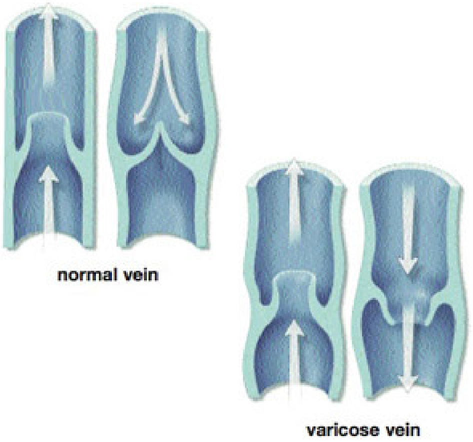
Chapter 16

Semiconductors, Diodes and Their Applications

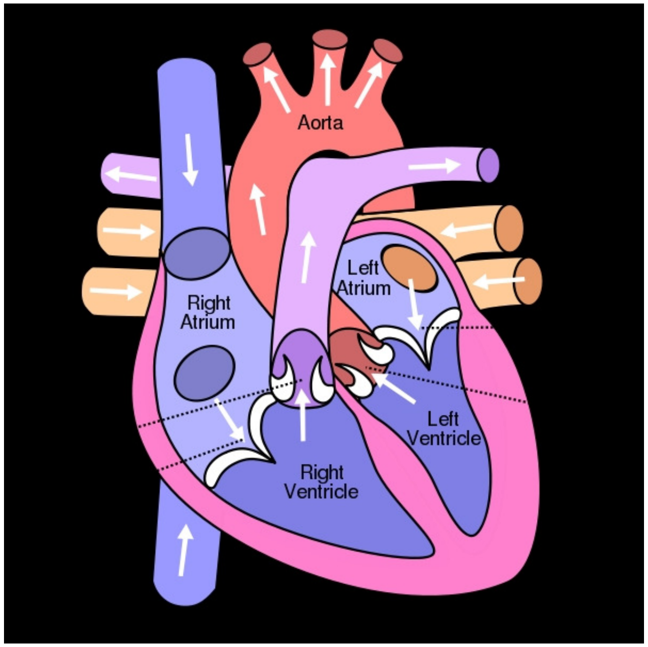
A diode is a one-way valve for Current

Examples of One-Way Valves

Air Check Valve

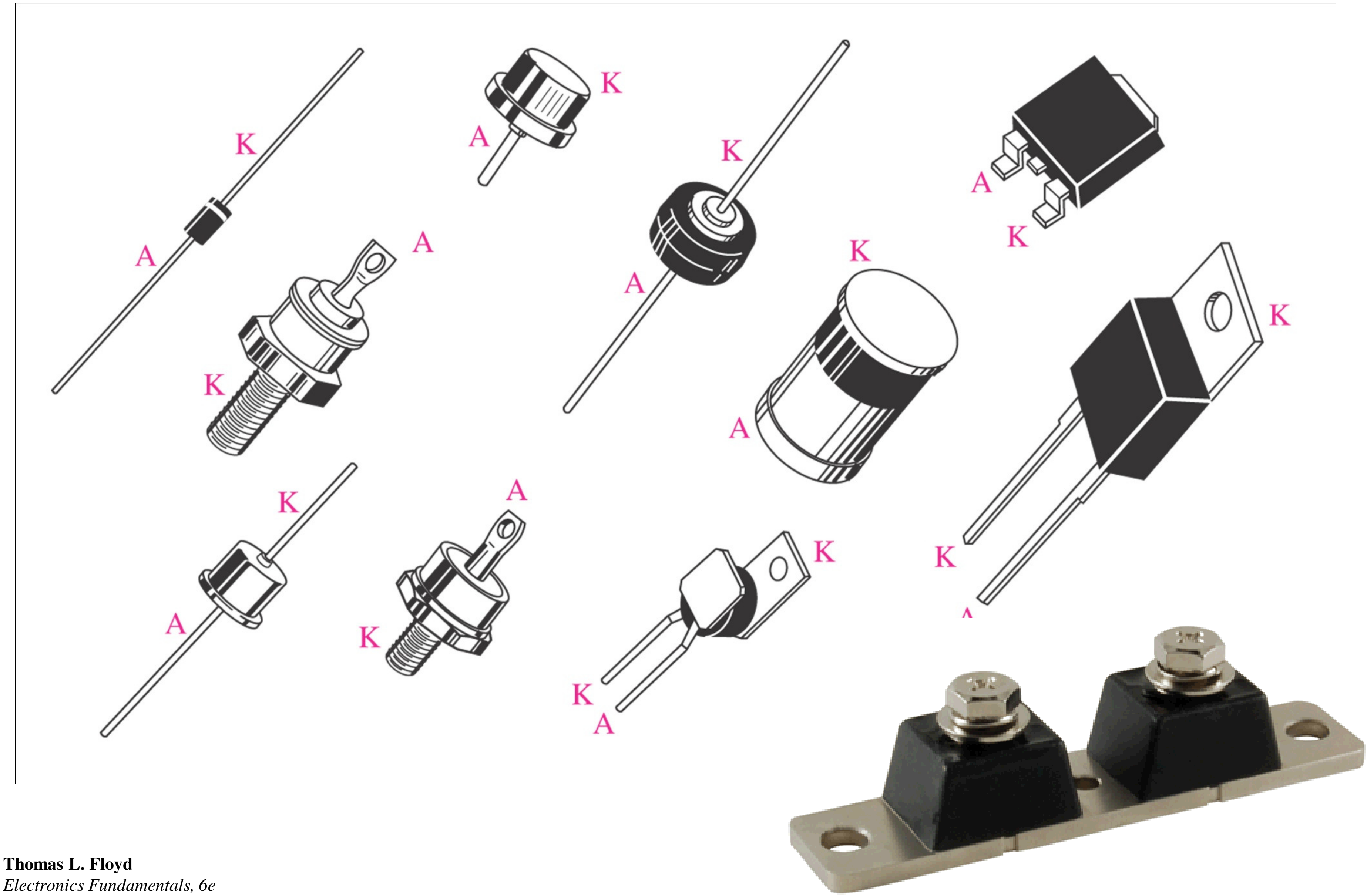


Leg Vein Valves



Heart Valves

Typical diode packages and terminal identification. *A* is anode and *K* is cathode.



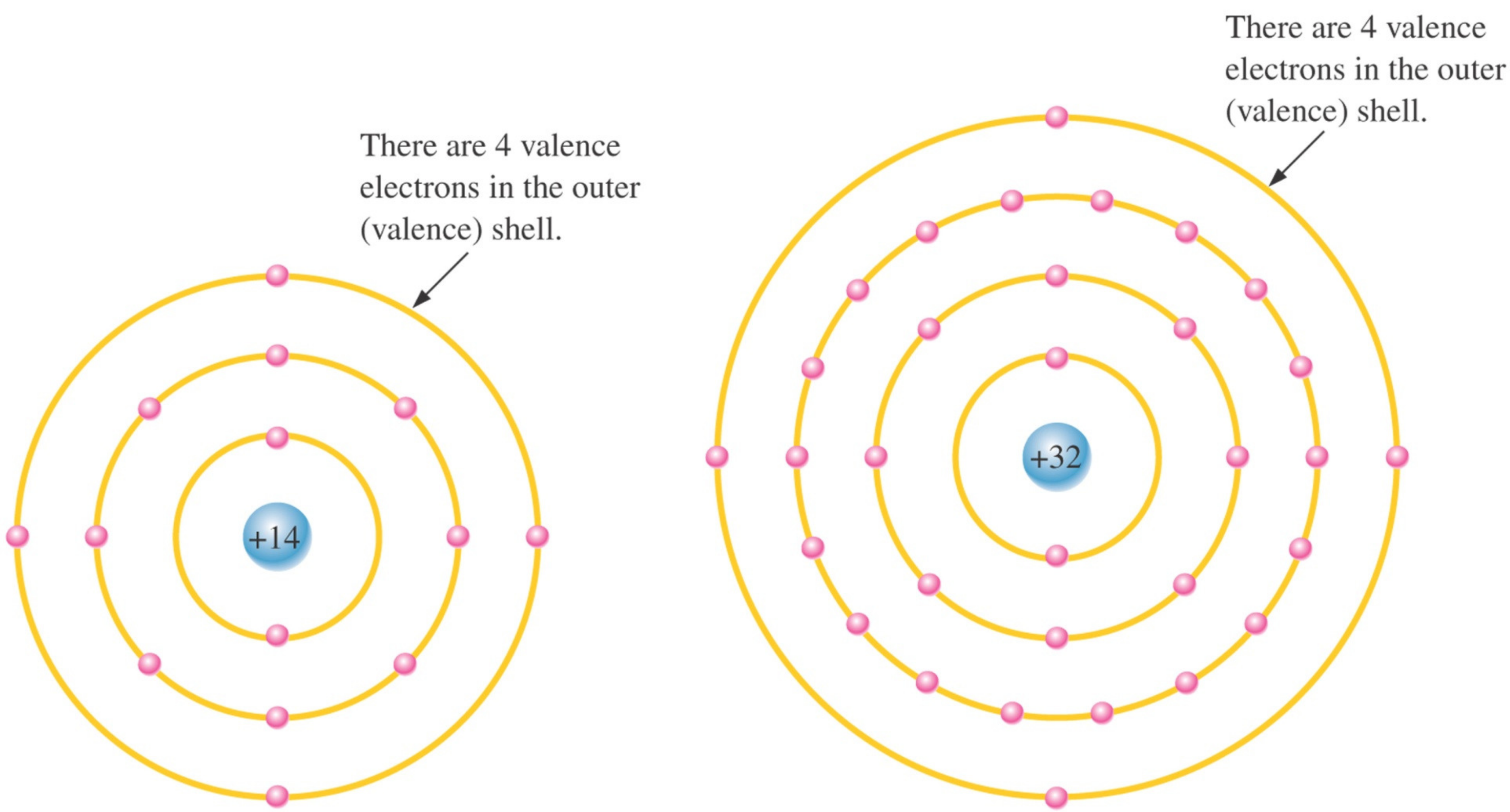
Introduction to Semiconductor Materials

- Two types of semiconductive materials are silicon and germainium
  - both have four valance electrons
- When silicon and germanium atoms combine into molecules to form a solid material, they arrange themselves in a fixed pattern called a crystal
  - atoms within the crystal structure are held together by covalent bonds (atoms share valence electrons)
- An intrinsic crystal is one that has no impurities

Introduction to Semiconductor Materials

- In an intrinsic semiconductor, there are relatively few free electrons
  - pure semiconductive materials are neither good conductors nor good insulators
- Intrinsic semiconductive materials must be modified by increasing the free electrons and holes to increase its conductivity and make it useful for electronic devices
  - by adding impurities, *n*-type and *p*-type extrinsic semiconductive material can be produced

Diagrams of the silicon and germanium atoms



(a) Silicon atom

(b) Germanium atom

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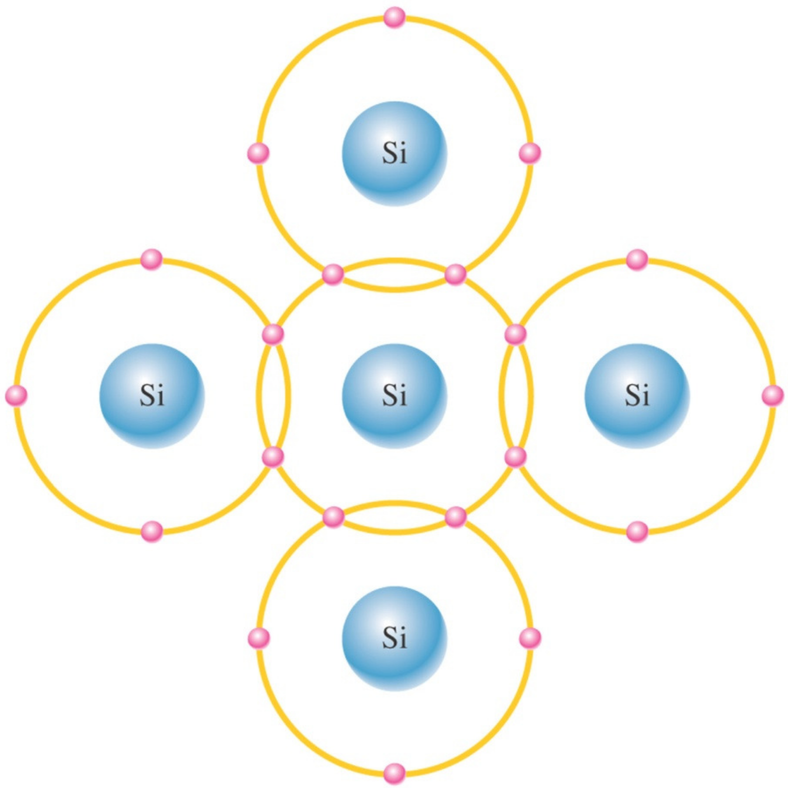
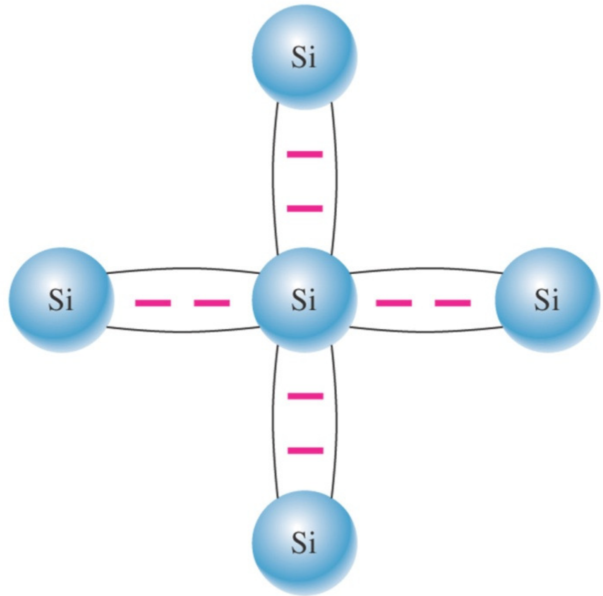
Covalent bonds in a silicon crystal. The actual crystal is 3-dimensional.



(a) The center atom shares an electron with each of the four surrounding atoms creating a covalent bond with each. The surrounding atoms are in turn bonded to other atoms, and so on.



(b) Bonding diagram. The red negative signs represent the shared valence electrons.

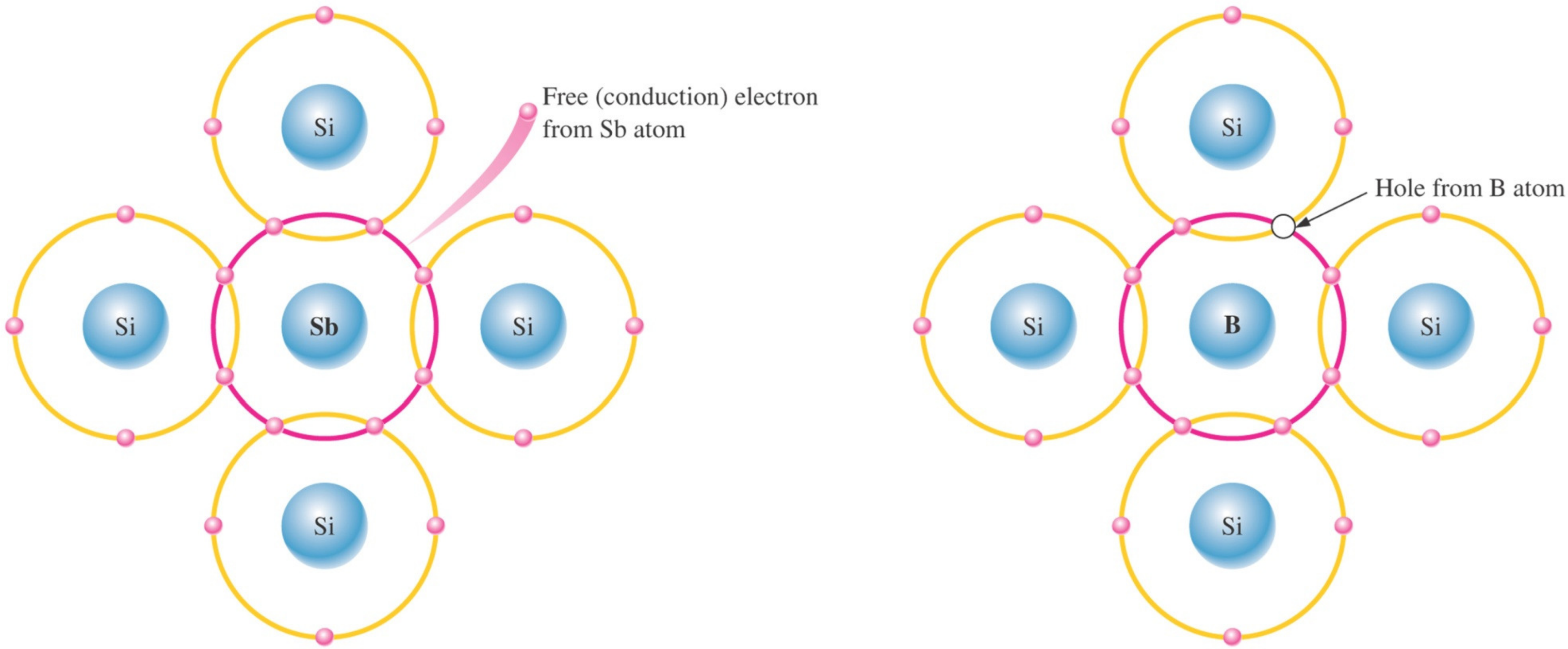
Introduction to Modified Semiconductor Materials

- Doping is the process of adding impurities to intrinsic semiconductive materials to increase and control conductivity within the material
  - *n*-type material is formed by adding **pentavalent** (5 valence electrons) impurity atoms
    - electrons are called **majority carriers** in *n*-type material
    - holes are called **minority carriers** in *n*-type material
  - *p*-type material is formed by adding **trivalent** (3 valence electrons) impurity atoms
    - holes are called **majority carriers** in *p*-type material
    - electrons are called **minority carriers** in *p*-type material

The PN Junction Diode

- A Semiconductor diode consists of an *n* material region and a *p* material region separated by a *pn* junction
  - the *n* region has many conduction electrons
  - the *p* region has many holes
- As a result of recombination, a large number of positive (in the *n* region) and negative (in the *p* region) ions builds up near the *pn* junction, essentially depleting the region of any conduction electrons or holes - termed the *depletion region*

Impurity atoms



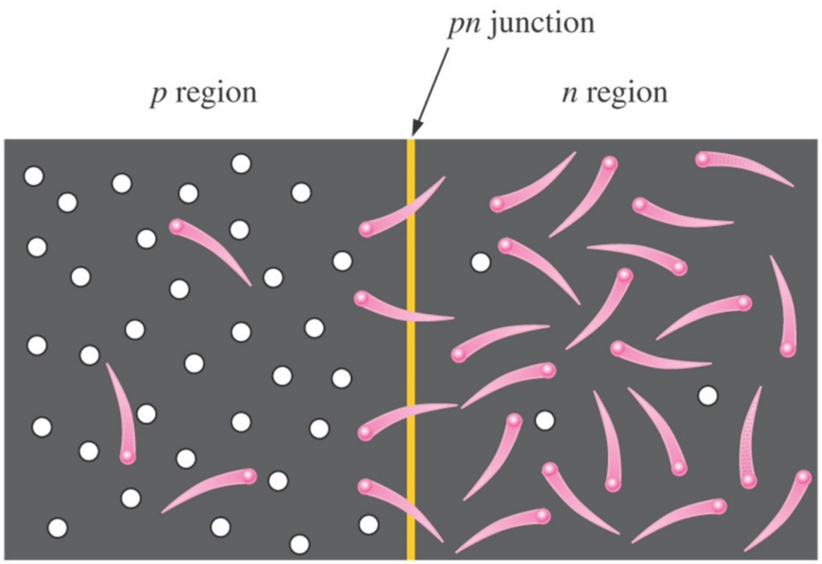
(a) Pentavalent impurity atom in a silicon crystal. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.

(b) Trivalent impurity atom in a silicon crystal. A boron (B) impurity atom is shown in the center.

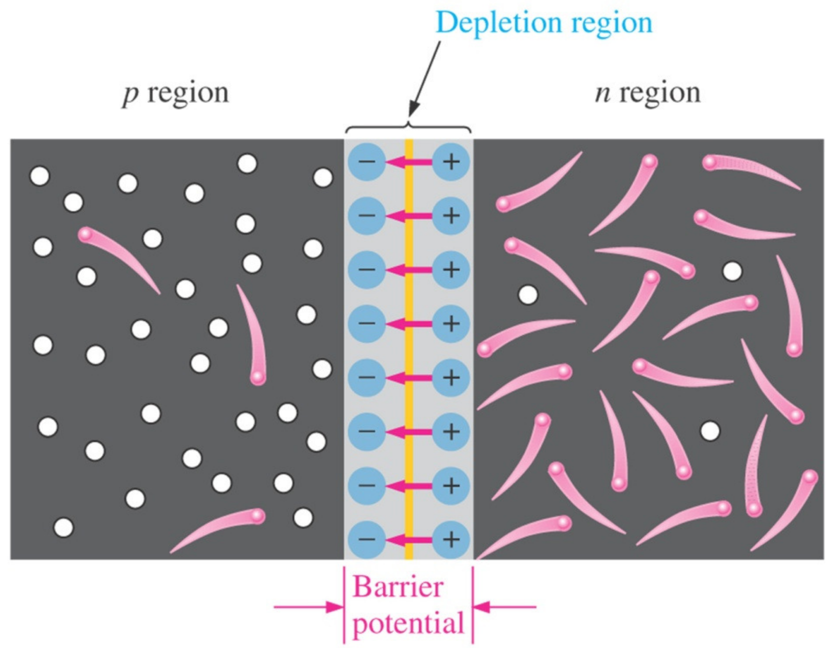
The PN Junction Diode

- The **barrier potential**, V_B, is the amount of voltage required to move electrons through the electric field
  - At 25°C, it is approximately 0.7 V for silicon and 0.3 V for germanium
  - As the junction temperature increases, the barrier potential decreases, and vice versa

Formation of the depletion region in a *pn* junction diode

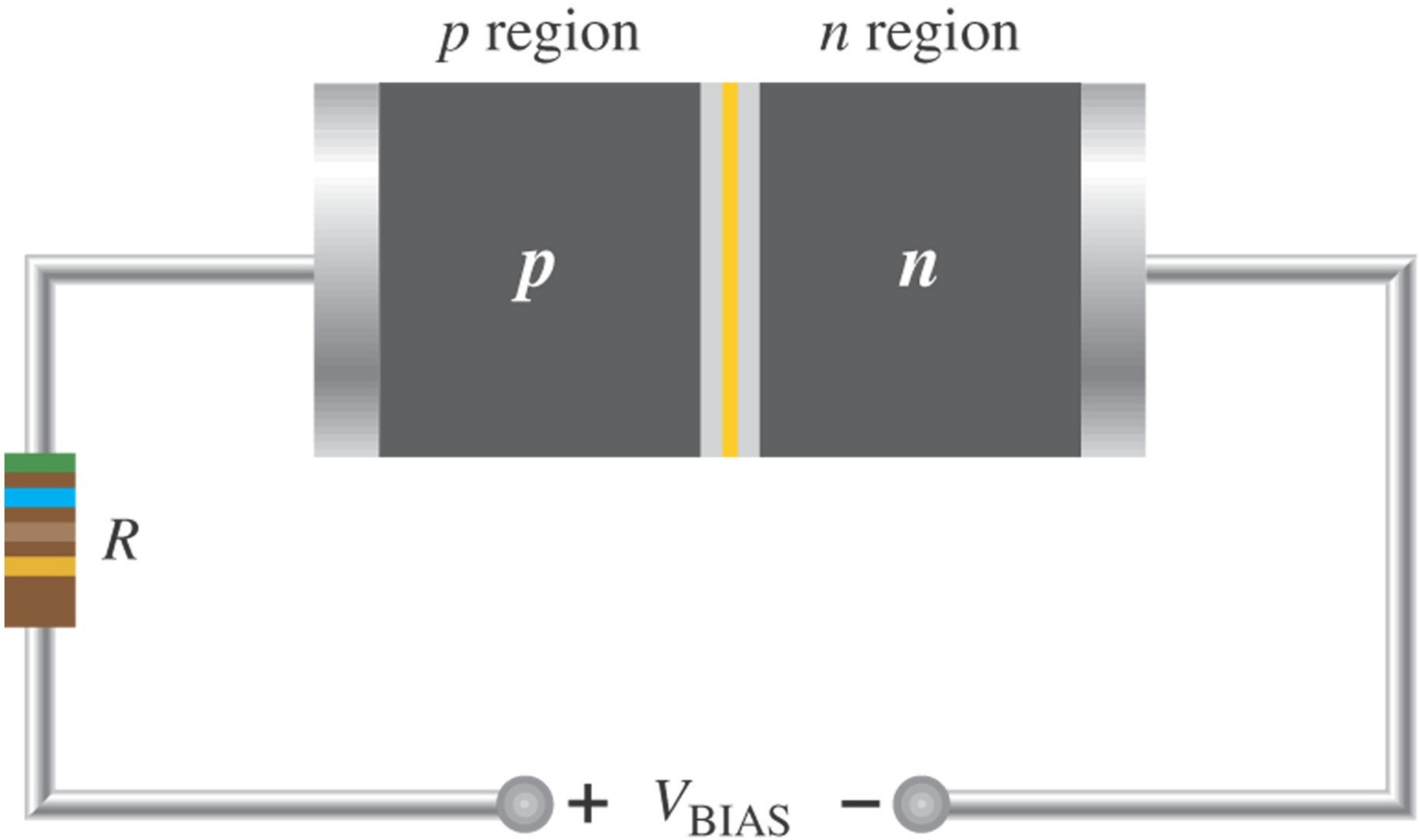


(a) At the instant of junction formation, free electrons in the *n* region near the *pn* junction begin to diffuse across the junction and fall into holes near the junction in the *p* region.



(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion.

Forward-bias connection
The resistor limits the forward current in order to prevent damage to the diode



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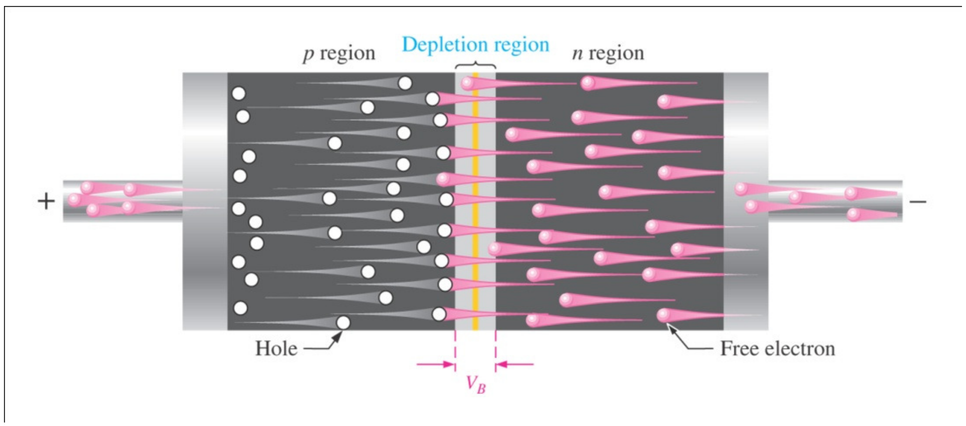
The PN Junction Diode

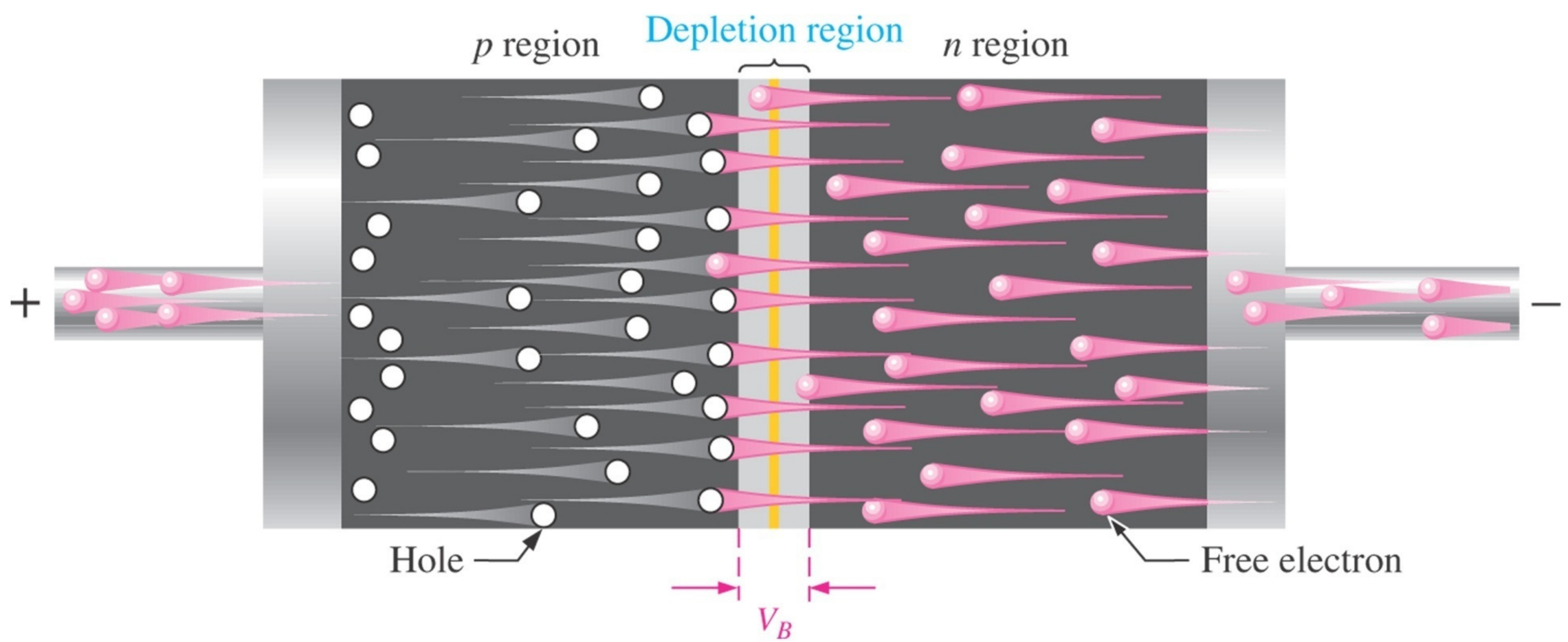
- Forward bias is the condition that permits current through a diode
  - the negative terminal of the V_{BIAS} source is connected to the *n* region, and the positive terminal is connected to the *p* region



The PN Junction Diode

- The negative terminal of the bias-voltage source pushes the conduction-band electrons in the *n* region toward the *pn* junction, while the positive terminal pushes the holes in the *p* region toward the *pn* junction
- When it overcomes the barrier potential (V_B), the external voltage source provides the *n* region electrons with enough energy to penetrate the depletion region and move through the junction

Current in a forward-biased diode



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Barrier potential and dynamic resistance equivalent for a diode

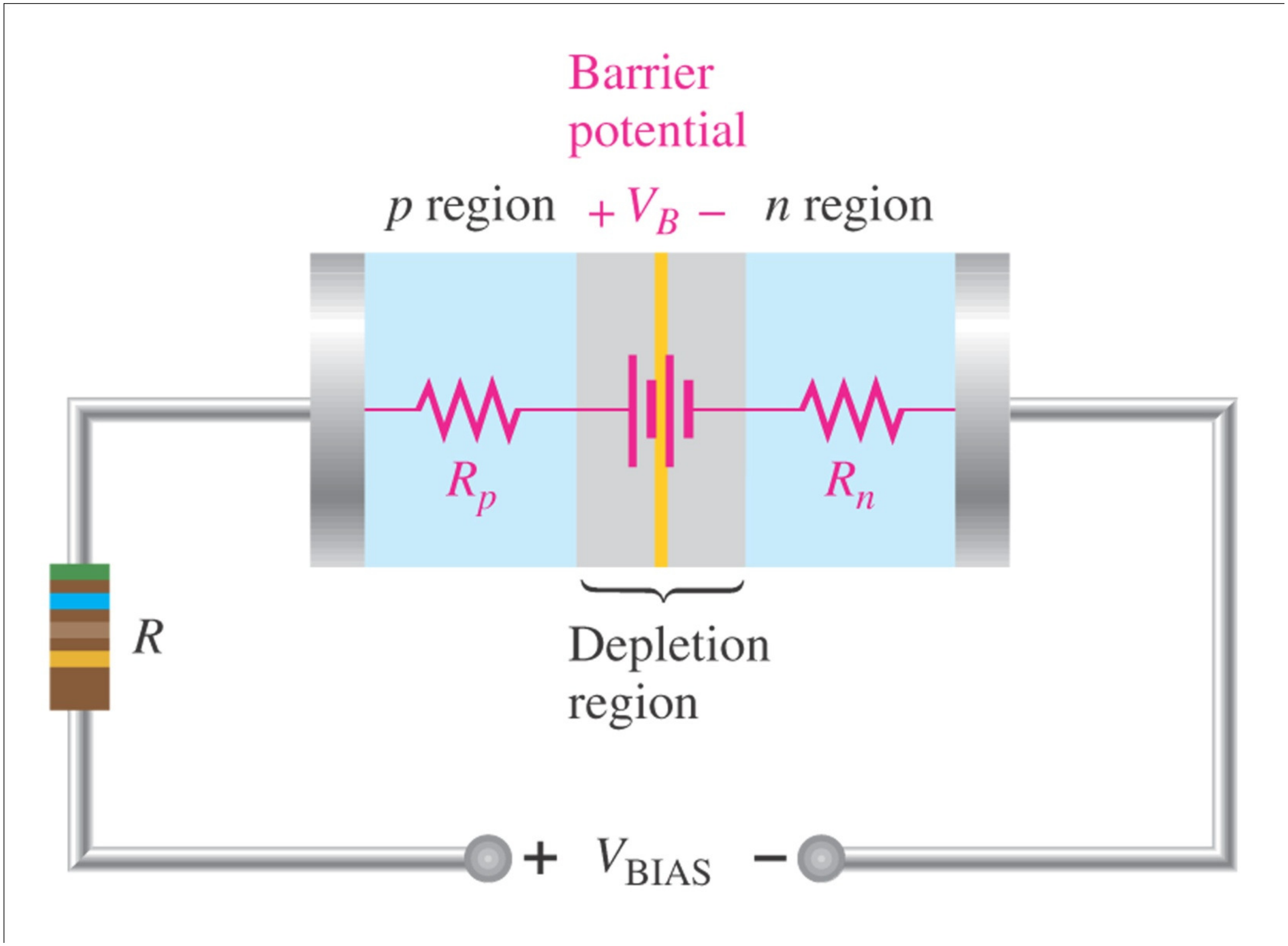

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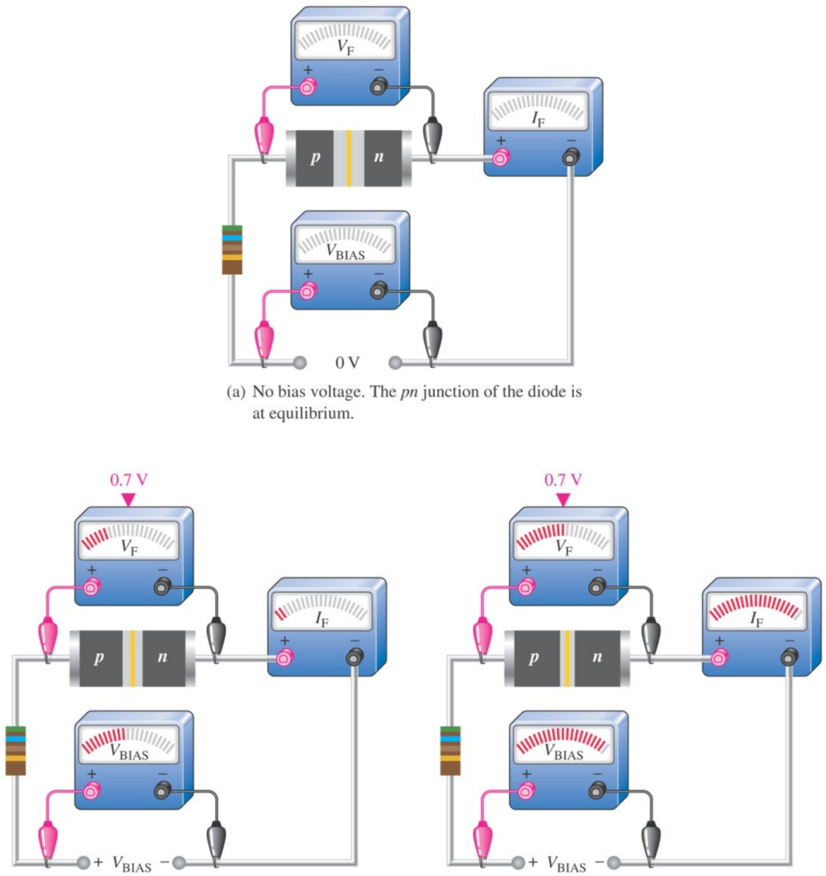
Illustration of diode operation under forward-bias conditions



(a) No bias voltage. The *pn* junction of the diode is at equilibrium.

(b) Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.

(c) Forward voltage reaches and remains at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

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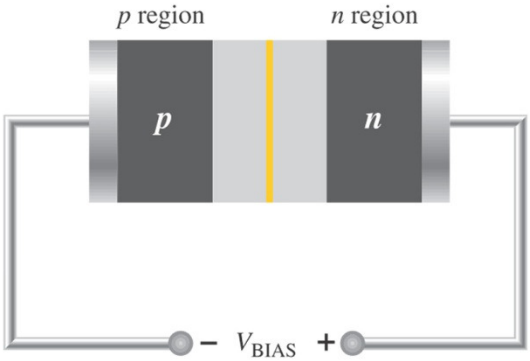
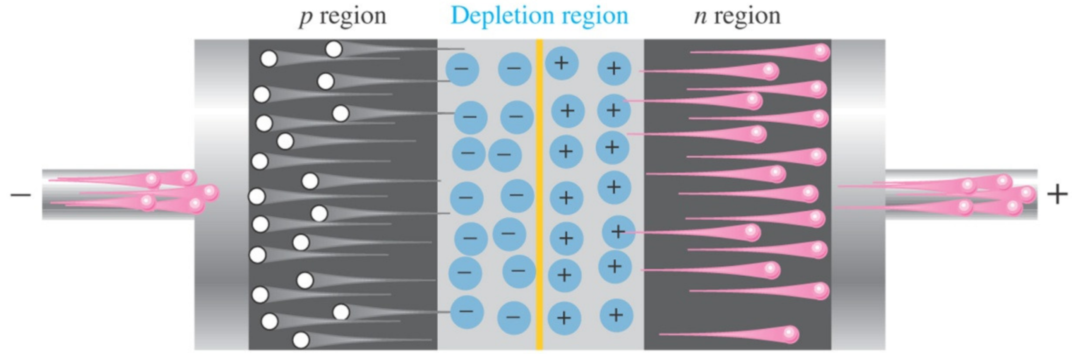
The PN Junction Diode

- Reverse bias is the condition that prevents current through the diode
  – the negative terminal of the V_{BIAS} source is connected to the *p* region, and the positive terminal is connected to the *n* region
- If the external reverse-bias voltage is increased to a large enough value, **reverse breakdown** occurs
  – minority conduction-band electrons acquire enough energy from the external source to accelerate toward the positive end of the diode, colliding with atoms and knocking valence electrons into the conduction band

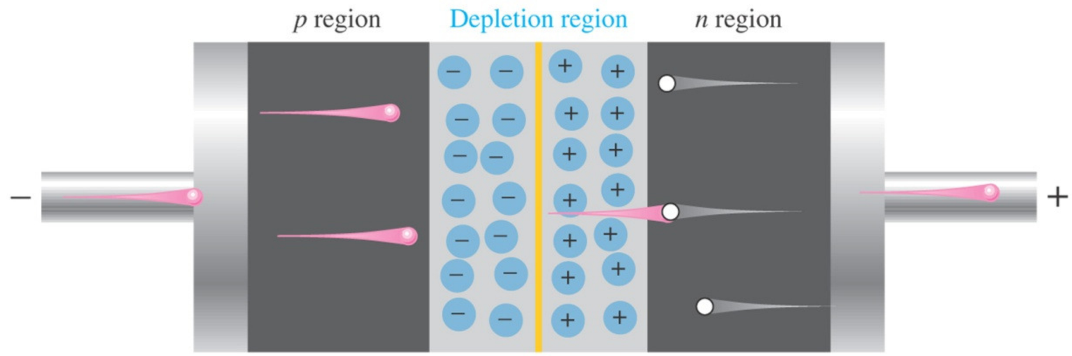
Illustration of reverse bias



(a) Reverse-bias connection.



(b) There is transient current as depletion region widens.



(c) Majority current ceases when barrier potential equals bias voltage. There is an extremely small reverse current due to minority carriers.

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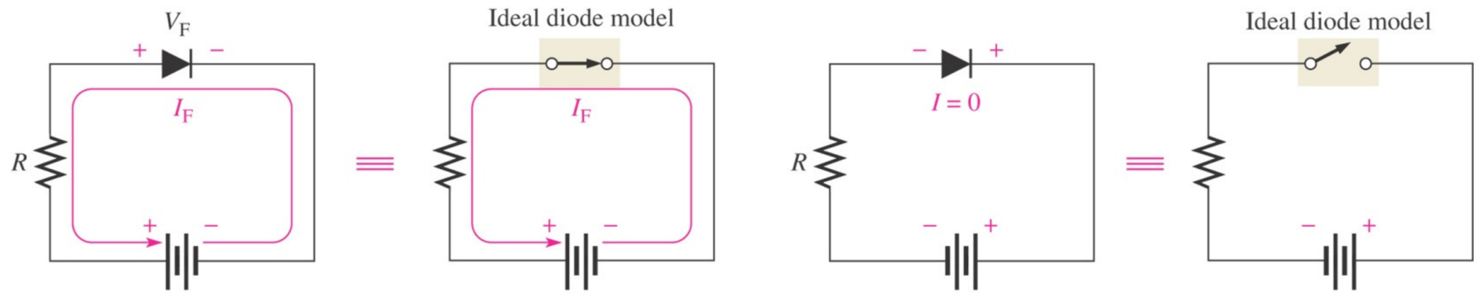
Diode Characteristics

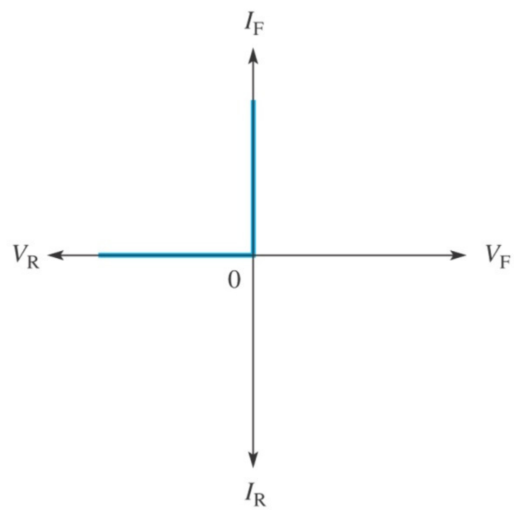
- The simplest way to visualize diode operation is to think of it as a switch
  - When forward-biased, the diode ideally acts as a closed (on) switch
  - When reverse-biased, it acts as an open (off) switch

Ideal model of the diode as a switch



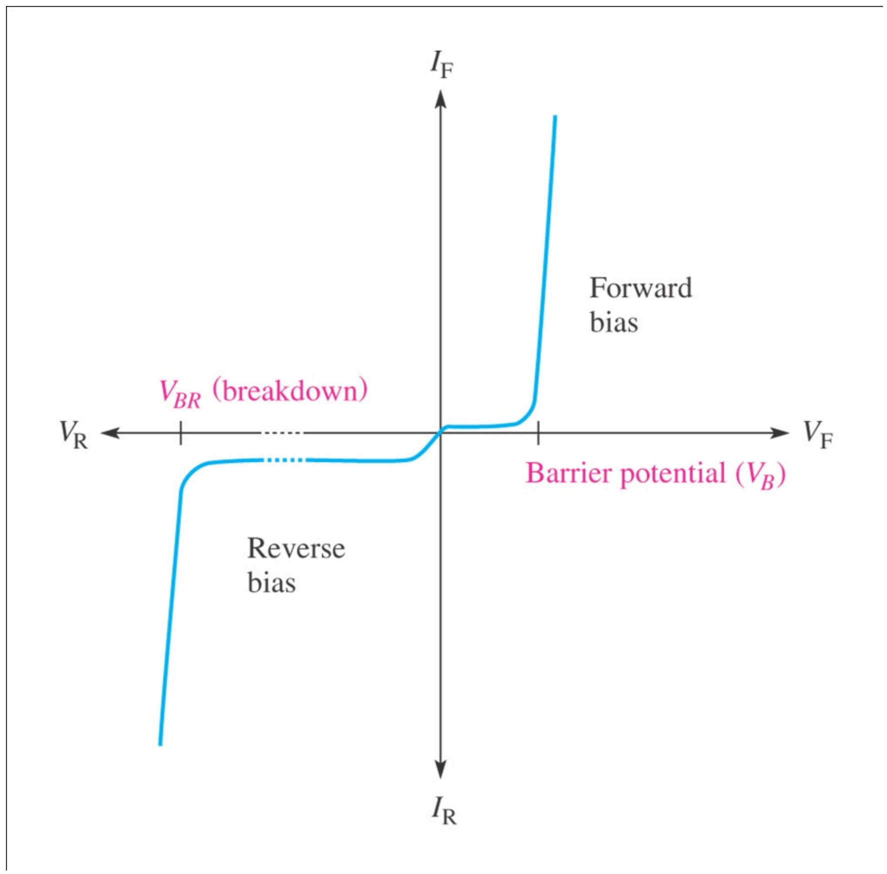
(a) Forward bias

(b) Reverse bias



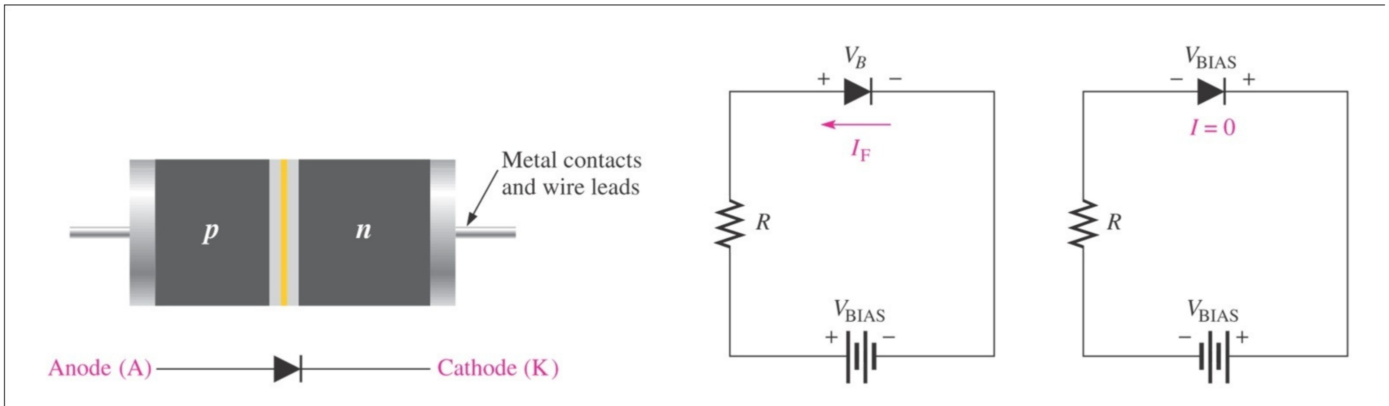
(c) Ideal *V-I* characteristic curve (blue)

Actual Diode Characteristics



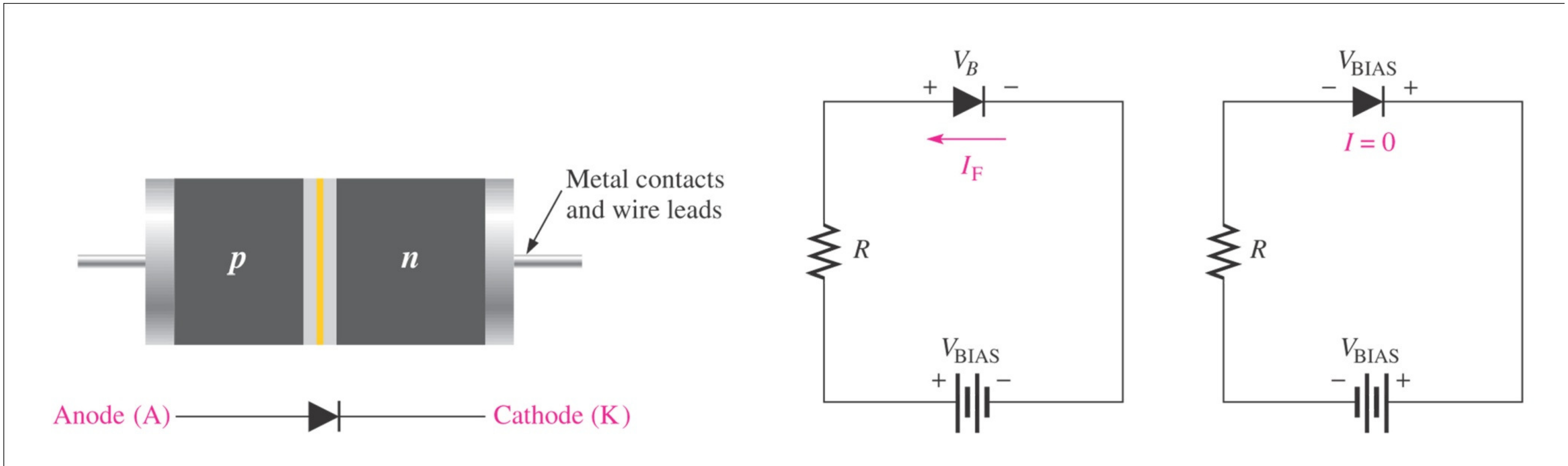
Diode Characteristics

- The “arrowhead” in the diode symbol points in the direction opposite the electron flow
  - The **anode** (A) is the *p* region
  - The **cathode** (K) is the *n* region



(a) Basic diode structure and symbol (b) Forward bias (c) Reverse bias

Diode structure, schematic symbol, and bias circuits
V_{BIAS} is the bias voltage, and V_B is the barrier potential



(a) Basic diode structure and symbol (b) Forward bias (c) Reverse bias

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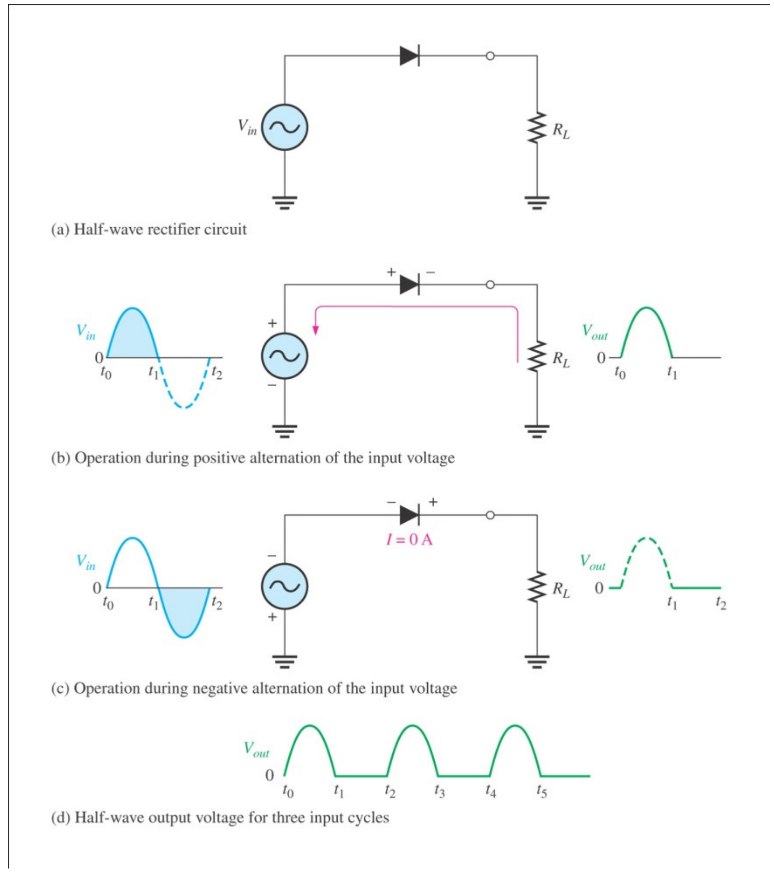
Half Wave Diode Rectifier

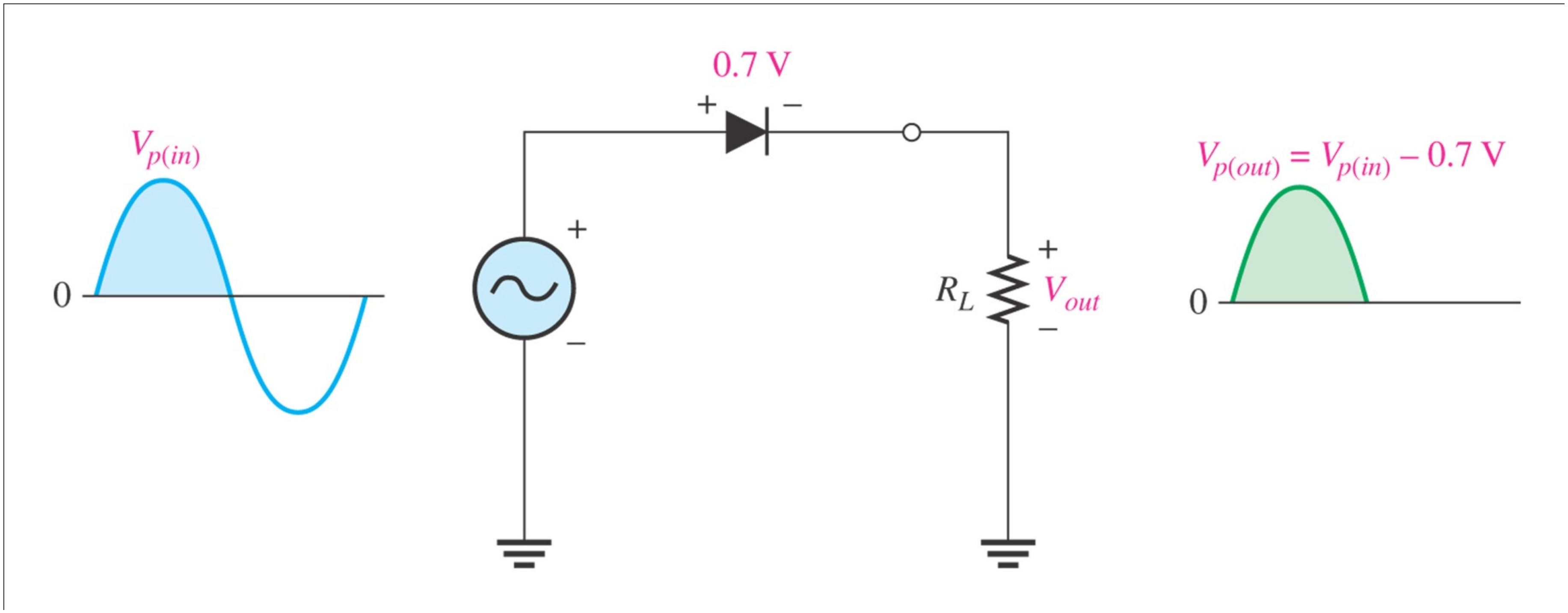
- A diode is connected to an ac source that provides the input voltage, V_{in}, and to a load resistor, R_L, forming a half-wave rectifier
  - on the positive half-cycle, the diode is forward biased



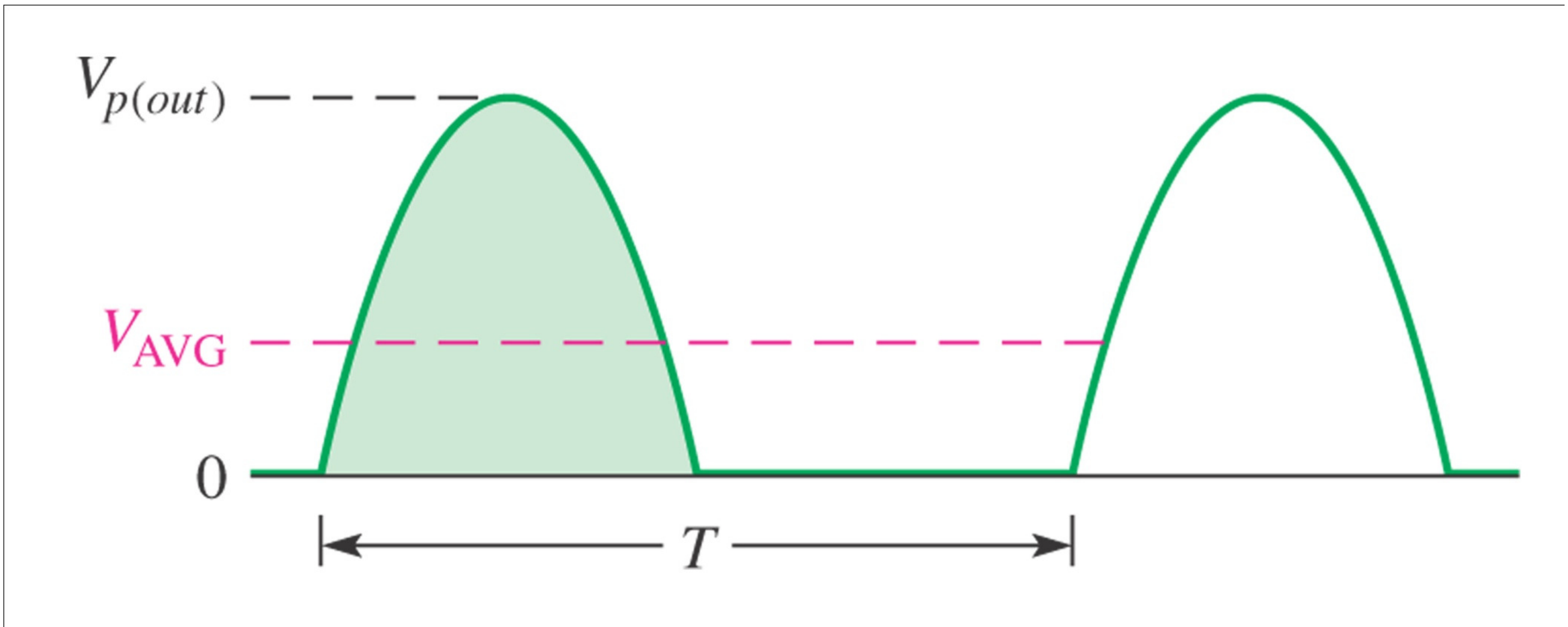
Half Wave Diode Rectifier

- When the diode barrier potential is taken into account, as in the practical model, the input voltage must overcome the barrier potential before the diode becomes forward-biased
  - This results in a half-wave output voltage with a peak value that is 0.7 V less than the peak value of the input voltage
  - It is often practical to neglect the effect of barrier potential when the peak value of the applied voltage is much greater (10X) than the barrier potential

Effect of barrier potential on half-wave rectified output voltage (silicon diode shown)



Average value of the half-wave rectified signal.



The output of a *half-wave* rectifier
(what you would measure with a voltmeter) before filtering
is determined by its average voltage:

$$V_{avg} = \frac{V_{P(out)}}{\pi}$$

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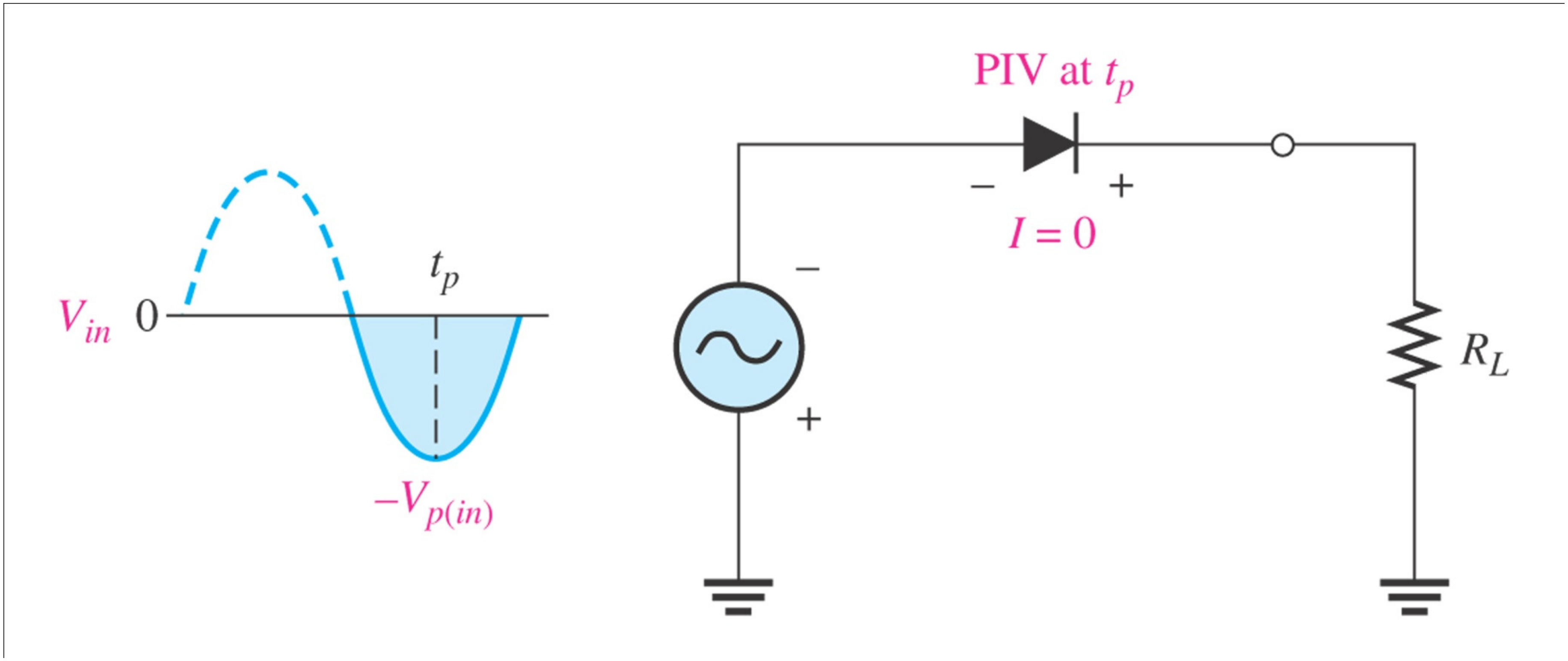
The Peak Inverse Voltage (PIV) occurs at the peak of each half-cycle of the input voltage when the diode is reverse-biased.
In this circuit, the PIV occurs at the time (t_p) of the peak of each negative half-cycle.



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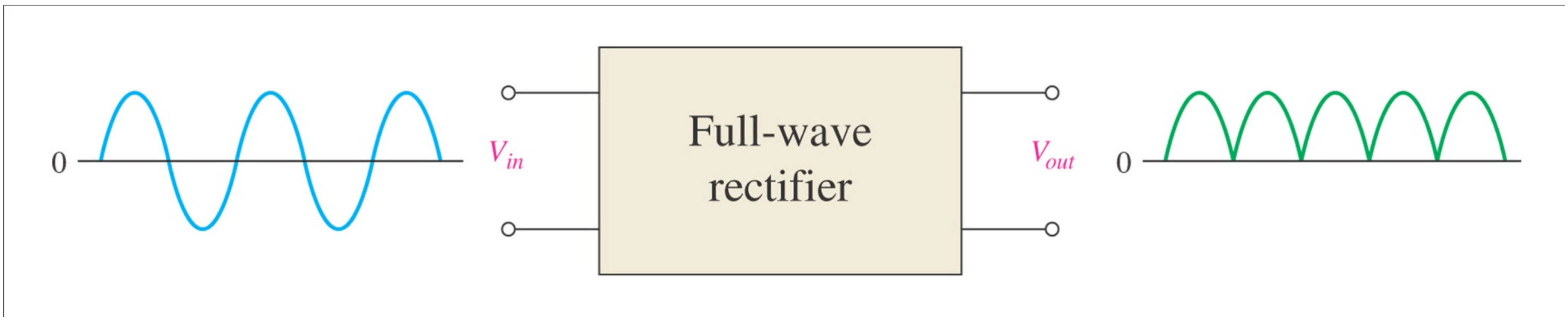
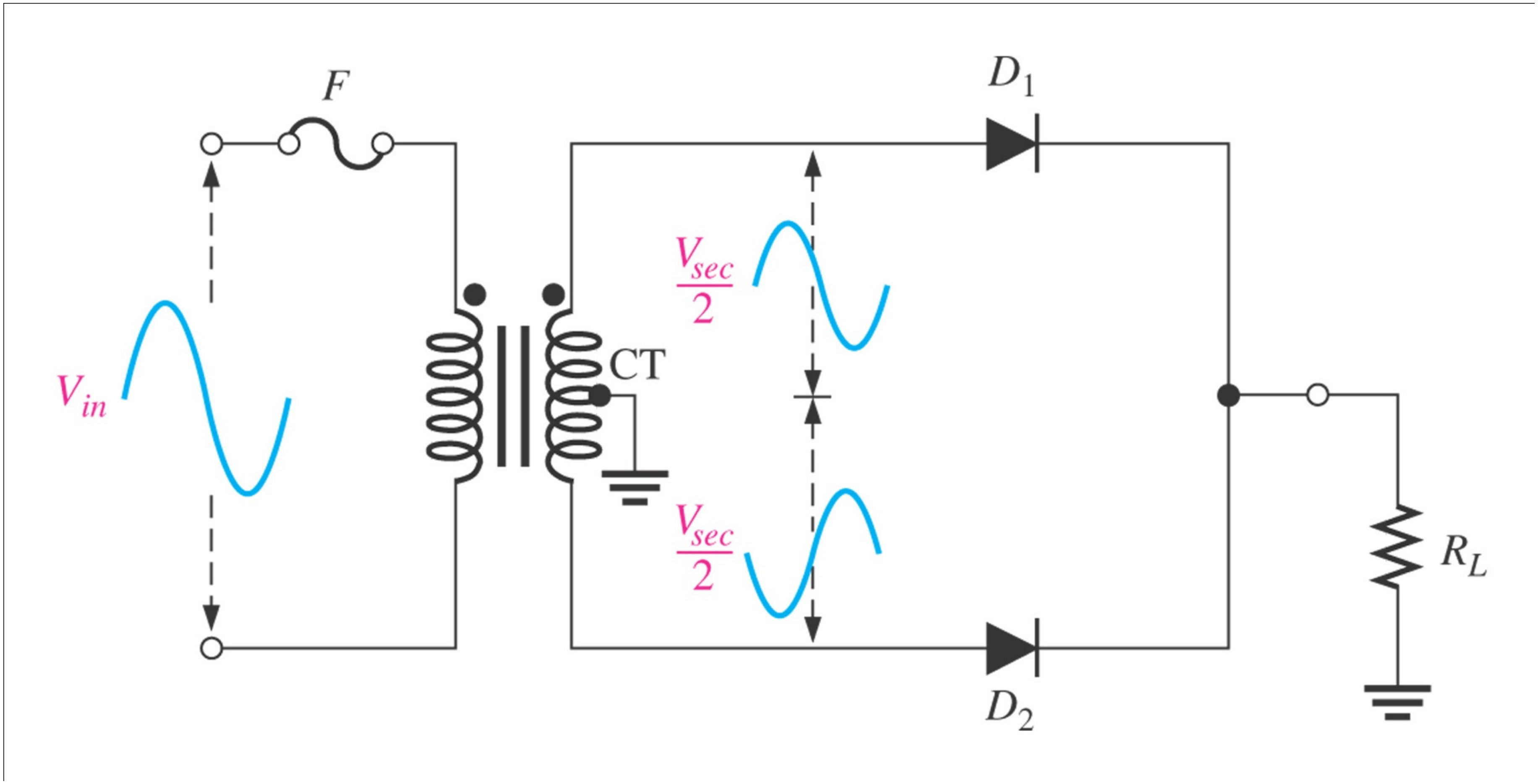
Full Wave Diode Rectifier

- The full-wave bridge rectifier uses four diodes, as shown on the next slide
  - When the input cycle is positive as in part (a), diodes D_1 and D_2 are forward-biased and conduct current, while diodes D_3 and D_4 are reverse-biased
  - When the input cycle is negative as in part (b), diodes D_3 and D_4 are forward-biased and conduct current, while diodes D_1 and D_2 are reverse-biased

Full-wave rectification



A center-tapped (CT) full-wave rectifier



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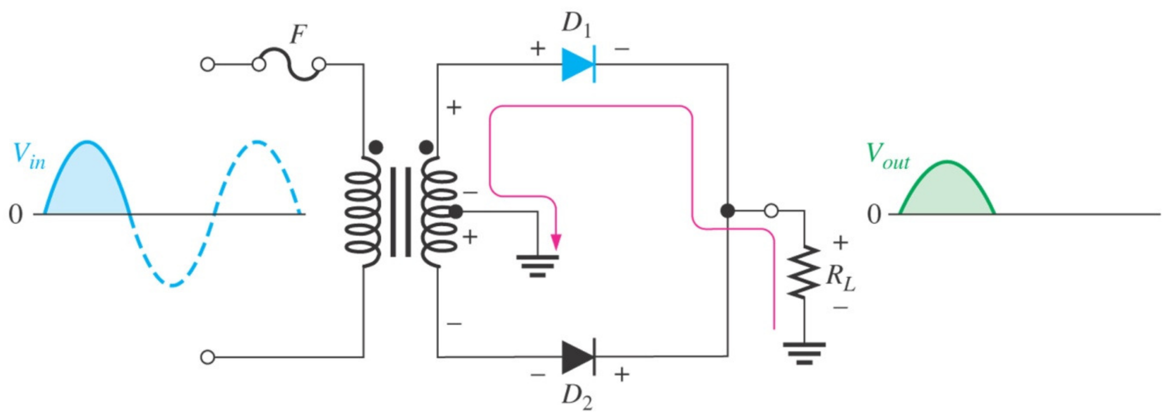
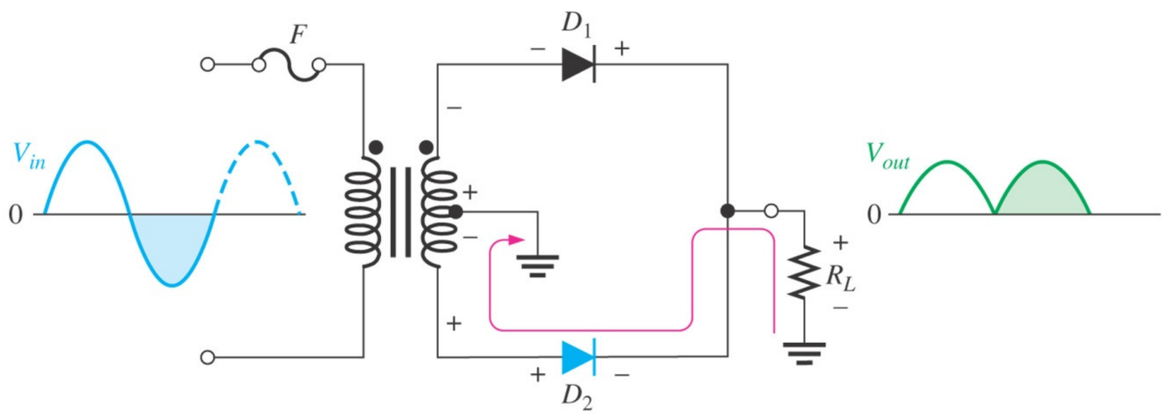
Basic operation of a center-tapped full-wave rectifier.
Note that the current through the load resistor is in the same direction during the entire input cycle.



(a) During positive half-cycles, D_1 is forward-biased and D_2 is reverse-biased.



(b) During negative half-cycles, D_2 is forward-biased and D_1 is reverse-biased.

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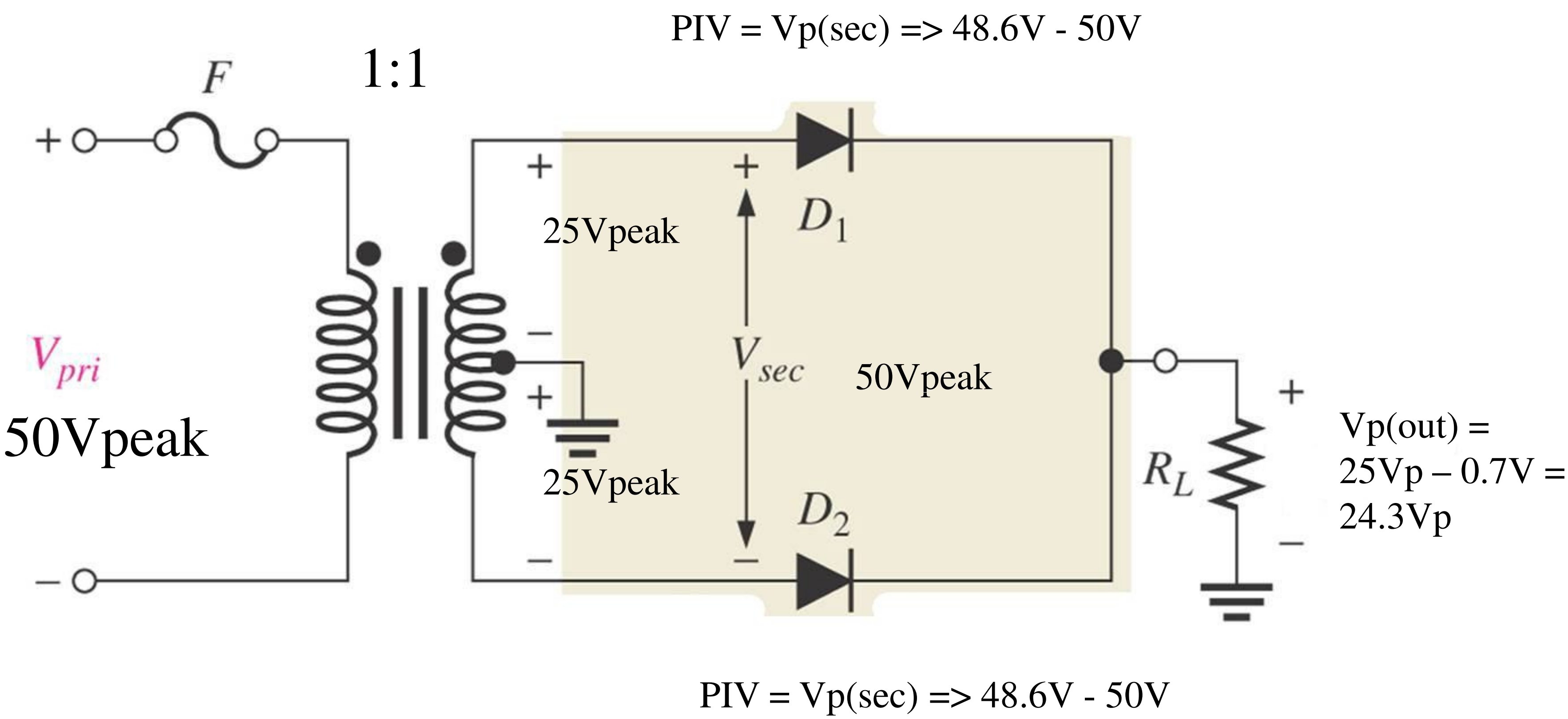
CT Full Wave Diode Rectifier

- *Peak Inverse Voltage* (PIV) is the maximum value of reverse voltage that a diode can withstand
- A full-wave rectifier allows unidirectional current to the load during the entire input cycle
  - whereas the half-wave rectifier allows this only during one-half of the cycle
- The average value for a *full-wave* rectifier output voltage (what you would measure with a voltmeter) before filtering is twice that of the half-wave rectifier

$$\mathbf{V_{AVG} = 2V_{P(out)} / \pi}$$

Diode D_1 is shown forward-biased and D_2 is reverse-biased with PIV across it.
The PIV across either diode is approximately twice the peak value of the output voltage.



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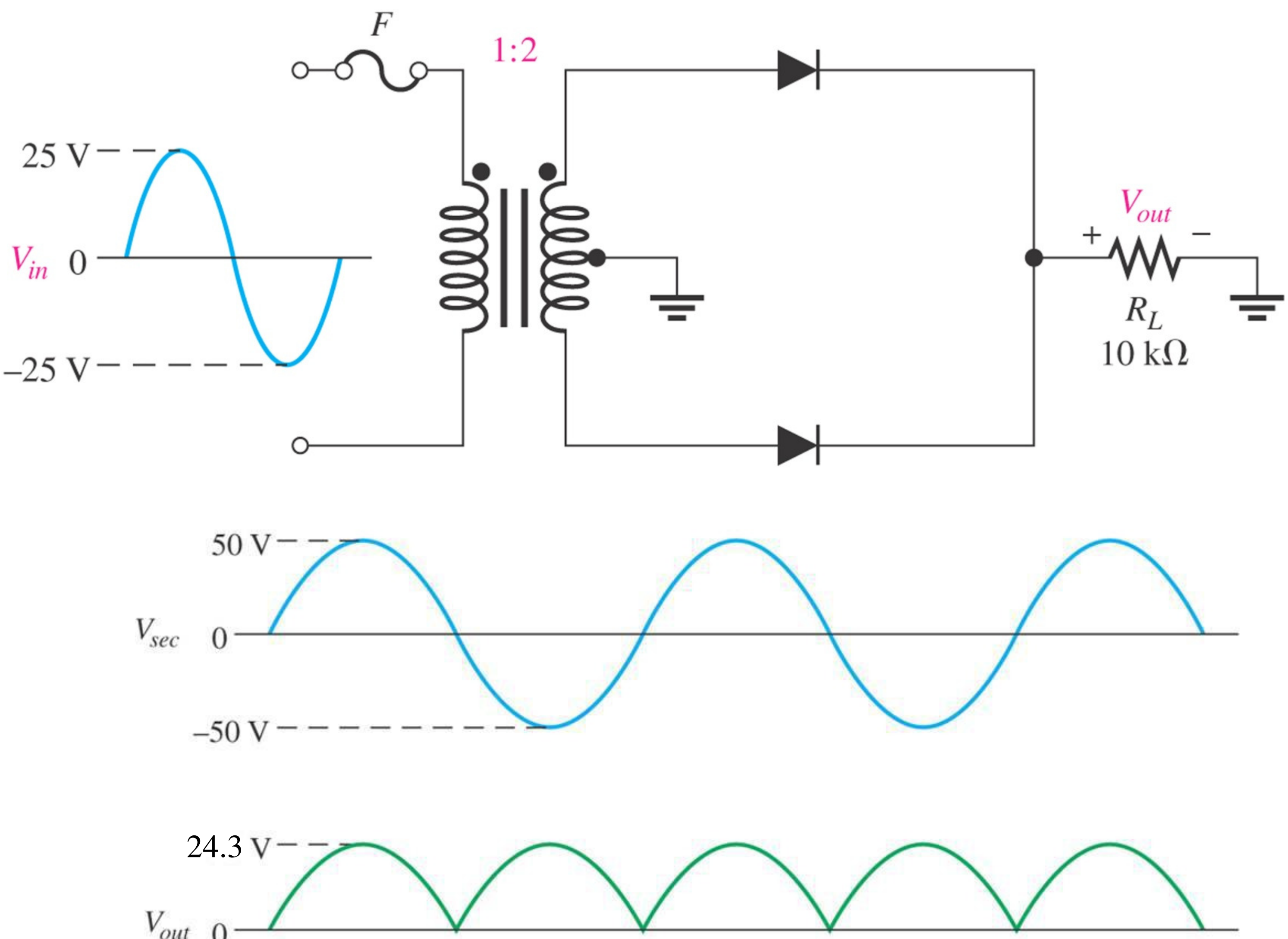
Using a 1:2 Step Up Transformer to Obtain Output Voltage = Input Voltage



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Full Wave Diode Rectifiers

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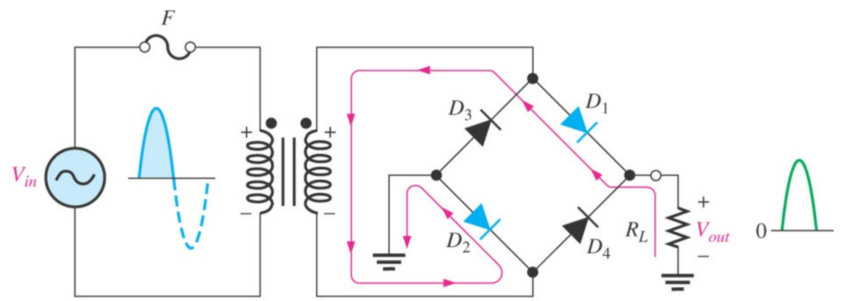
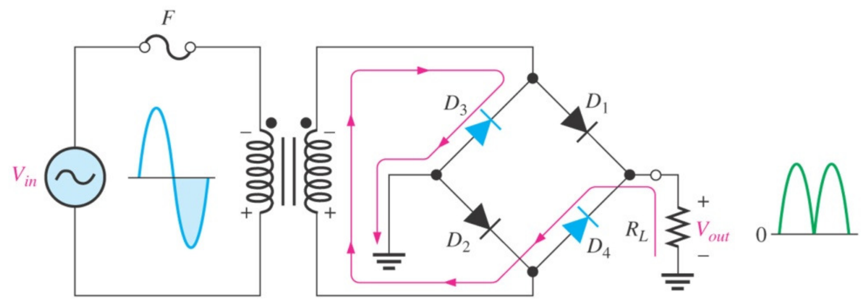
  - When the input cycle is negative as in part (b), diodes D_3 and D_4 are forward-biased and conduct current, while diodes D_1 and D_2 are reverse-biased

Full-Wave Bridge Rectifier



(a) During positive half-cycle of the input, D_1 and D_2 are forward-biased and conduct current. D_3 and D_4 are reverse-biased.



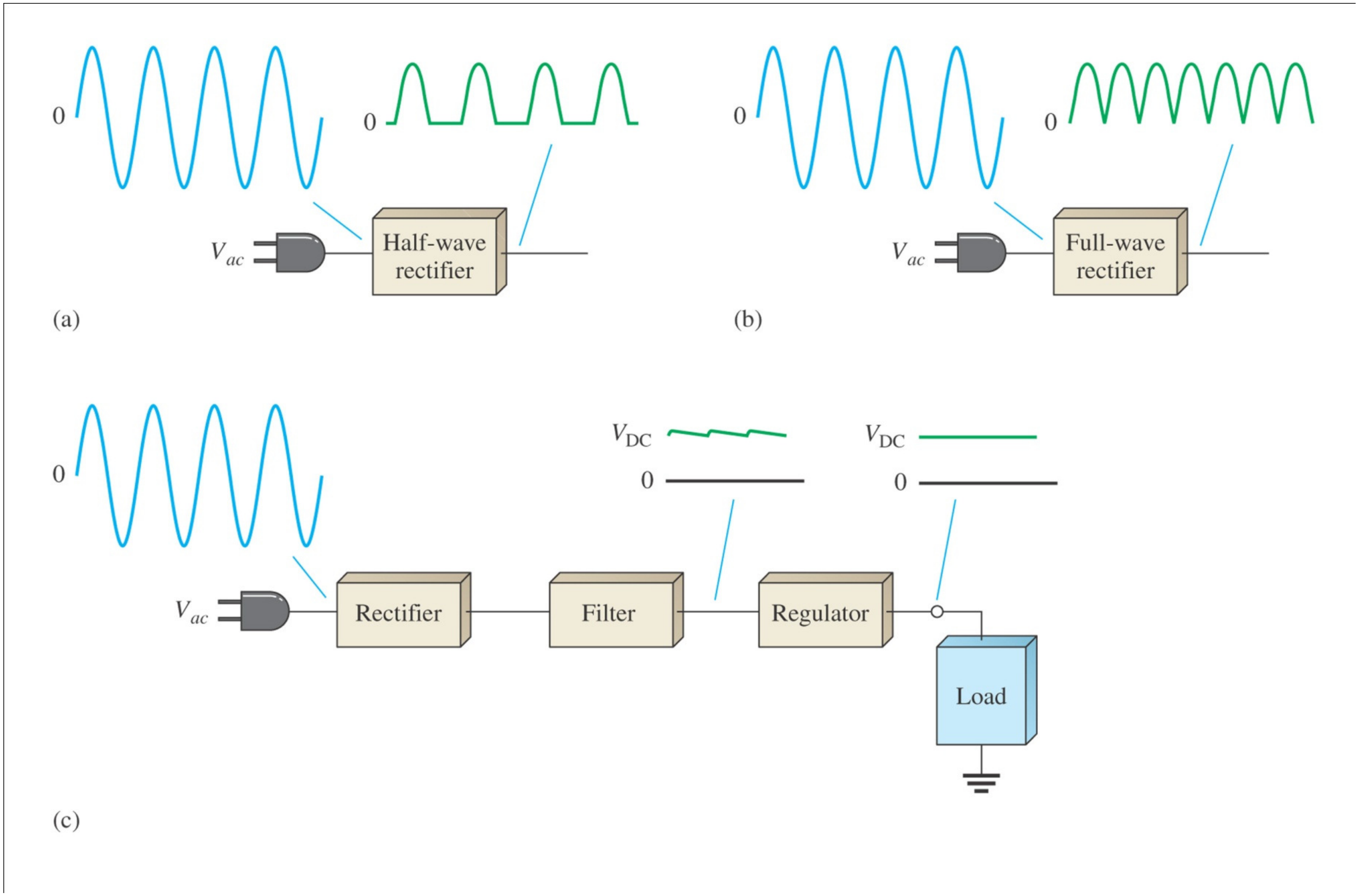
(b) During negative half-cycle of the input, D_3 and D_4 are forward-biased and conduct current. D_1 and D_2 are reverse-biased.

Power Supplies

- The dc power supply converts the standard 110 V, 60 Hz ac available at the wall outlets into a constant dc voltage
  - dc voltage is used in most electronic circuits
- A capacitor is used to filter the output of the rectifier, charging during each quarter-cycle that the input voltage exceeds the capacitor voltage, and discharging through the load when the input voltage decreases below the capacitor voltage, at which point the diodes become reverse biased

Block diagrams showing basic operation of a rectifier and of a regulated dc power supply

DC Power Supplies



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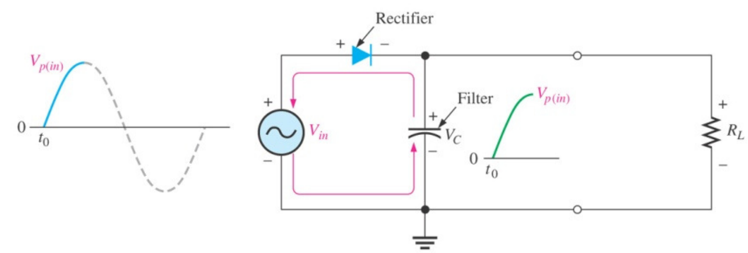
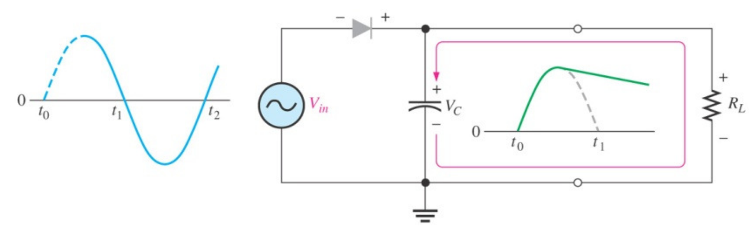
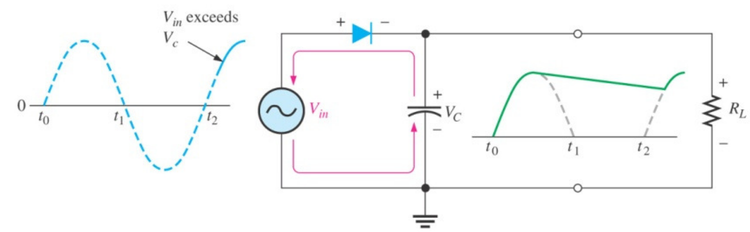
Operation of a half-wave rectifier with a capacitor-input filter



(a) Initial charging of capacitor (diode is forward-biased) happens only once when power is turned on.



(b) The capacitor discharges through R_L after peak of positive alternation when the diode is reverse-biased. This discharging occurs during the portion of the input voltage indicated by the solid blue curve.



(c) The capacitor charges back to peak of input when the diode becomes forward-biased. This charging occurs during the portion of the input voltage indicated by the solid blue curve.

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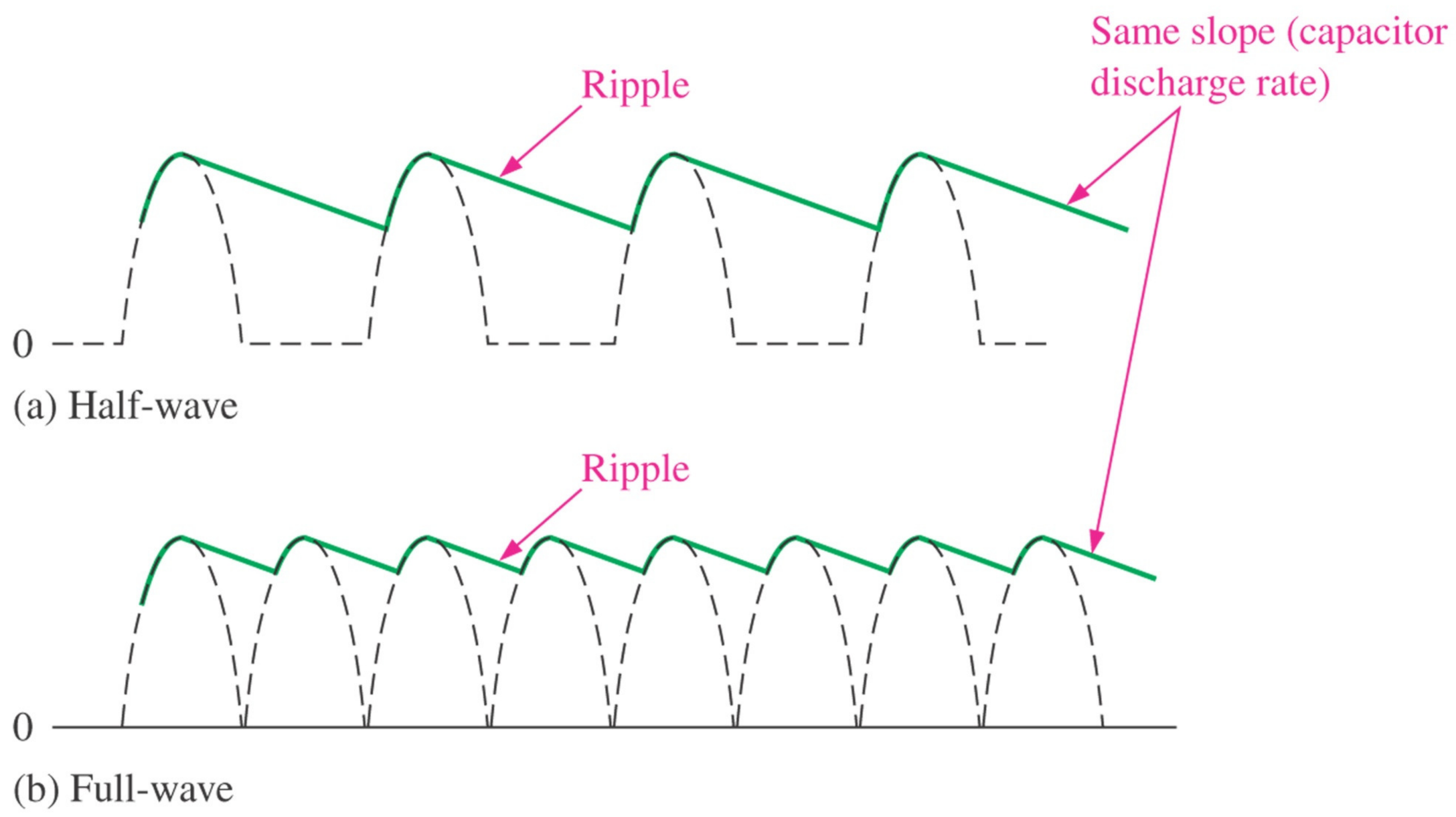
Comparison of ripple voltages for half-wave and full-wave signals with same filter and same input frequency



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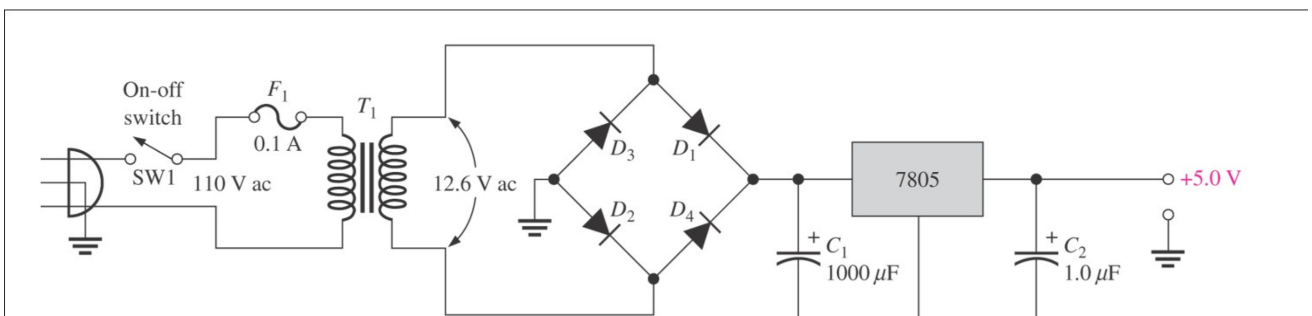
Voltage Regulators

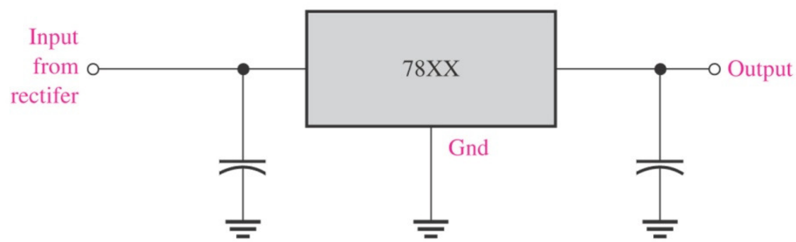
- An integrated circuit regulator (three-terminal regulator) is a device that is connected to the output of a filtered rectifier
- It maintains a constant output voltage despite changes in the input voltage or the current load



D_1–D_4 are 1N4001 silicon rectifier diodes.

The 7800 series three-terminal fixed positive voltage regulators

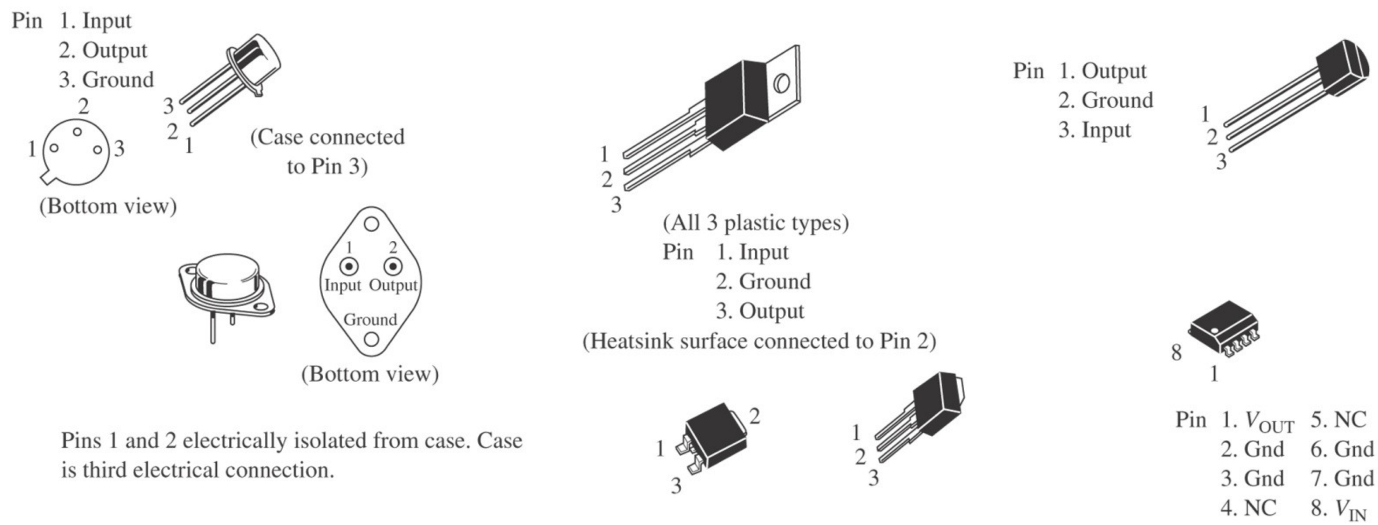
Voltage Regulators



(a) Standard configuration

Type number	Output voltage
7805	+5.0 V
7806	+6.0 V
7808	+8.0 V
7809	+9.0 V
7812	+12.0 V
7815	+15.0 V
7818	+18.0 V
7824	+24.0 V

(b) The 7800 series



(c) Typical metal and plastic packages

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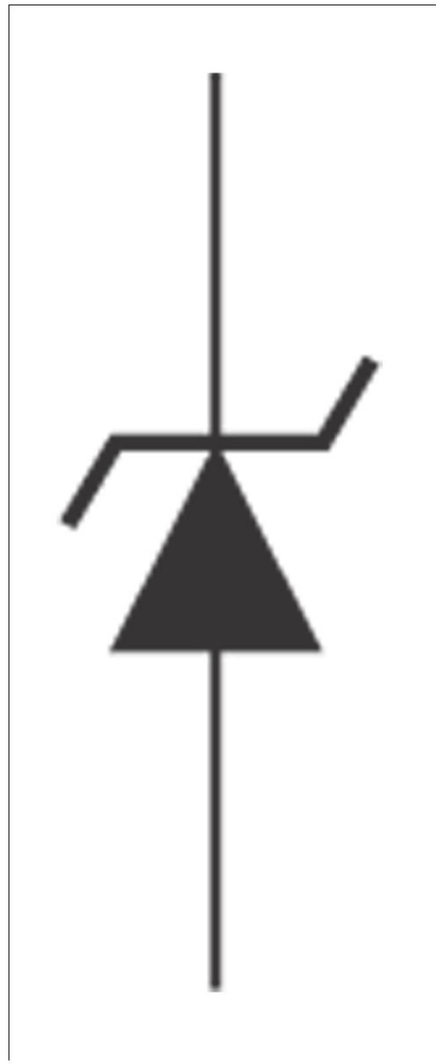
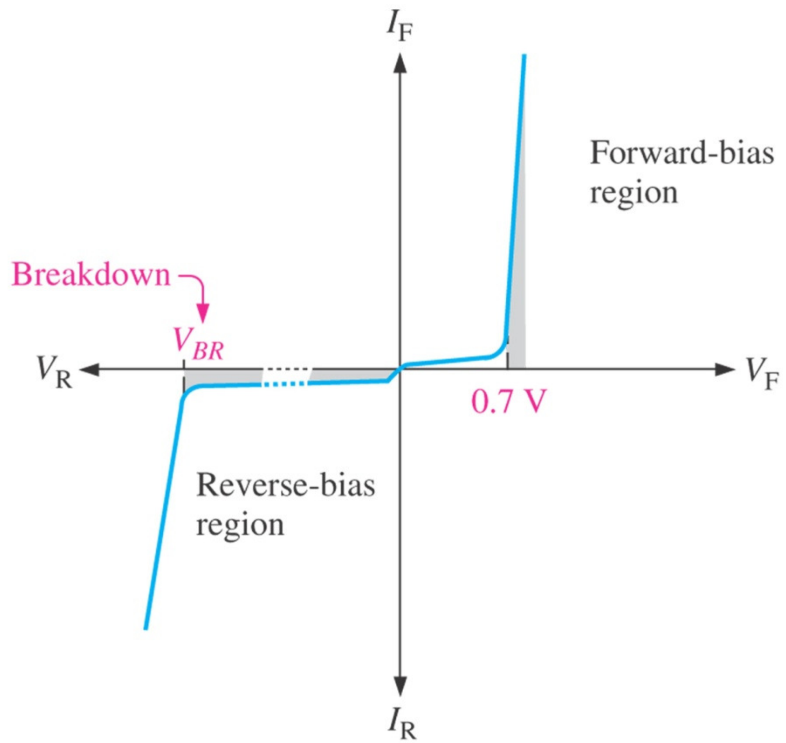
Zener Diodes

- The zener diode is used to provide an output reference voltage that is stable despite changes in input voltage
  - Used as a reference in regulated power supplies
  - The zener diode is designed for operation in the reverse breakdown region, where the voltage remains almost constant over a wide range of reverse current values

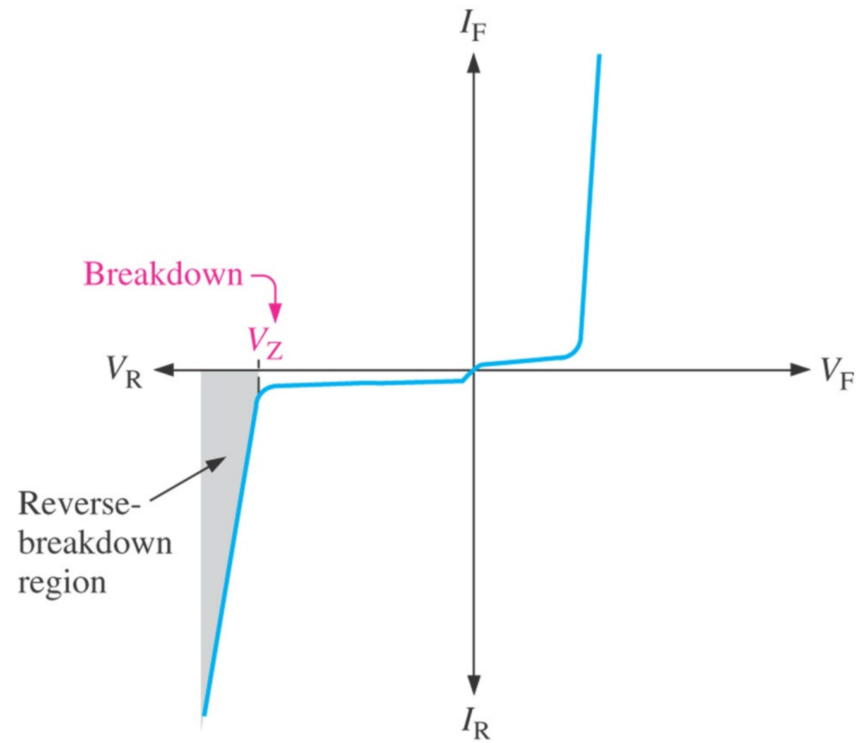
Zener diode symbol



Diode V-I characteristic illustrating the operation of a zener diode compared to a rectified diode. The slope of the reverse-breakdown region is exaggerated to show detail.



(a) The normal operating regions for a rectifier diode are shown as shaded areas.



(b) The normal operating region for a zener diode is shaded.

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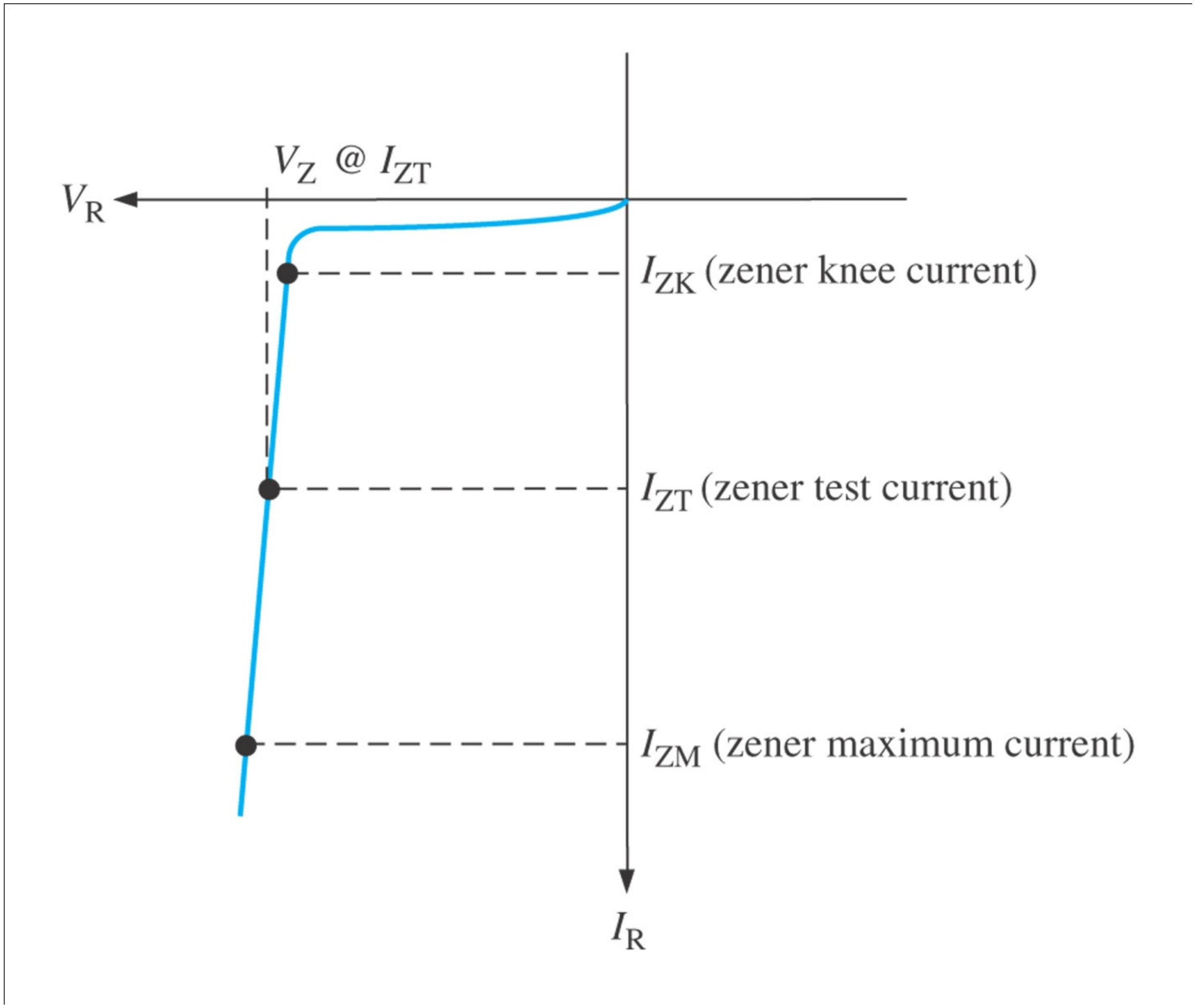
Reverse characteristic of a zener diode.

V_Z is usually specified at the zener test current, I_{ZT}, and is designated V_{ZT}.



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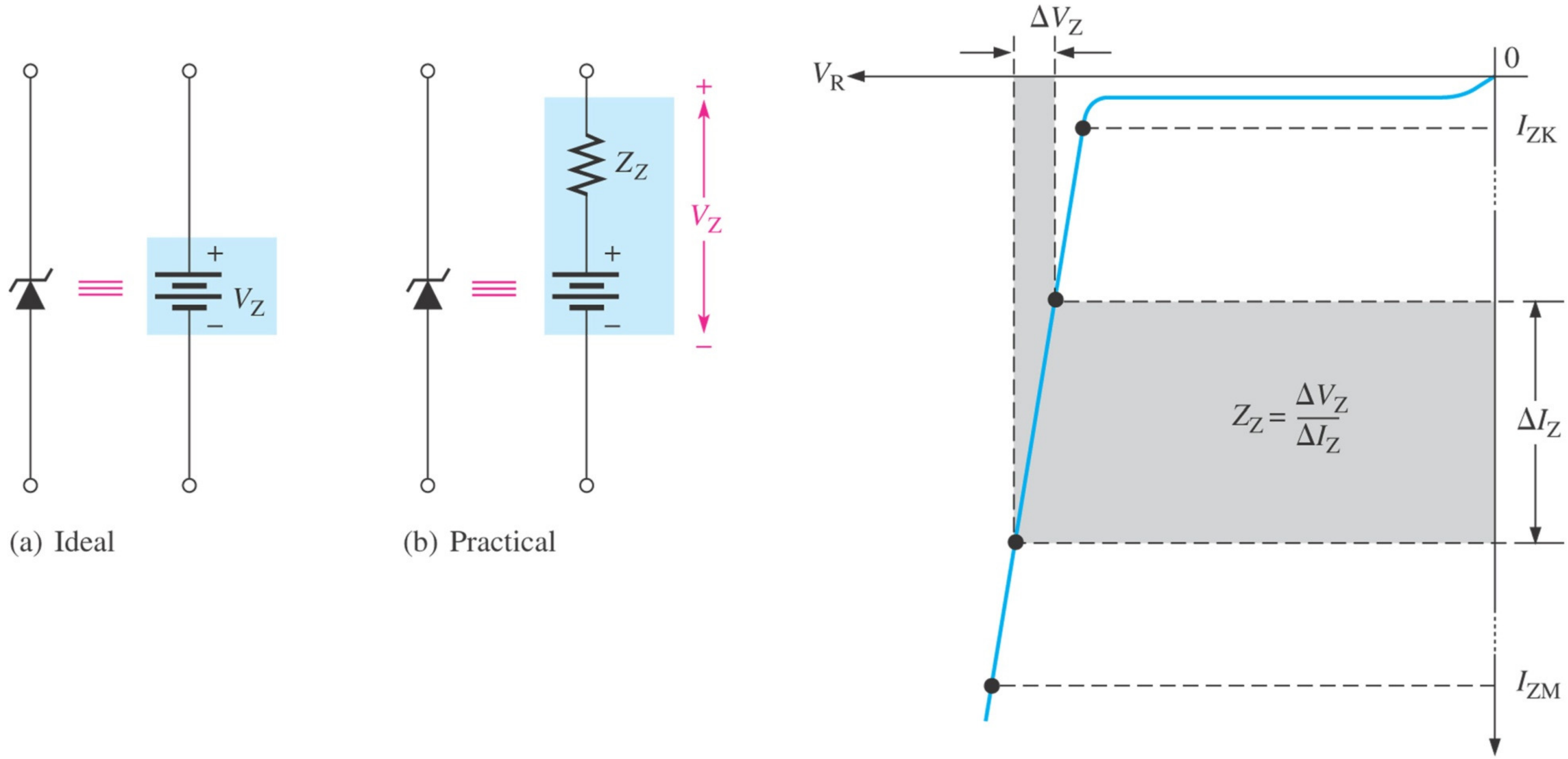
Zener equivalent circuits



(a) Ideal

(b) Practical

(c) Characteristic curve

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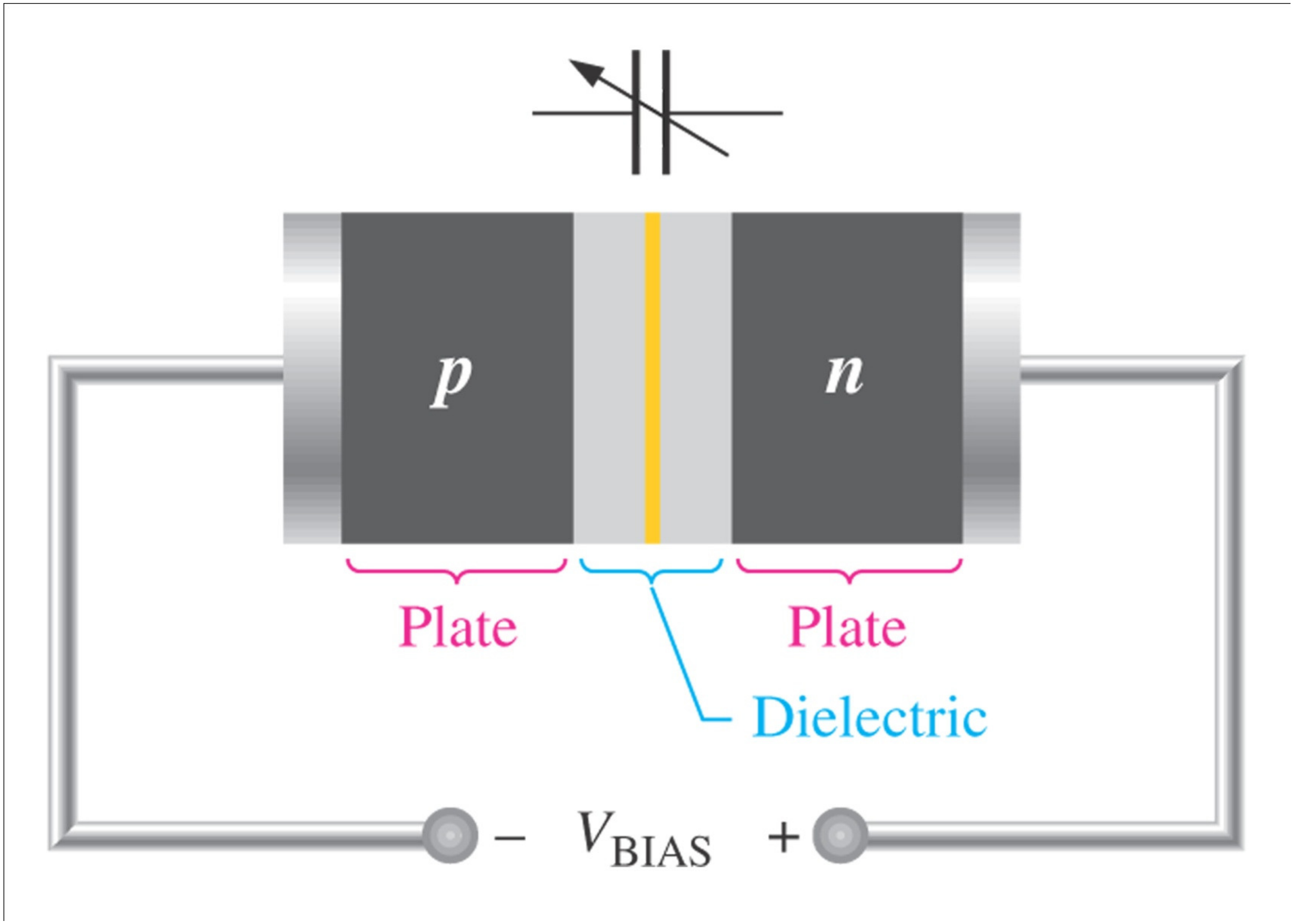
Varactor Diodes

- A varactor diode utilize the inherent capacitance of the depletion region of a reverse-biased *pn* junction to vary capacitance by changing the reverse voltage
  - The *p* and *n* regions are conductive, and act as the capacitor plates
  - The depletion layer created by the reverse bias acts as a capacitor dielectric because it is nonconductive
    - as the reverse bias increases, the depletion region widens, and the capacitance across the diode decreases
    - as the reverse bias decreases, the depletion region narrows, and the capacitance across the diode increases

The reverse-biased varactor diode acts as a variable capacitor.



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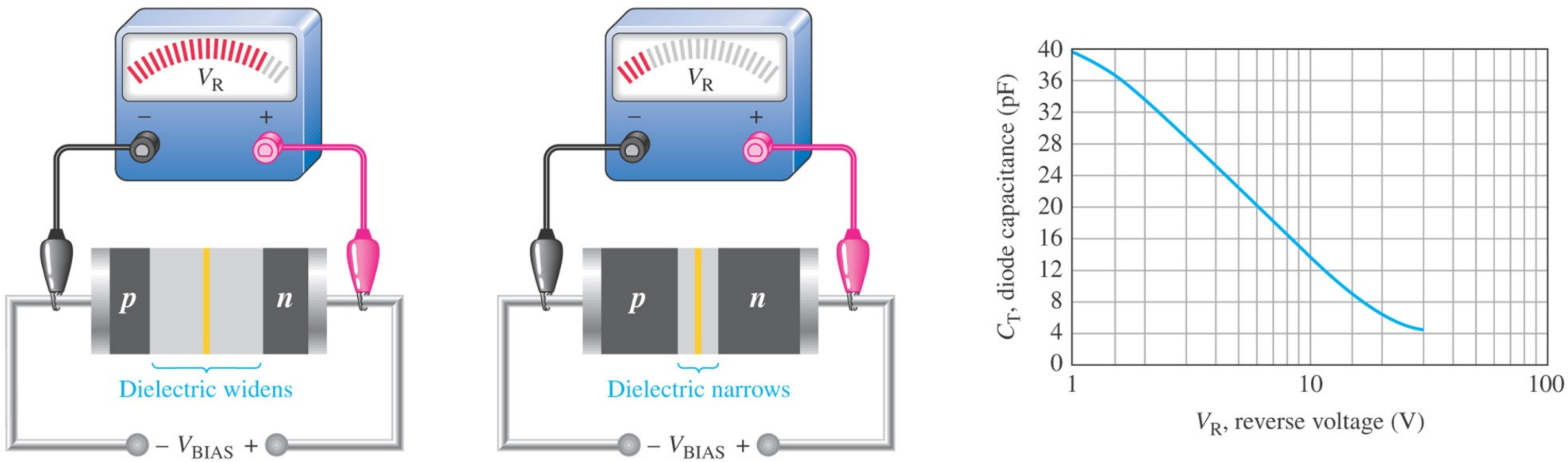
Varactor diode capacitance varies with reverse voltage

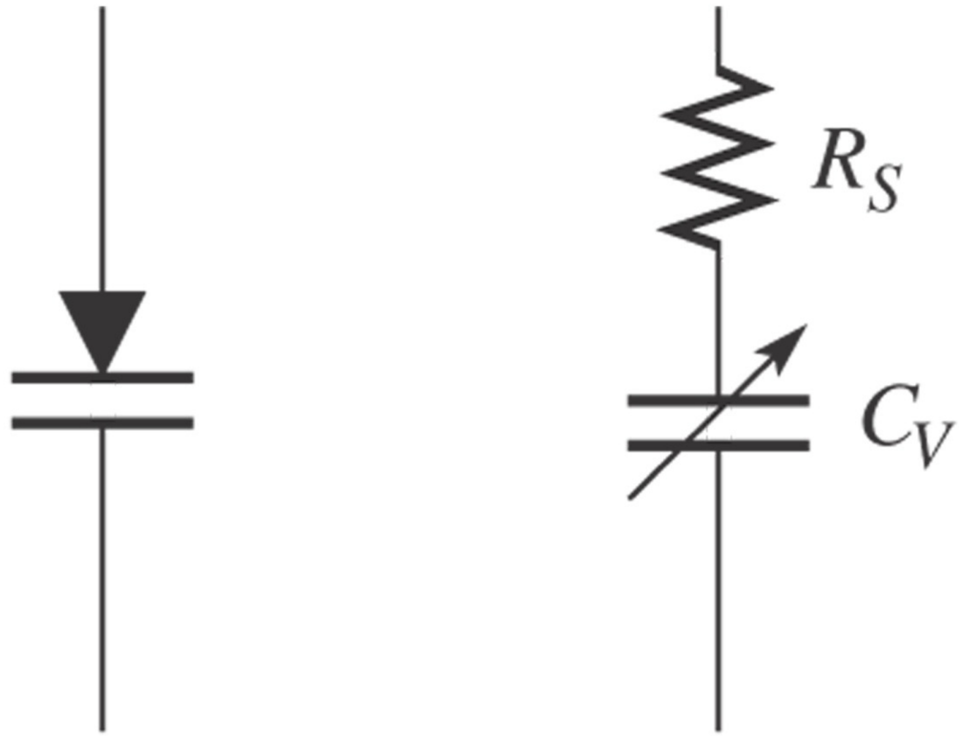


(a) Greater reverse bias, less capacitance

(b) Less reverse bias, greater capacitance

(c) Graph of diode capacitance versus reverse voltage

Varactor diode

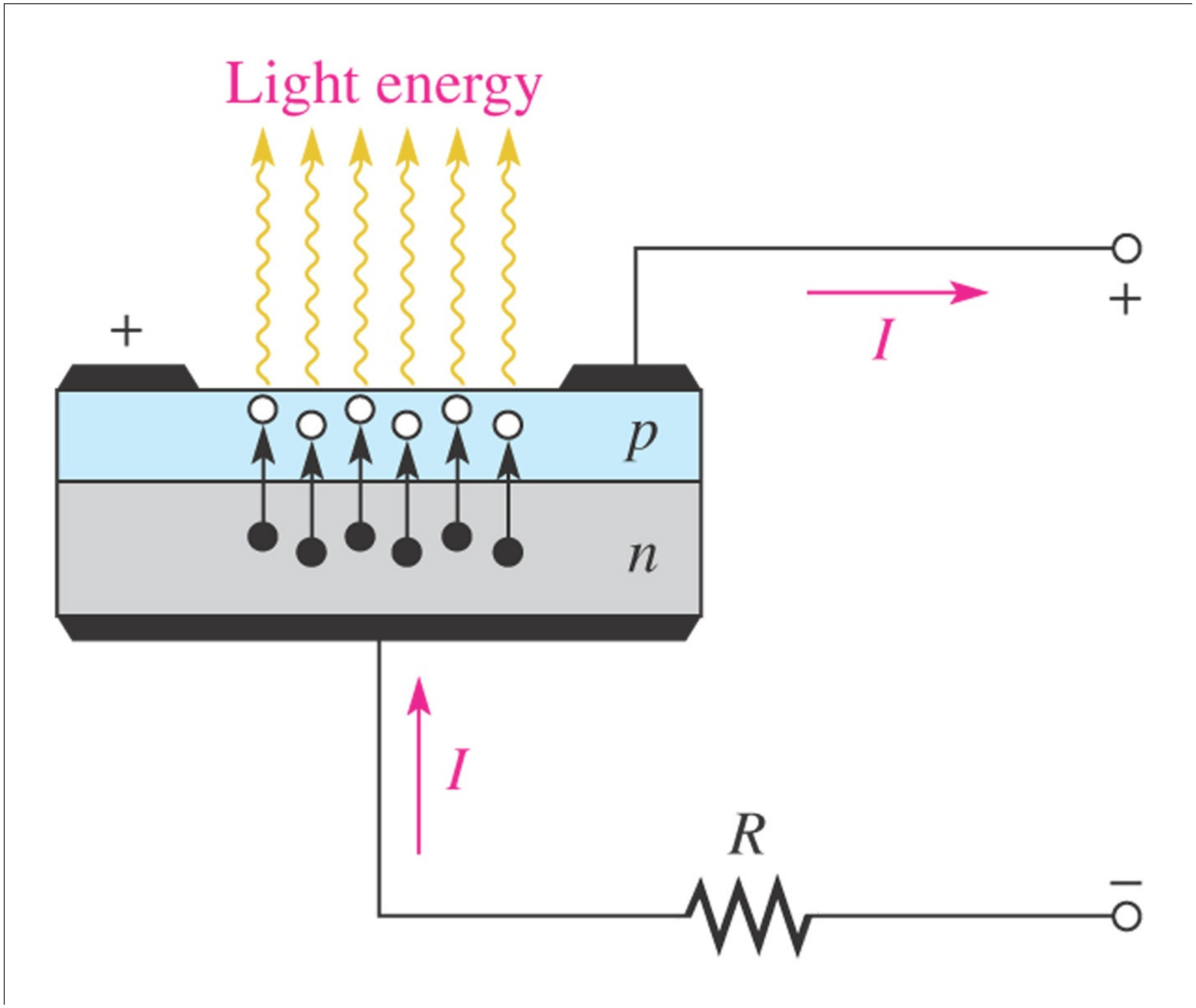


(a) Symbol (b) Equivalent circuit

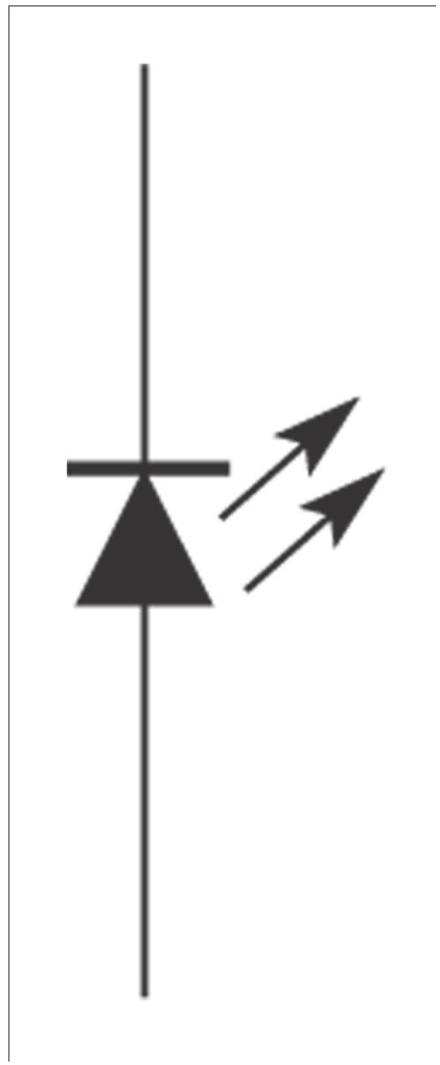
Light Emitting Diodes

- The light-emitting diode (LED)
  - when the device is forward-biased, electrons cross the *pn* junction from the *n*-type material and recombine with holes in the *p*-type material
  - Since the electrons in the conduction band are at a higher energy level than the holes in the valence band, when recombination takes place, energy is released in the form of heat and light
  - A large exposed surface on one layer of the LED permits the photons to be emitted as light, termed *electroluminescence*

Electroluminescence in an LED



Symbol for an LED



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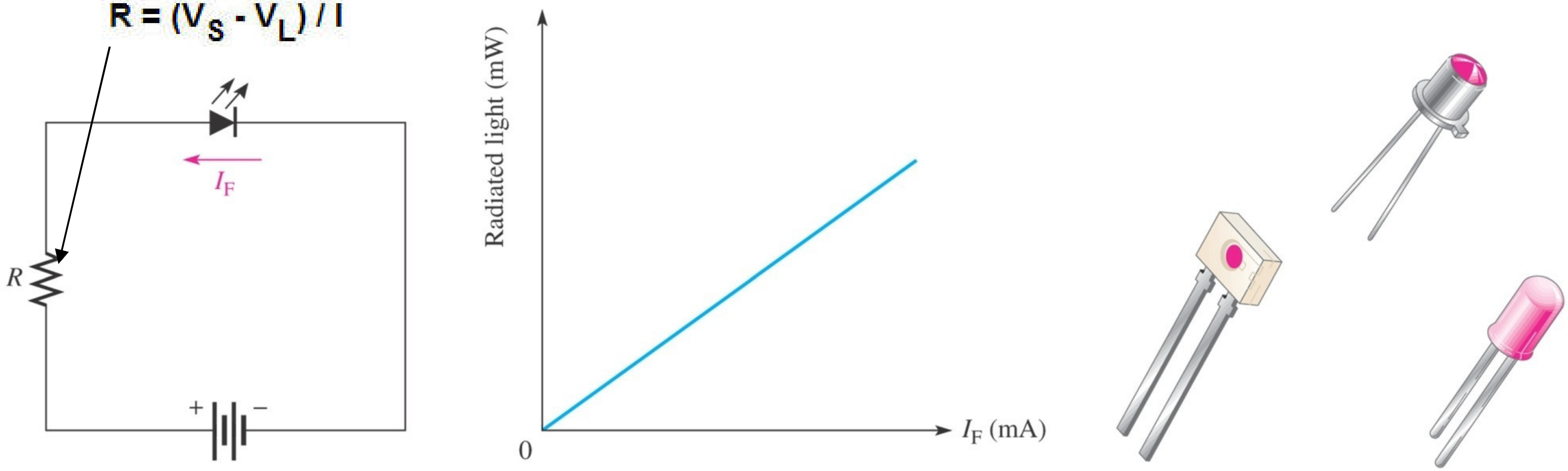
Light-emitting diodes (LEDs)

Always have a current-limiting resistor in a LED circuit.
Usually 1K – 2K Ohms.

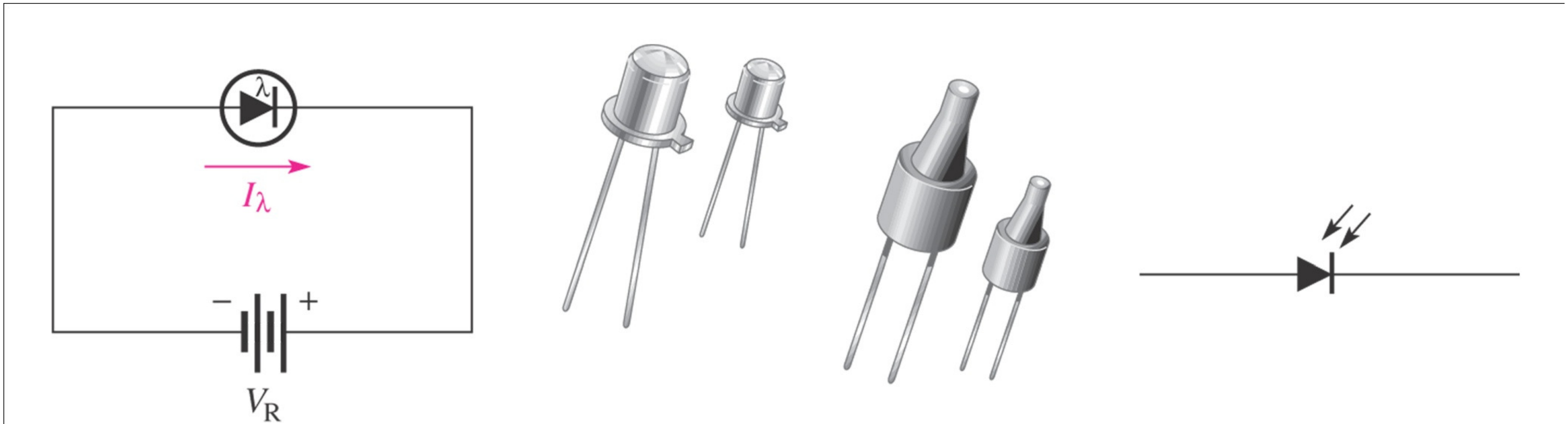
$R = (V_S - V_L) / I$



(a) Forward-biased operation (b) Typical light output versus forward current (c) Typical LEDs

Barrier Potential (Vb) = 1.0V – 2.0V

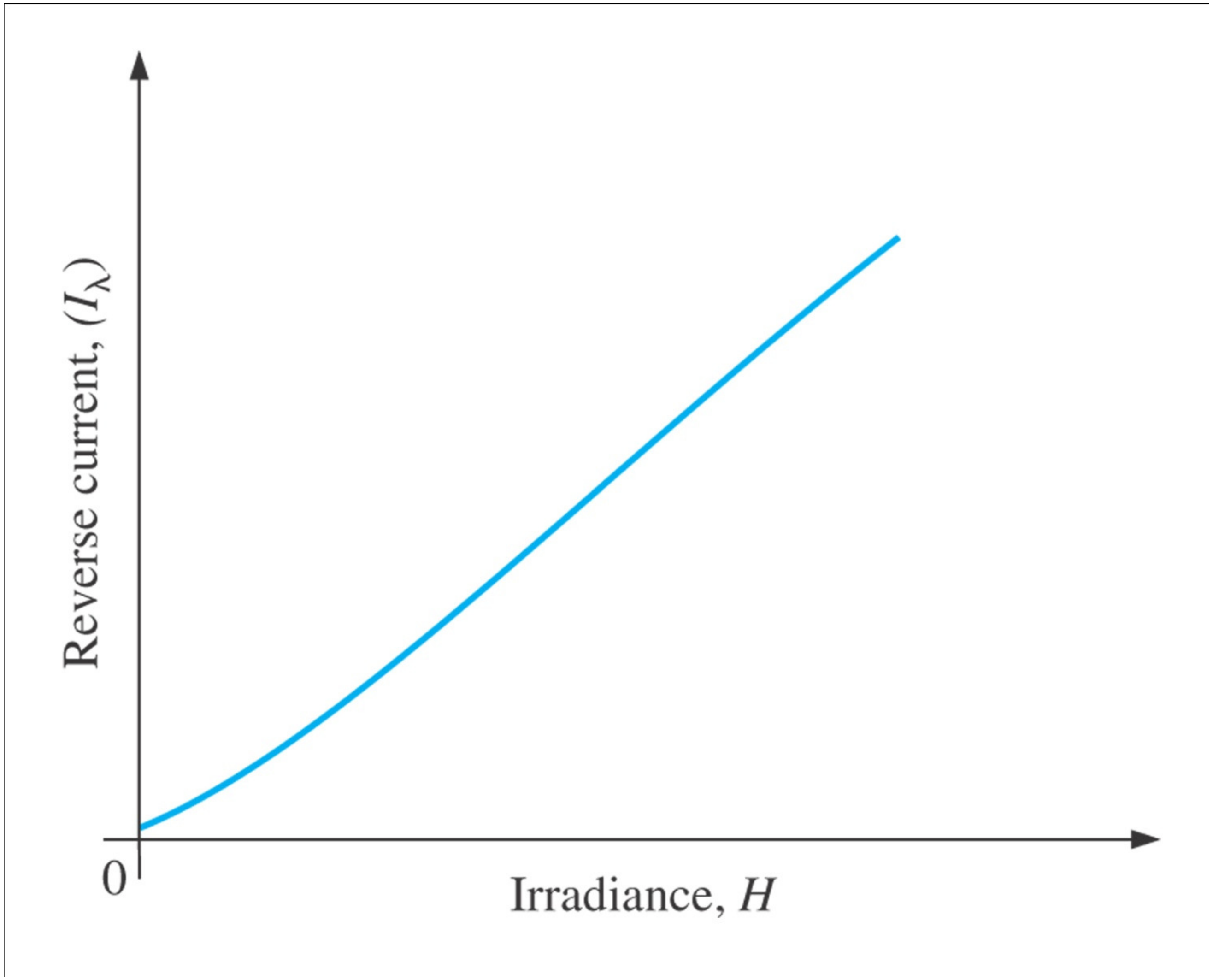
Photodiodes



(a) Reverse-bias operation (b) Typical devices (c) Alternate symbol

A photodiode is operated in Reverse Bias
They typically have a small window to let light in

General graph of reverse current versus irradiance for a photodiode



A Photodiode's reverse current increases with exposure to Light

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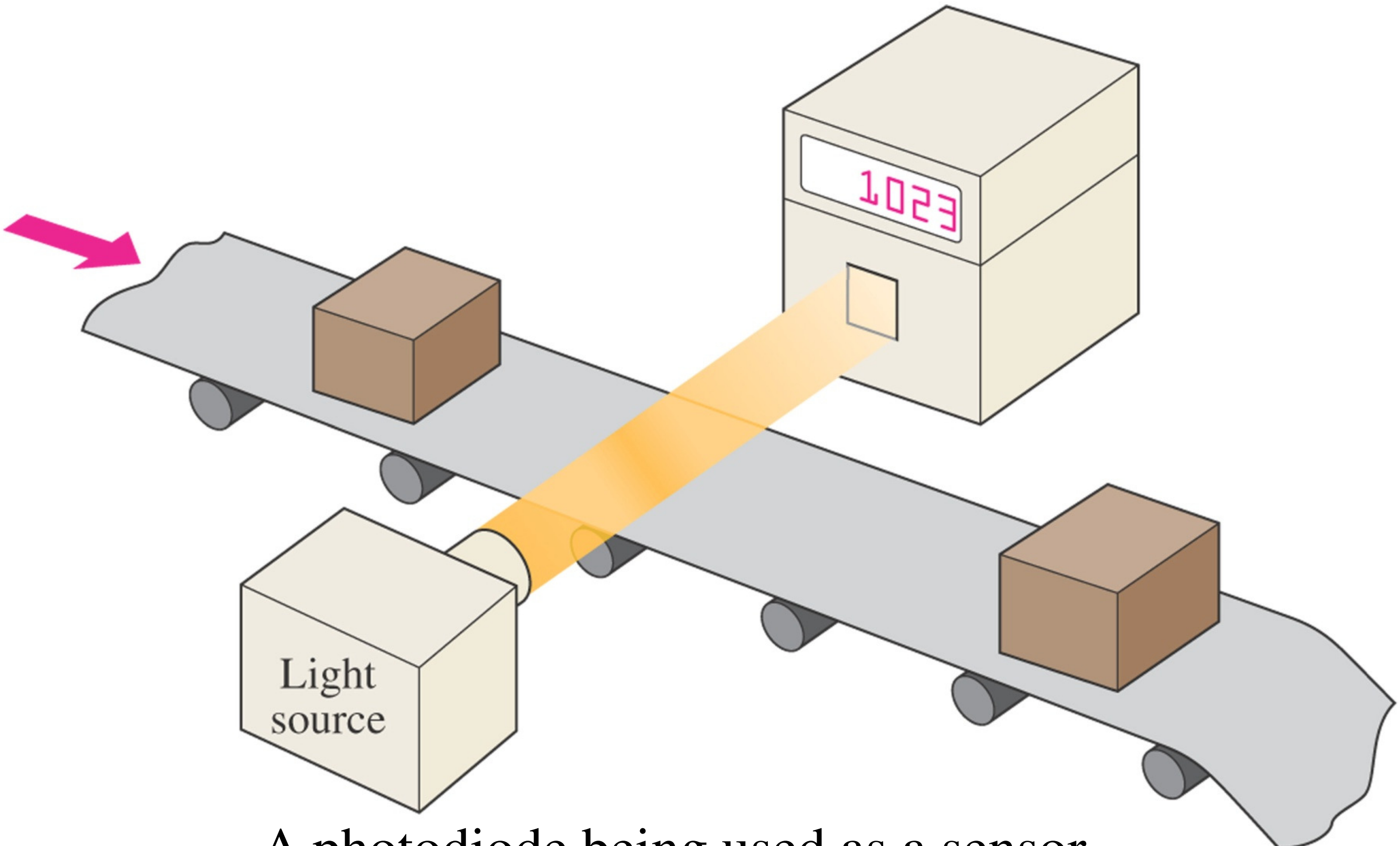
A photodiode circuit used in a system that counts objects as they pass on a conveyor belt



A photodiode being used as a sensor

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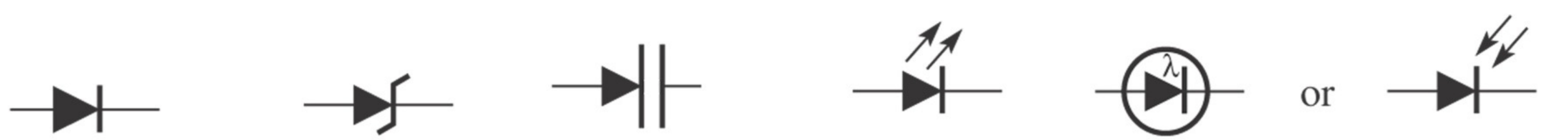
Summary of Common Diodes

- Zener diodes can be used as voltage references in a variety of applications
- A varactor diode acts as a variable capacitor under reverse-biased conditions
- The capacitance of a varactor diode varies inversely with reverse-biased voltage



(a) Rectifier (b) Zener (c) Varactor (d) LED (e) Photodiode