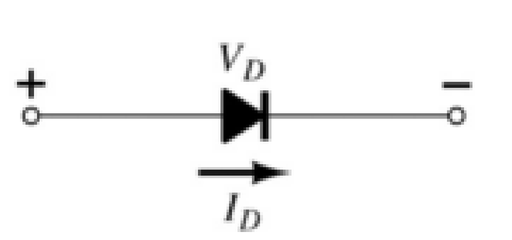
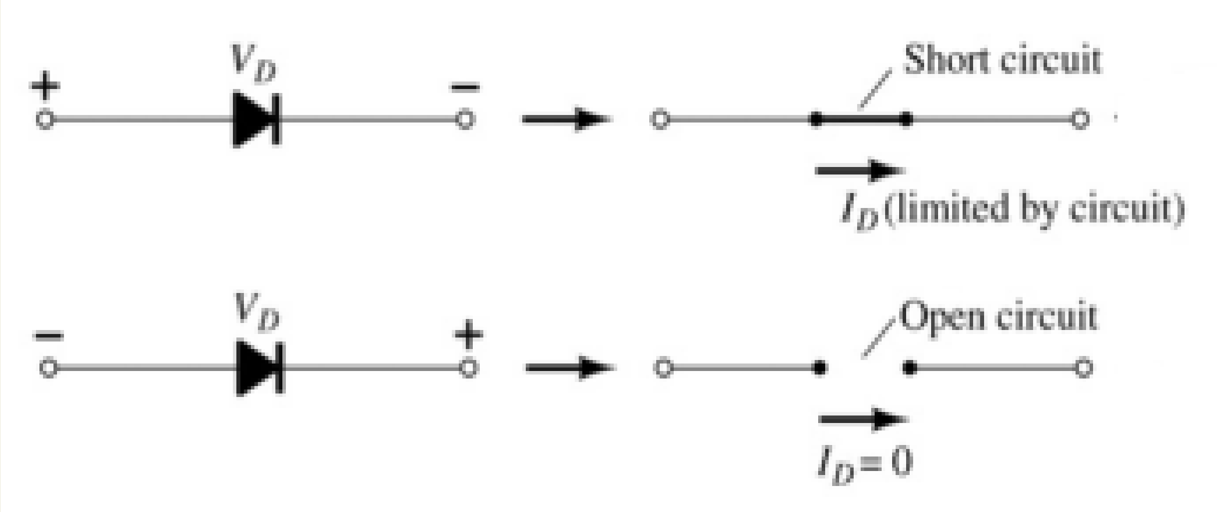
Chapter 1: Semiconductor Diodes

Diodes

A diode is a 2-terminal device.



A diode ideally conducts current in only one direction.



1.2 Semiconductor Materials

Common materials used in the development of semiconductor devices:

- **Silicon (Si)**
- **Germanium (Ge)**
- **GaAs**

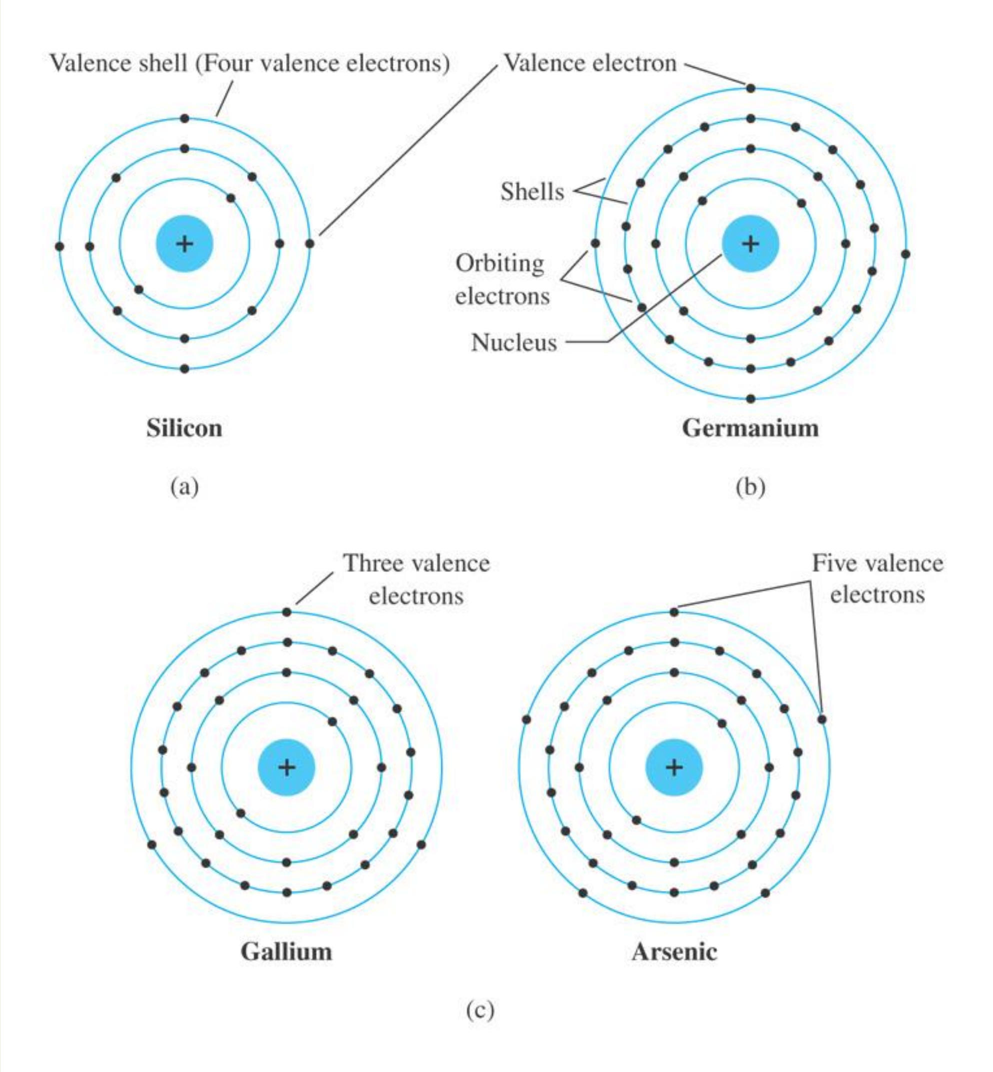


Fig. 1.3 Atomic structure of (a) silicon; (b) germanium; and (c) gallium and arsenic.

1.3 Covalent Bonding and Intrinsic Materials

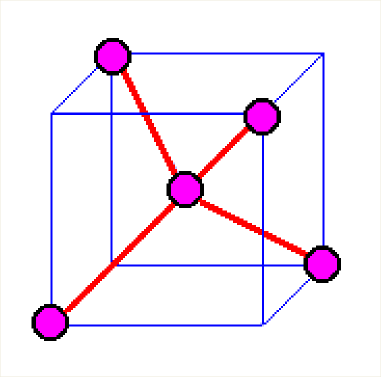
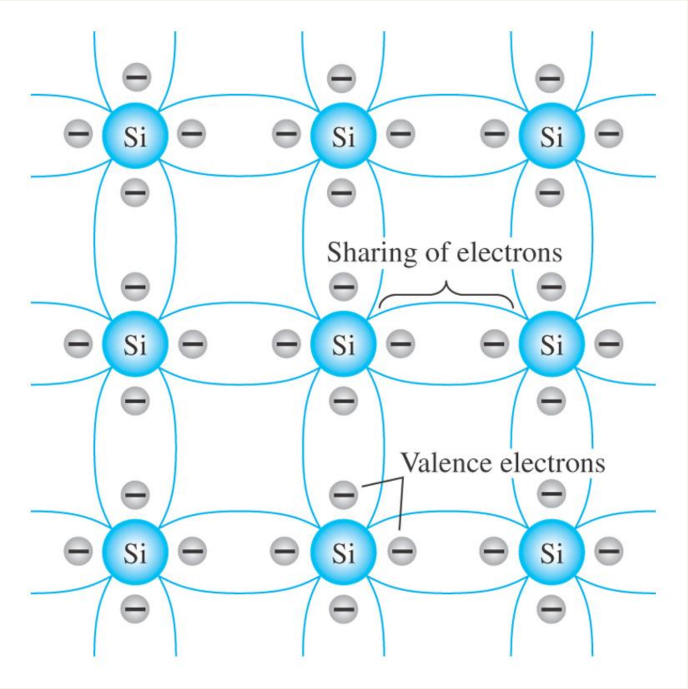


Fig. 1.4 Covalent bonding of the silicon atom.



The single-crystal formed by pure semiconductor materials is called intrinsic semiconductor.

Intrinsic Semiconductors

- **Holes**: Vacancies in the covalent bond
- **Electron-hole pairs**: a free electron and a hole is generated from the covalent bond by thermal energy
- **Movement of Holes**: by movement of covalent electrons from adjacent covalent bonds
- Two types of **charged particles (Intrinsic carriers) in a semiconductor**
  - free electrons n_i
  - holes p_i $\quad n_i = p_i$
- Electrical conductivity of intrinsic semiconductors is determined by the concentration of free electrons and holes

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

1.4 Extrinsic Materials: n-Type and p-Type Materials

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

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**
- The **majority carriers** in *n*-type materials are electrons.
- The **minority carriers** in *n*-type materials are holes.

Phosphorus impurity in n-type material.

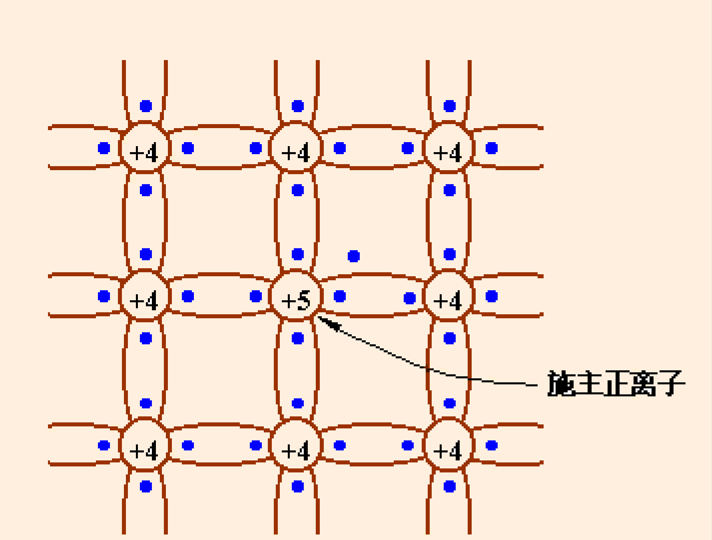
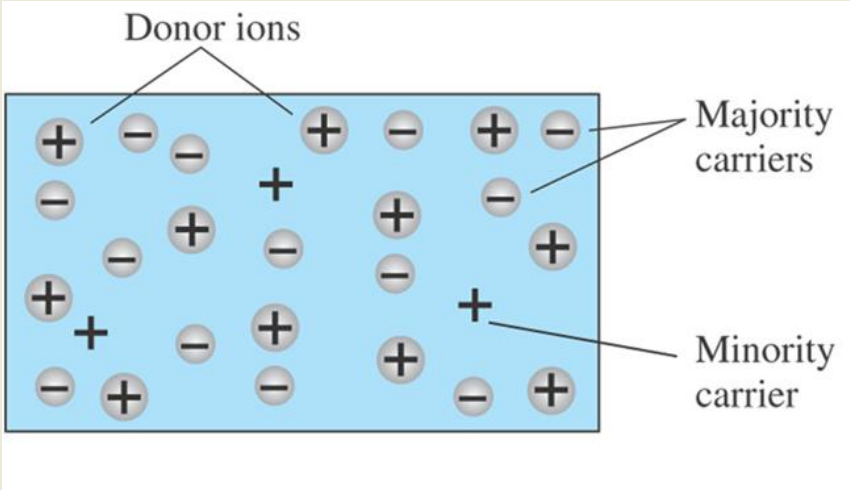


图2.1.6 N型半导体的共价键结构

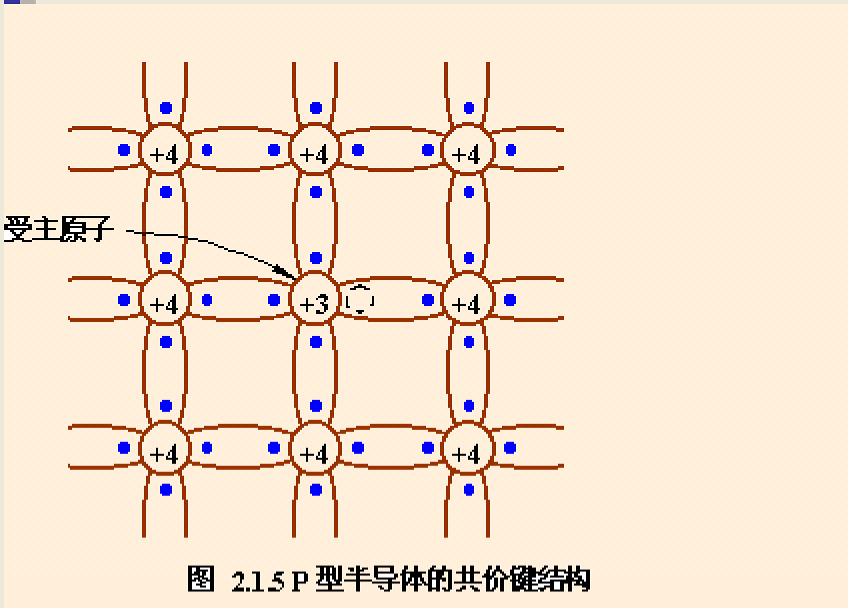


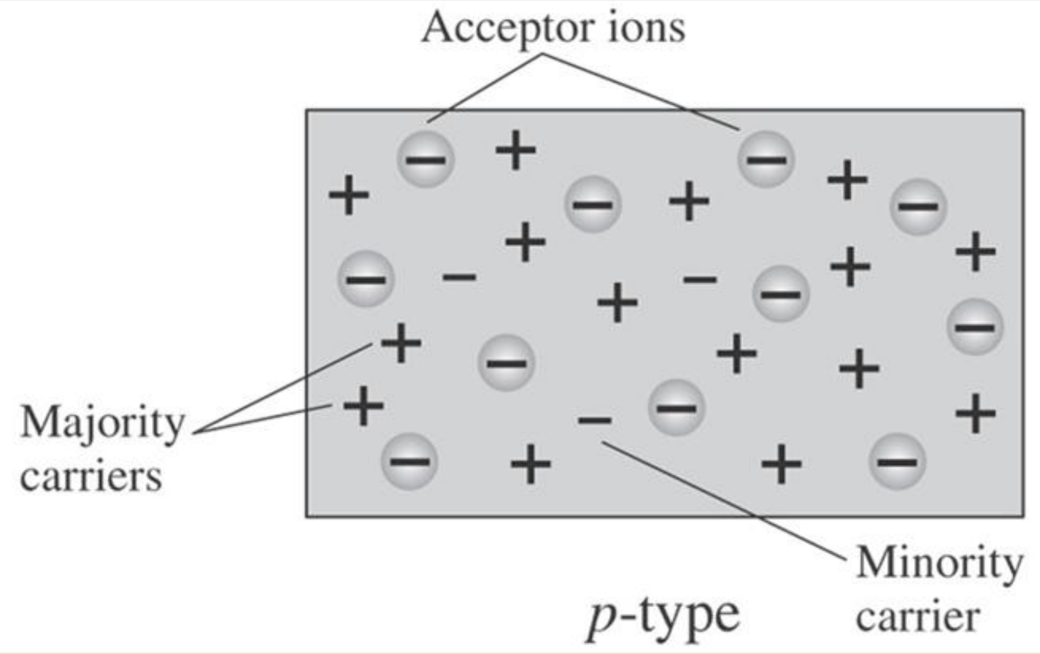
n-type

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**
- The **majority carriers** in *p*-type materials are holes.
- The **minority carriers** in *p*-type materials are electrons.

Boron impurity in p-type material.





intrinsic semiconductor → **doping**

↓

n-type ← **extrinsic semiconductor** → **p-type**

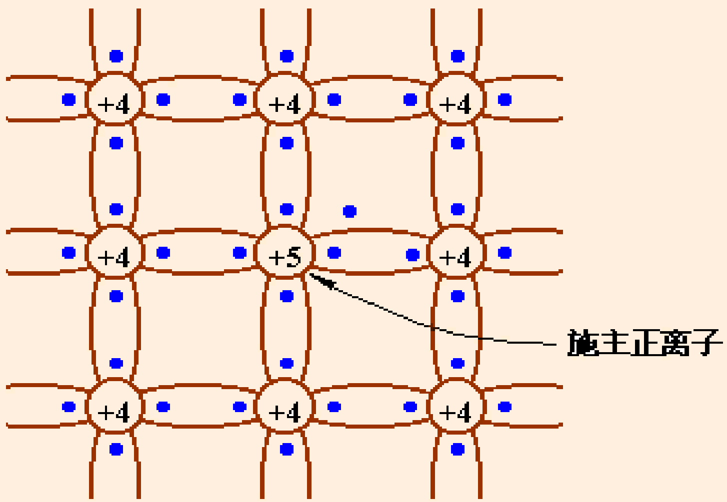


图2.1.6 N 型半导体的共价键结构

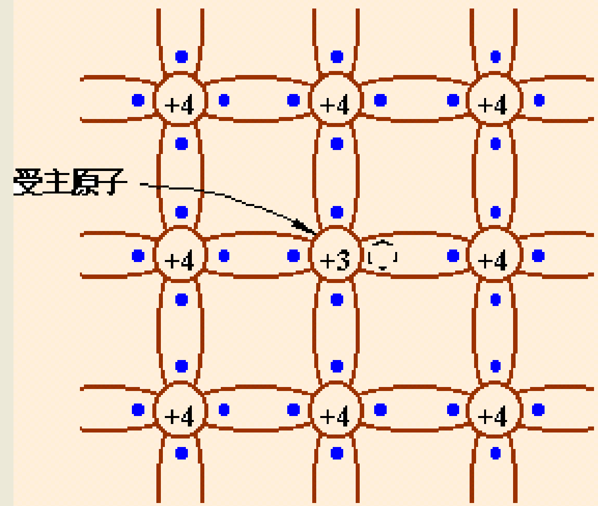


图 2.1.5 P 型半导体的共价键结构

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

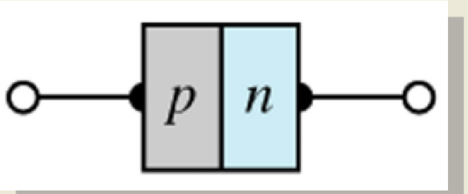
mass-action law: $np = n_i p_i$ **or** $np = n_i^2$

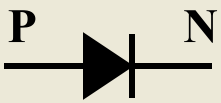
	n-type semiconductor	p-type semiconductor
majority carriers:	electrons	holes
minority carriers:	holes	electrons

1.5 Semiconductor Diode

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.

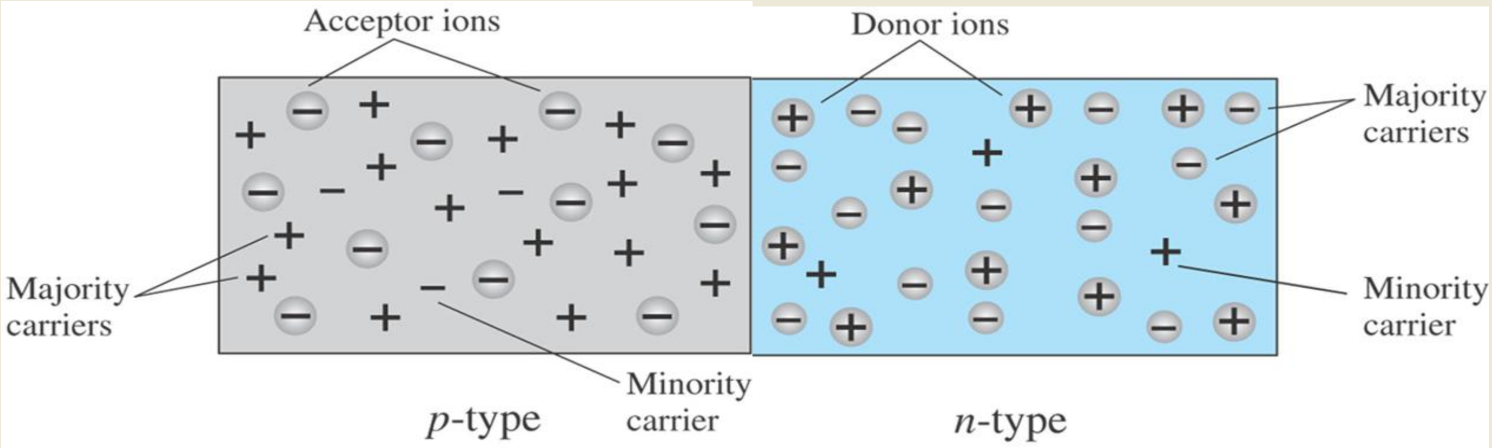
The result is a *p-n* junction.



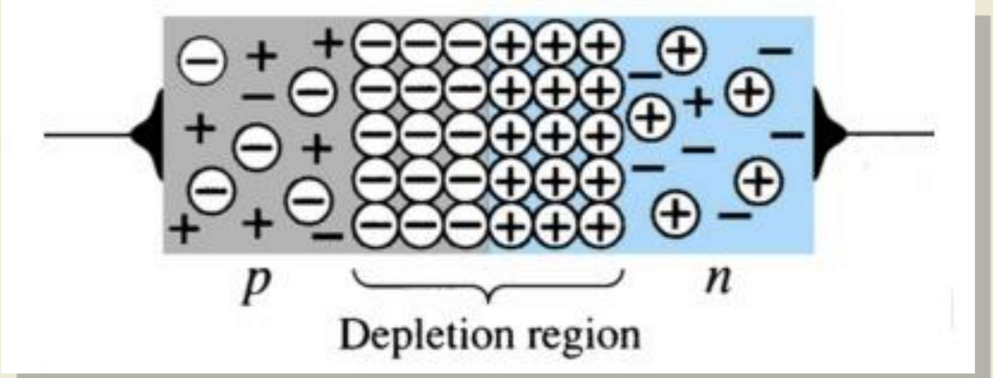


Anode (A)

Cathode (K)



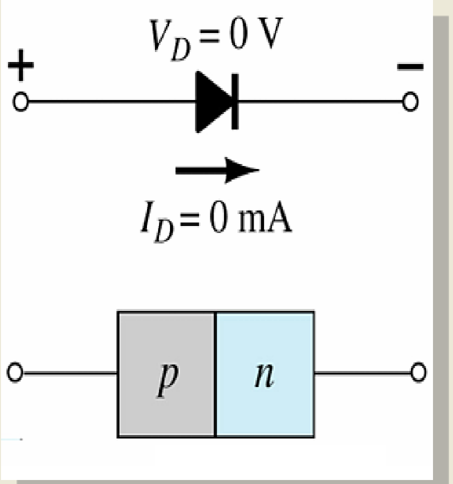
The result is the formation of a depletion region around the junction.



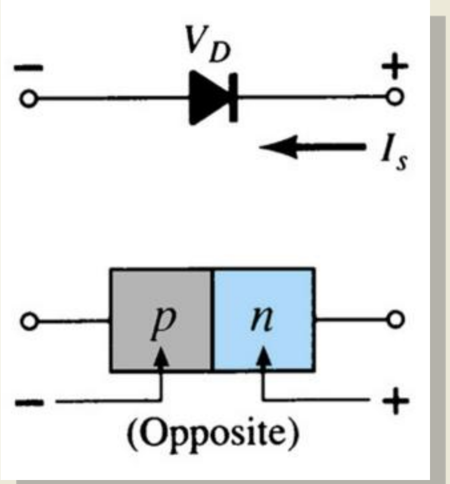
Diode Operating Conditions

A diode (or p-n junction) has three operating conditions:

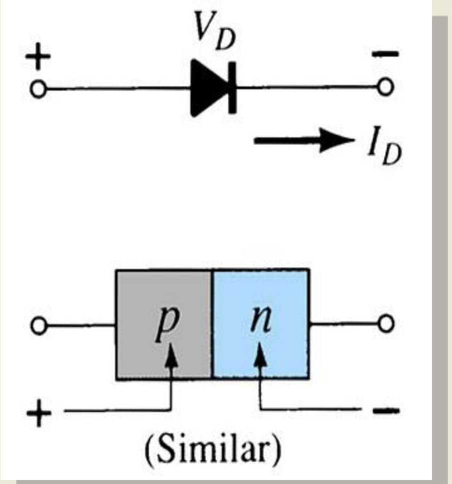
- **No bias**



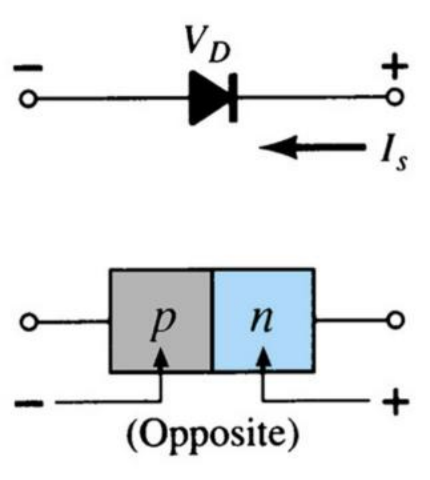
- **Reverse bias**



- **Forward bias**

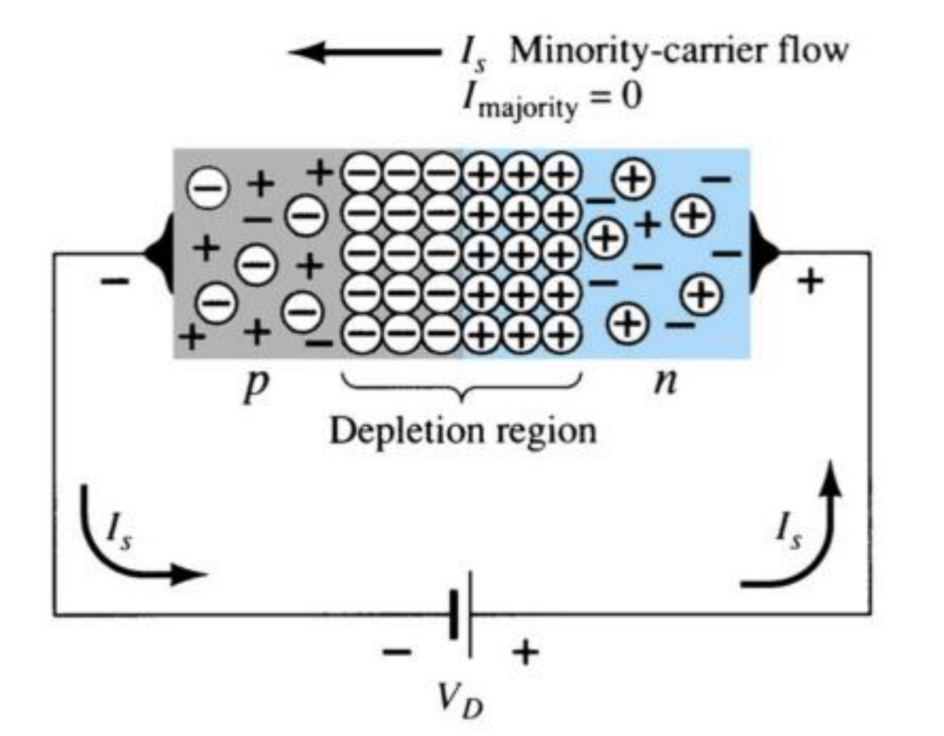


Diode Operating Conditions: Reverse Bias



Reverse Bias

External voltage is applied across the *p-n* junction in the opposite polarity of the *p*- and *n*-type materials.

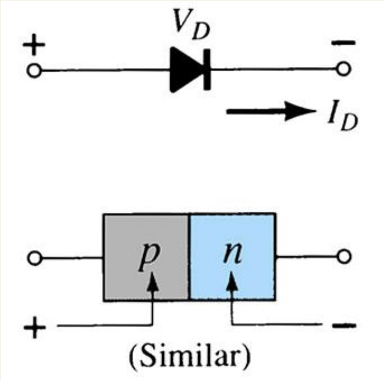


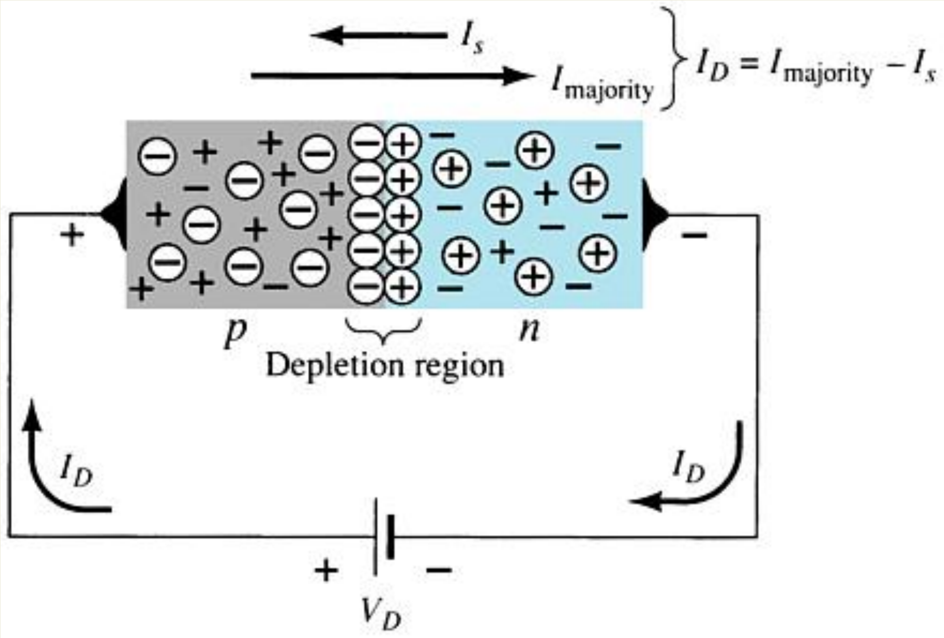
- The reverse voltage causes the depletion layer to widen.
- The electrons in the *n*-type material are attracted toward the positive terminal.
- The holes in the *p*-type material are attracted toward the negative terminal.

Diode Operating Conditions: Forward Bias

Forward Bias

External voltage is applied across the *p-n* junction in the same polarity as the *p-* and *n-*type materials.





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

The forward bias voltage required:

- **silicon diode ≅ 0.7V**
- **germanium diode ≅ 0.3V**

I-V Characteristics of Semiconductor Diodes

$$Shockley's\ equation$$

$$I_D = I_S(e^{V_D/nV_T} - 1)$$

$$V_T = \frac{kT}{q}$$

$$T = 300K\ \ (room\ temperature)$$

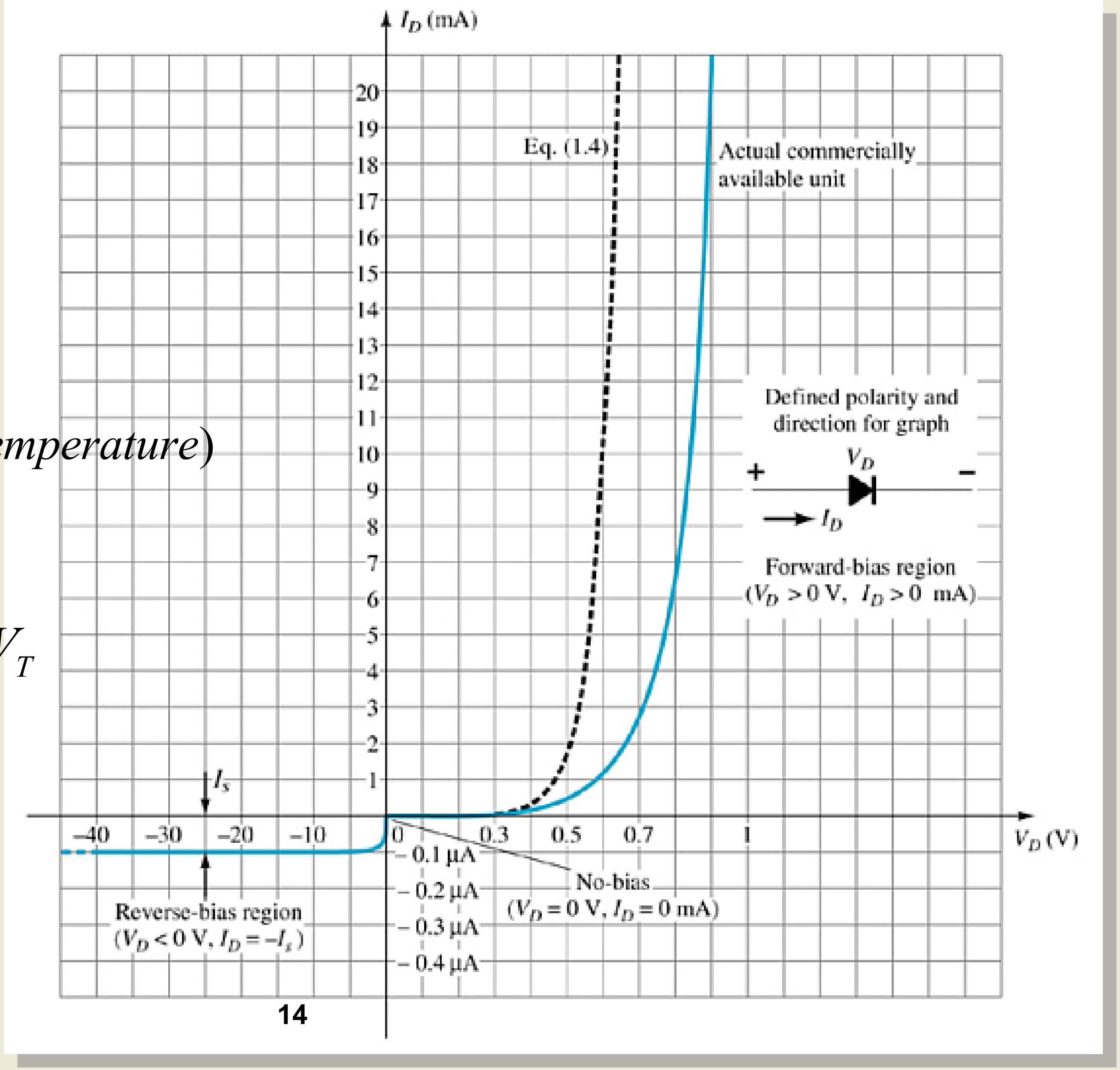
$$V_T \cong 26mV$$

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

$$I_D \cong I_S e^{V_D/V_T}$$

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

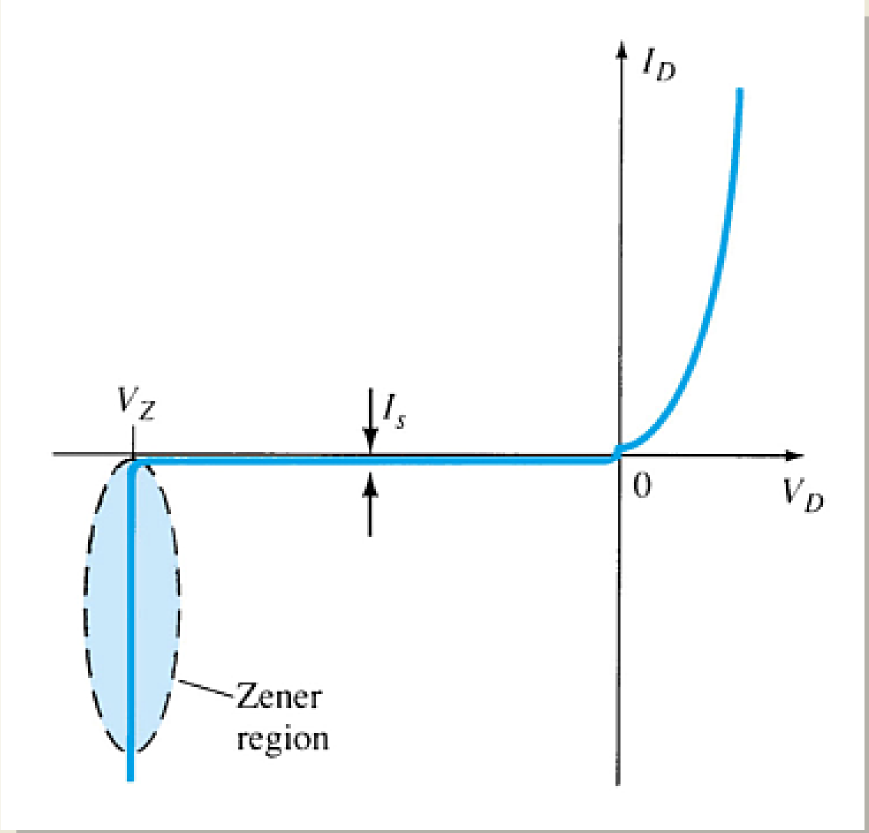
$$I_D \cong -I_S$$



Zener Region

The Zener region is in the diode's reverse-bias region.

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



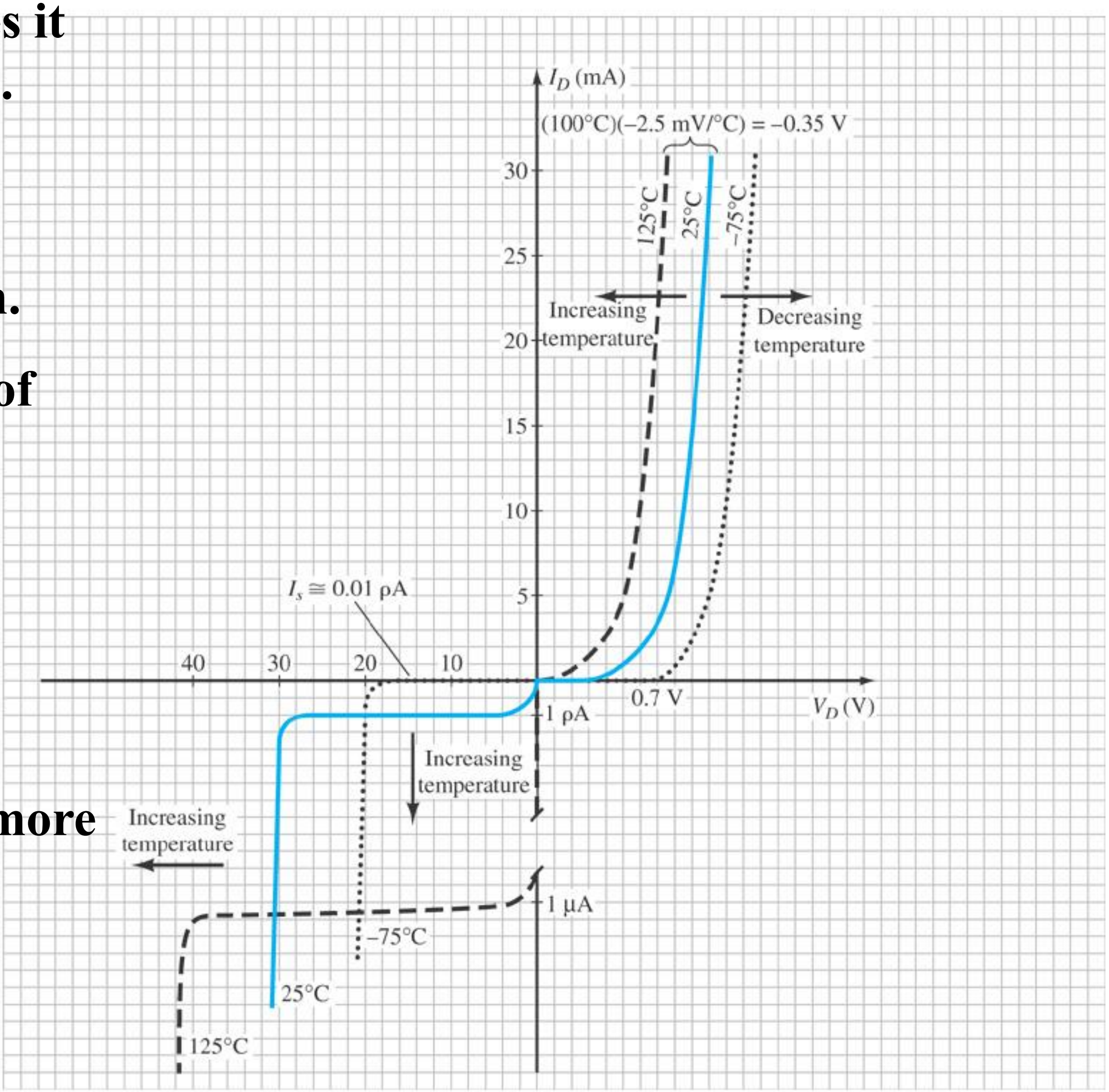
Two mechanisms of electrical breakdown

- **Avalanche breakdown**
- **Zener breakdown**

The maximum reverse-bias voltage that can be applied before entering the Zener region is called the **Peak Inverse Voltage (PIV)** or **Peak Reverse Voltage (PRV)**

Temperature Effects

- As temperature increases it adds energy to the diode.
- It reduces the required forward bias voltage for forward-bias conduction.
- It increases the amount of reverse current in the reverse-bias condition.
- It increases maximum reverse bias avalanche voltage.
- Germanium diodes are more sensitive to temperature variations than silicon diodes.



1.7 Resistance Levels

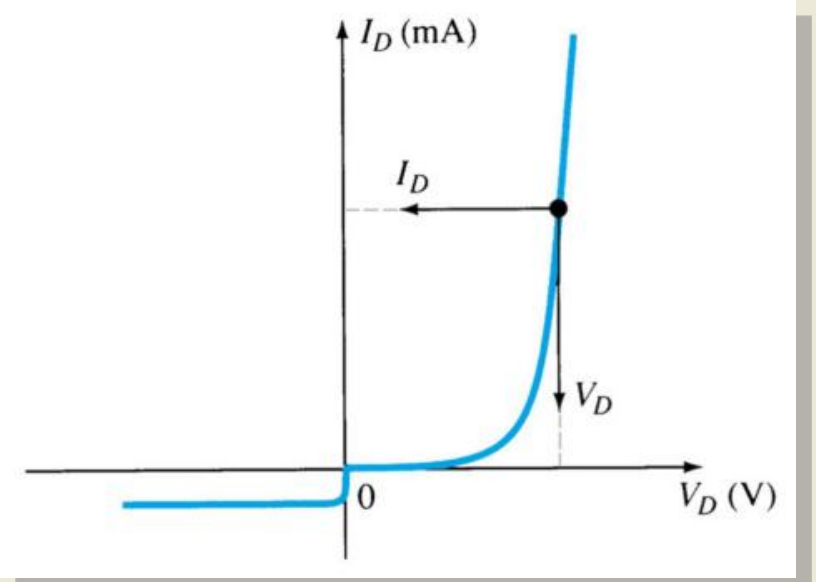
Semiconductor diodes (/pn junction) act differently to DC and AC currents.

There are three types of resistances:

- **DC, or static, resistance**
- **AC, or dynamic, resistance**
- **Average AC resistance**

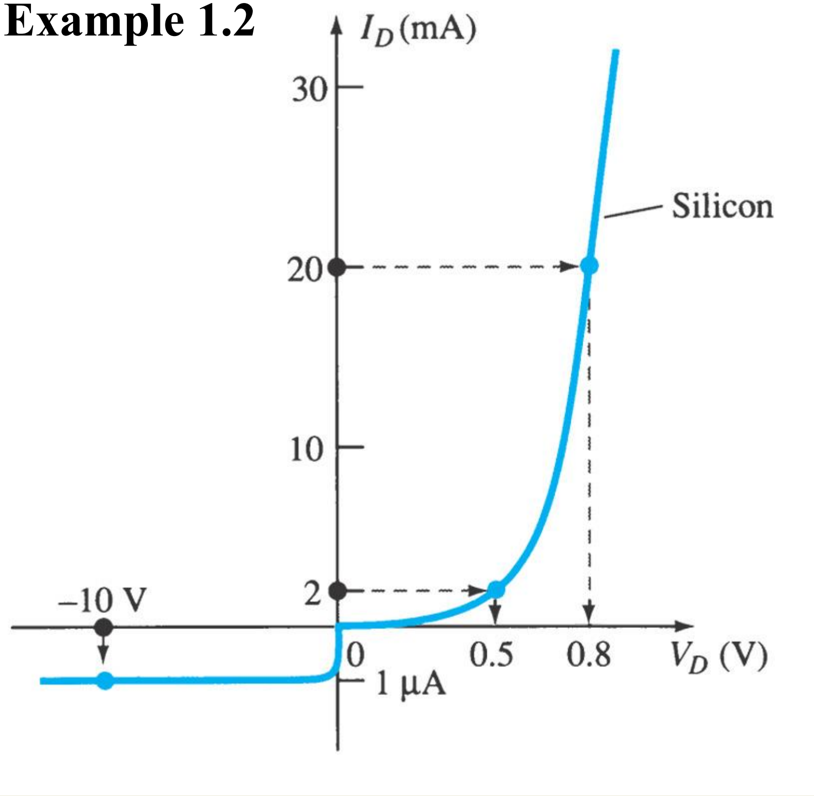
DC, or Static, Resistance

For a specific applied DC voltage V_D, the diode has a specific current I_D, and a specific resistance R_D.



$$R_D = \frac{V_D}{I_D}$$

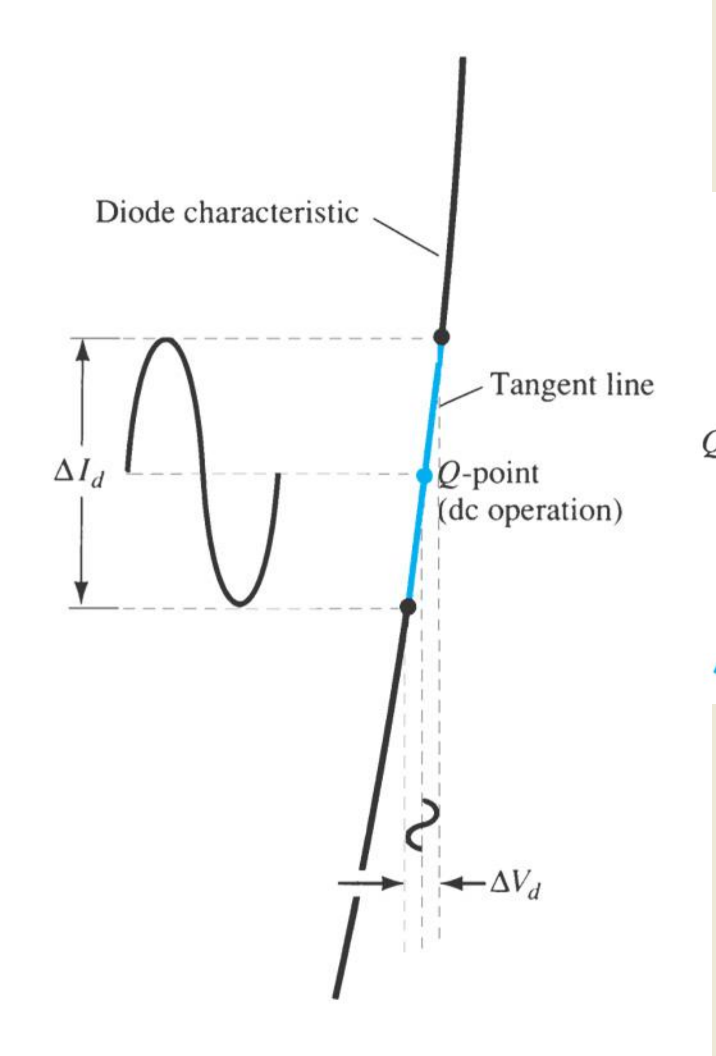
Example 1.2

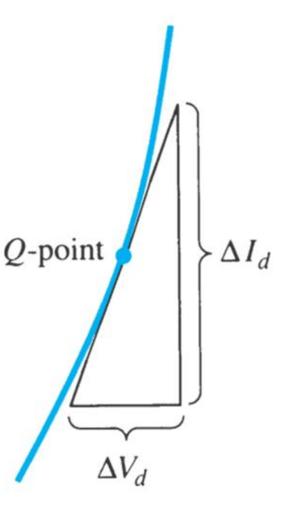


AC, or Dynamic, Resistance

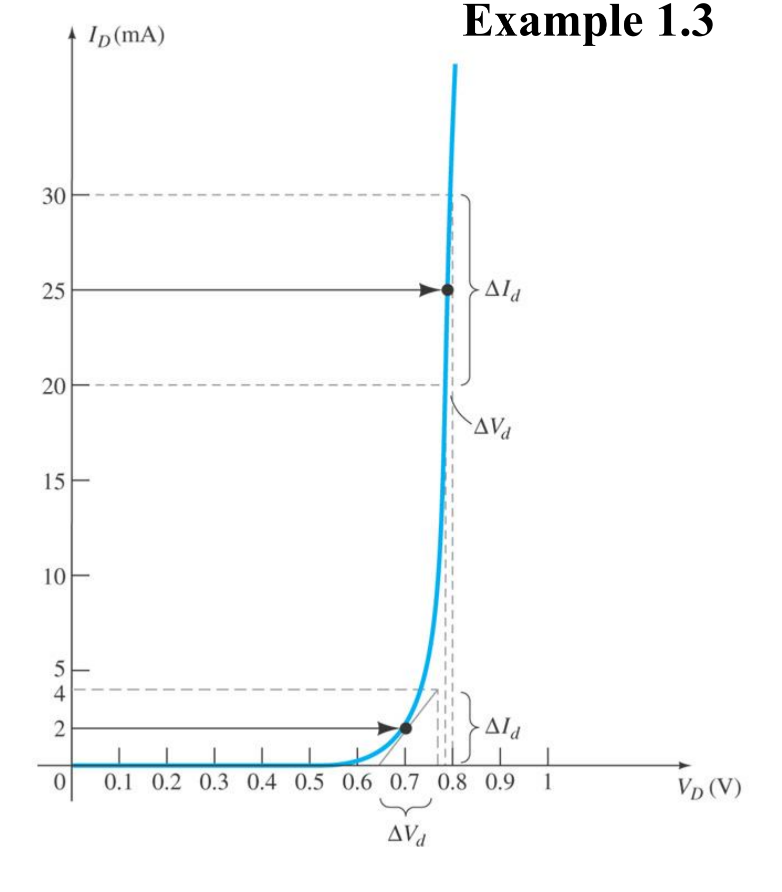
$$r_d = \left.\frac{dV_D}{dI_D}\right|_Q \cong \left.\frac{\Delta V_d}{\Delta I_d}\right|_Q \qquad r_d \cong \frac{V_T}{I_D}$$

$$I_D = I_S(e^{V_D/V_T} - 1)$$





Example 1.3



AC, or Dynamic, Resistance

In the forward bias region:

$$r_d = \frac{26\,\text{mV}}{I_D} \longrightarrow r'_d = \frac{26\,\text{mV}}{I_D} + r_B$$

- **The ac resistance depends on DC operating point (I_D) in the diode.**
- **r_B : body resistance and contact resistance. It is very small ($0.1\Omega \sim 2\Omega$). In some cases r_B can be ignored.**

In the reverse bias region:

$$r'_d = \infty$$

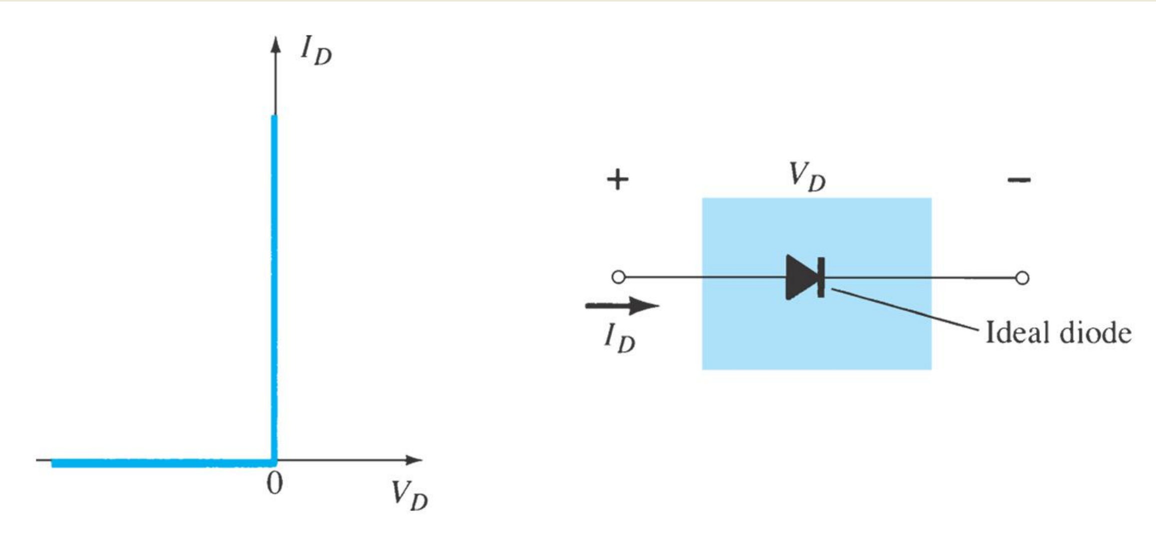
The resistance is essentially infinite. The diode acts like an open.

1.8 Diode Equivalent Circuits

There are three equivalent circuits for a diode:

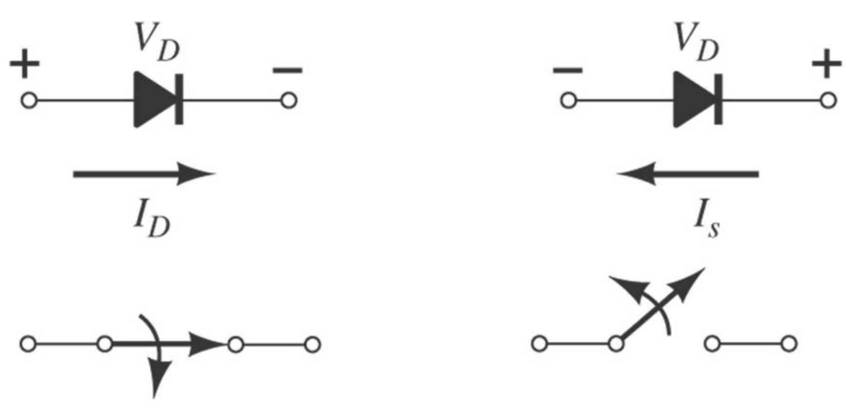
- **Ideal Equivalent Circuit**
- **Piecewise-Linear Equivalent Circuit**
- **Simplified/Approximate Equivalent Circuit**

Ideal Equivalent Circuit

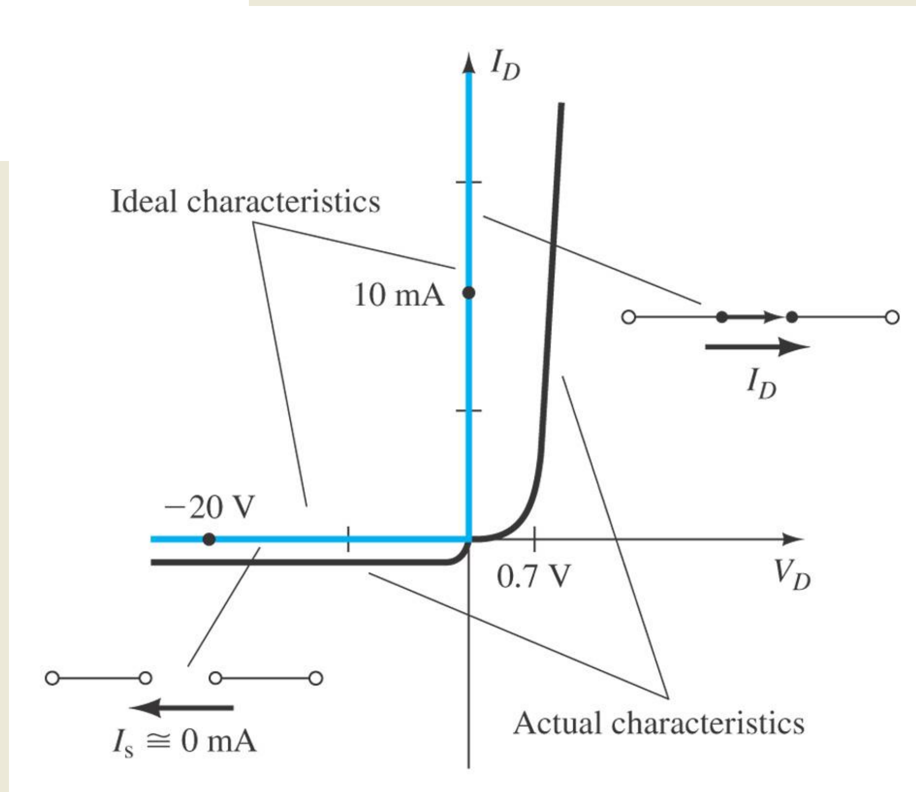


On-off Switch

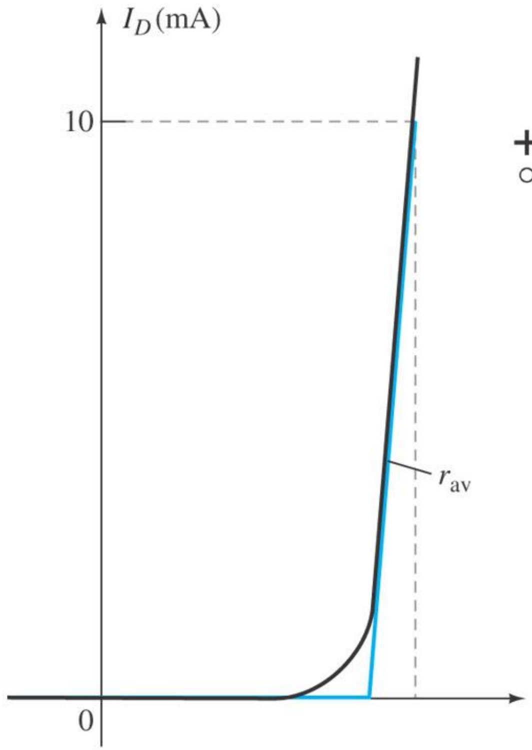
Conduction in one direction

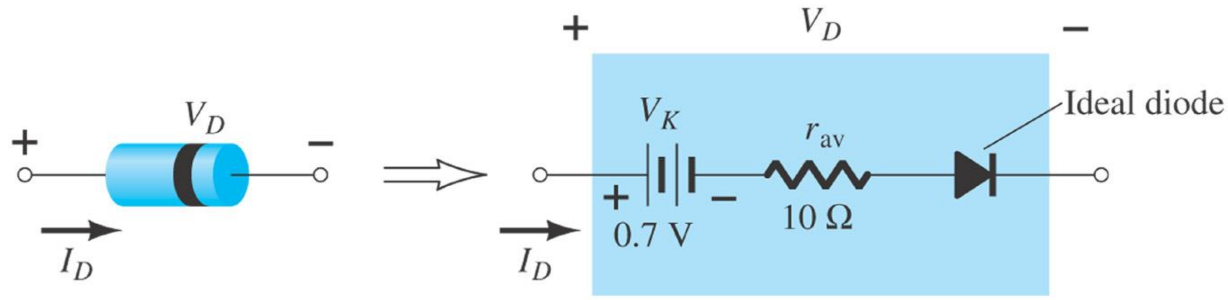


(a) (b)

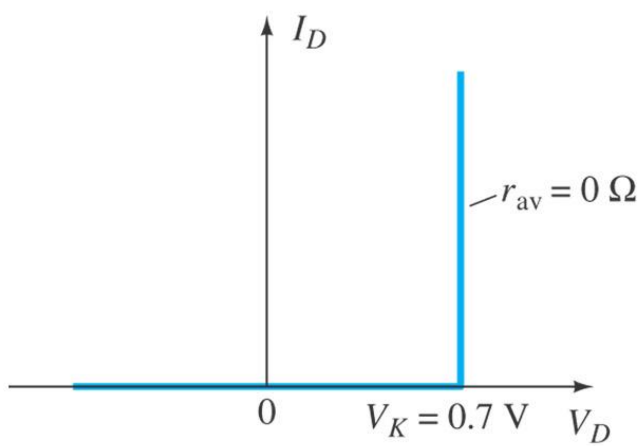


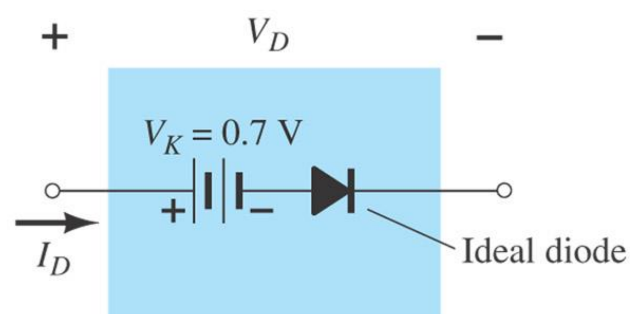
Piecewise-Linear Equivalent Circuit



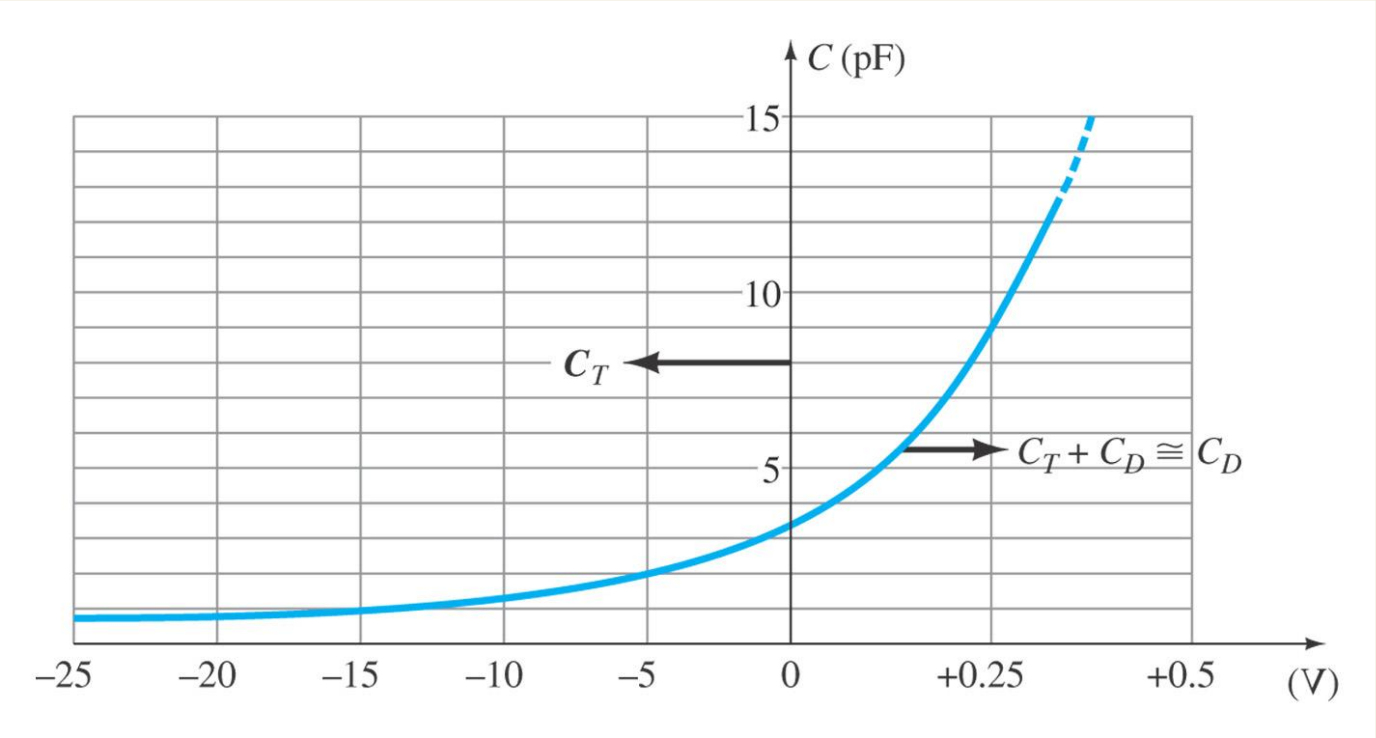


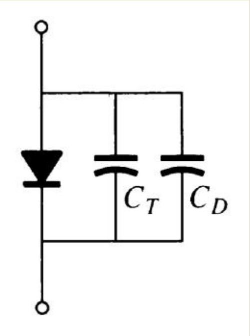
Simplified Equivalent Circuit





1.9 Diode Capacitance





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 storage capacitance or diffusion capacitance (C_D) exists besides barrier capacitance as the diode voltage increases.

1.11 Diode Specification Sheets

Data about a diode is presented uniformly for many different diodes. This makes cross-matching of diodes for replacement or design easier.

1. **V_F, forward voltage at a specific current and temperature**
2. **I_F, maximum forward current at a specific temperature**
3. **I_R, maximum reverse current at a specific temperature**
4. **PIV or PRV or V(BR), maximum reverse voltage at a specific temperature**
5. **Power dissipation, maximum power dissipated at a specific temperature**
6. **C, capacitance levels in reverse bias**
7. **t_{rr}, reverse recovery time**
8. **Temperatures, operating and storage temperature ranges**

Other Types of Diodes

- **Zener diode**
- **Light-emitting diode (LED)**
- **Photodiode**
- **Varactor diode**

1.13 Zener Diode

A Zener is a diode operated in reverse bias at the Zener voltage (V_Z).

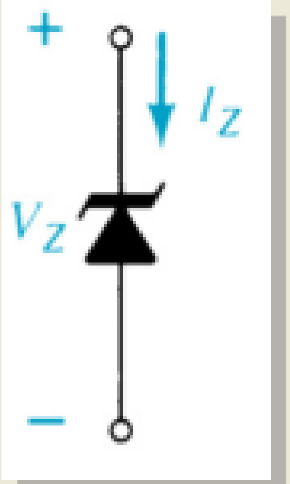
Common Zener voltages are beween 1.8 V and 200 V

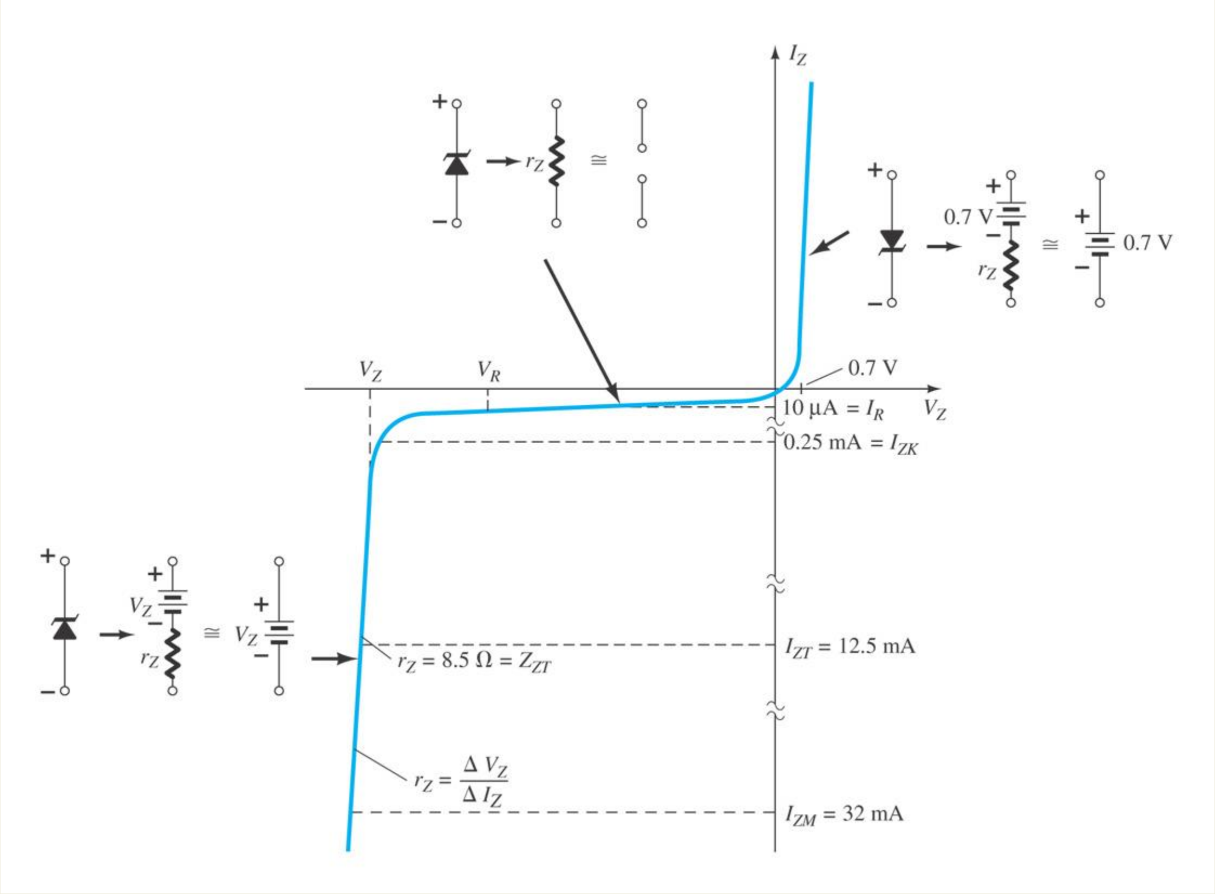
Important parameters for Zener Diodes:

$$V_Z$$

$$I_{ZM}$$

$$P_{ZM} = I_{ZM} V_Z$$





Summary of Chapter 1

➢ Key Items

- Construction of a p-n junction
- Characteristics of a semiconductor diode (/p-n junction)
    - Electrical conduction in only one direction
- DC resistance and AC resistance
- Equivalent circuits for a semiconductor diode