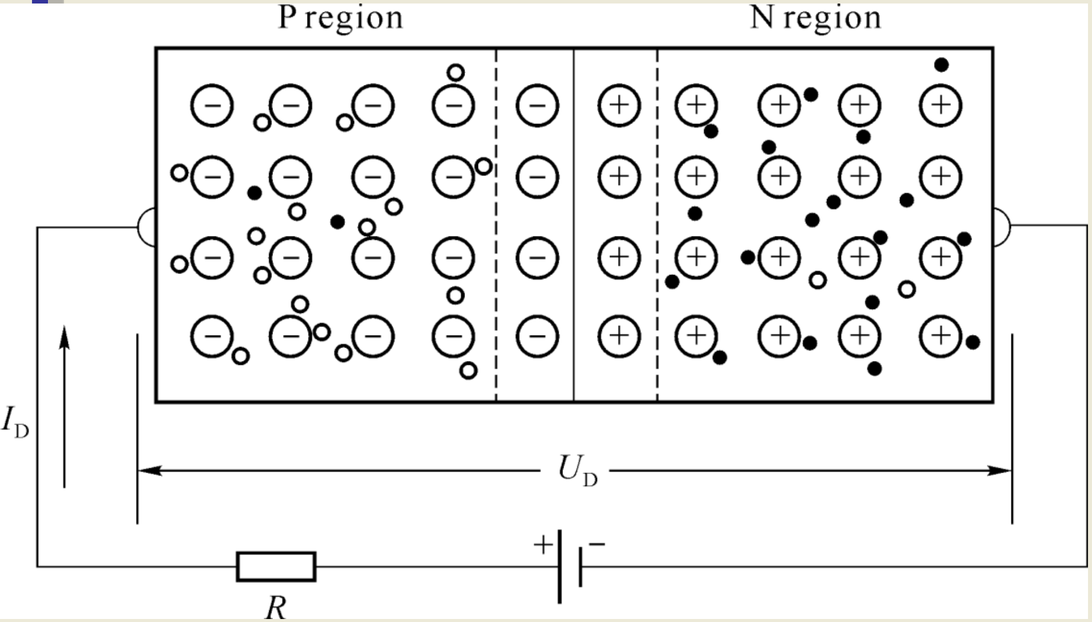
Magic!

(1) PN Junction Operating Conditions: *Forward Bias*

Forward Bias:

External voltage is applied across the PN junction with the positive polarity on the P side and the negative polarity on the N side.





- The forward voltage causes the depletion layer ***narrower***.
- The electrons and holes are pushed toward the PN junction.
- The electrons and holes have sufficient energy to cross the PN junction.

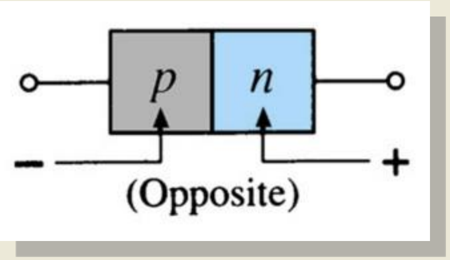
The forward bias voltage required:

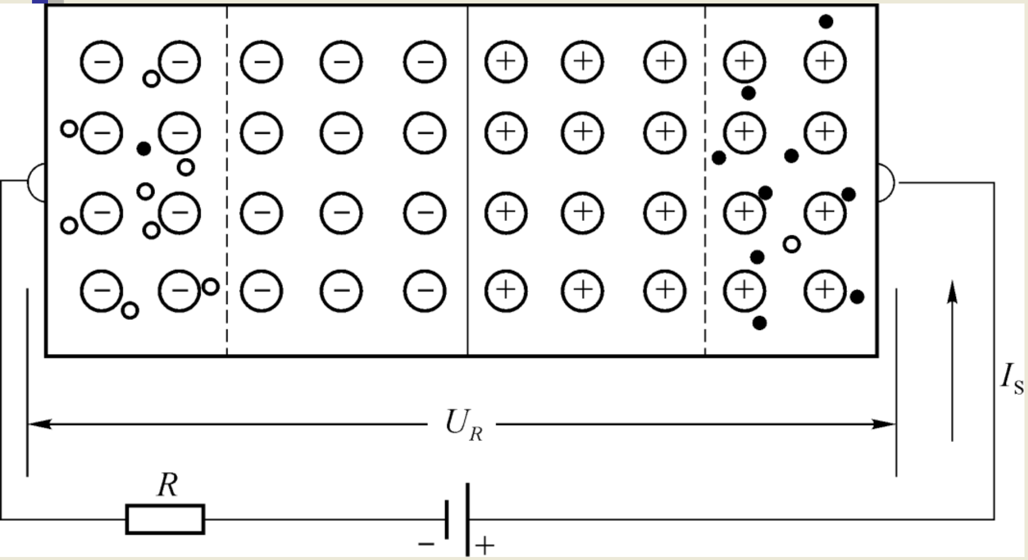
- ***Silicon: $U_D \approx 0.7V$***
- ***Germanium: $U_D \approx 0.3V$***

(2) PN Junction Operating Conditions: *Reverse Bias*

Reverse Bias:

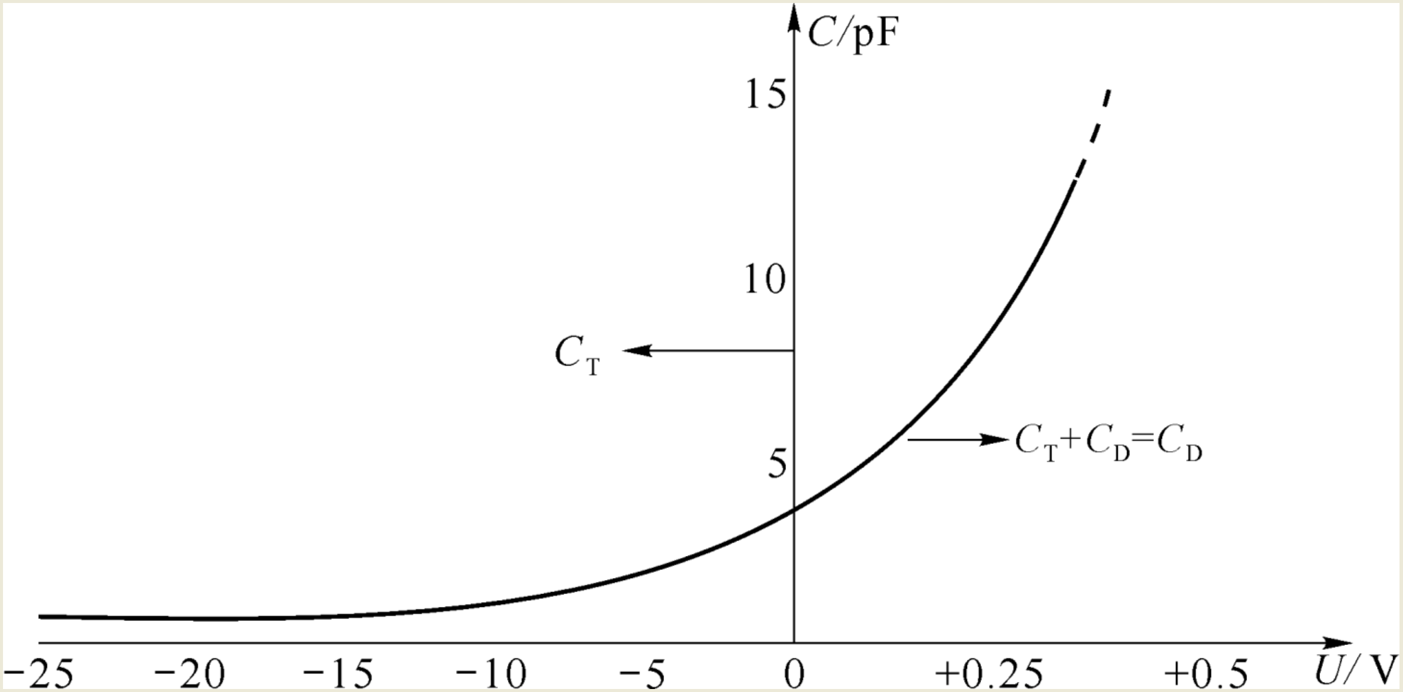
External voltage is applied across the PN junction with the positive polarity on the N side and the negative polarity on the P side.

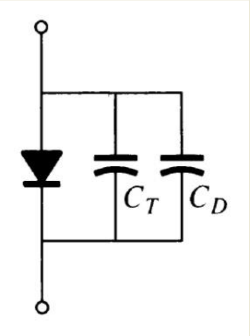




- The reverse voltage causes the depletion layer ***wider***.
- The electrons in the N type material are attracted toward the positive terminal.
- The holes in the P type material are attracted toward the negative terminal.

(3) Capacitance of the PN junction





In reverse bias, the depletion layer is very large. The diode's strong positive and negative polarities create transition- or depletion-region capacitance, C_T. The amount of capacitance depends on the reverse voltage applied.

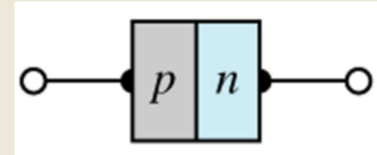
In forward bias diffusion capacitance (C_D) exists besides barrier capacitance as the voltage increases.

1.3 Semiconductor Diodes

Breakdown is harmful for diodes, but sometimes it can be utilized.

- Zener breakdown
- Avalanche breakdown

PN junction



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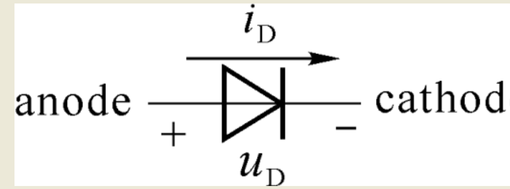
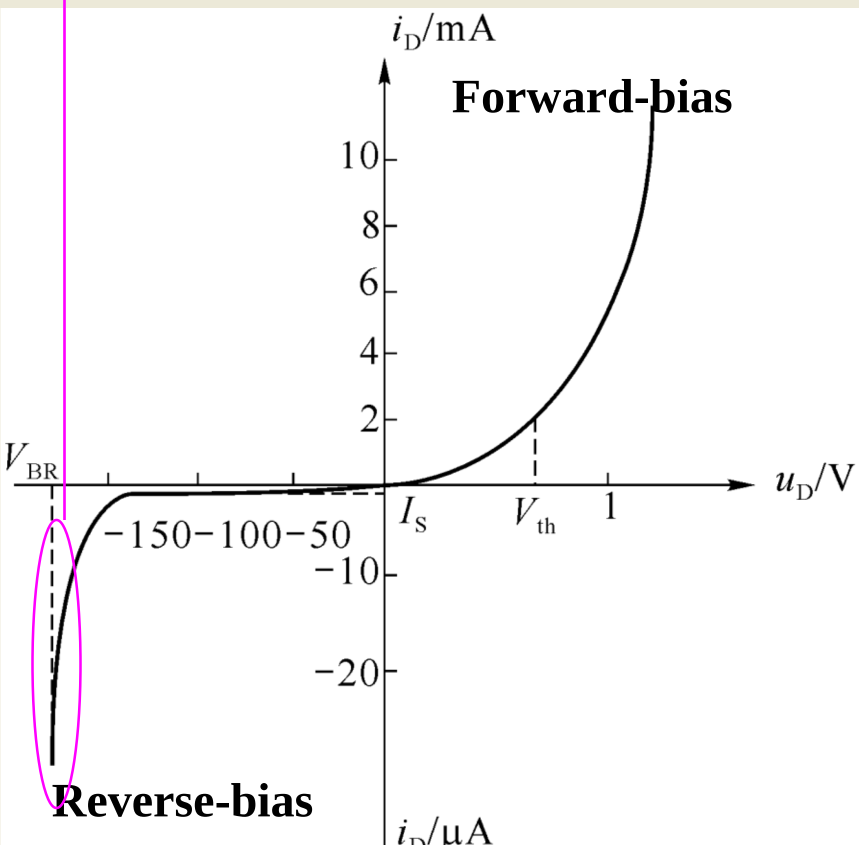
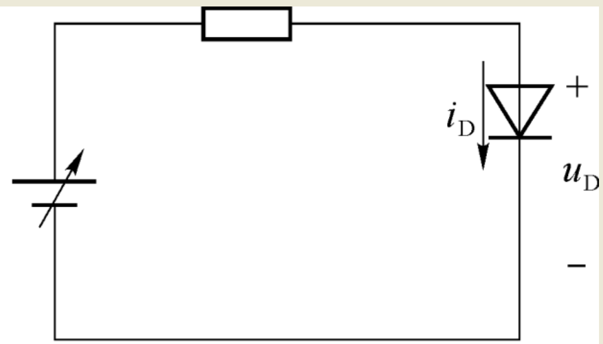
Diode







Forward-bias

$0 < u_D < V_{th}$: the diode is off

$u_D > V_{th}$: the diode is on

Reverse-bias

$-V_{BR} < u_D < 0$: the diode is off

$u_D < -V_{BR}$: the diode is breakdown

IV Characteristics and *Shockly* Equation of Diodes

Important Parameters of Diodes

- Forward rating current: I_F
- Peak Inverse Voltage (PIV): V_{BR}
- Reverse saturation current: I_S

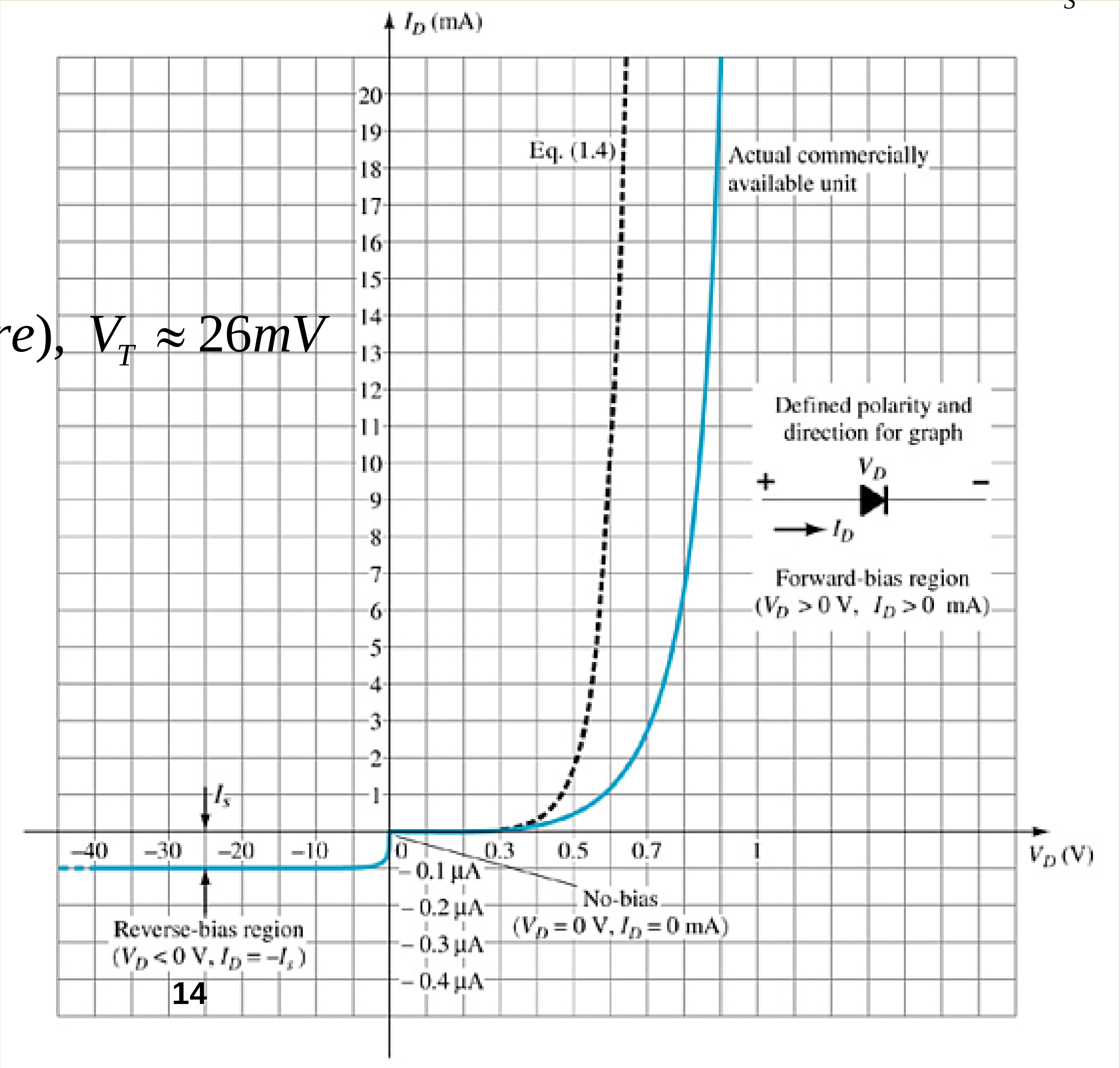
Shockley equation

$$i_D = I_S(e^{u_D/nV_T} - 1)$$

$$V_T = \frac{kT}{q} \quad \text{thermal voltage}$$

$$T = 300K \ (room\ temperature),\ V_T \approx 26mV$$

I_S reverse saturation current



$$\text{Forward bias}: u_D >> V_T$$

$$i_D \approx I_S e^{u_D/V_T}$$

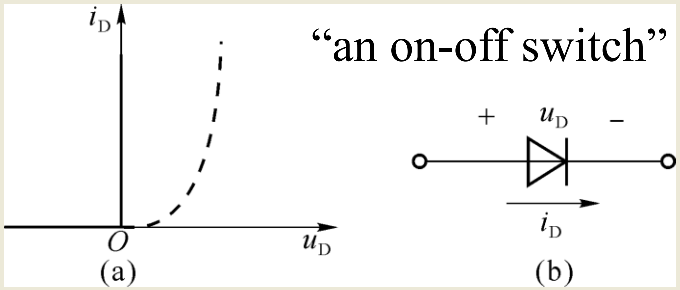
$$\text{Reverse bias}: u_D < 0$$

$$i_D \approx -I_S$$

1.3.2 Models of Diodes

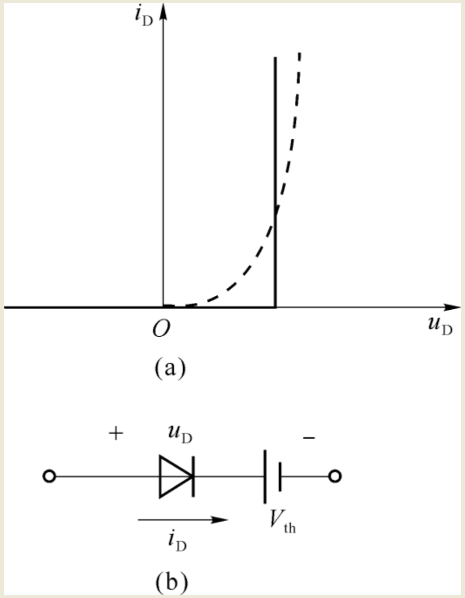
There are three types to model a diode:

(1) Ideal Model



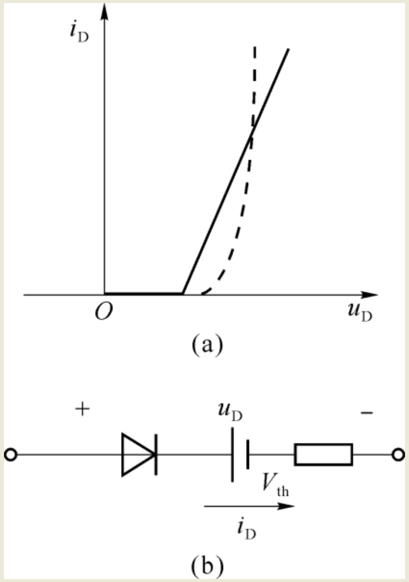
An ideal diode conduct in one direction

(2) Constant Voltage Drop Model



“an on-off switch with a forward voltage drop”

(3) Segment Linear Model



1.3.3 Equivalent Circuits of Diodes

Semiconductor diodes (/PN junction) act differently to DC and AC currents.

Different equivalent circuits to DC and AC signals are defined to simplify circuit analysis:

- **DC, or static, resistance**

$$R_D = \frac{U_Q}{I_Q}$$

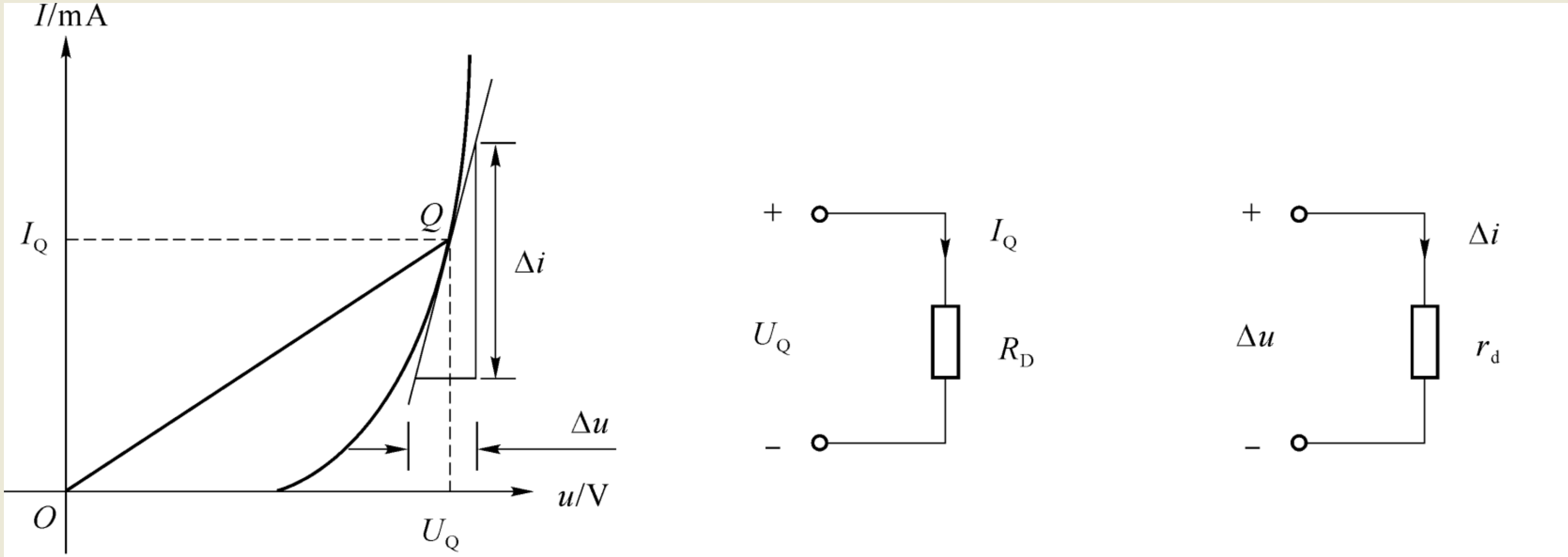
- **AC, or dynamic, resistance**

$$r_d = \left.\frac{\Delta u}{\Delta i}\right|_Q \approx \left.\frac{du}{di}\right|_Q$$

$$\text{Shockley equation}: i_D = I_S\left(e^{u_D/nV_T} - 1\right)$$

$$\frac{1}{r_d} = \left.\frac{di_D}{du_D}\right|_Q \approx \frac{I_Q}{V_T} \qquad r_d \approx \frac{V_T}{I_Q}$$

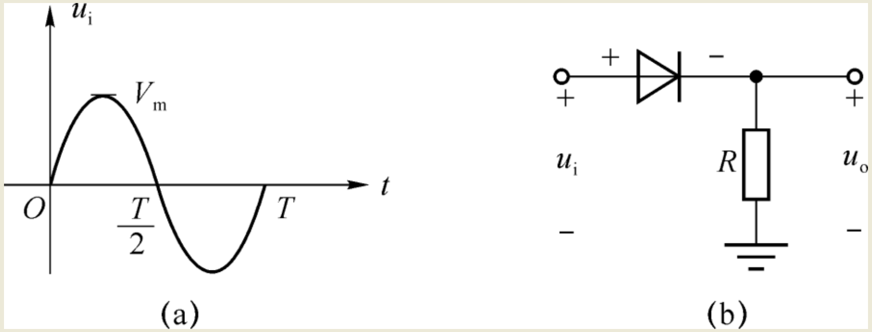
$$r_d \approx \frac{26\text{mV}}{I_Q}$$ (at room temperature)



(a) graphical method (b) DC equivalent resistance (c) AC equivalent resistance

Examples

Example1.3.1The circuit with an ideal diode is illustrated in Figure 1.3.7(b), where the input voltage u_i is shown in Figure 1.3.7(a). Sketch the output voltage u_o , and calculate the DC voltage V_{DC} from u_o. Determine the PIV of the diode.



(a) (b)

Solutions

$u_i > 0$ the diode is “on” and equivalent to “short”

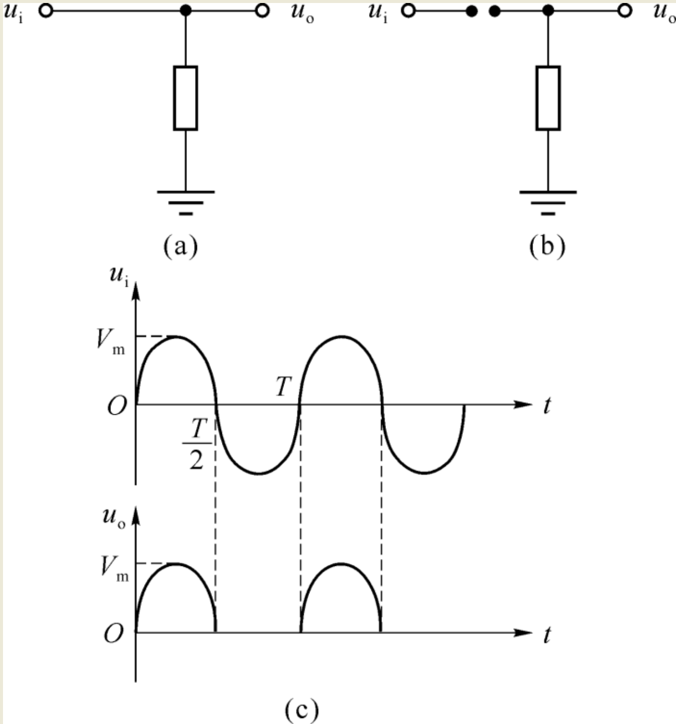
$u_o = u_i$

$u_i < 0$ the diode is “off” and equivalent to “open”

$u_o = 0$

$$V_{DC} = \frac{1}{T}\int_0^T v_0(t)dt = \frac{1}{2\pi}\int_0^{\pi} V_m \sin\theta d\theta = \frac{V_m}{\pi} \approx 0.318V_m$$

PIV> V_m

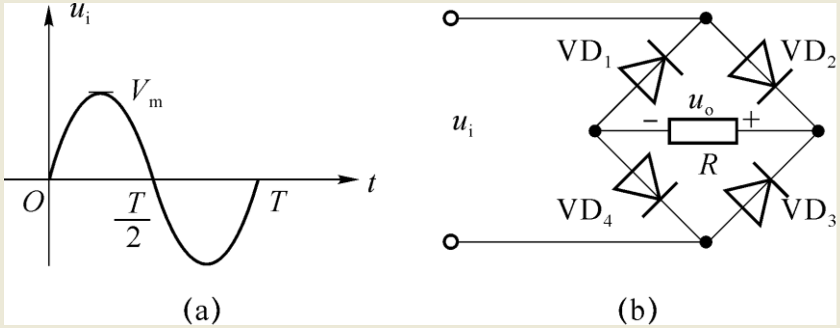


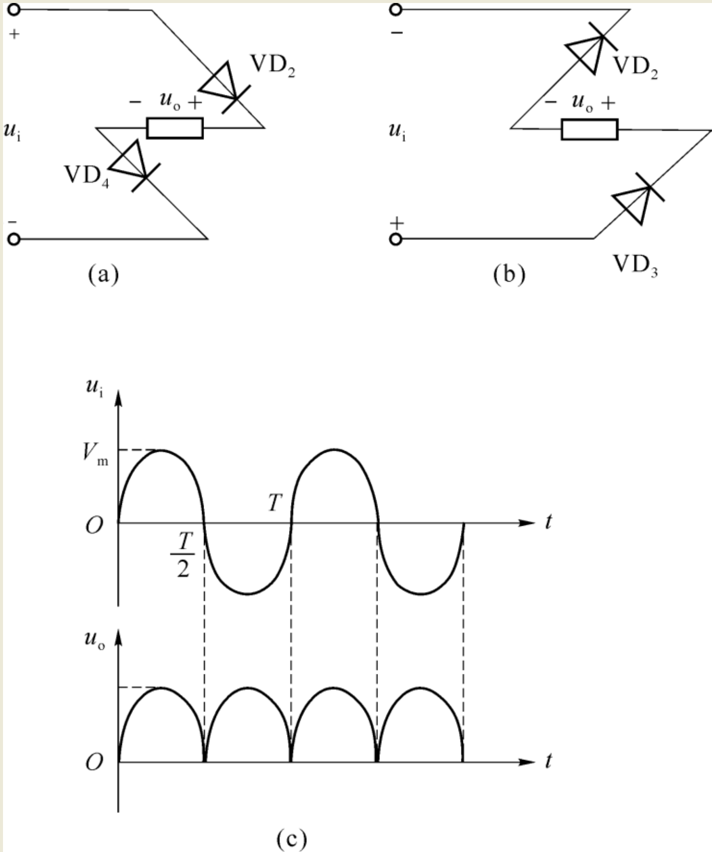
(a) (b)

(c)

Examples

Example1.3.2 The circuit with ideal diodes is shown in Figure 1.3.9(b) with an input voltage u_i shown in Figure 1.3.9(a). Sketch the output voltage u_o and calculate the DC component from u_o.





Solutions

$u_i > 0$ VD2 and VD4 are "on" and equivalent to "short"
VD1 and VD3 is "off" and equivalent to "open"

$$u_o = u_i$$

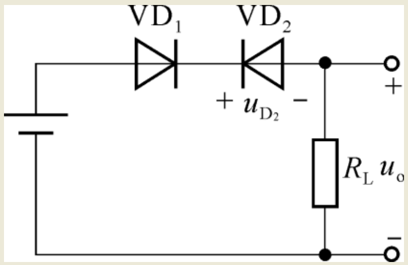
$u_i < 0$ VD1 and VD3 are "on" and equivalent to "short"
VD2 and VD4 is "off" and equivalent to "open"

$$u_o = -u_i$$

$$V_{DC} = \frac{1}{T}\int_0^T v_0(t)dt = \frac{2}{2\pi}\int_0^{\pi} V_m \sin\theta d\theta = \frac{2V_m}{\pi} \approx 0.636V_m$$

Examples

Example 1.3.3 A Diode circuit is illustrated in Figure 1.3.11. Diodes and are both ideal silicon diodes whose knee voltage could be omitted. Determine u_{D2} and u_o.



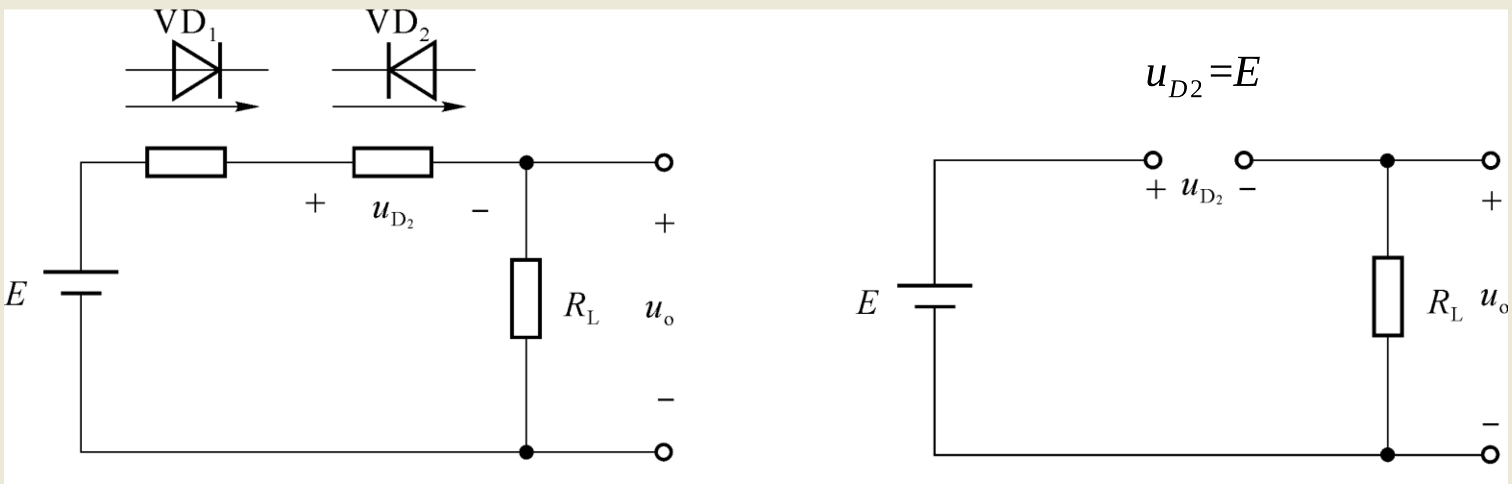
Analysis method:

Step 1. Make assumptions (‘short/on’ or ‘open/off’)

Step 2. Analysis/Check assumptions

Step 3. Make final decision

Solutions



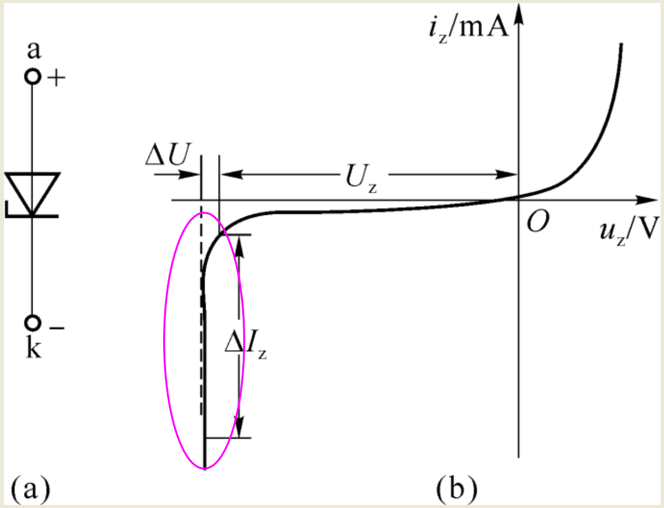
(a) (b)

$u_o = 0$

1.3.4 Zener Diodes

The Zener diode works in the diode's reverse-bias region/zener region.

At some point the zener voltage is so large the diode breaks down and the reverse current increases dramatically.



Main parameters:

Regulation voltage/zener voltage U_Z: The reverse breakdown voltage with a regulated current range.

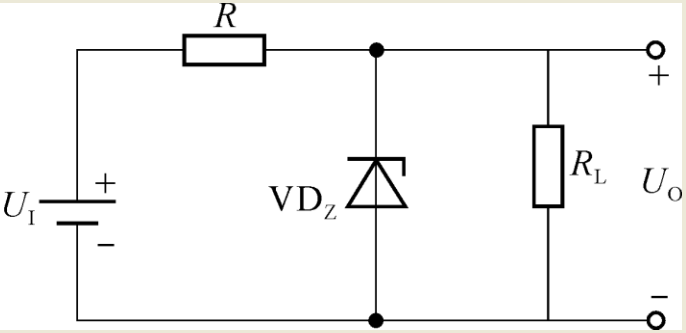
Regulation current I_Z : The reference current for a zener diode working in regulation region. A resistor R is commonly used in a zener diode circuit to limit the current swinging between $I_{Z\max}$ and $I_{Z\min}$

The maximum regulation current I_{ZM}

Dynamic resistance: $r_Z = \Delta U / \Delta I_Z$

Examples

Example 1.3.5 A voltage regulation circuit with a silicon zener diode is shown in Figure 1.3.14. The regulation voltage of the zener diode D_Z is denoted by U_Z. If the DC input voltage is U_I, discuss the output voltage U_o.



Solutions

Analysis methods:

Step1. Determine the state of the Zener diode by removing it from the network and calculating the voltage across the resulting open circuit.

Step2. Substitute the appropriate equivalent and solve for the desired unknowns.

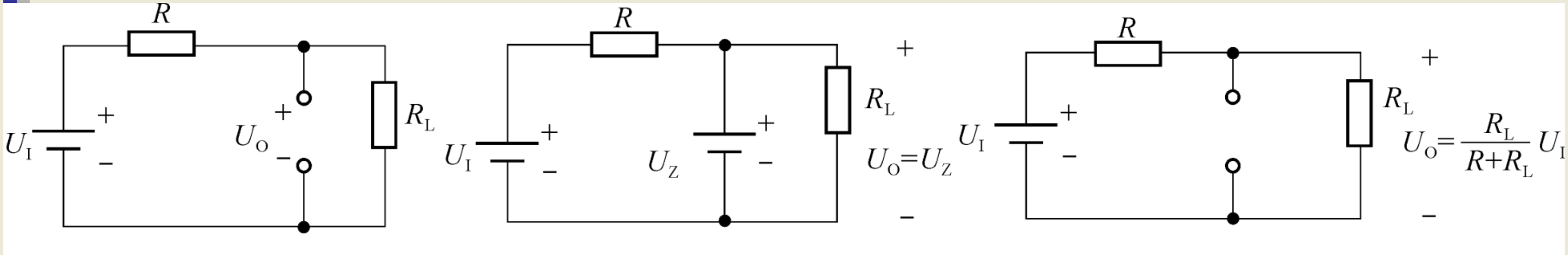
$$U'_O = \frac{R_L}{R+R_L} U_I$$

If $\frac{R_L}{R+R_L} U_I > U_Z$

Then, $U_O = U_Z$

If $0 < \frac{R_L}{R+R_L} U_I < U_Z$

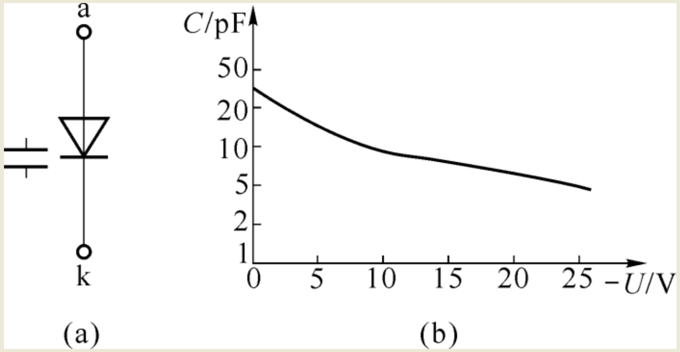
Then, $U_O = \frac{R_L}{R+R_L} U_I$



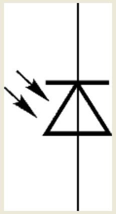
(a) (b) (c)

1.3.5 Some Other Types of Diodes

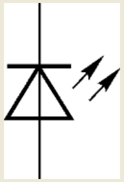
- **Varactor diode**



- **Photodiode**



- **Light-emitting diode (LED)**



Summary of Chapter 1

➢ **Key Items**

- **Semiconductor basis**
  - ***Carriers***
- **PN junction**
  - ***Construction of a PN junction***
  - ***Bias a PN junction (no bias/forward/reverse)***
- **Diodes**
  - ***Characteristics of a semiconductor diode (/PN junction)***

    - Electrical conduction in only one direction
  - ***DC resistance and AC resistance***
  - ***Equivalent circuits for a semiconductor diode***

Chapter 1

- **Weekly Assignments**
  - **Semiconductor**
    - **Problem 1.2**
    - **Problem 1.3**
  - **Diode**
    - **Problem 1.9**
    - **Problem 1.10**
  - **Zener Diode**
    - **Problem 1.14**
    - **Problem 1.15**