Chapter 1 Semiconductor Diodes

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Contents

- Semiconductor Materials
- The *PN* Junction(Diode)
- Analysis of Diode Circuits
- The Applications of Diode Circuits
- Zener Diodes

Semiconductor Materials

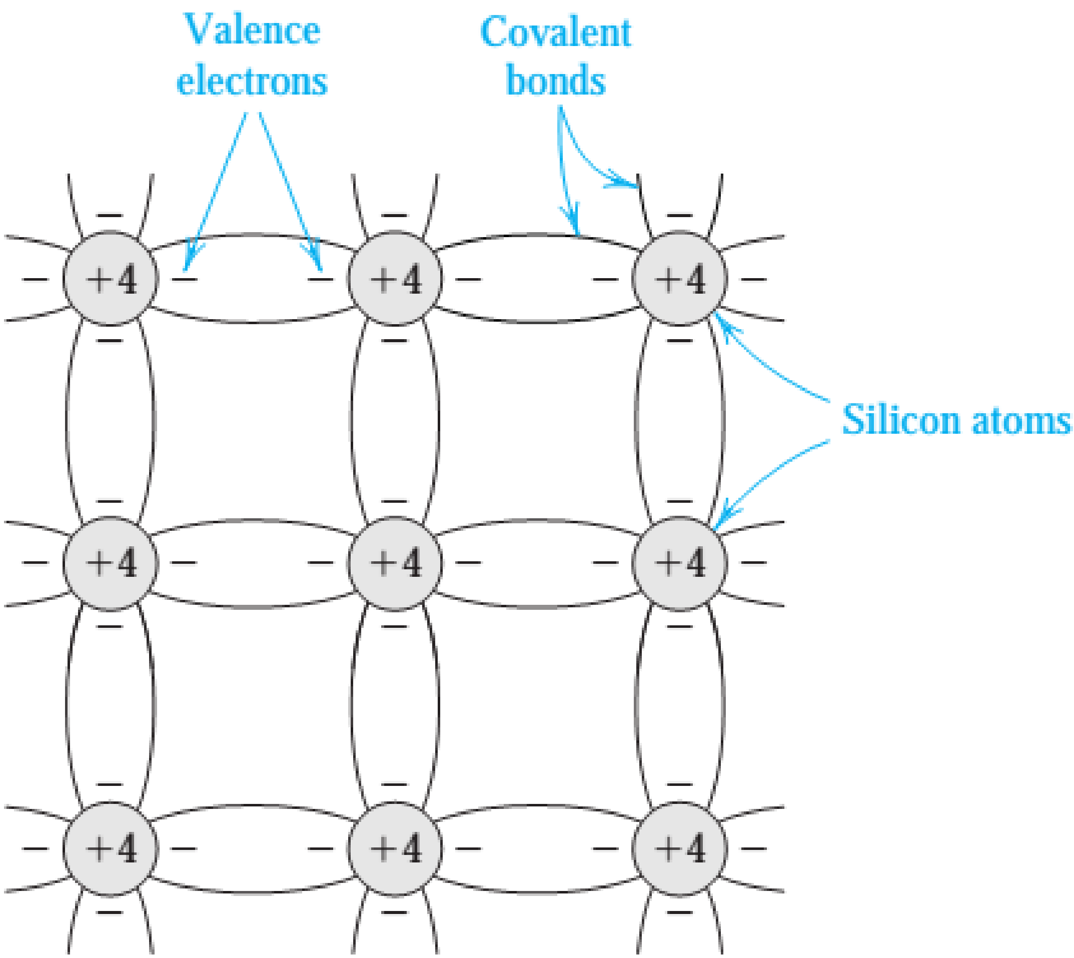
Semicondutors *are a special class of elements having a conductivity between that of a good conductor and that of an insulator.*

(Germanium(锗), Silicon（硅）, Gallium arsenide（砷化镓）)

Intrinsic Semicondutors（本征半导体）

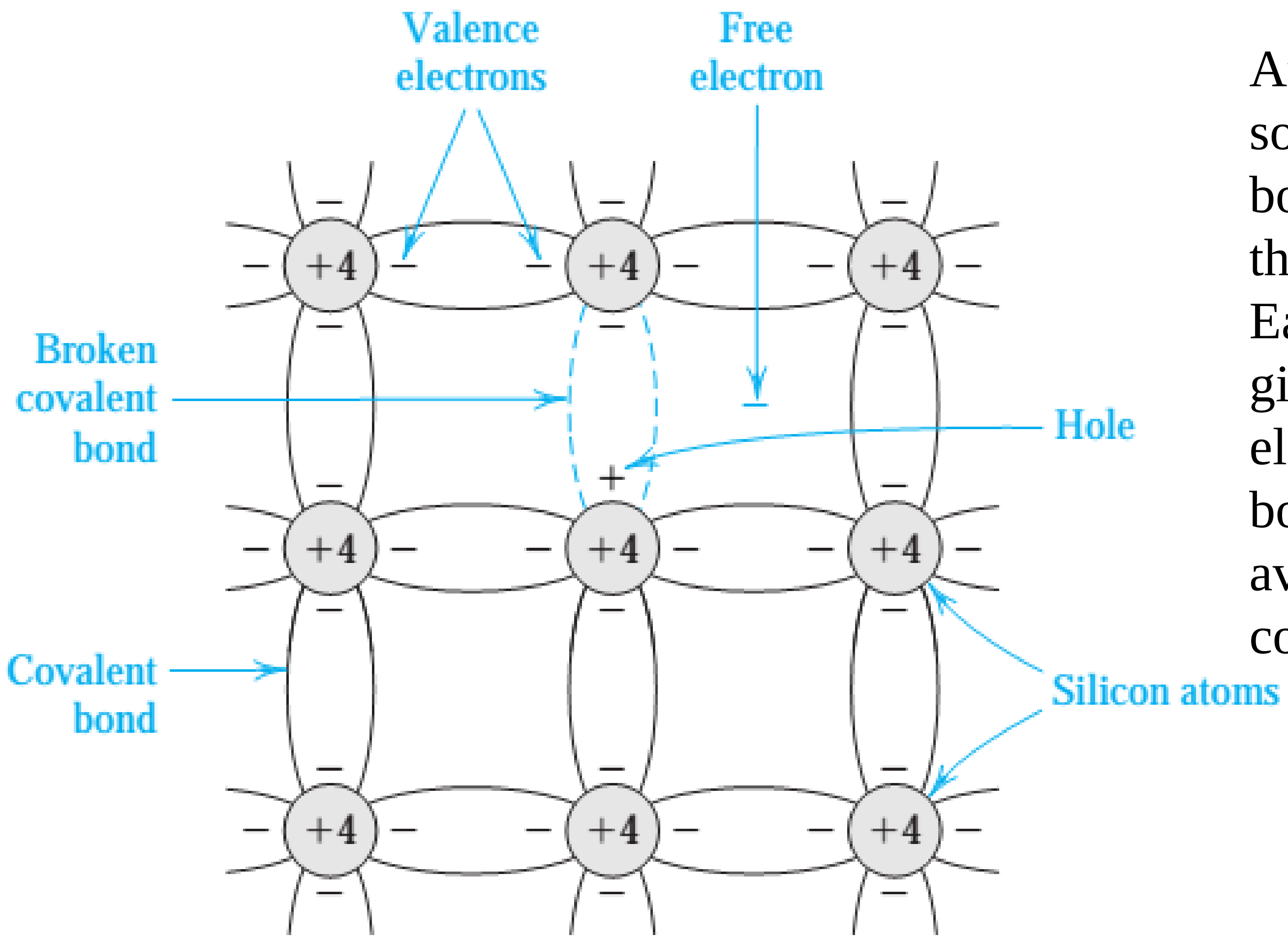
Extrinsic Semiconductors（杂质半导体）

Intrinsic Semiconductors



The circles represent the inner core of silicon atoms, with +4 indicating its positive charge of +4q, which is neutralized by the charge of the four valence electrons. Observe how the covalent bonds are formed by sharing of the valence electrons. At 0 K, all bonds are intact and no free electrons are available for current conduction.

Intrinsic Semiconductors



At room temperature, some of the covalent bonds are broken by thermal ionization. Each broken bond gives rise to a free electron and a hole, both of which become available for current conduction.

Intrinsic Semiconductors

An ***intrinsic semiconductor*** is a single-crystal semiconductor material with no other types of atoms within the crystal.(纯净的晶体结构)

Carriers(载流子)

Free electrons----produced by thermal ionization, it can move freely in the lattice structure.

Holes----empty position in broken covalent bond,can be filled by free electron, positive charge.

Recombination----

Thermal equilibrium----

Extrinsic Semiconductors

N type ----To increase the concentration of free electrons, silicon is doped with An element with a valence of 5, such as phosphorus.

Donor---- pentavalent impurity provides free electrons (usually entirely ionized at room temperature)

Positive bound charge----impurity atom donating electron gives rise to positive bound charge.

Carriers----

Free electron----majority（多子）, generated mostly by ionized and slightly by thermal ionization.

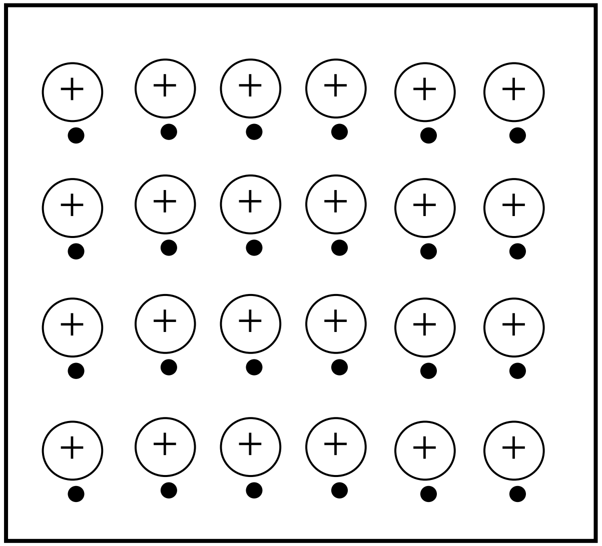
Hole---minority（少子）, only generated by thermal ionization.

Extrinsic Semiconductors

***Carriers*----**

***Free electron*----majority（多子）, generated mostly by ionized and slightly by thermal ionization.**

***Hole*---minority（少子）, only generated by thermal ionization.**



N type

Extrinsic Semiconductors

P type ----To increase the concentration of holes, silicon is doped with an element having a valence of 3,such as boron.

Acceptor---- trivalent impurity provides holes (usually entirely ionized)

Negatively bound charge----impurity atom accepting hole give rise to negative bound charge

Carriers

Hole----majority（多子）, generated generated mostly by ionized and slightly by thermal ionization.

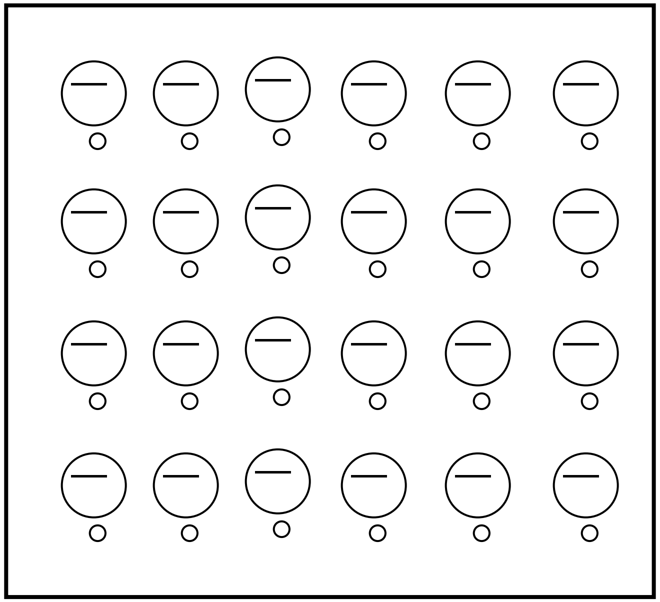
Free electron----minority（少子）, only generated by thermal ionization

Extrinsic Semiconductors

Carriers

Hole----majority（多子）, generated generated mostly by ionized and slightly by thermal ionization.

Free electron----minority（少子）, only generated by thermal ionization



P type

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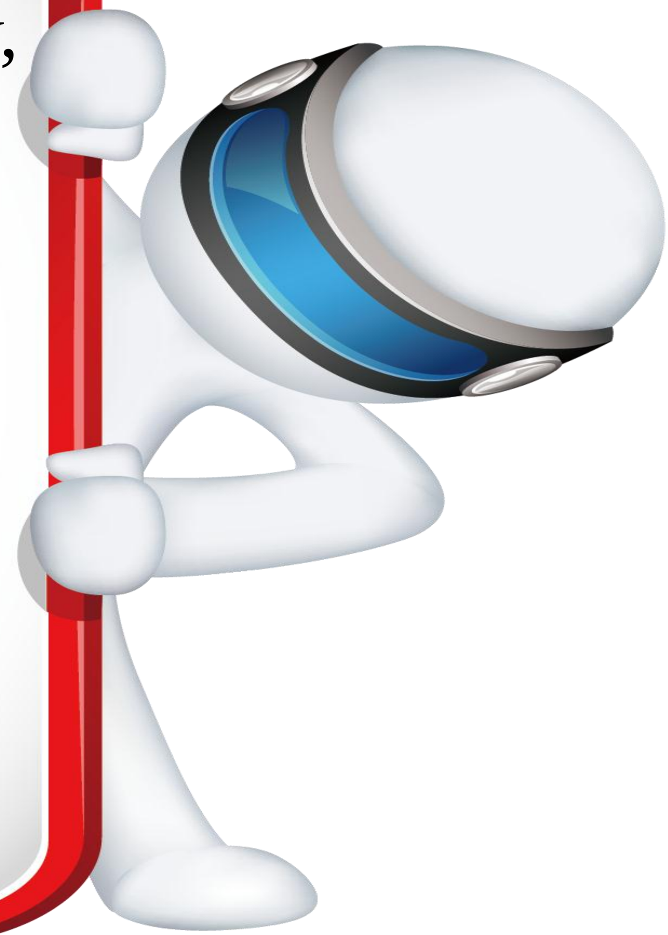
Conclusion

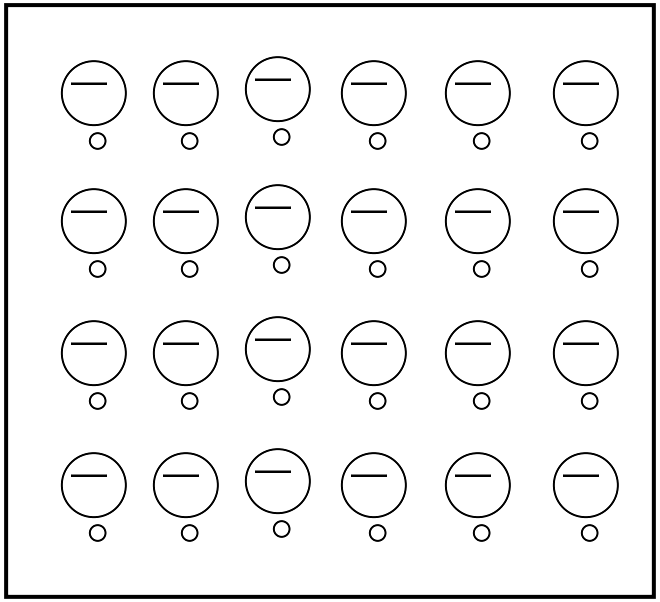
- Majority carrier is only determined by the impurity, but independent of temperature.
- Minority carrier is strongly affected by temperature.



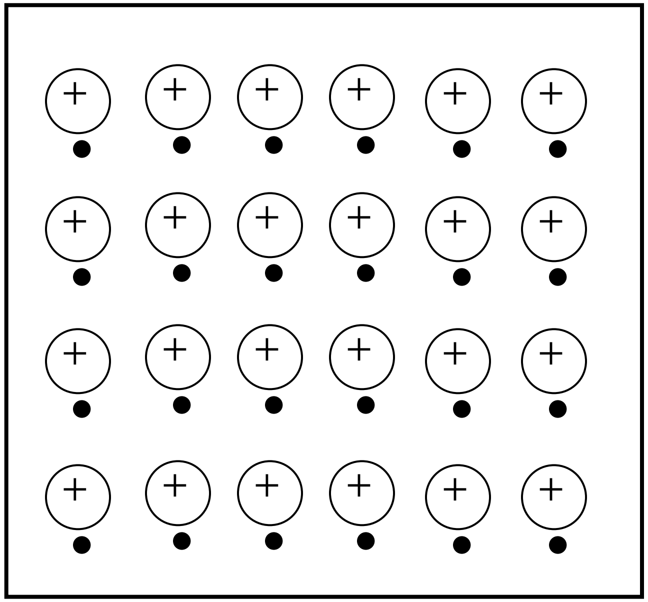
Carriers Movement

- ***Drift***--- The carrier motion is generated by the electrical field across a piece of silicon. This motion will produce drift current(漂移电流).
- ***Diffusion***--- The carrier motion is generated by the different concentration of carrier in a piece of silicon. The diffused motion, usually carriers diffuse from high concentration to low concentration, will give rise to diffusion current（扩散电流）.

The *pn* Junction



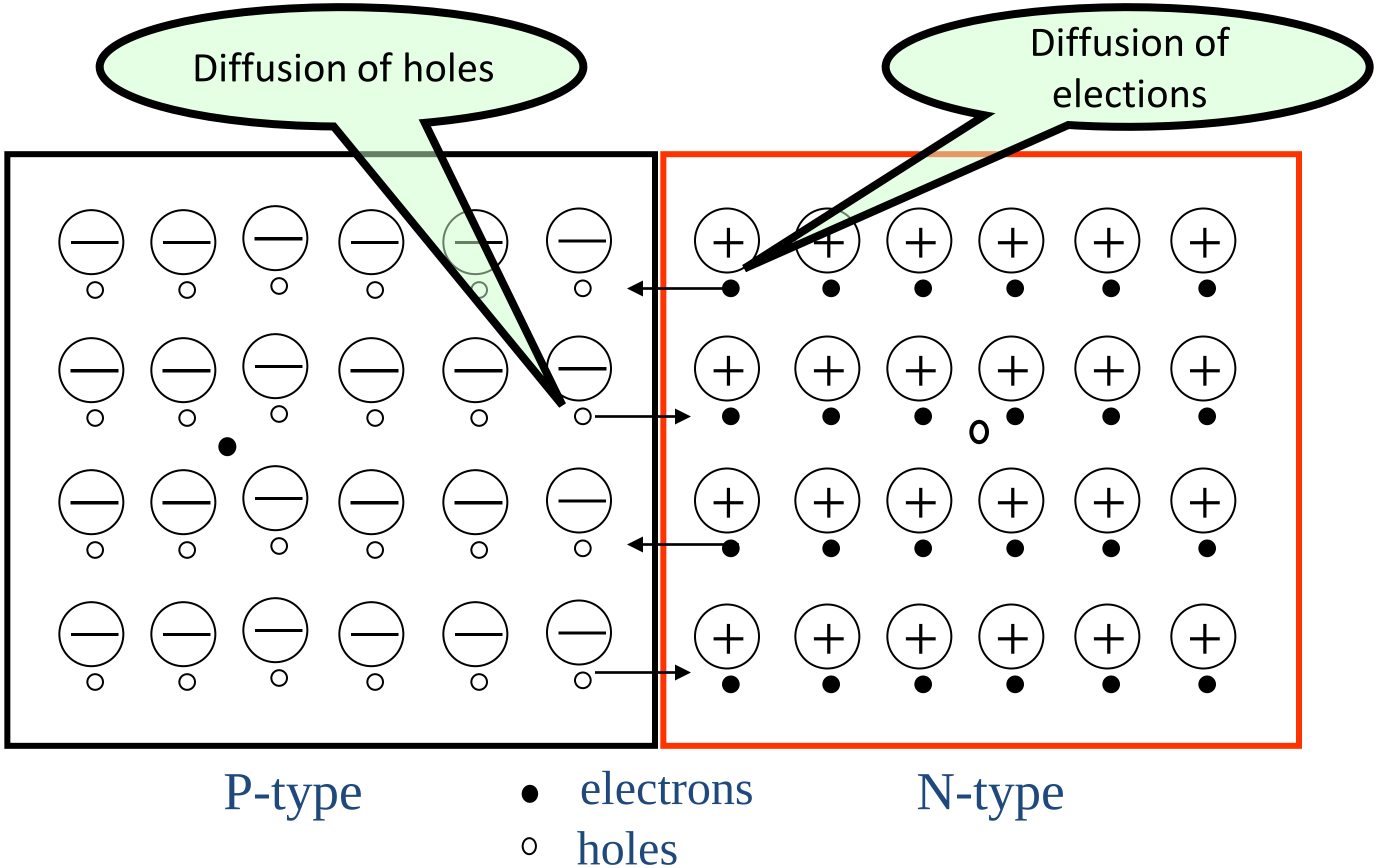
P type



N type

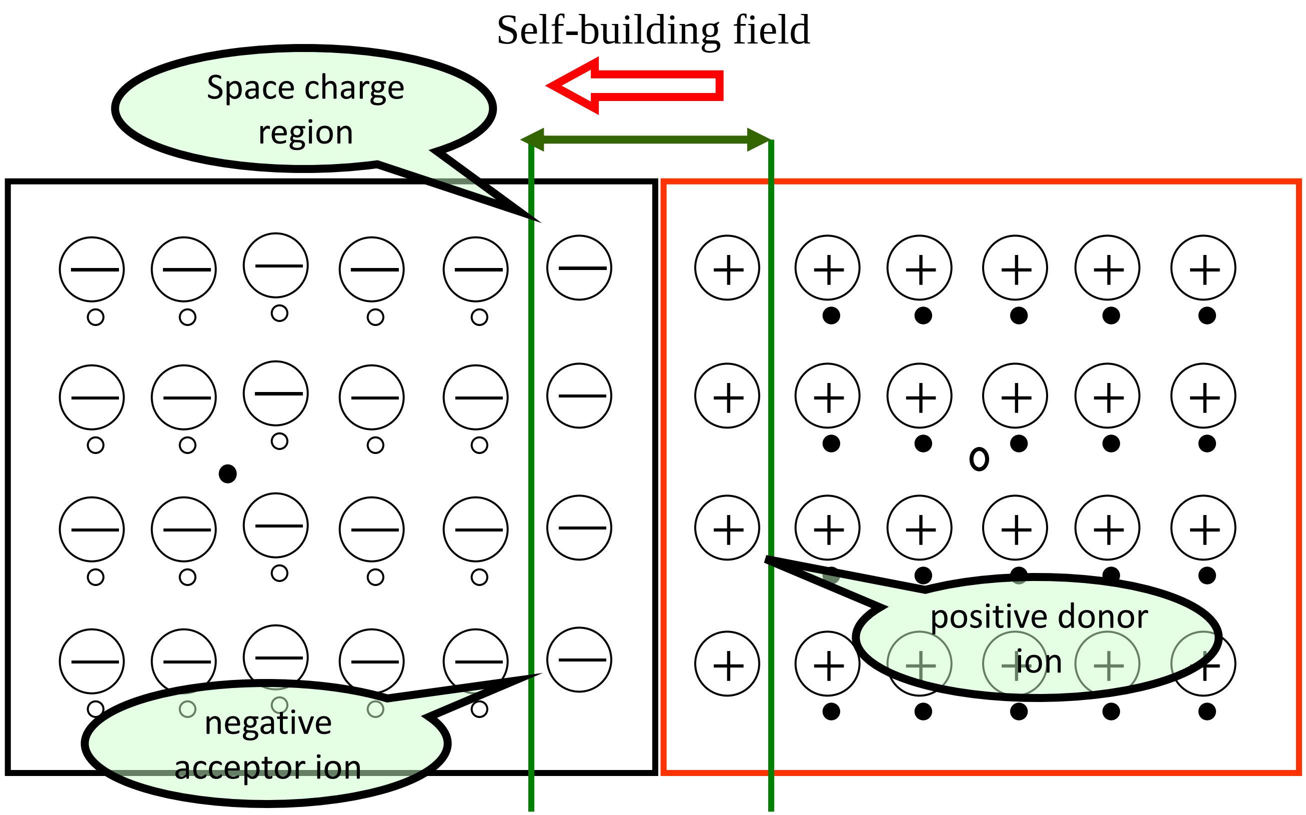
What will happen when N type meets P type?

When N-type meets P-type



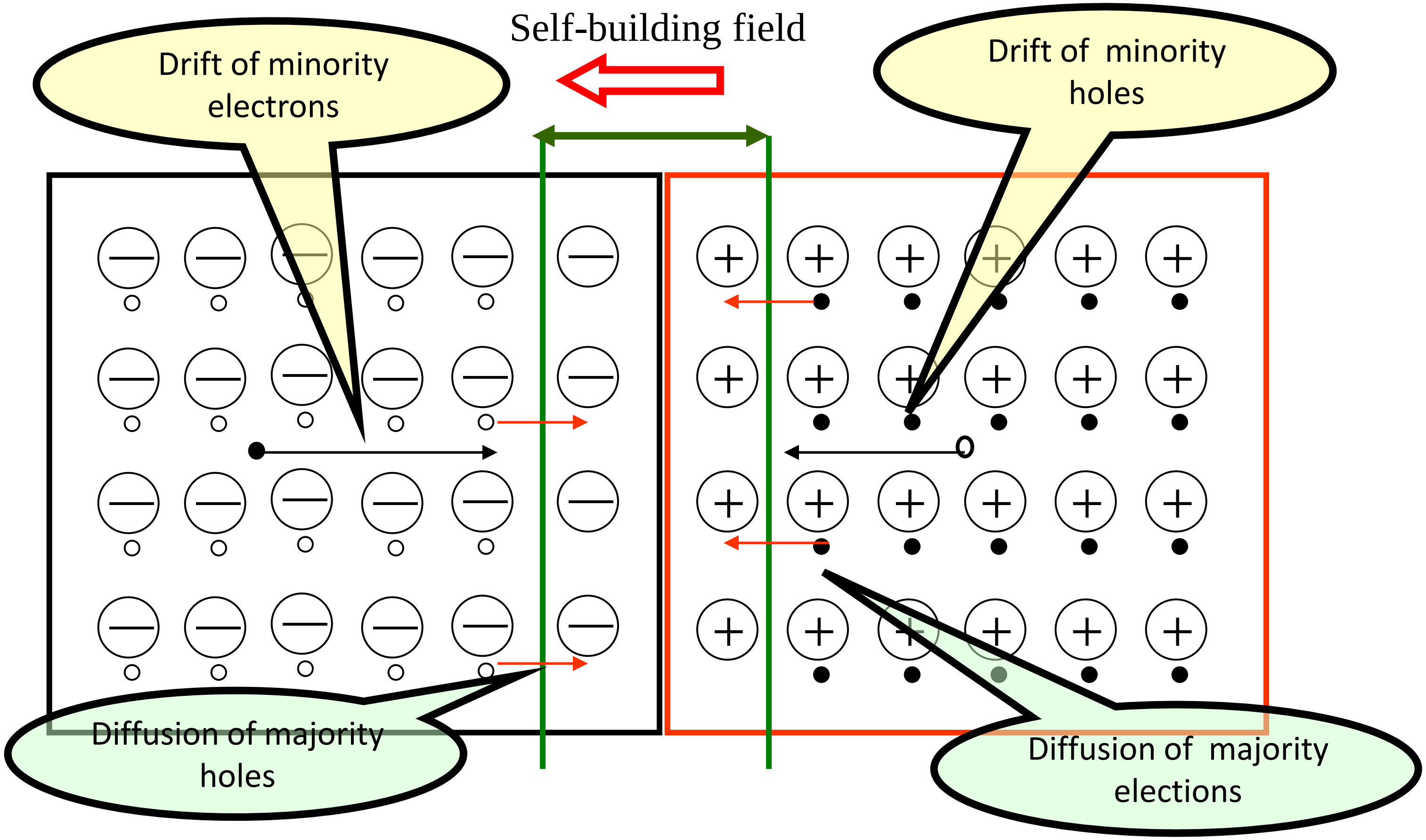
The concentration difference around the contact surface will cause the diffusion of majority carriers.

When N-type meets P-type



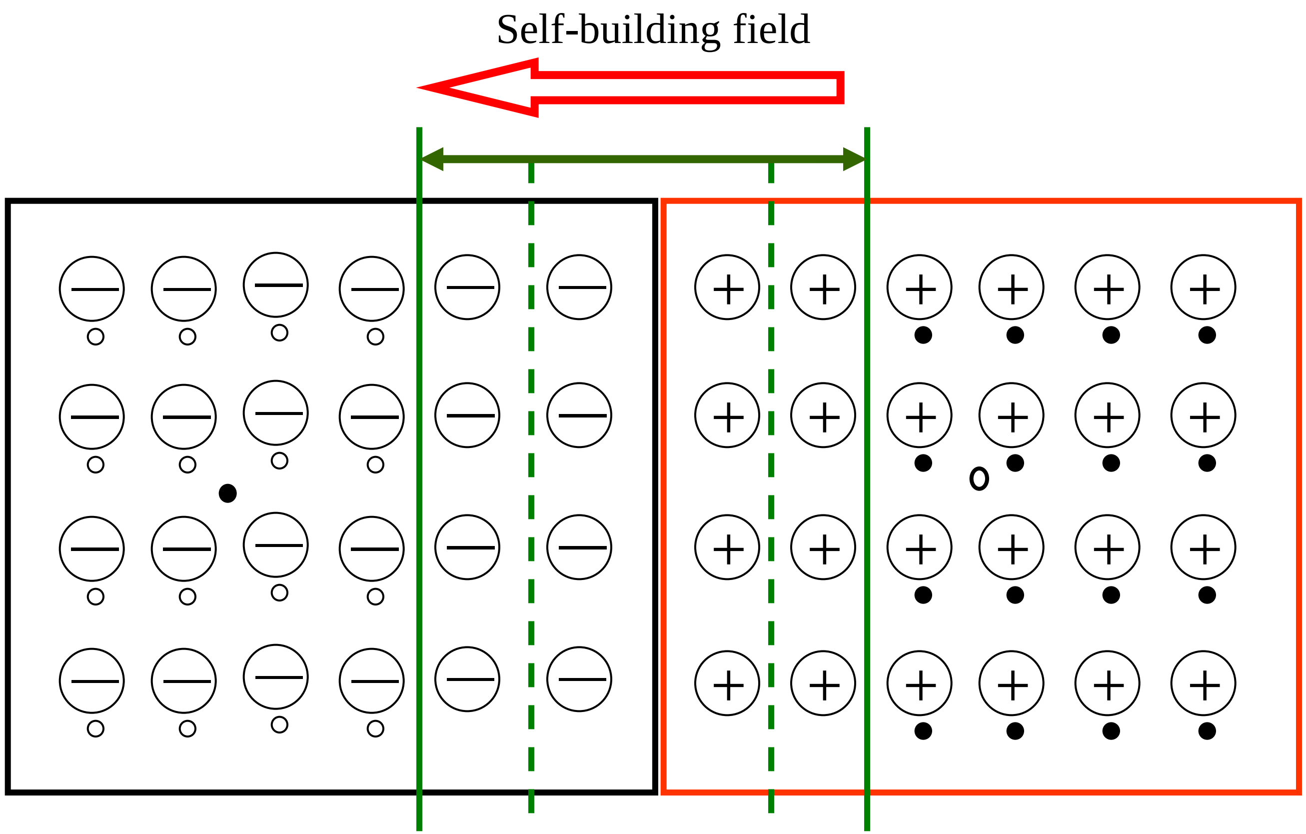
- Lost their electrons/holes, donors/acceptors become charged ions.
- Charged ions are fixed and form a space charge region (空间电荷区).
- Space charge region results in an self-building field (自建场).

When N-type meets P-type



The self-building field will enforce the drift of minority carriers, and restrict the diffusion of majority carriers.

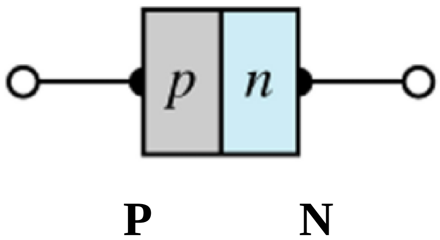
When N-type meets P-type

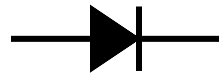


With the self-building field's expansion, drift of minority carriers is strengthened, while diffusion of majority carriers is weakened.

At last, the thermal equilibrium 动态平衡 is reached.

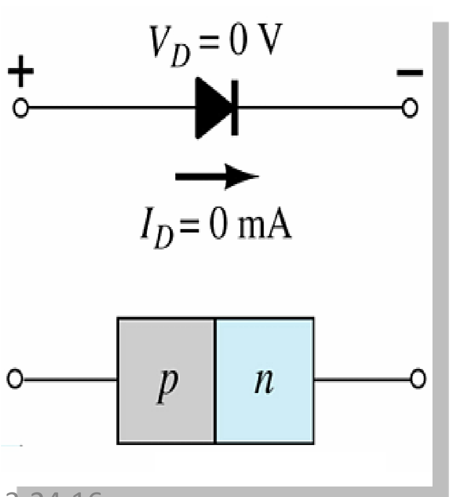
Semiconductor Diode

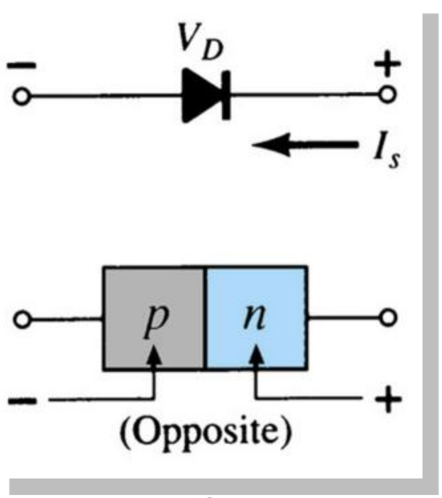


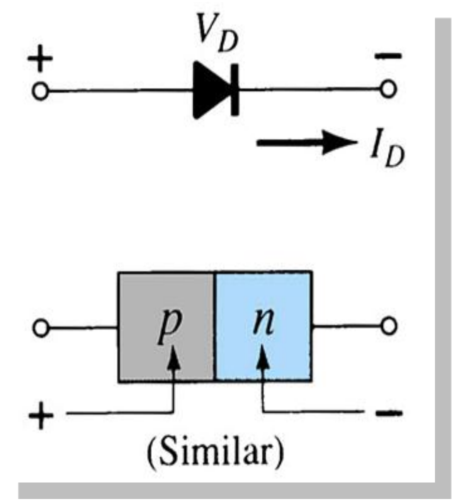


A diode (or p-n junction) has three operating conditions:

- **No bias**
- **Reverse bias**
- **Forward bias**

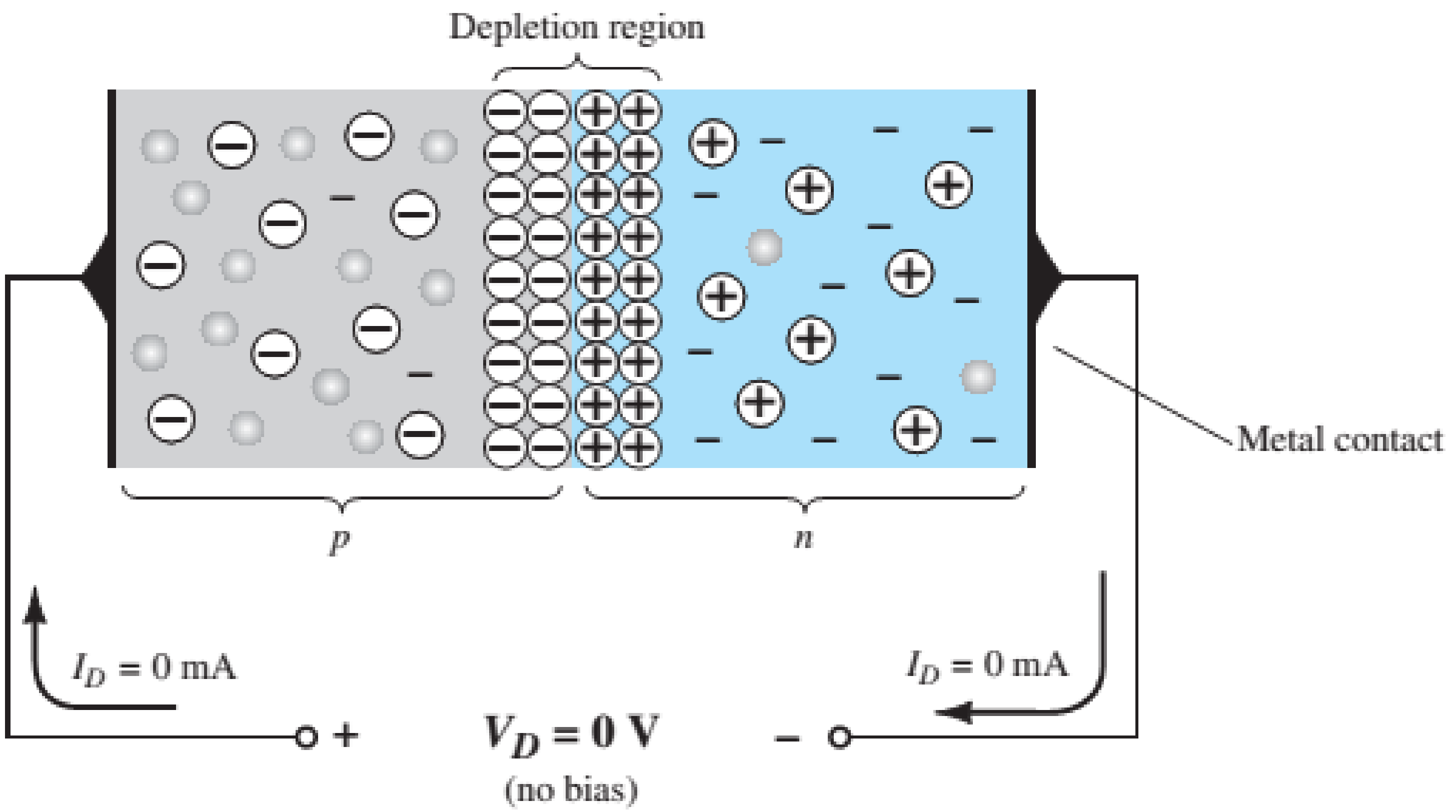






Semiconductor Diode

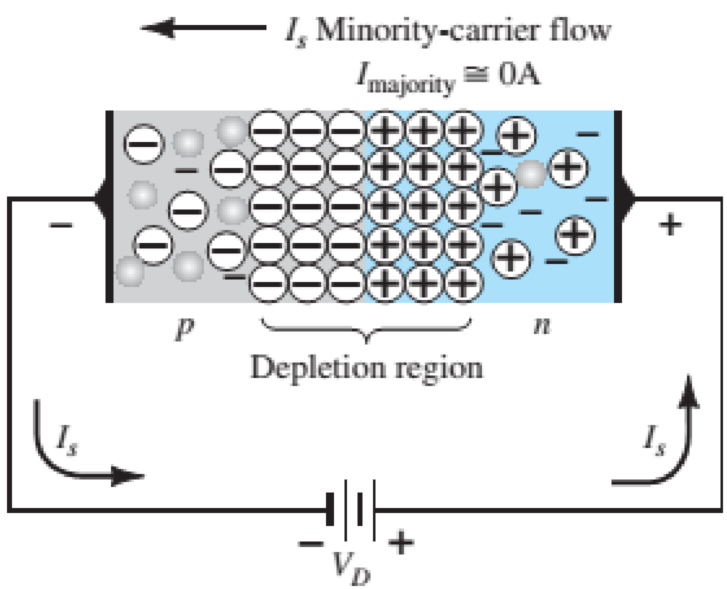
No Applied Bias



The current under no-bias conditions is zero.

Semiconductor Diode

Revease-Bias Condition



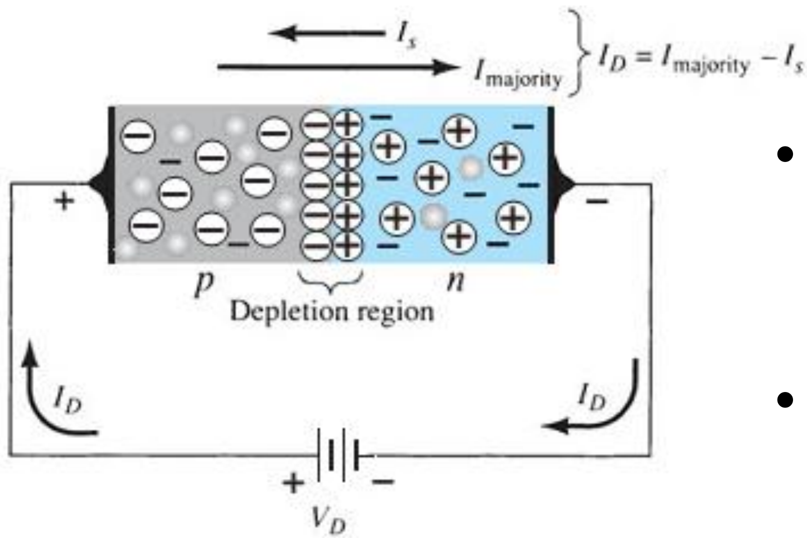
- **The reverse voltage causes the depletion layer to widen.**
- **The electrons in the *n*-type material are attracted toward the positive terminal.**
- **The holes in the *p*-type material are attracted toward the negative terminal.**

Blocking state 截止状态

Reverse biased p-n junction behaves like a resistor with a big value (normally above 100 kilo-Ohm).

Semiconductor Diode

Forward-Bias Condition

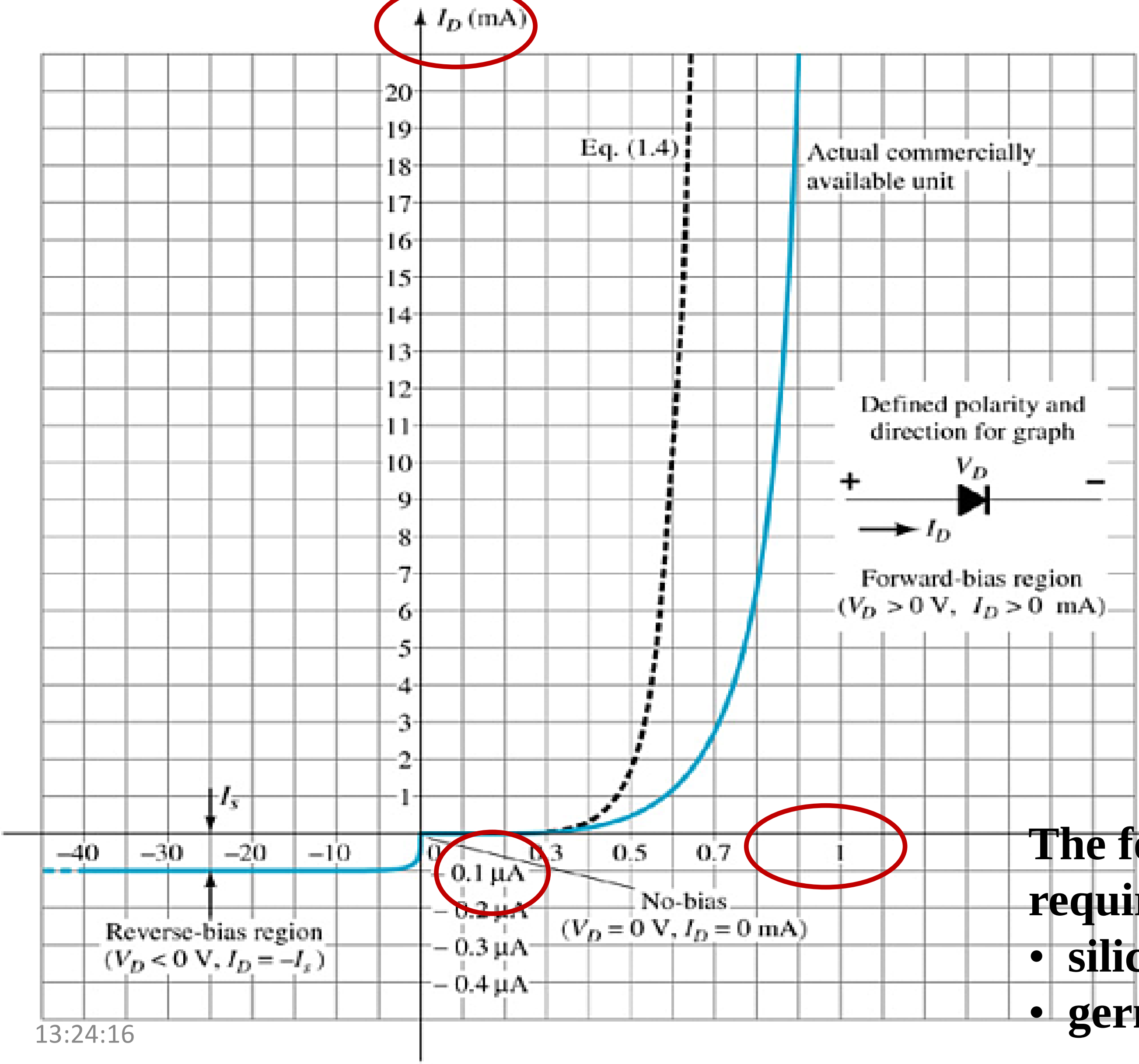


- **The forward voltage causes the depletion layer to narrow.**
- **The electrons and holes are pushed toward the *p-n* junction.**
- **The electrons and holes have sufficient energy to cross the *p-n* junction.**

Conduction state 导通状态

Forward biased p-n junction behave like a resistor with a small value (normally tens to hundreds Ohm).

The *I*-*V* Relationship



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The forward bias voltage required:

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

The *I*-*V* Relationship

$$Shockley's equation$$

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

V_T: thermal voltage(热电压)

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

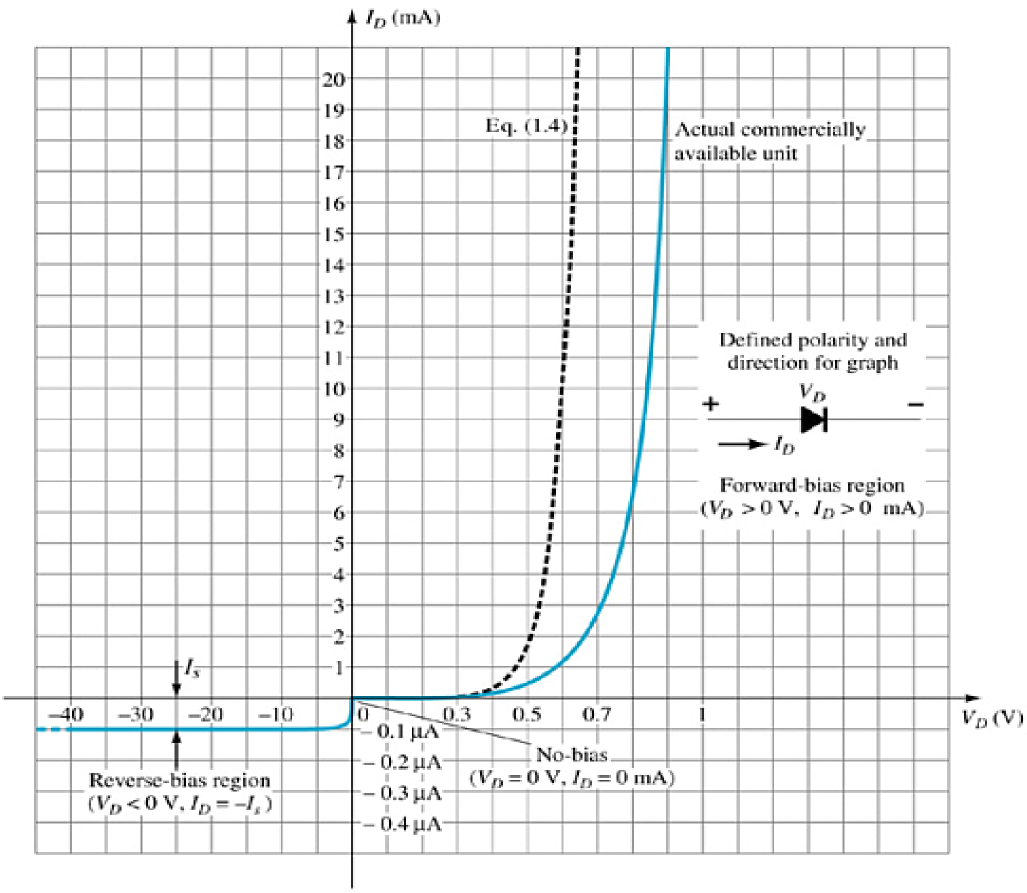
$$V_T \cong 26mV$$

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

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

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

$$I_D \cong -I_S$$



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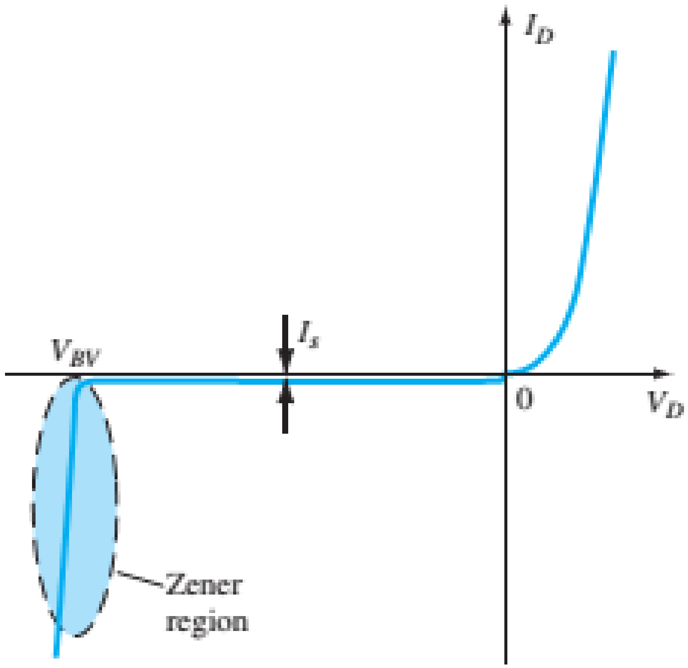
Zener Region

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

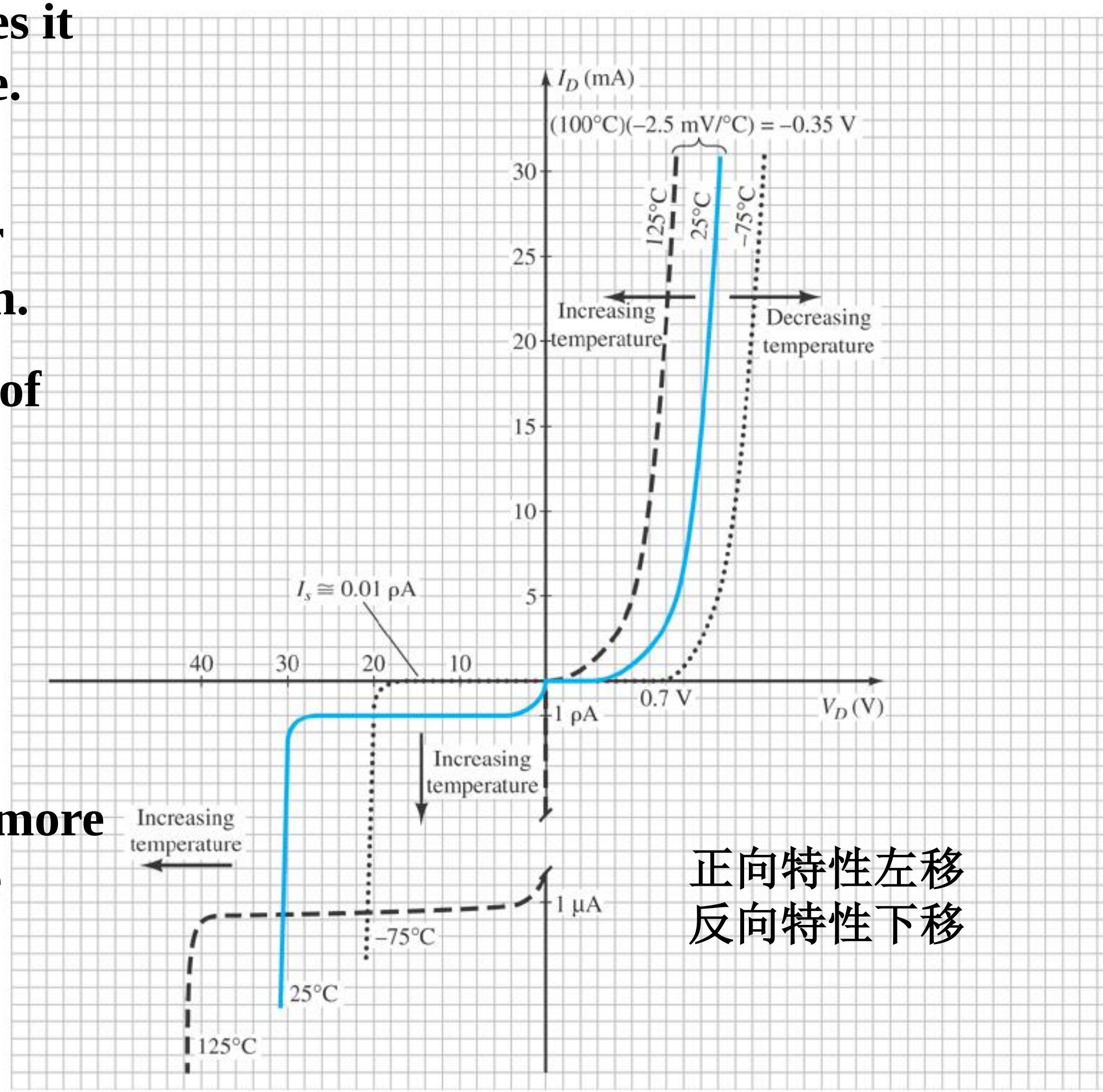
At some point the reverse bias voltage is so large the diode breaks down and the reverse current increases dramatically.



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)

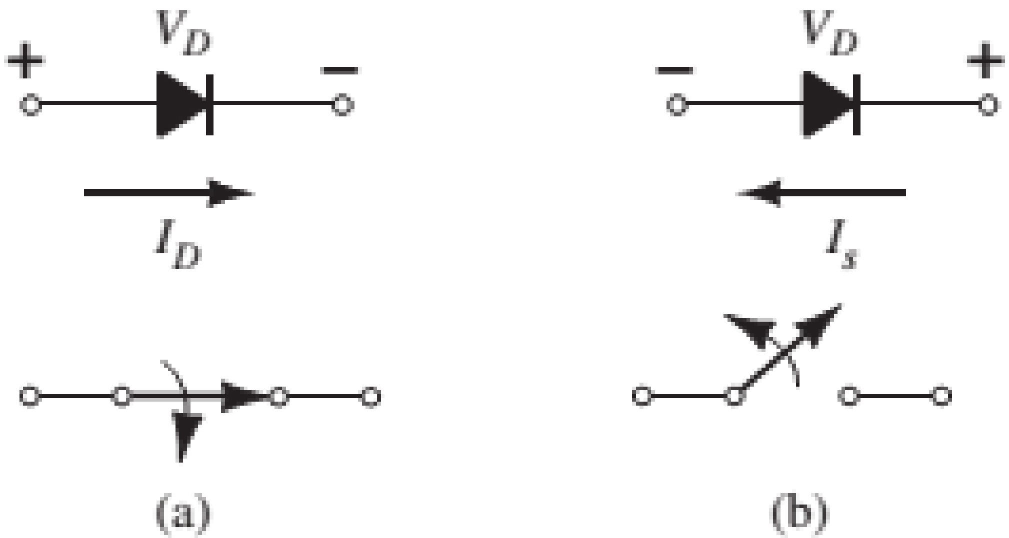
Temperature Effects

- 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.



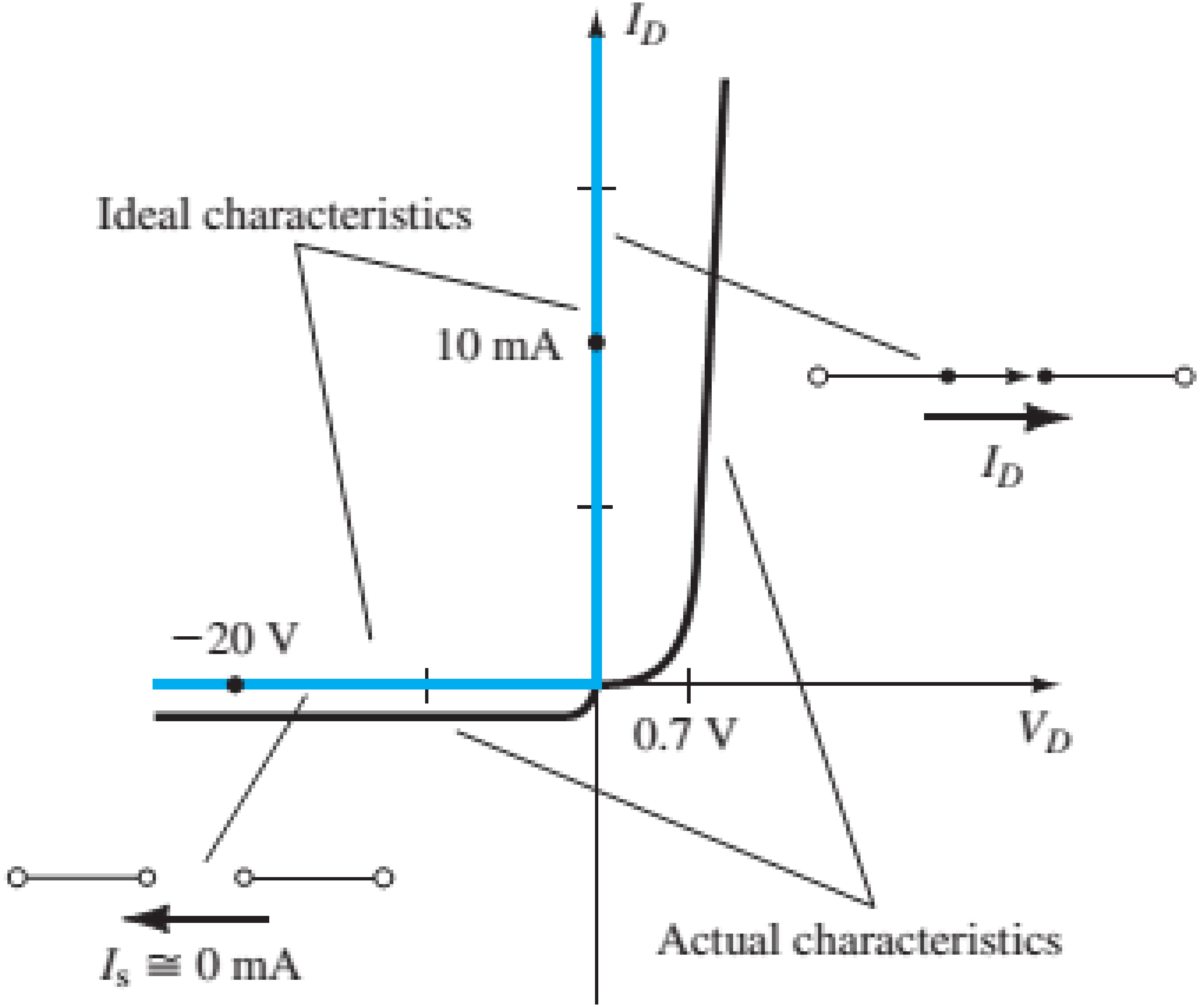
正向特性左移
反向特性下移

Ideal Versus Practical



The semiconductor diode behaves in a manner ***similar to a mechanical switch*** *in that it can control whether current will flow between it's two terminals.*

The semiconductor diode is different from a mechanical switch in the sense that when the switch is closed it will only permit current to flow ***in one direction****.*



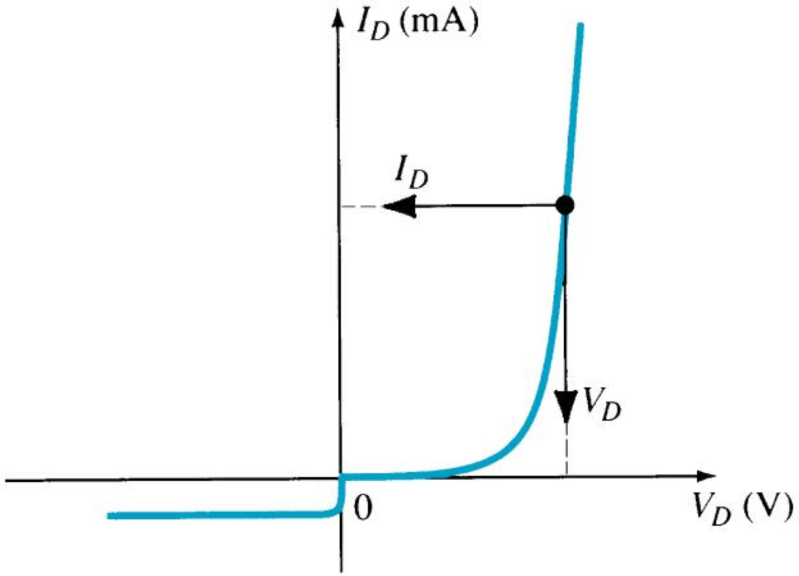
I_D
Ideal characteristics
10 mA
-20 V
0.7 V
V_D
I_D
$I_s \cong 0$ mA
Actual characteristics

Resistance Levels

As the operating point of a diode moves from one region to another the resistance of the diode will also change due to the nonlinear shape of the characteristic curve.

- 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).

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

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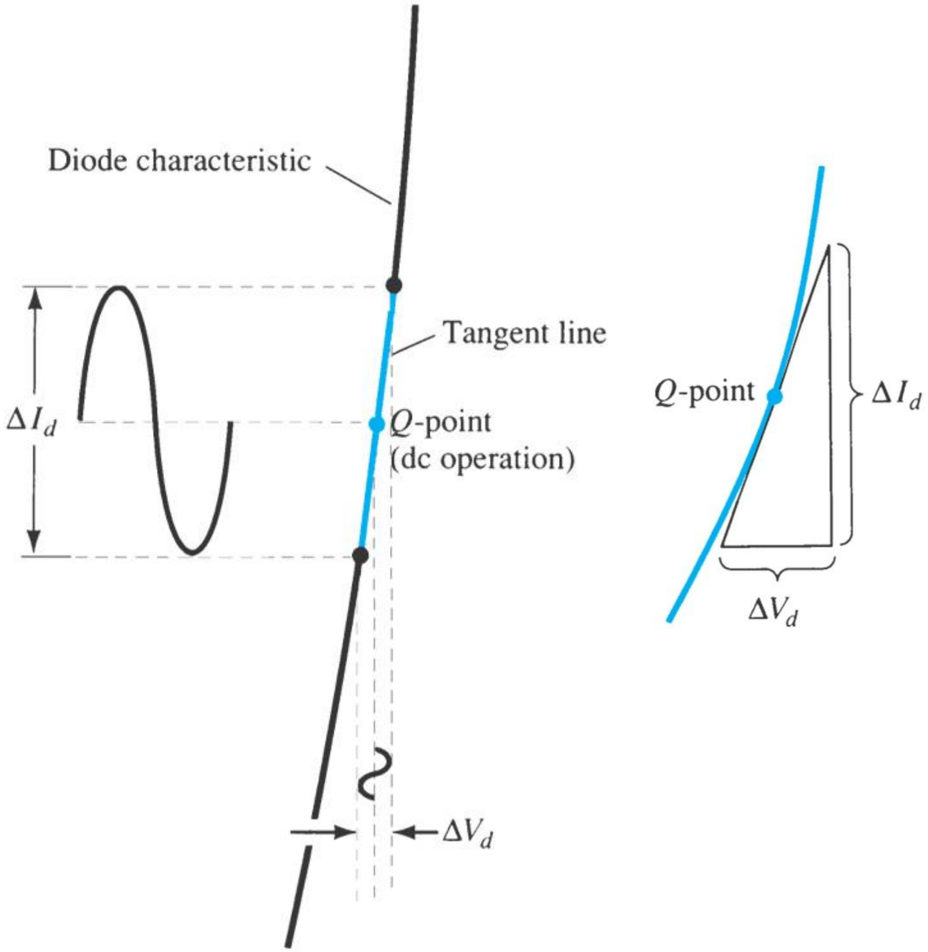
AC or Dynamic Resistance



$$r_d = \frac{26\,\text{mV}}{I_D}$$

- The ac resistance depends on DC operating point (I_D) in the diode.

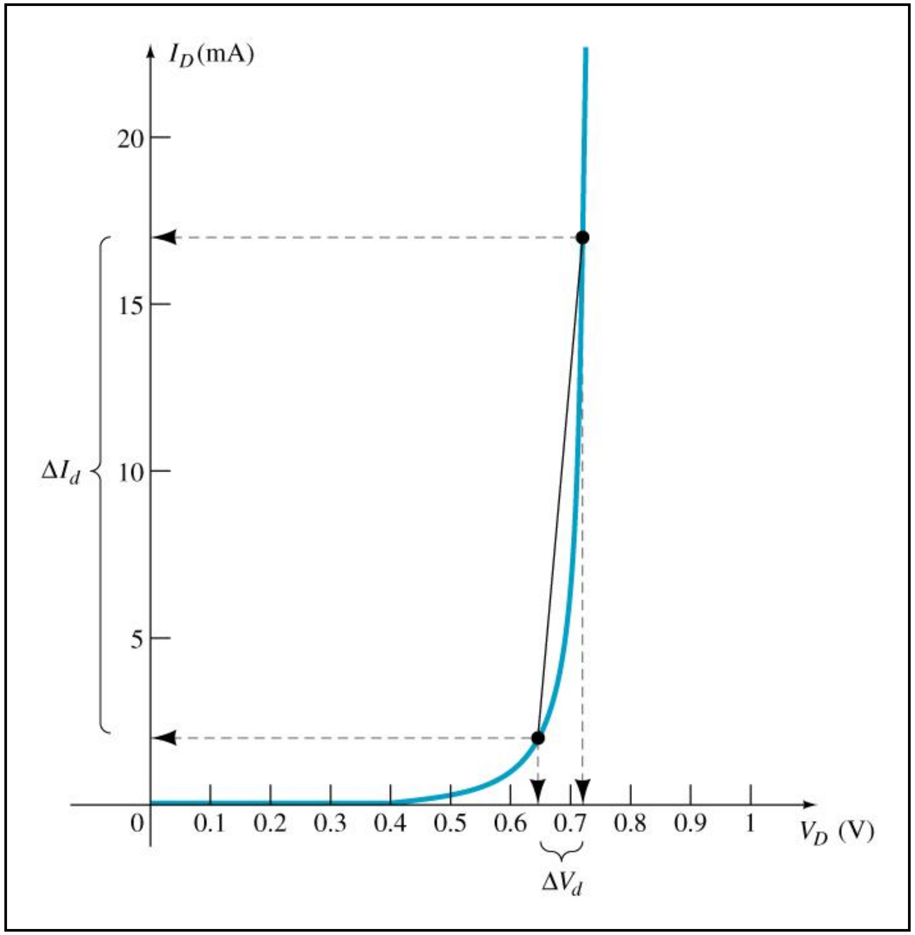
In the reverse bias region:

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

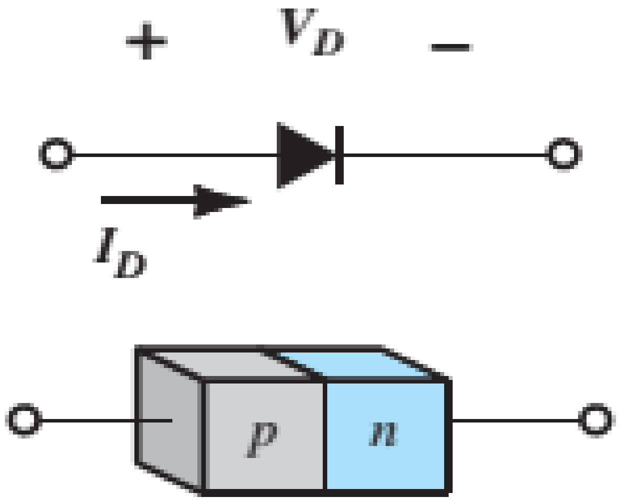
Average AC Resistance

$$r_{av} = \frac{\Delta V_d}{\Delta I_d} \bigg| \, pt.\, to\, pt.$$

AC resistance can be calculated using the current and voltage values for two points on the diode characteristic curve.



Diode Equivalent Circuits



Semiconductor diode

Two-terminal device

Nonlinear I-V charateristics

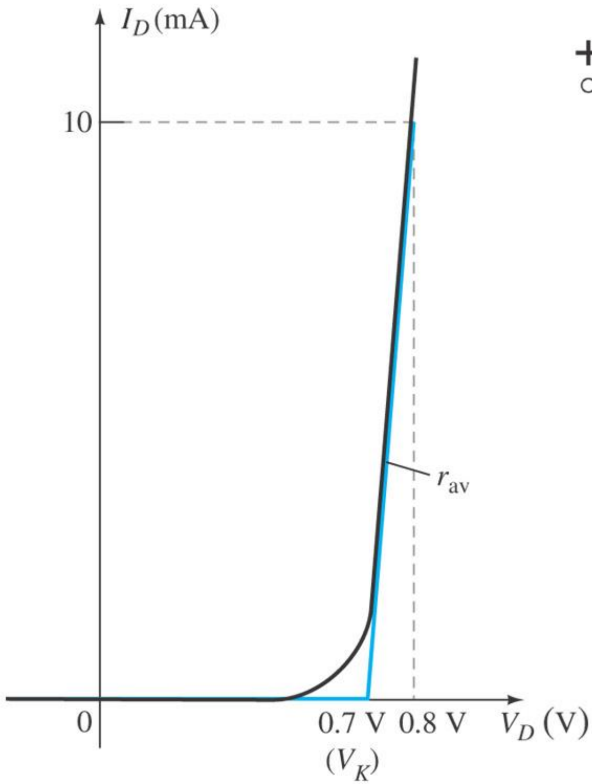
Diode Equivalent Circuits

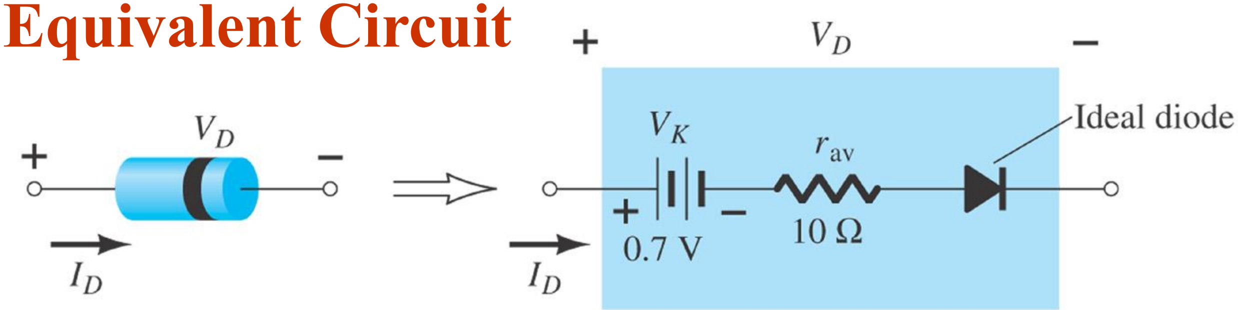
*An **equivalent circuit** is a combination of elements properly chosen to best represent the actual terminal characteristics of a device or system in a particular operating region.*

- Piecewise-Linear Equivalent Circuit
- Simplified Equivalent Circuit ♥
- Ideal Equivalent Circuit ♥

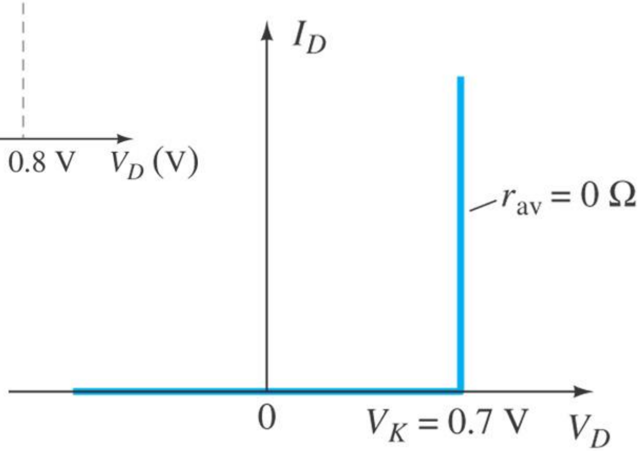
Diode Equivalent Circuits

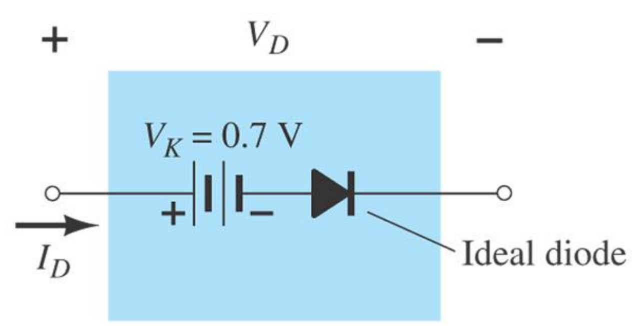
Piecewise-Linear Equivalent Circuit





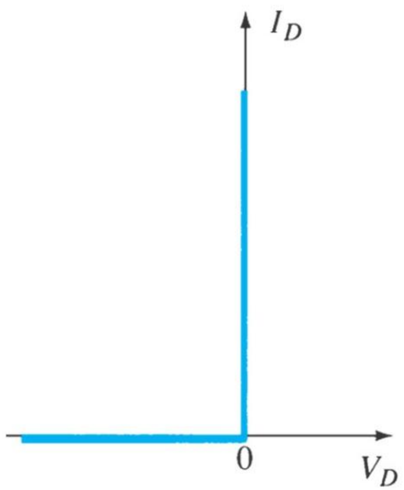
Simplified Equivalent Circuit

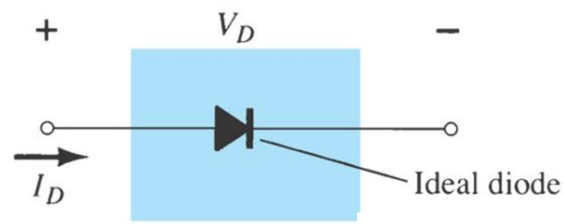




Diode Equivalent Circuits

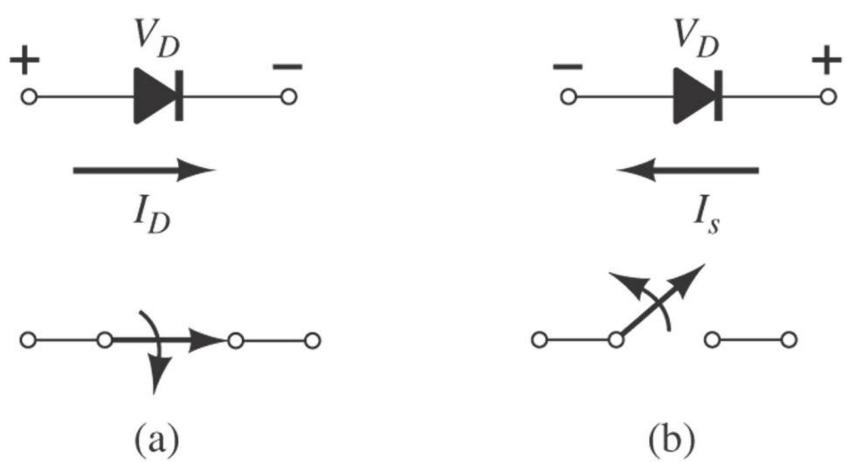
Ideal Equivalent Circuit

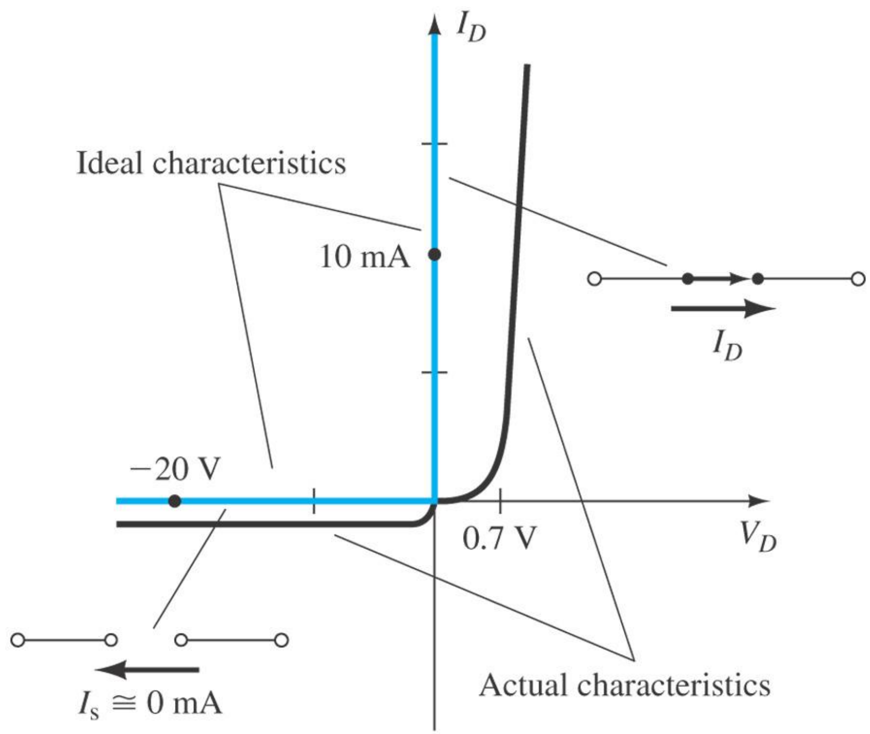




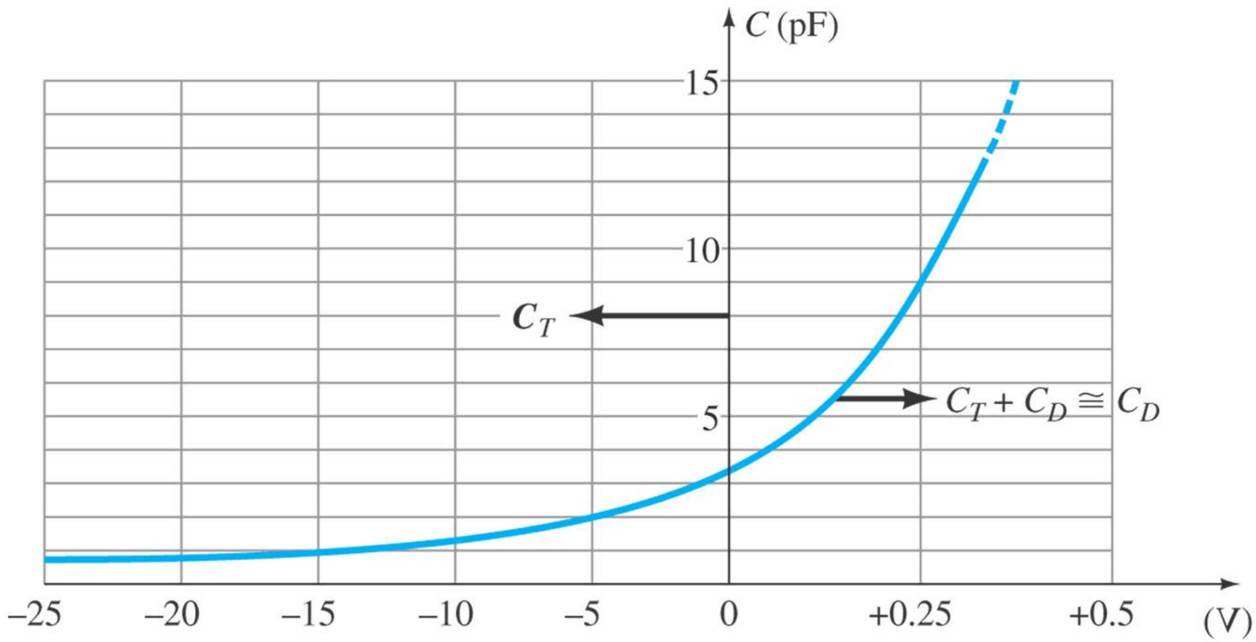
On-off Switch

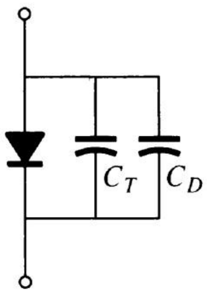
Conduction in one direction





Transition and Diffusion Capacitance





For low- or mid- frequency applications, the capacitor is normally not included in the diode symbol.

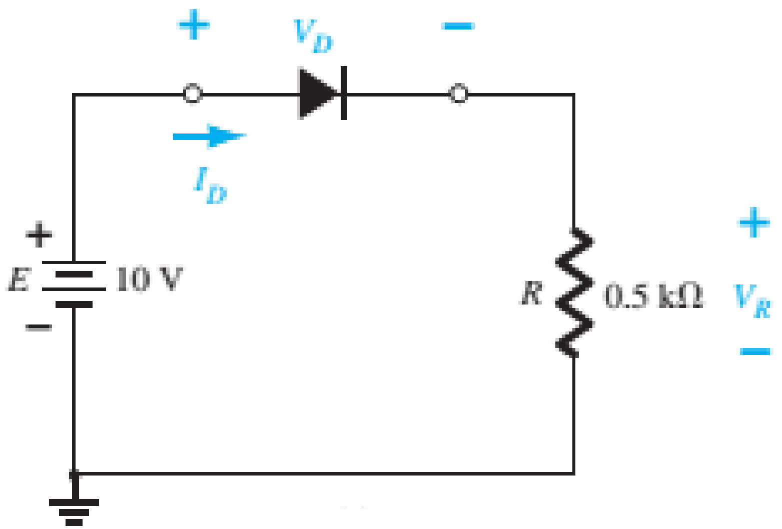
Diode Specification Sheets

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**

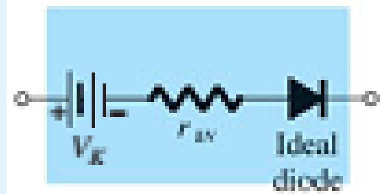
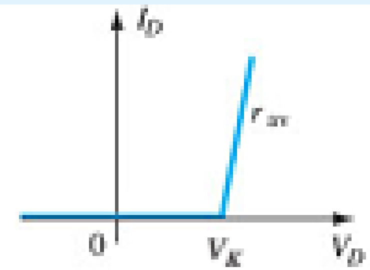
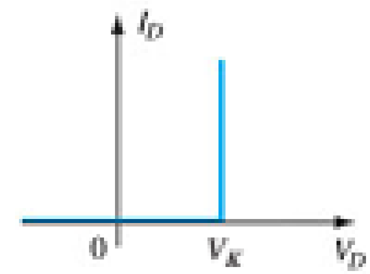
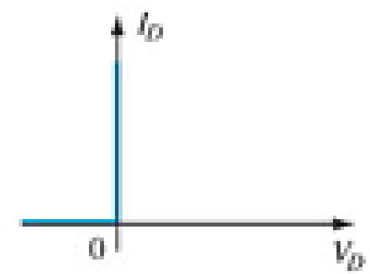
Example

1.Determine I_D, using the ideal diode model .

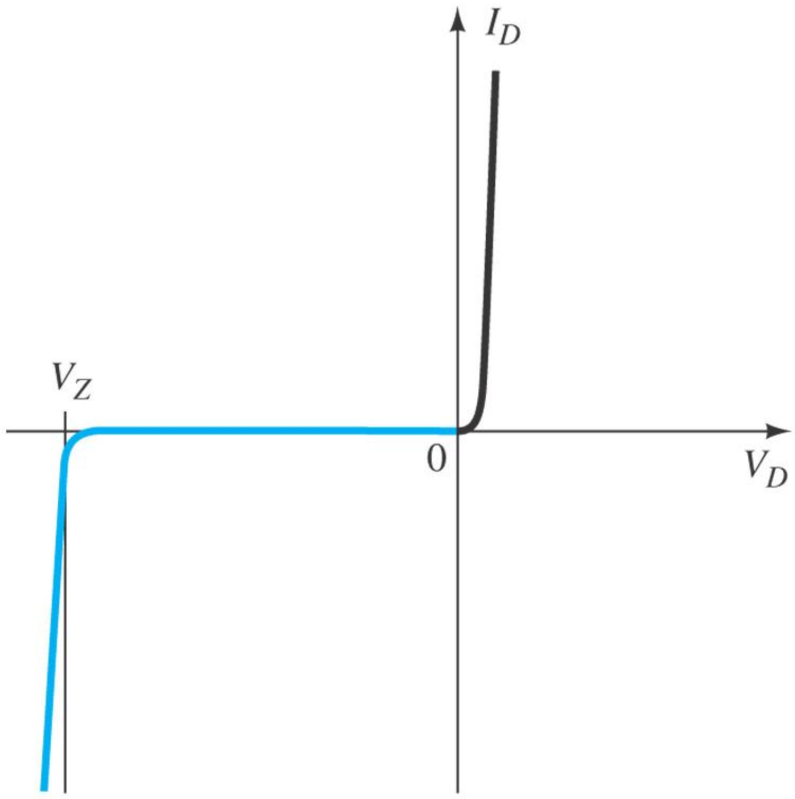


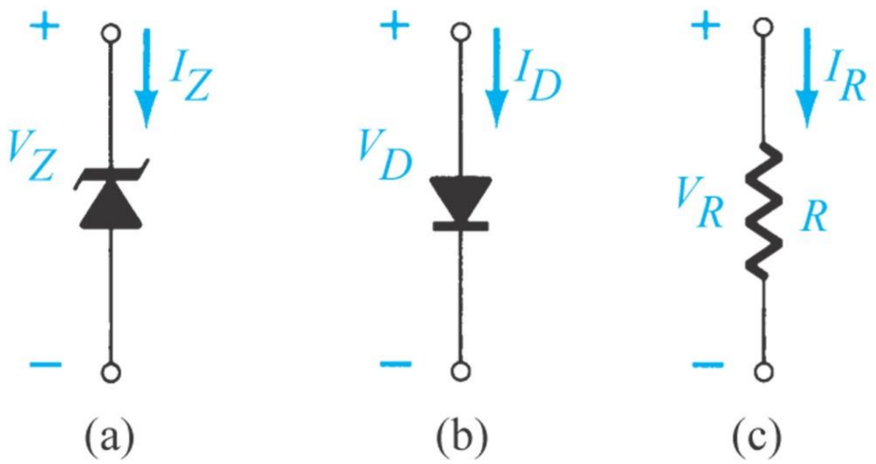
Kirchhoff's voltage law *applies both to nonlinear and linear circuits*

Diode Equivalent Circuits

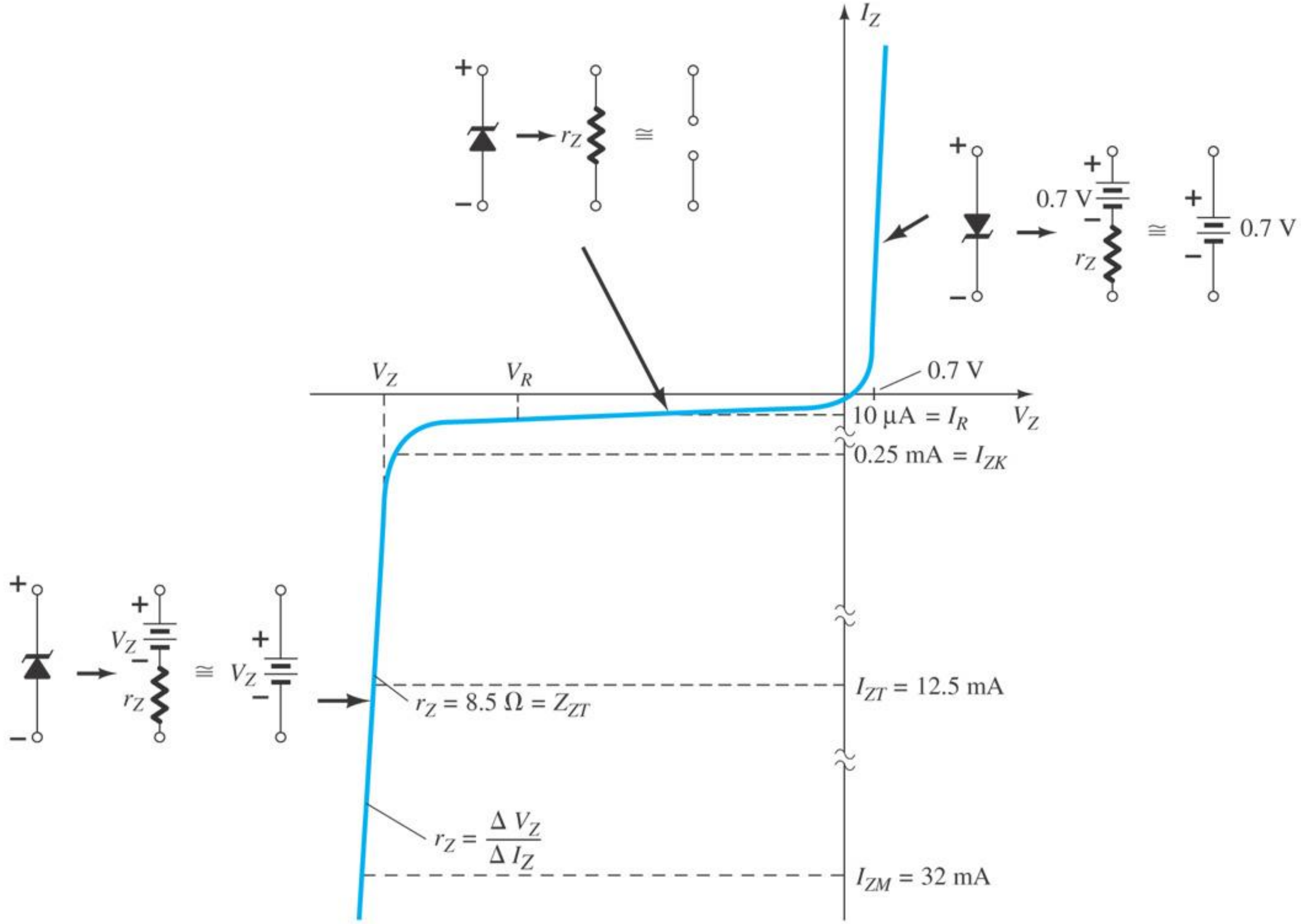
Type	Conditions	Model	Characteristics
Piecewise-linear model			
Simplified model	$R_{network} \gg r_{av}$		
Ideal device	$R_{network} \gg r_{av}$ $E_{network} \gg V_K$		

1.13 Zener Diodes

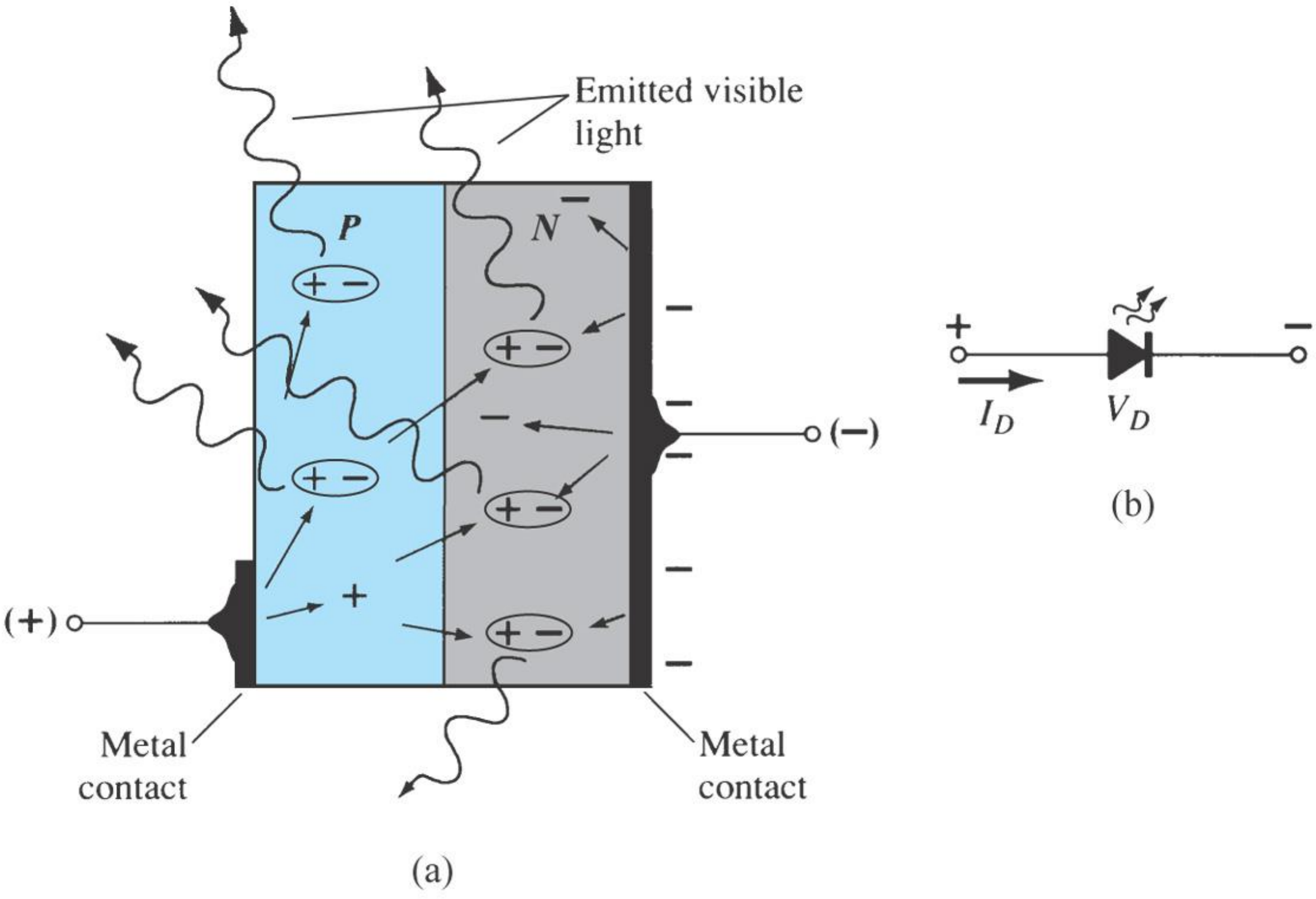




Zener Diodes



Light-Emitting Diodes



Summary

- Construction of a p-n junction
- Characteristics of a semiconductor diode (p-n junction)
    - Electrical conduction in only one direction
- Equivalent circuits for a semiconductor diode
- Zener Diodes

Chapter 2
Diodes Applications

Analysis of Diode Circuits

Methods of analysis

- **Graphical Aalysis(**using the actual characteristics**)**

The graphical analysis technique is all about finding the current and voltage levels that will satisfy both the characteristics of the diode and the chosen network parameters at the same time.

- **Equivalent Model Analysis**

Applying an approximate model for the device

Graphical Analysis(Load-Line Analysis)

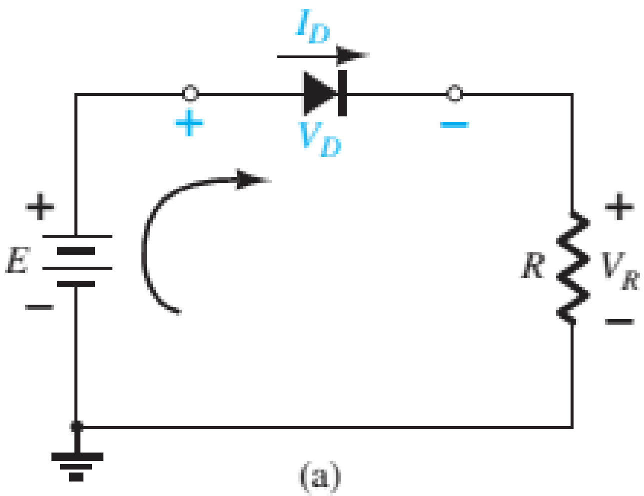
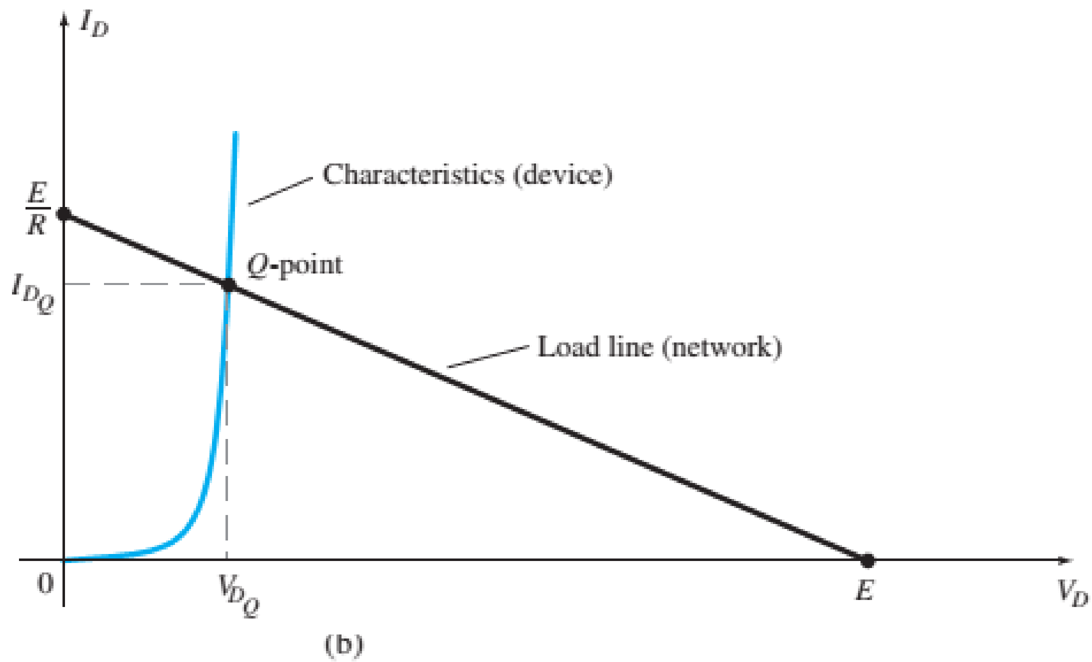


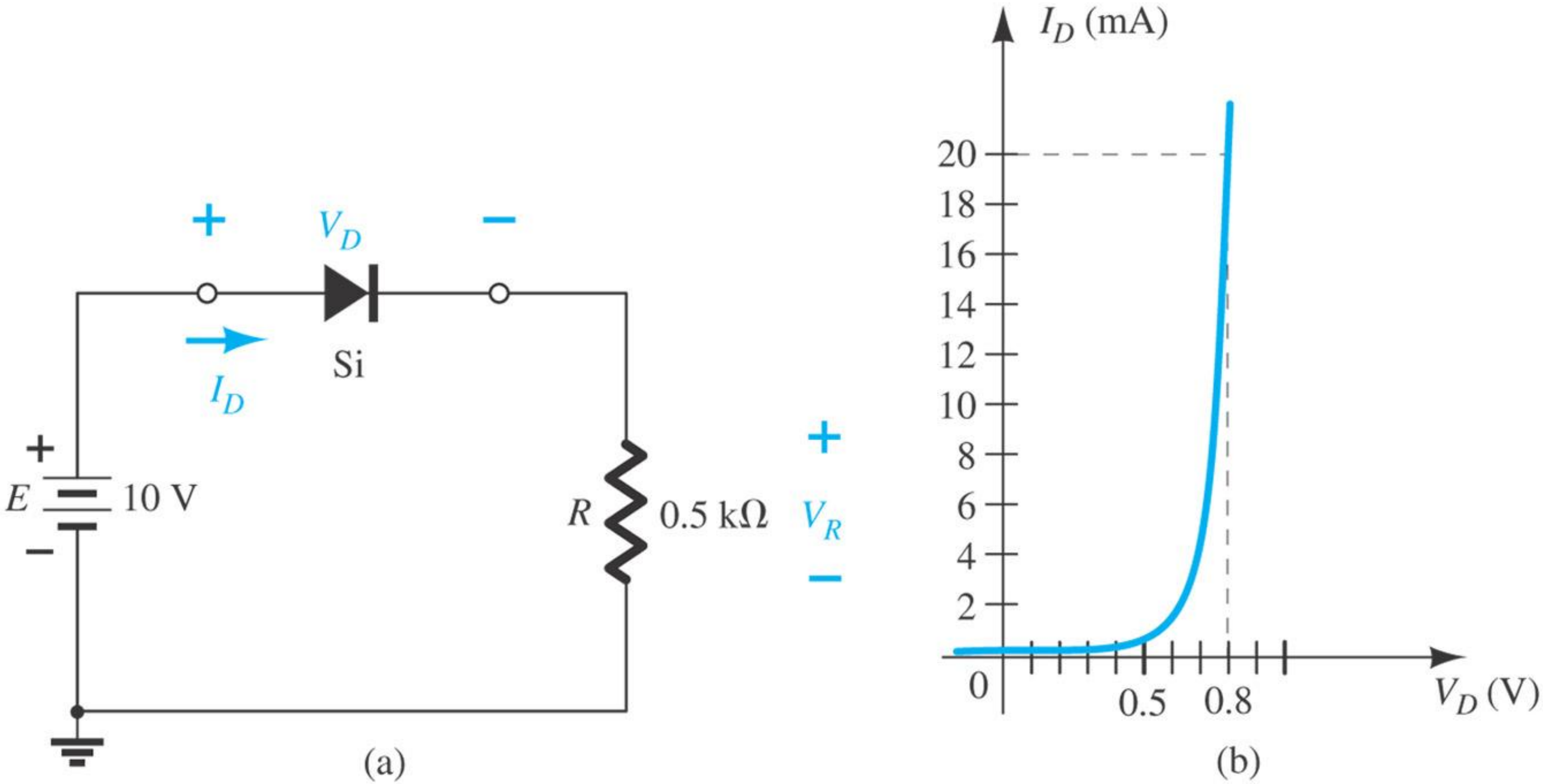
Fig 2.1 Circuit

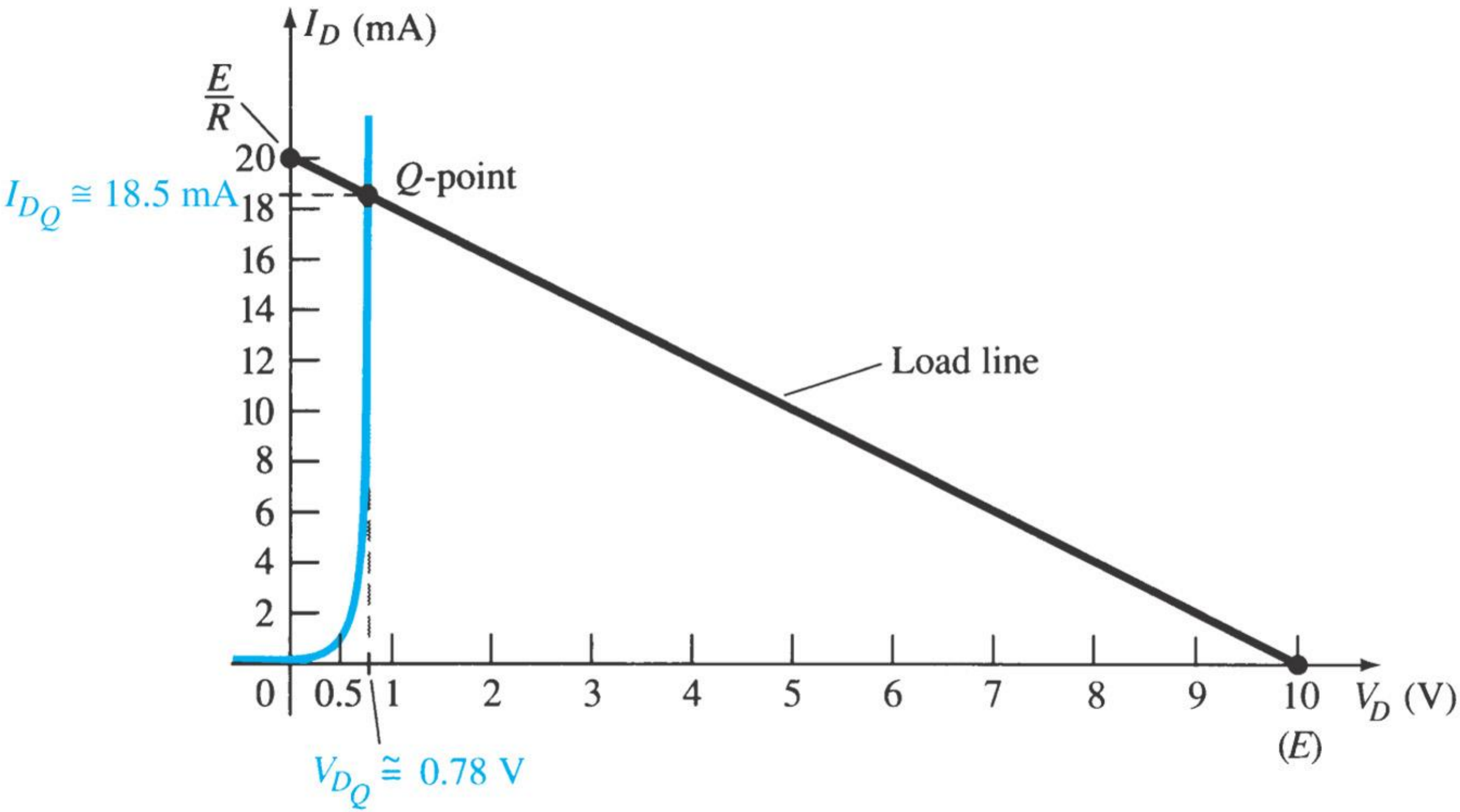


The load line is determined solely by the applied network,where the characteristics are defined by the chosen device.

Quiesent Point: abbreviated "Q-point" to reflect its "still, unmoving" qualities as defined by a dc network.

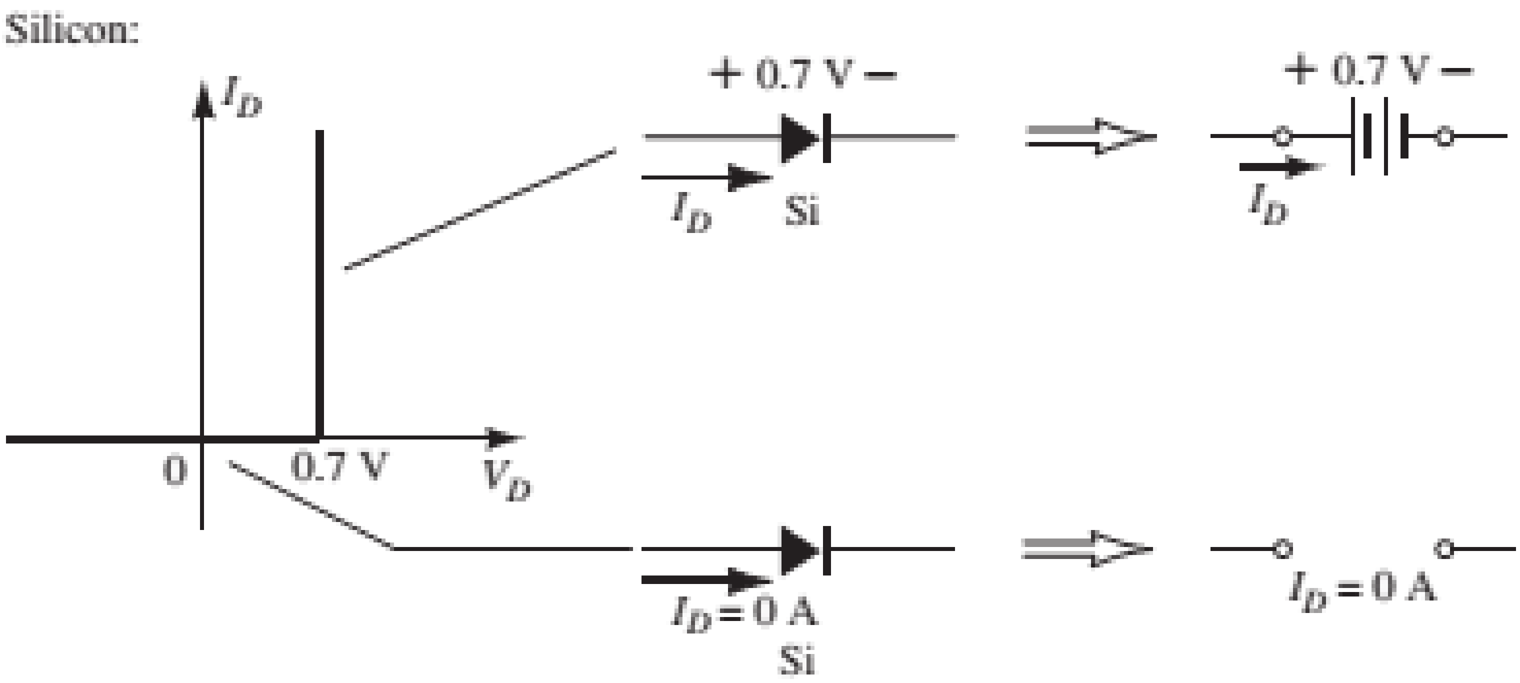
Example 2.1





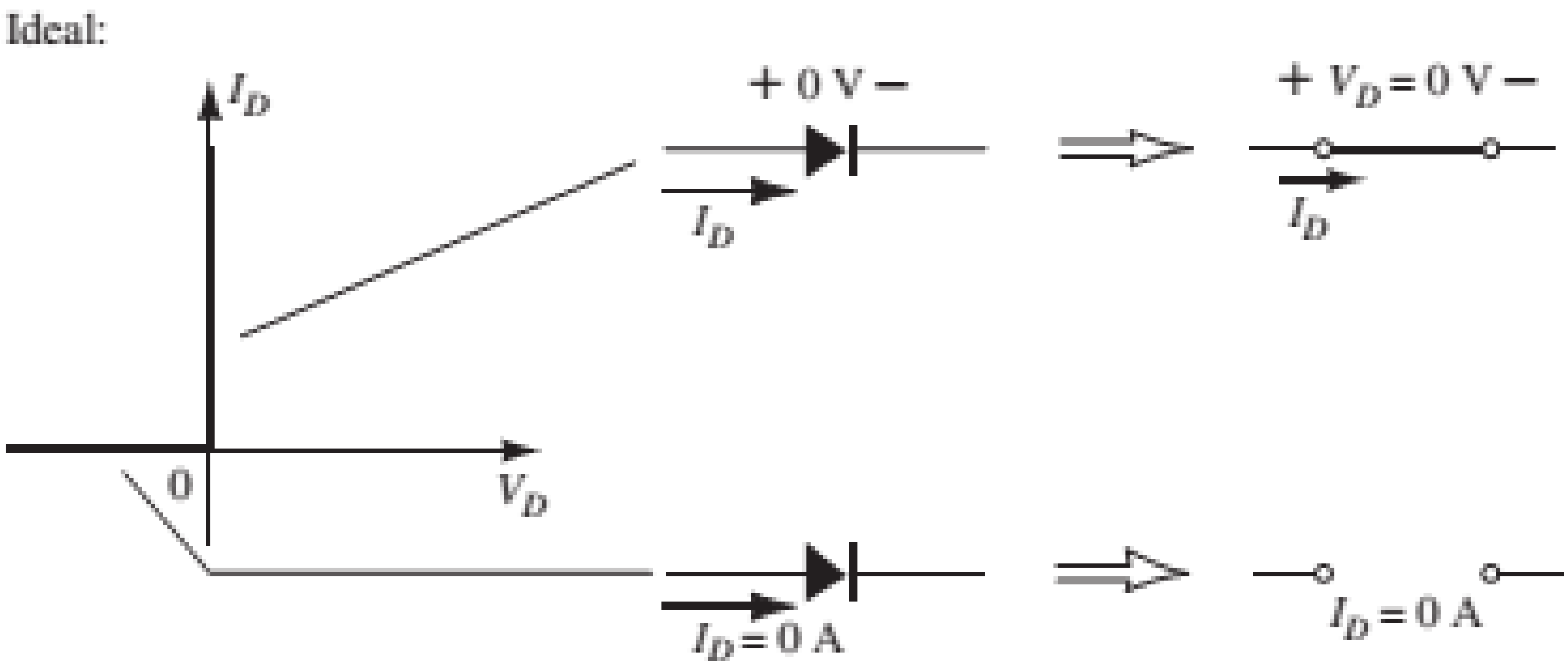
I_D (mA)
$\frac{E}{R}$
20
$I_{D_Q} \cong 18.5$ mA
18
16
14
12
10
8
6
4
2
Q-point
Load line
0
0.5
1
2
3
4
5
6
7
8
9
10
(E)
V_D (V)
$V_{D_Q} \cong 0.78$ V

Equivalent Model Analysis



Approximate semiconductor diode model

Equivalent Model Analysis



Note: *The forward resistance of the diode is usually so small compared to the other series elements of the network that it can be ignored.*

Equivalent Model Analysis

- For each configuration the state of each diode must first be determined.

In general, a diode is in the "on" state if the current estabished by the applied source is such that its direction matches that of the arrow in the diode symbol, and $V_D \geq 0.7V$ *for silicon,* $V_D \geq 0.3V$ *for germanium.* （*Page 69*）

13:24:16

Equivalent Model Analysis

*For each configuration, **mentally** replace the diodes with resistive elements and note the resulting direction is a "match" with the arrow in the diode symbol, conduction through the diode will occur and the device is in the "on" stat. The description above is, of course, contingent on the supply having a voltage greater than the "turn-on" voltage of each diode.*

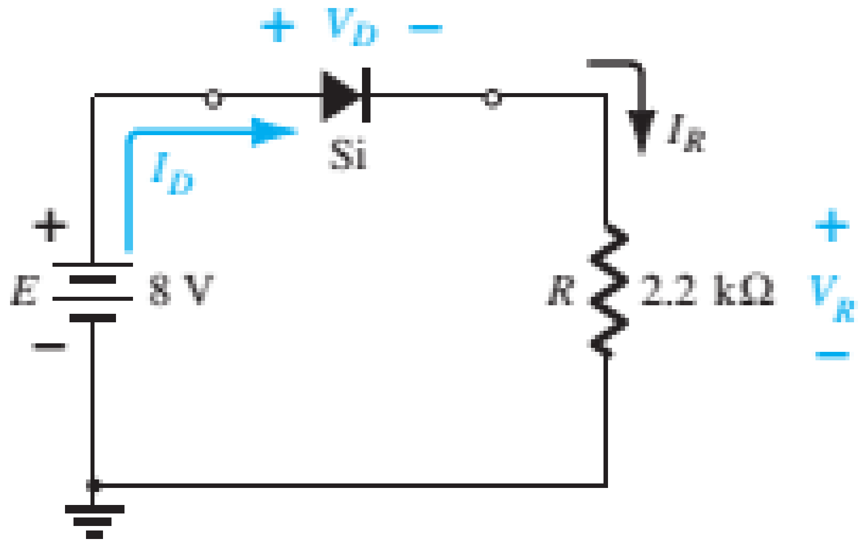
Equivalent Model Analysis

- If a diode is in the “on” state, one can either place a 0.7V drop across the element or redraw the network with the equivalent circuit as defined above.

Always keep in mide that under any circumstances — dc, ac instantaneous values, pulses, and so on— Kirchhoff’s voltage law must be satisfied!

Equivalent Model Analysis

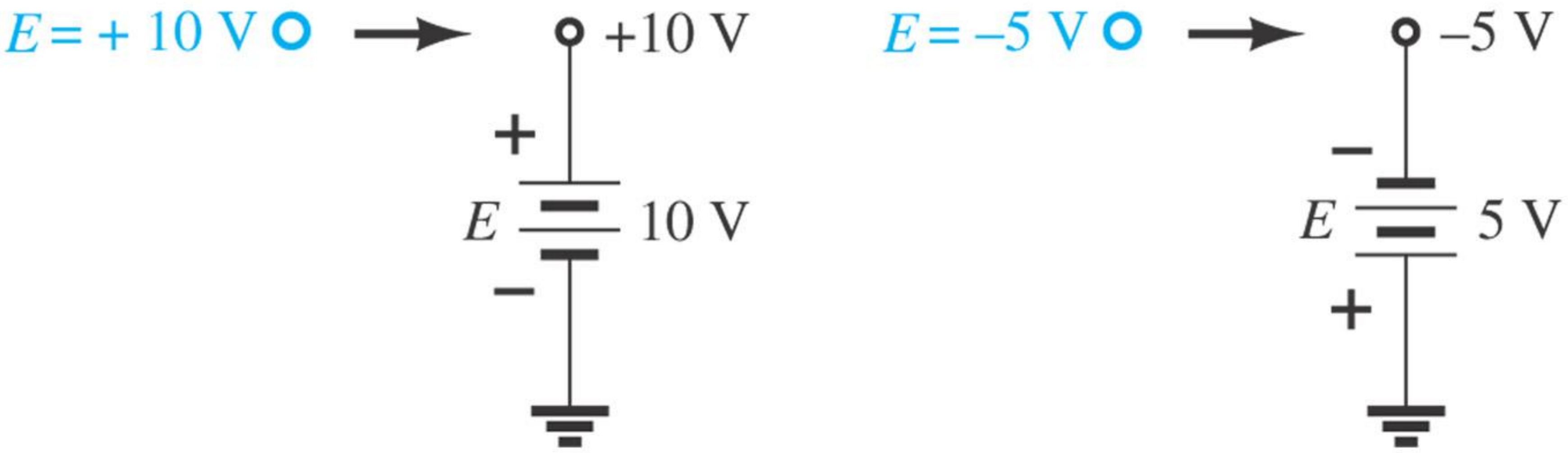
Example



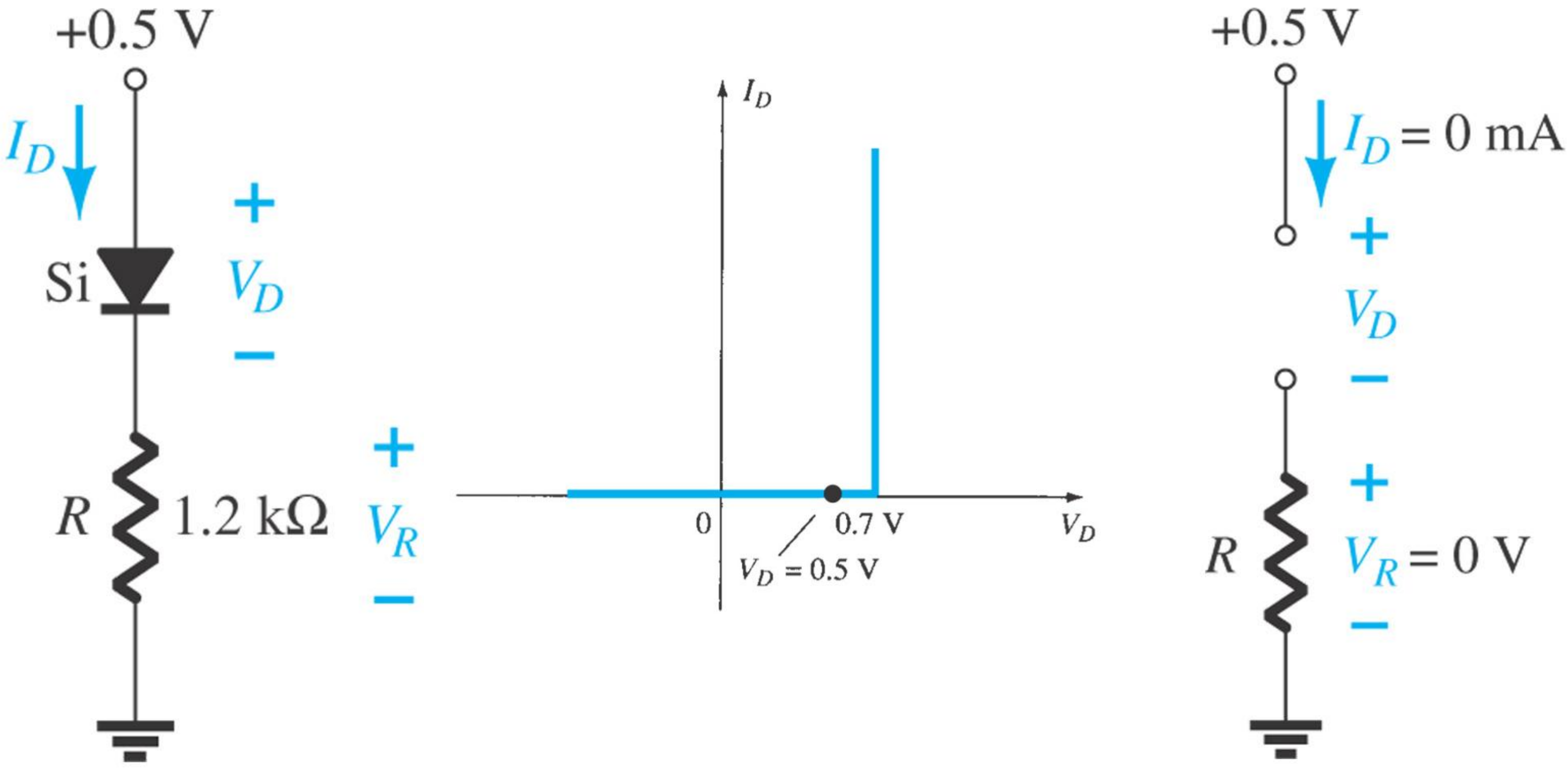
Repeat the example with the diode reversed.

An open circuit can have any voltage across its terminals, but the current is always 0 A. A short circuit has a 0-V drop across its terminals, but the current is limited only by the surrounding network.

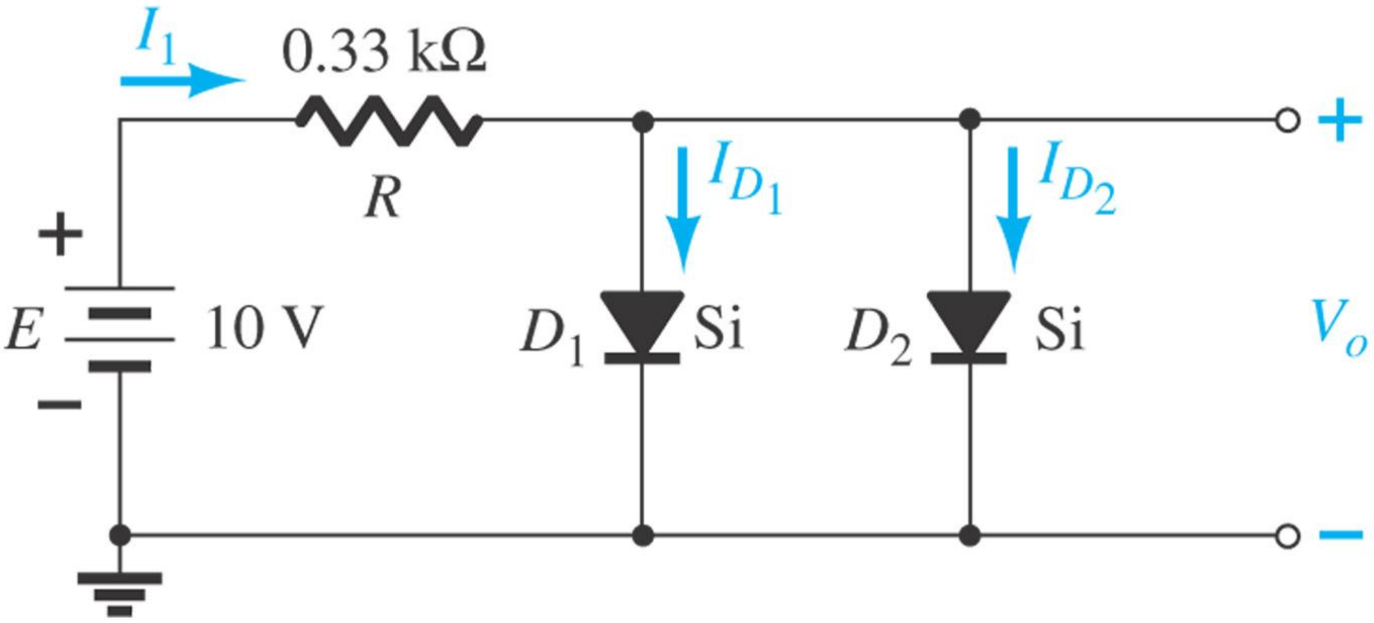
Notation:



Example:For the series diode configuration of Fig. 2.1 , determineV_D,V_R , andI_D



Determine V_O, I_1, I_{D1}, and I_{D2} for the parallel diode configuration of Fig. 2.2



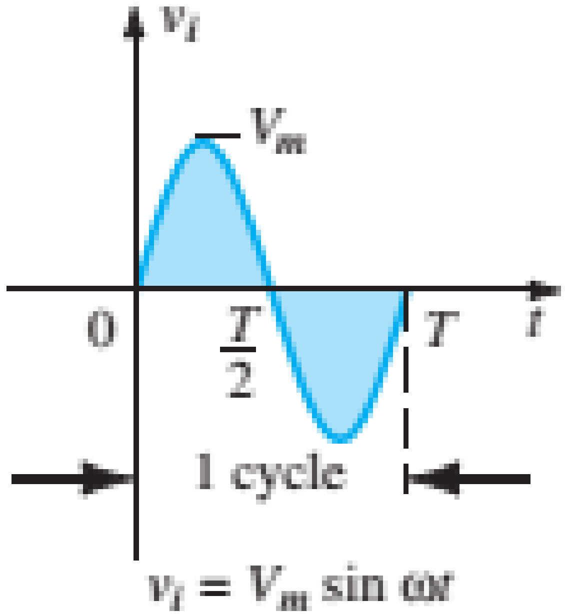
The Applications of Diode Circuits

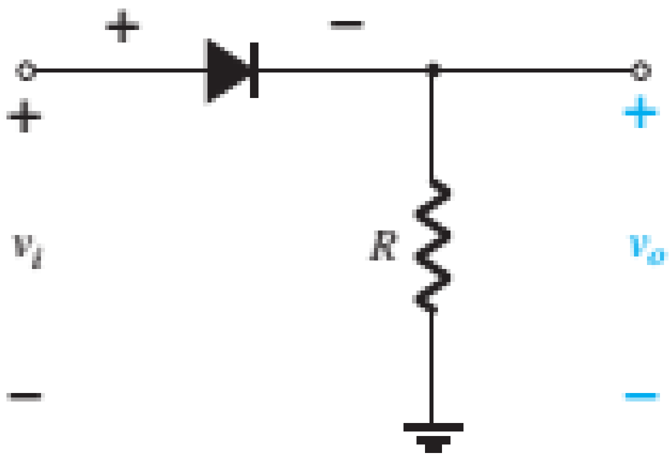
- Rectifier circuits(整流电路)
  - Half-wave rectifier
  - Full-wave rectifier

Use the ideal model

- Clippers*（限幅电路）
- Clampers*（钳位电路）

Half-wave Rectifier



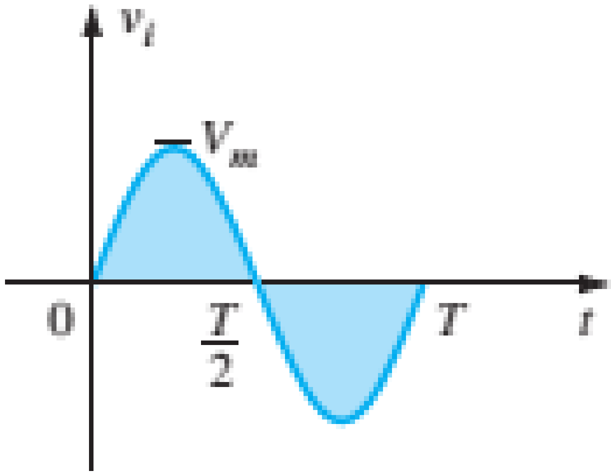


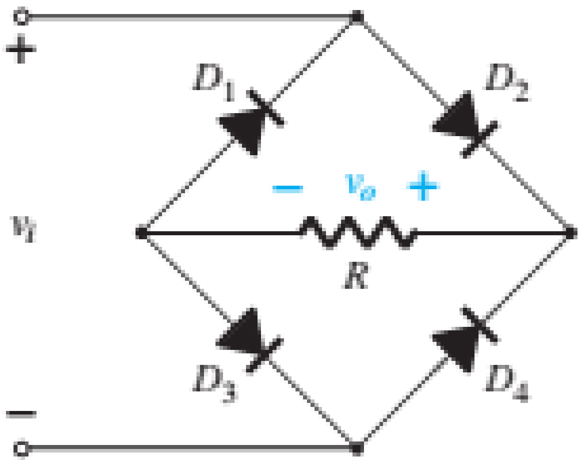
Page 76: Fig 2.27

$$V_{dc} = 0.318 V_m$$

$$PIV\ rating \geq V_m$$

Full-wave Rectifier





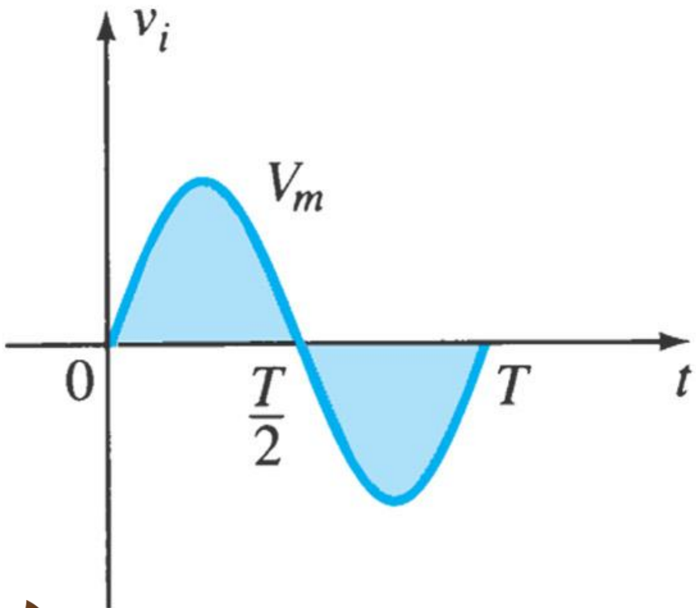
Page 78~79

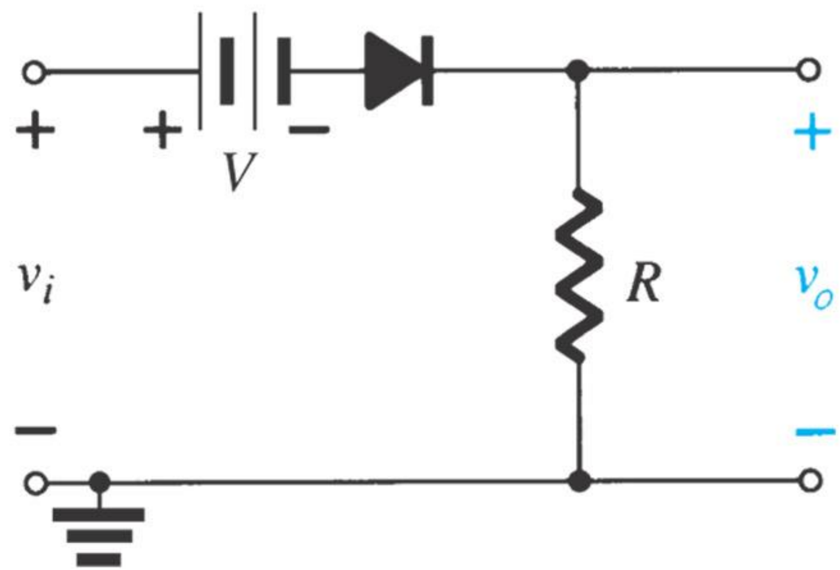
$$V_{dc} = 0.636V_m$$

$$PIV\ rating \geq V_m$$

Clippers

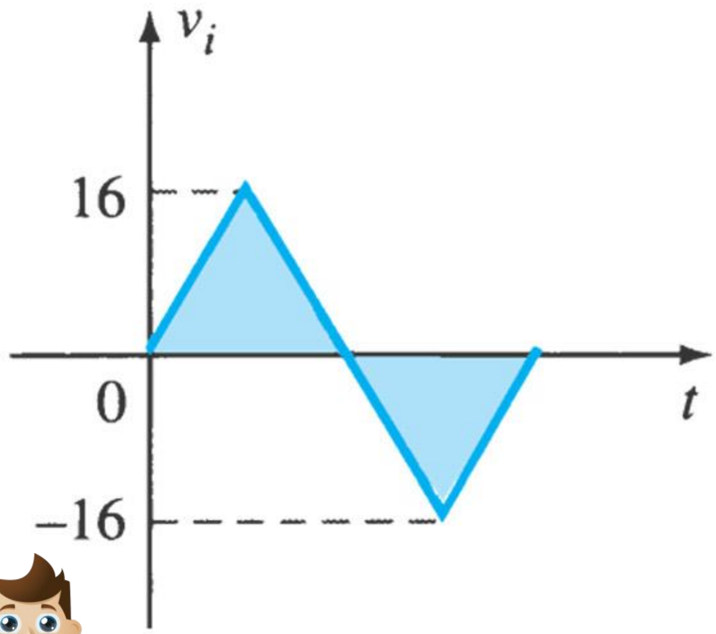
Series

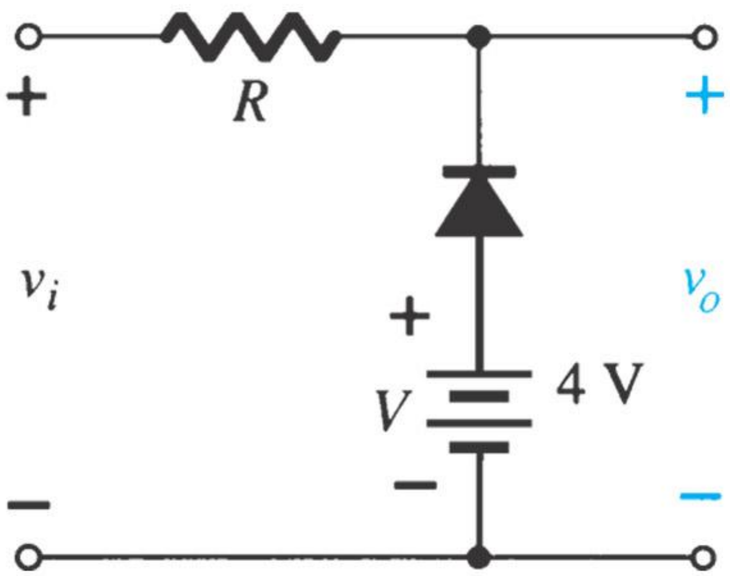




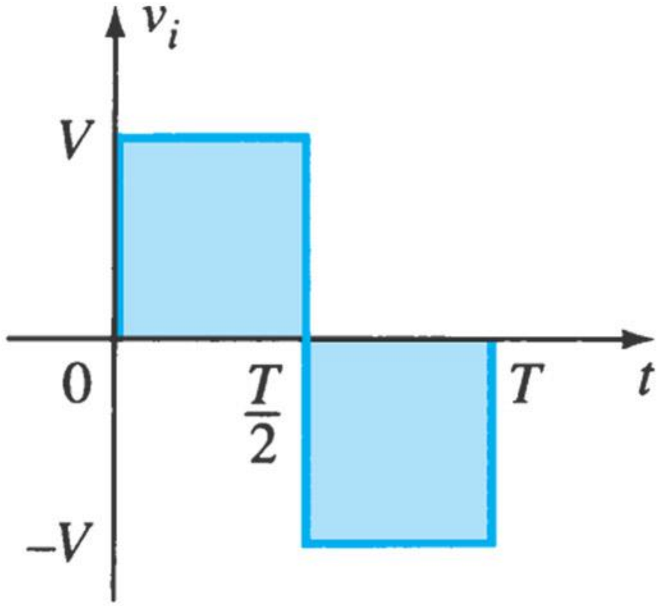
Clippers

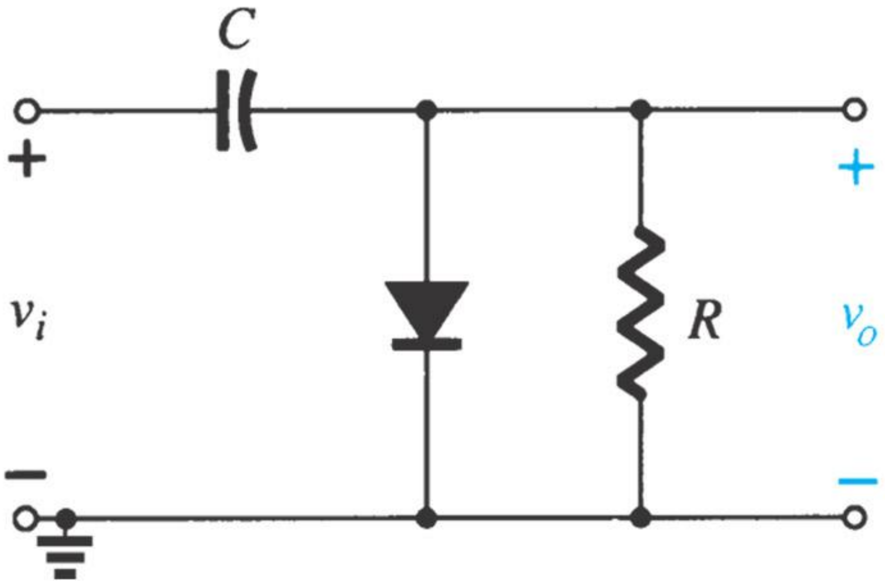
Parallel



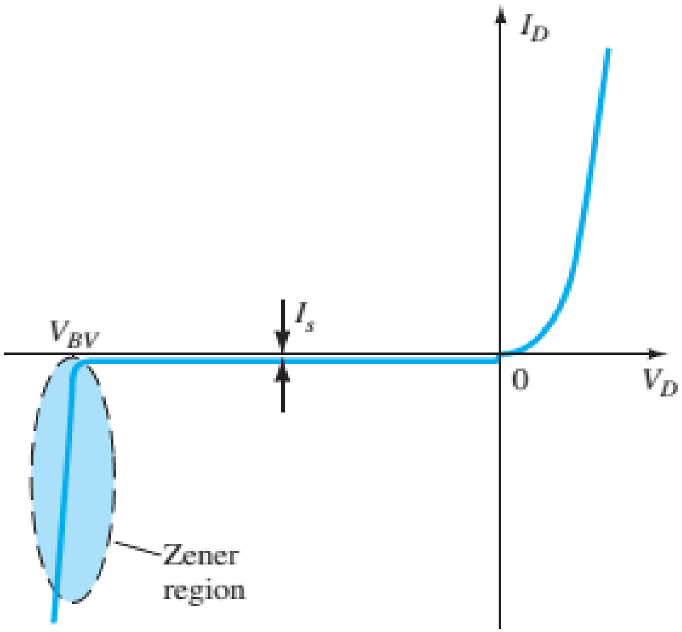


Clamper

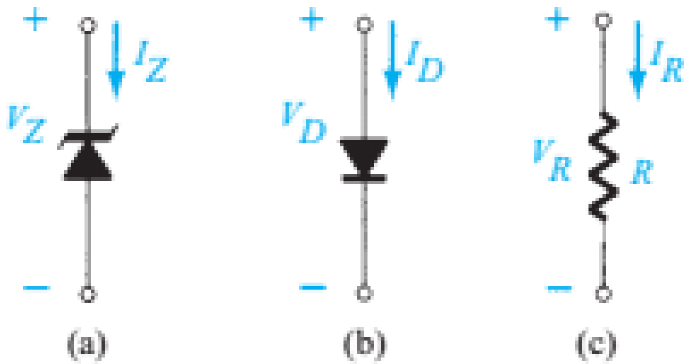




Zener Diodes



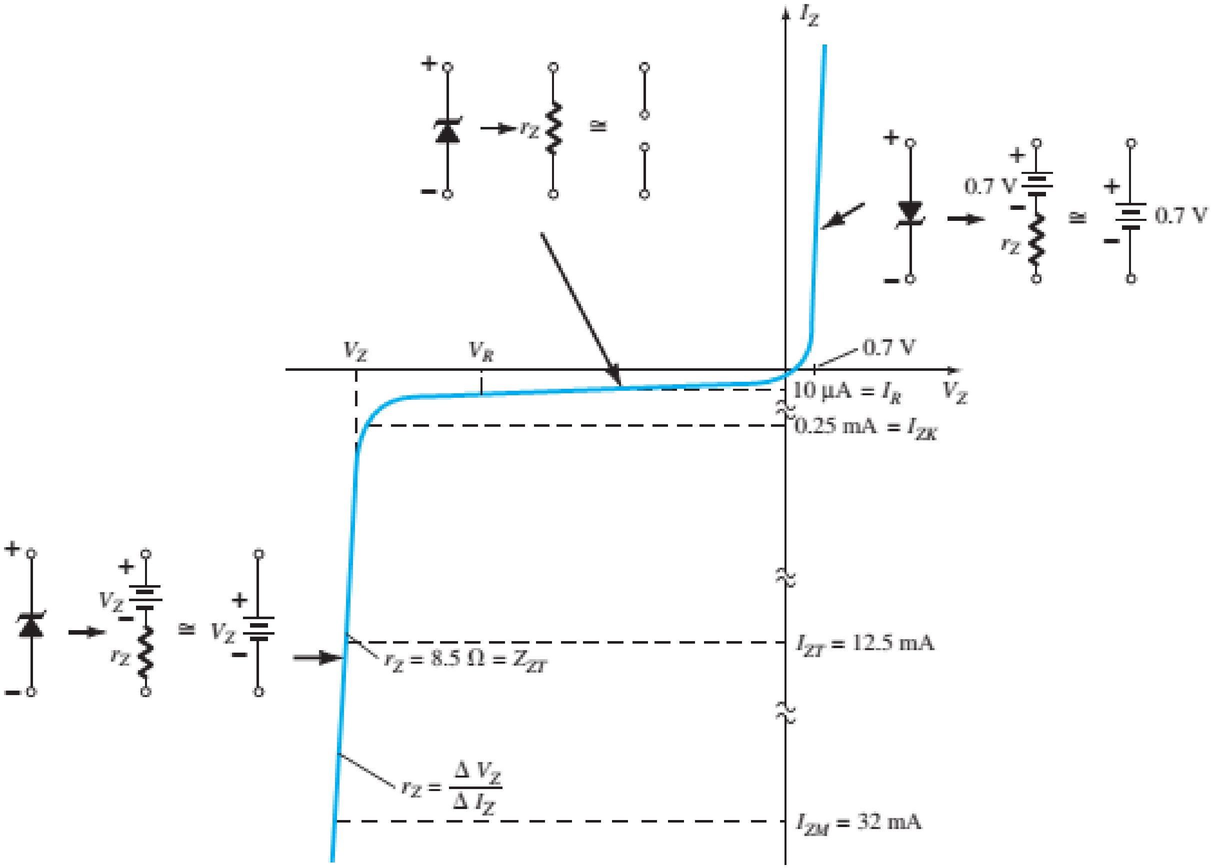
Zener region



Conduction direction

Semiconductor diode: support a current in the direction of the arrow in the symbol.
Zener diode: support a current opposite to that of the arrow in the symbol.

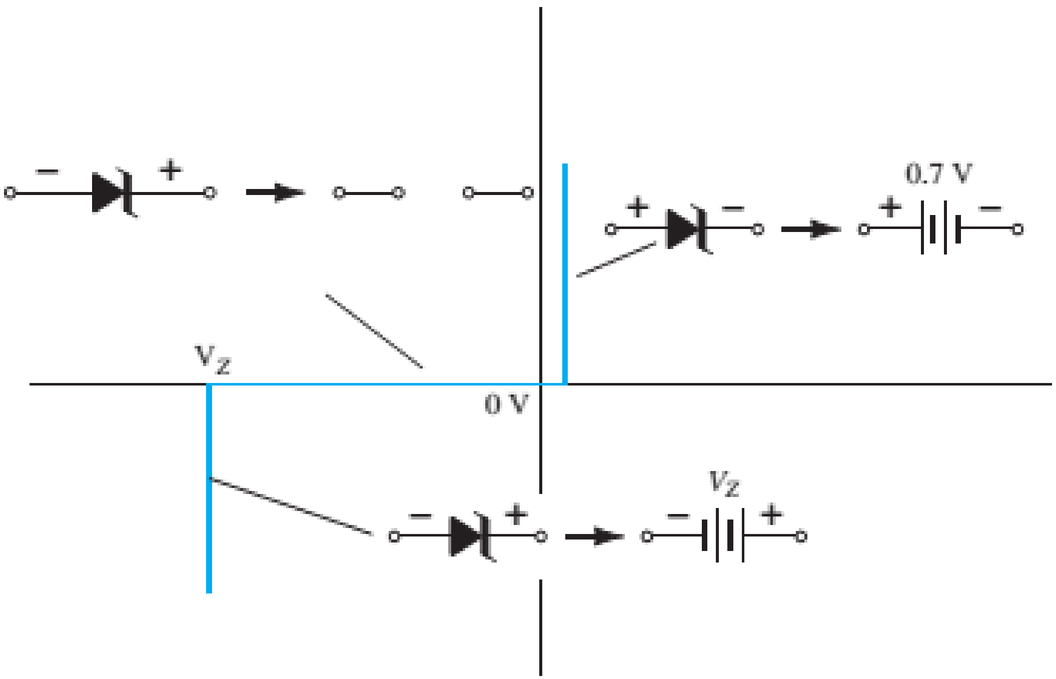
Zener Diodes



There are different equivalent models for each region.

Zener Diode Circuits

- *First the state of the diode must be determined, followed by a substitution of the appropriate model and a determination of the other unknown quantities of the network.*



Zener Diode Circuits

1. Act as protection device Example 2.16

2. Act as regulator

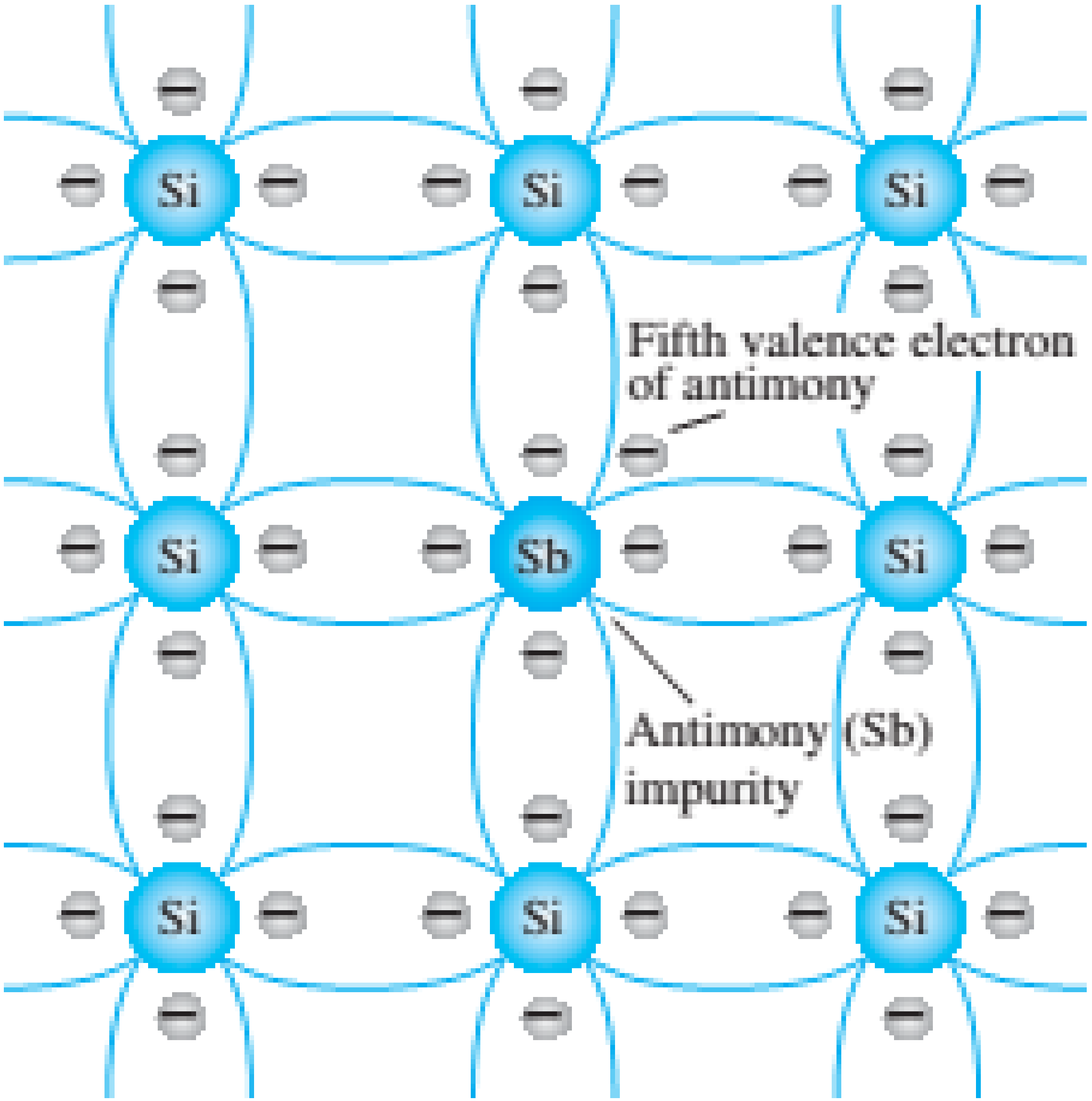
- V_i and R_L Fixed Example 2.17
- Fixed V_i and Variable R_L Example 2.18
- Fixed R_L and Variable V_i Example 2.19

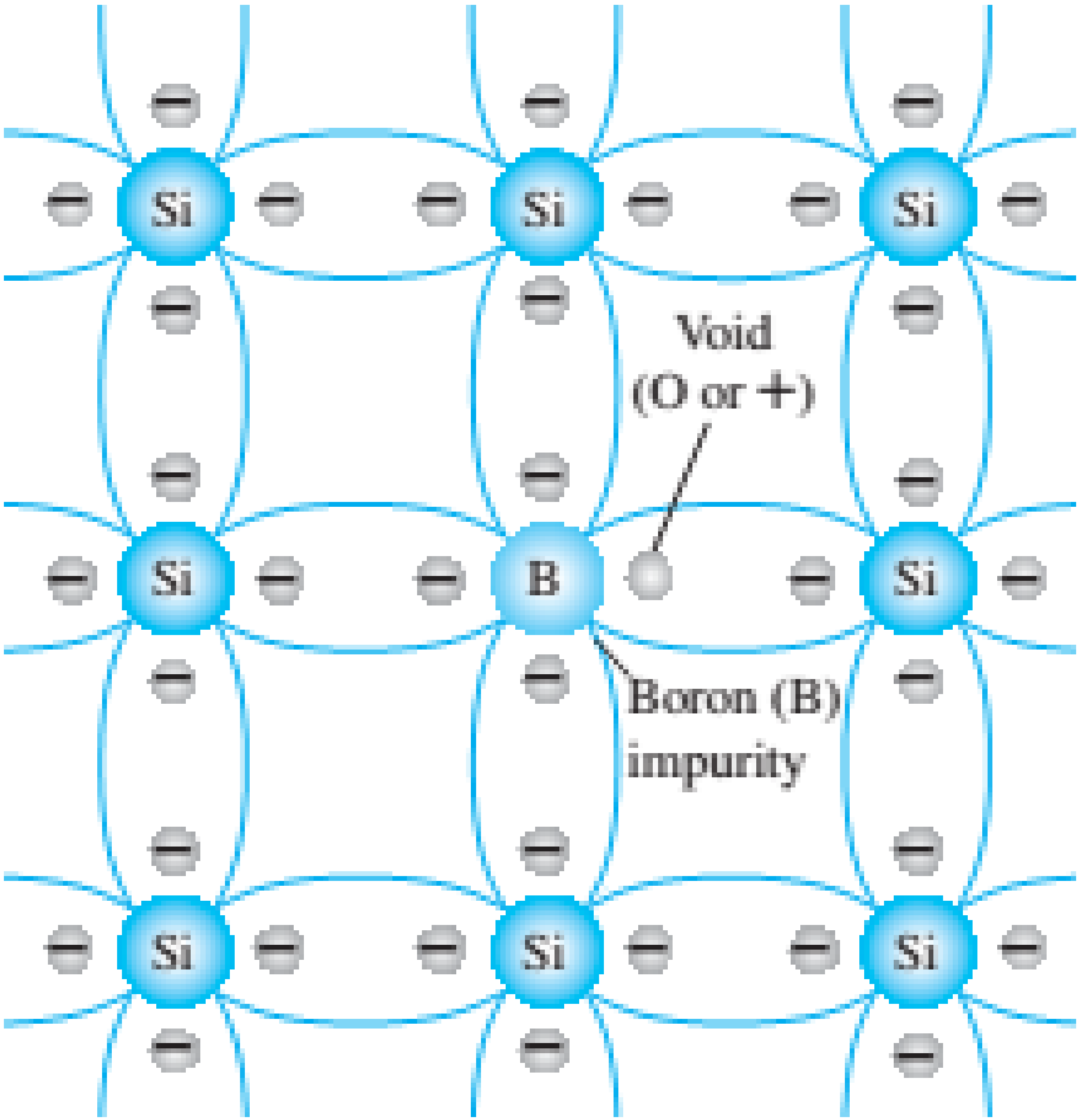
Summary

- **Analysis methods of diode circuits**
  - **Equivalent Model**
  - **Load-Line Analysis**

- **Application of Diodes**
  - **Rectifier**
    - **Conversions of AC to DC for DC operated circuits**
  - **Zener Diodes: Regulator**
    - **Over voltage Protection**
    - **Setting Reference Voltages**
  - **…**

理解原理，**掌握外特性！**


Si
Si
Si
Fifth valence electron of antimony
Si
Sb
Si
Antimony (Sb) impurity
Si
Si
Si


Si
Si
Si
Void
(O or +)
Si
B
Si
Boron (B)
impurity
Si
Si
Si