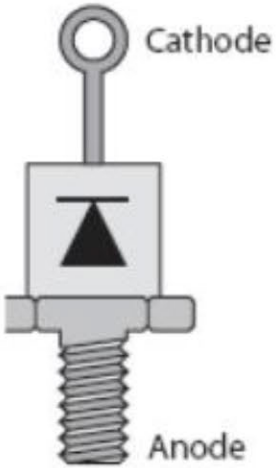
Semiconductor Diodes and Rectifiers

Diode Markings

Different size diodes are marked in different ways

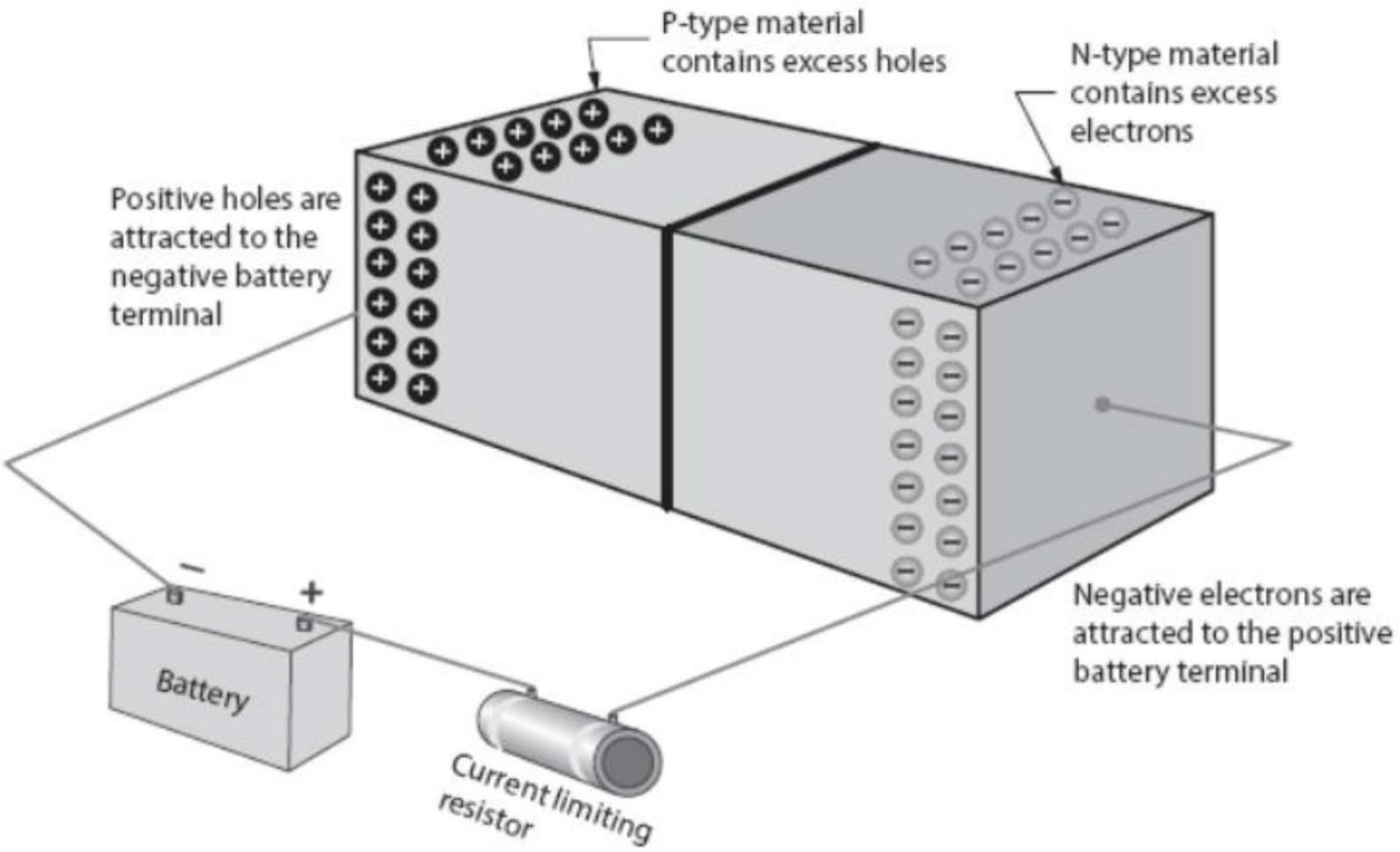


Large diodes often use a diode symbol to indicate proper polarity.

Small diodes use a line at one end to indicate the cathode. The cathode is the straight line in front of the arrow symbol.

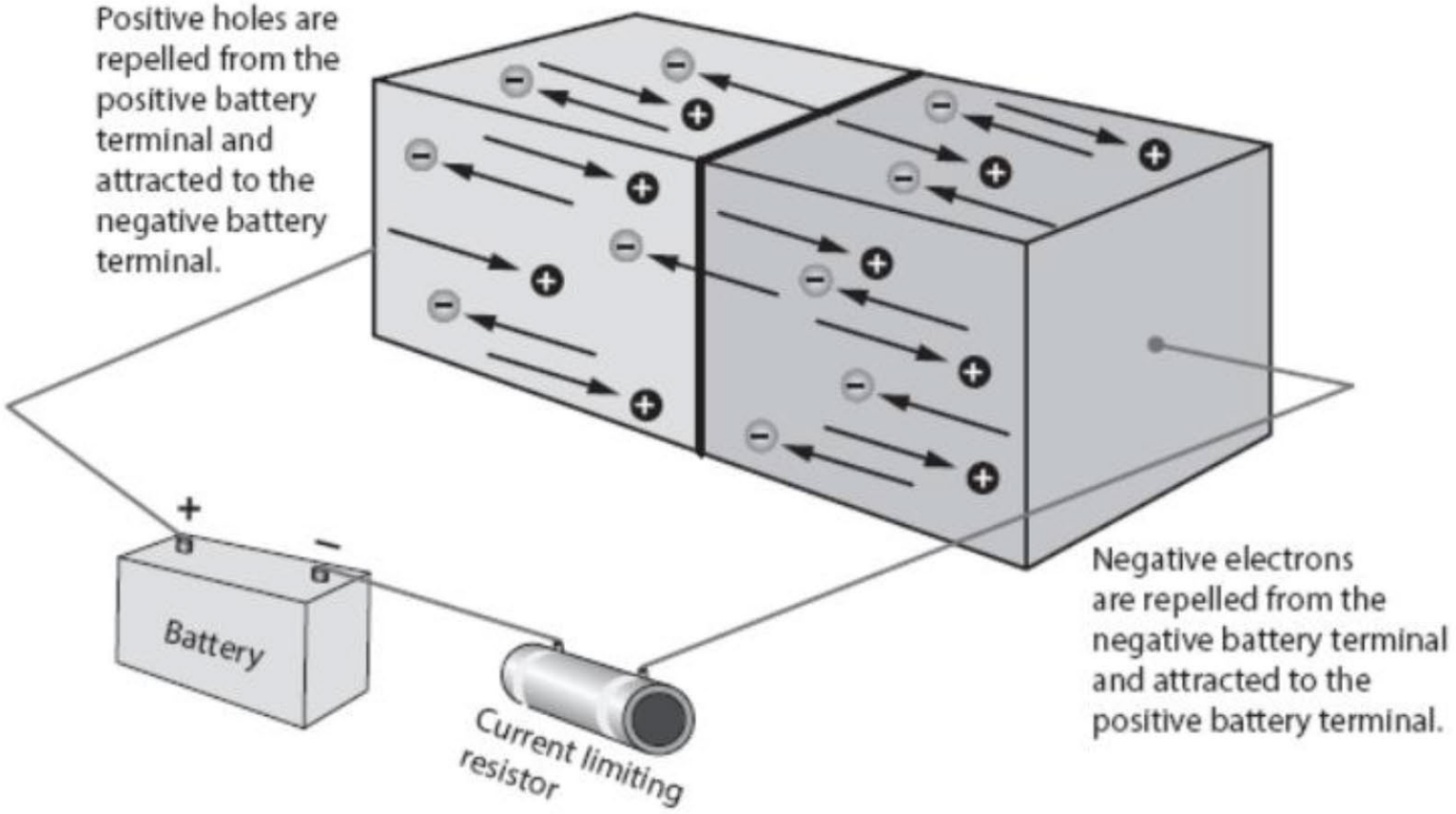
PN junction

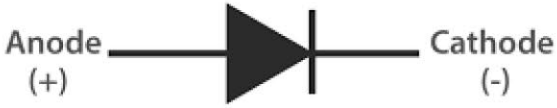
The PN junction will not conduct when reverse biased



PN junction

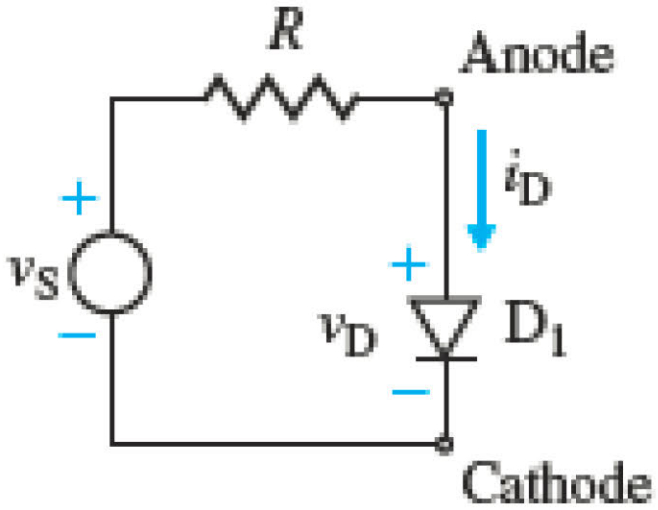
Current flows through the PN junction when it is forward biased



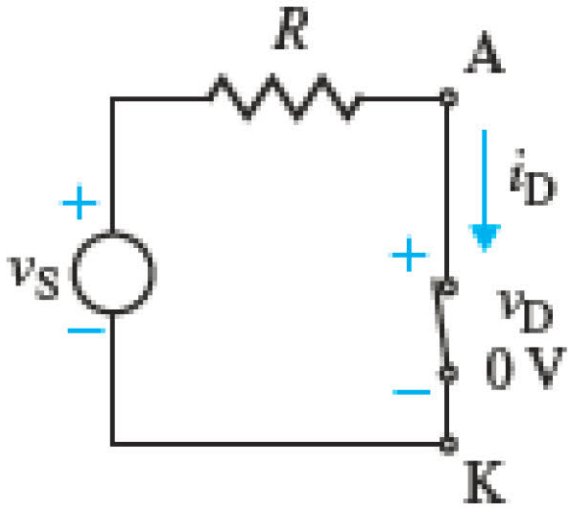


Ideal Diodes

- Two terminals are the anode and the cathode.
- If the anode voltage is held positive with respect to the cathode terminal, the diode conducts and offers a small forward resistance.
  - The diode is then said to be *forward biased*, and it behaves as a short circuit.



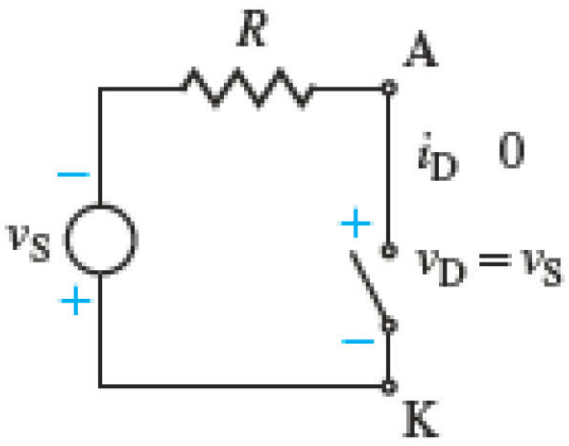
(a) Diode



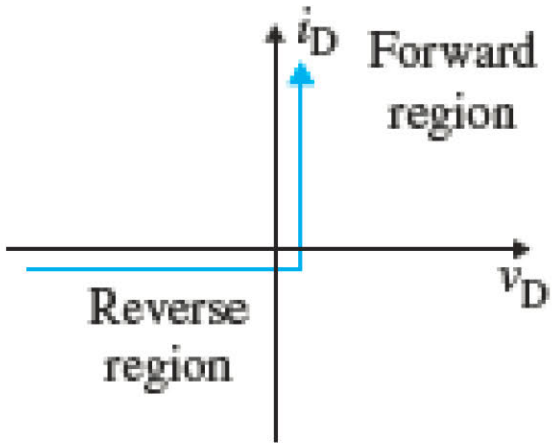
(b) Diode on

Ideal Diodes

- If the anode voltage is kept negative with respect to the cathode terminal, the diode offers a high resistance.
  - The diode is then said to be *reverse biased*, and it behaves as an open circuit.



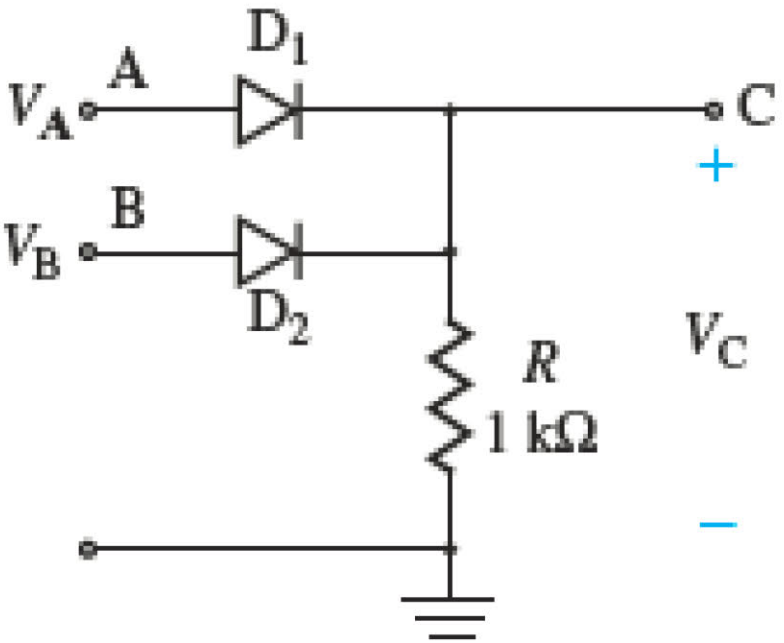
(c) Diode off



(d) Ideal *v-i* characteristic

Application as a Diode (OR Logic Function)

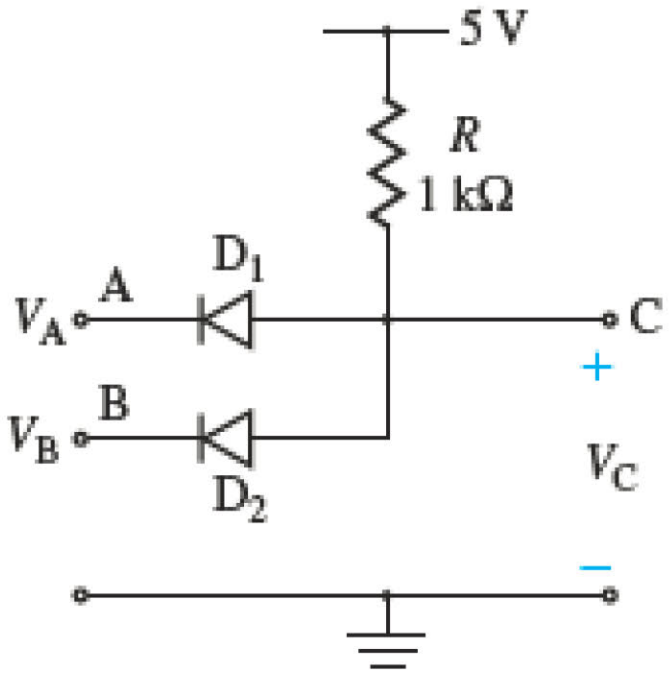
- A diode circuit that generates an OR logic function is shown below.
- A positive logic convention denotes logic 0 for 0 V and logic 1 for 5 V.



V_A	V_B	Output
0	0	0
0	1	1
1	0	1
1	1	1

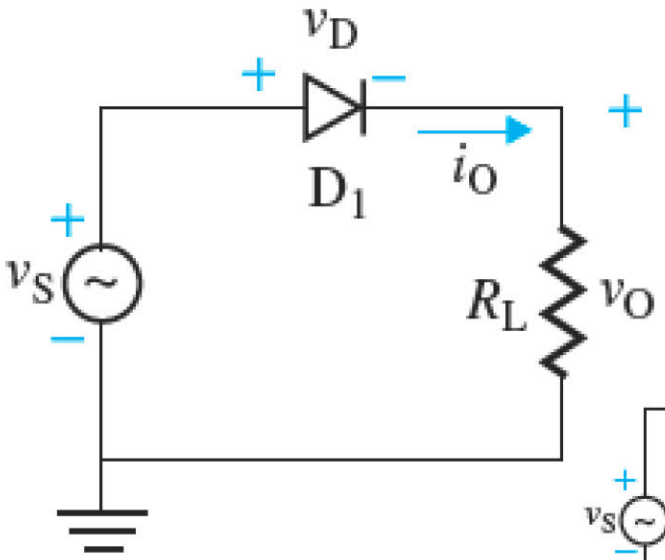
Application as a Diode AND Logic Function

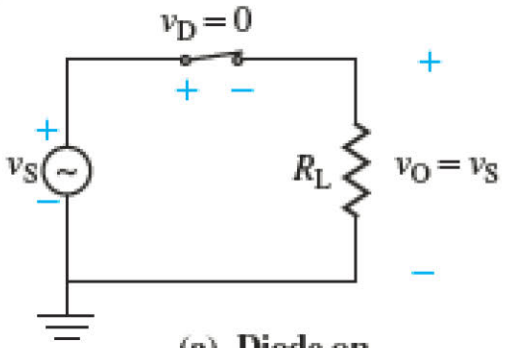
- A diode circuit that generates an AND logic function is shown below.
- A positive–logic convention denotes logic 0 for 0 V and logic 1 for 5 V.



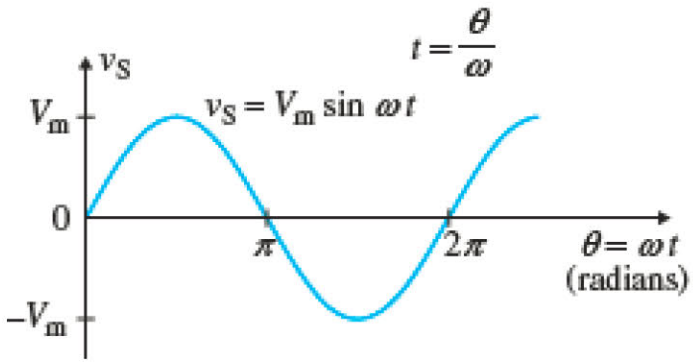
V_A	V_B	Output
0	0	0
0	1	0
1	0	0
1	1	1

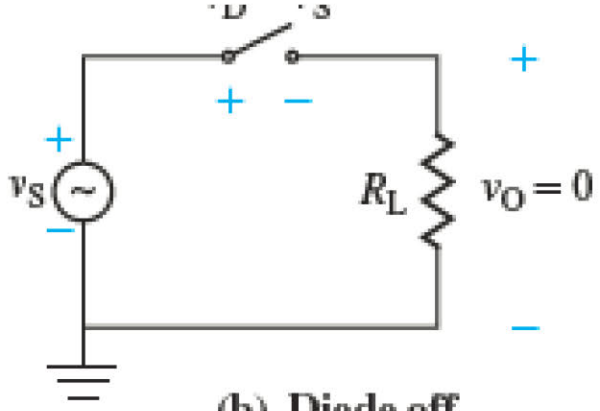
Application as a diode rectifier





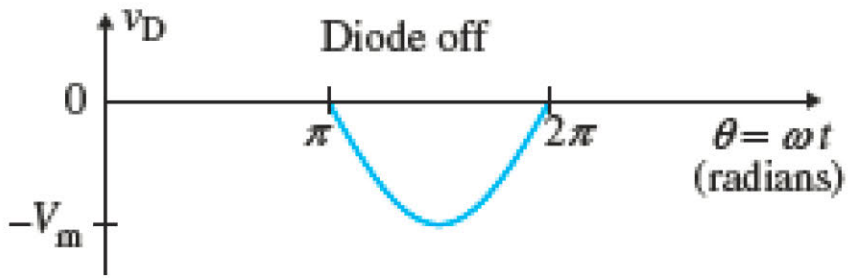
(a) Diode on





(b) Diode off

(radians)



(c) Waveforms

Characteristics of Practical Diodes

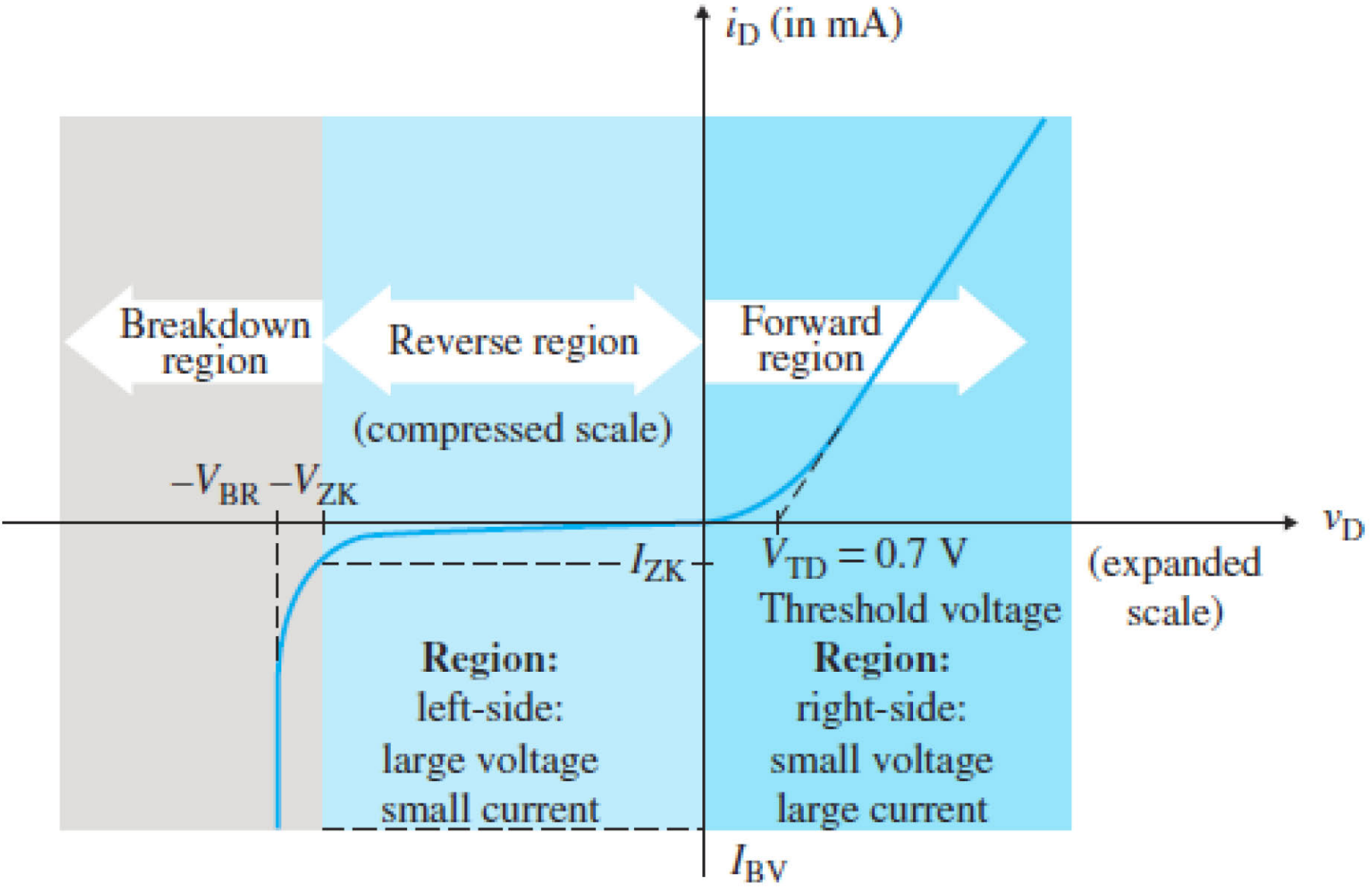
- Practical diode experiences a finite voltage drop when it conducts.
- This drop is typically in the range of 0.5 V to 0.7 V.
- If the input voltage to a diode circuit is high enough, this small drop can be ignored.

- **Shockley diode equation:**

$$i_D = I_S\left(e^{v_{D/nV_T}} - 1\right)$$

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

Voltage-versus-current characteristic of practical diode



Forward-Biased Region

- In the forward-biased region, $v_D > 0$. The diode current i_D is very small if the diode voltage v_D is less than a specific value $\mathbf{V_{TD}}$, known as the *threshold voltage* or the *cut-in voltage* or the *turn-on voltage* (typically **0.7 V**).

- The diode conducts fully if $\mathbf{v_D}$ is higher than V_{TD}.

- Thus, the threshold voltage is the voltage at which a forward-biased diode begins to conduct fully.

Reverse-Biased Region

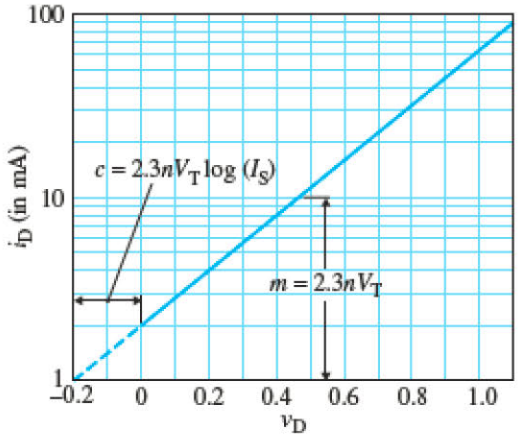
- In the reverse-biased region, $-V_{ZK} < v_D < 0$. That is, v_D is negative. If $|v_D| >> V_T$, which occurs for $v_D < -0.1$ V, the diode current i_D becomes:

$$i_D = I_S(e^{-|v_D|/nV_T} - 1) \approx -I_S$$

- The diode current i_D remains constant in the reverse direction and is equal to I_S in magnitude.

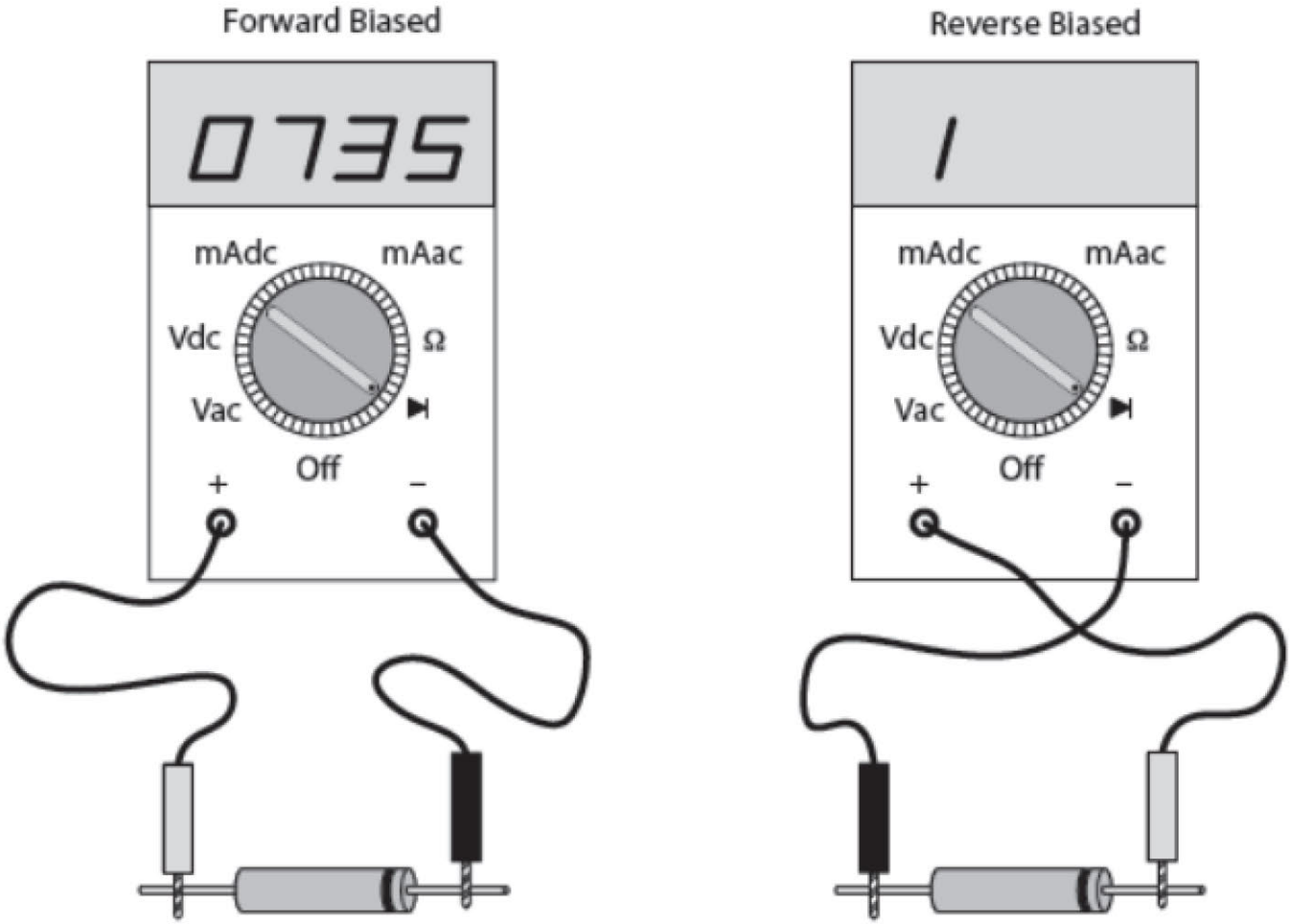
Breakdown Region

- In the breakdown region, the reverse voltage is high—usually greater than 100 V.
- If the magnitude of the reverse voltage exceeds a specified voltage known as the *breakdown voltage* V_{BR}, the corresponding reverse current I_{BV} increases rapidly for a small change in reverse voltage beyond V_{BR}.
- **Determination of Diode Constants**



Testing Diodes

Testing a diode with a digital multimeter



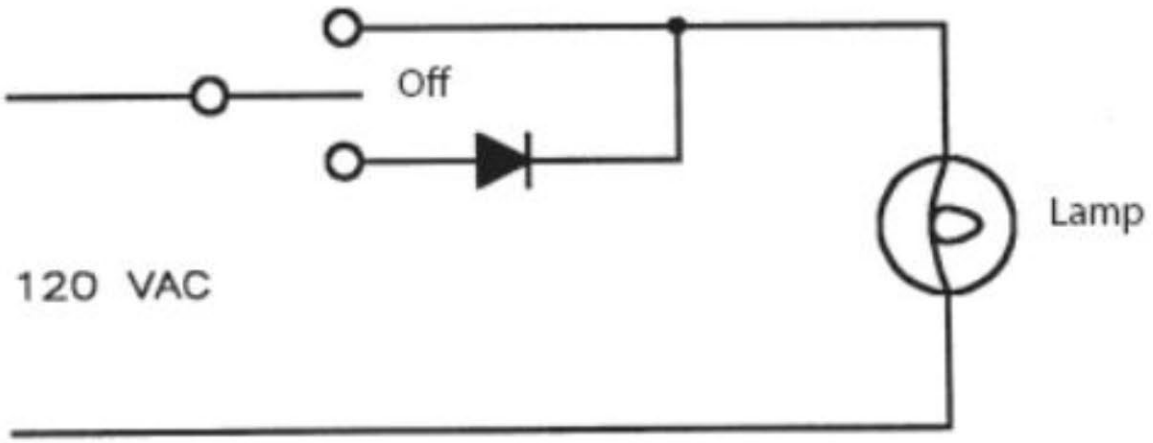
Electrical characteristics of diodes listed in the 1N registry

Type	Material	Identification	PRV (Volts)	V_F	I_F	I_R	trr (s) m
1N315	G	R	300	0.48	0.075	0.3 ma	25
1N1341	S	R	50	1.6	6.0	4.0 ma	150
1N223A	S	R	800		1.0	0.003 ma	20
1N2316	S	R	350	1.1	35	20 ma	300
1N4004	S	R	400	1.1	1.0	0.03 ma	30
1N4374	S	R	1500	1.75	0.75	0.1 ma	15
1N4596	S	R	1400	1.35	150	3.5 ma	3000

Application 1

the movable contact is changed to permit it to make connection with the lower stationary contact, the diode is connected in series with the lamp. Because the diode permits current to flow through it in only one direction, half of the AC waveform is blocked during each cycle. This permits only half the voltage to be applied to the lamp, causing it to burn at half brightness.

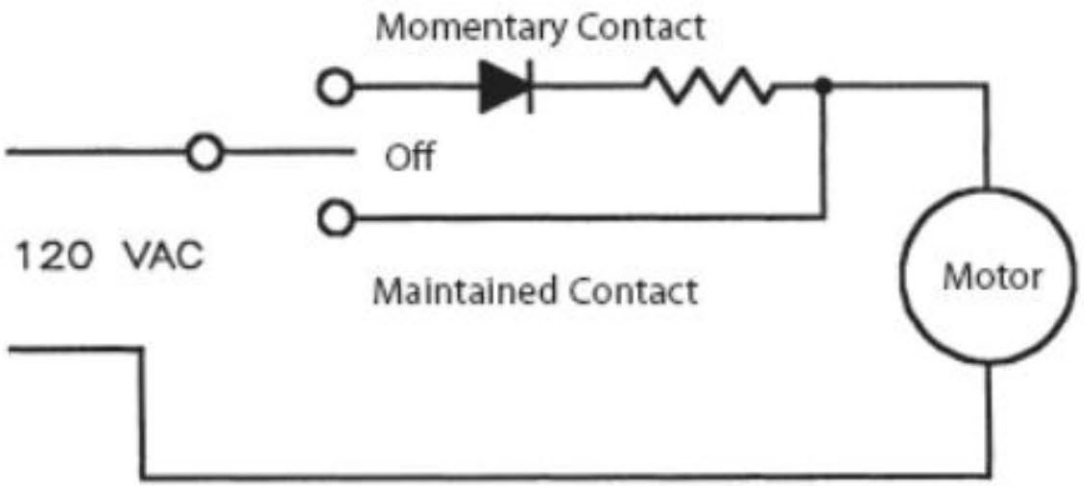
Light dimmer control



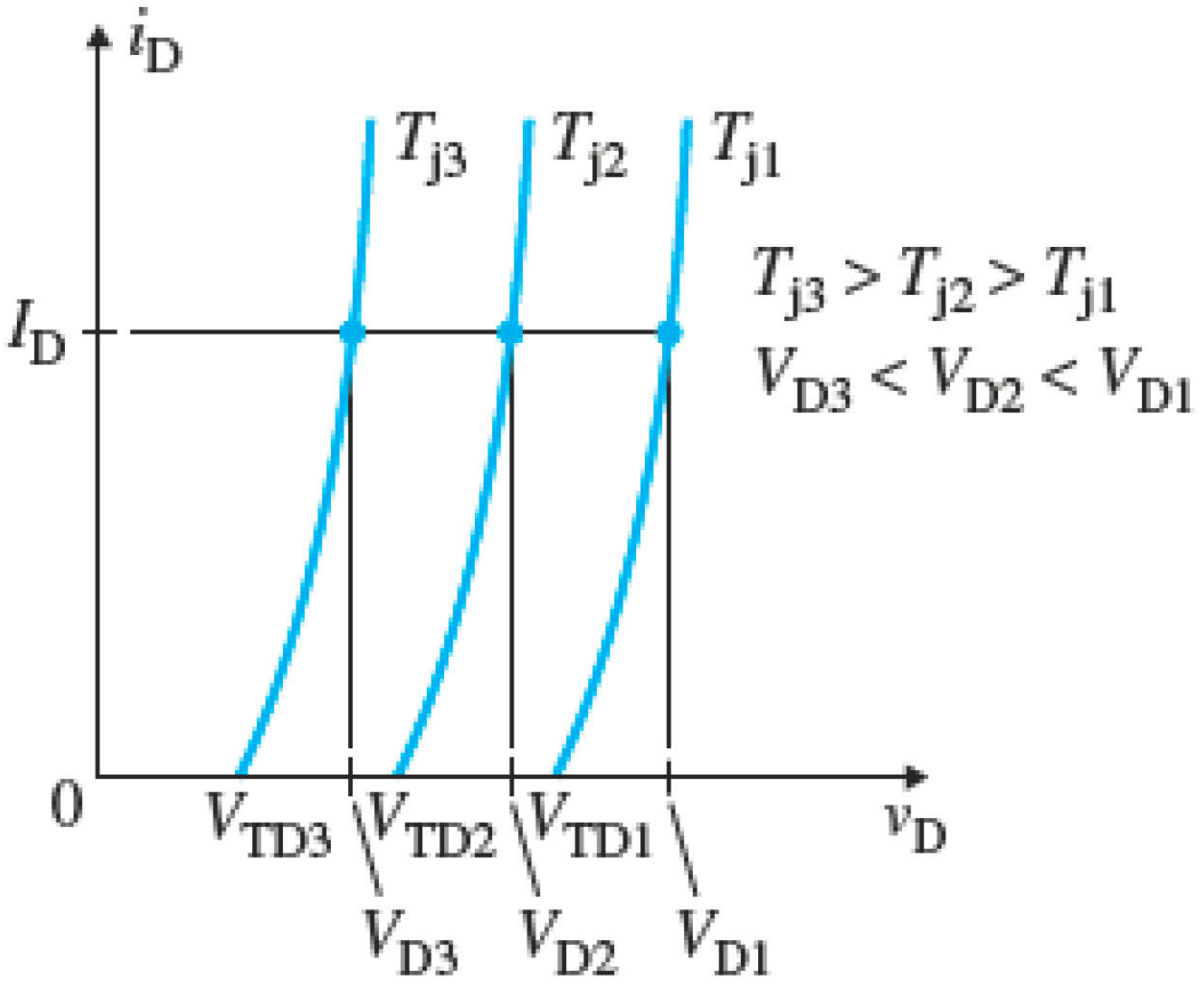
Application 2

This circuit is used to provide a dynamic brake for a small AC induction motor. AC induction motors can be braked by applying direct current to their stator windings. A diode permits current to flow through it in only one direction. Because the current never reverses direction, it is direct current.

Dynamic braking circuit for an AC induction motor



Temperature Effects on Diodes



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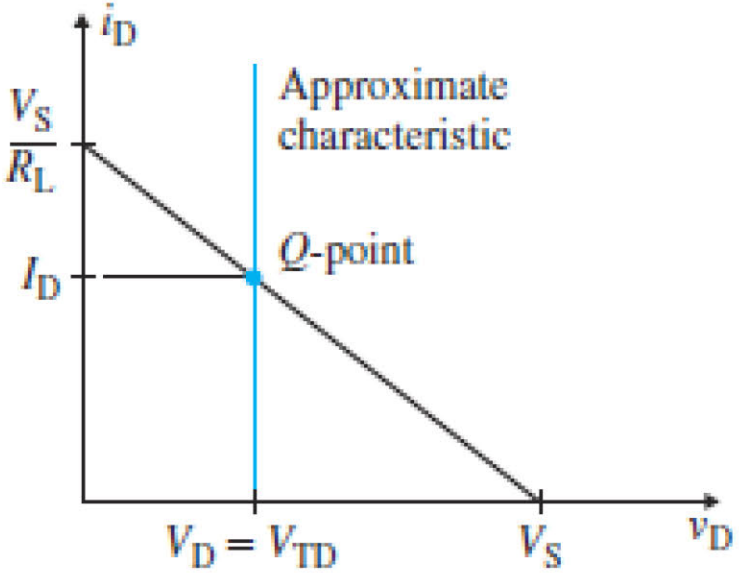
Modeling of Practical Diodes

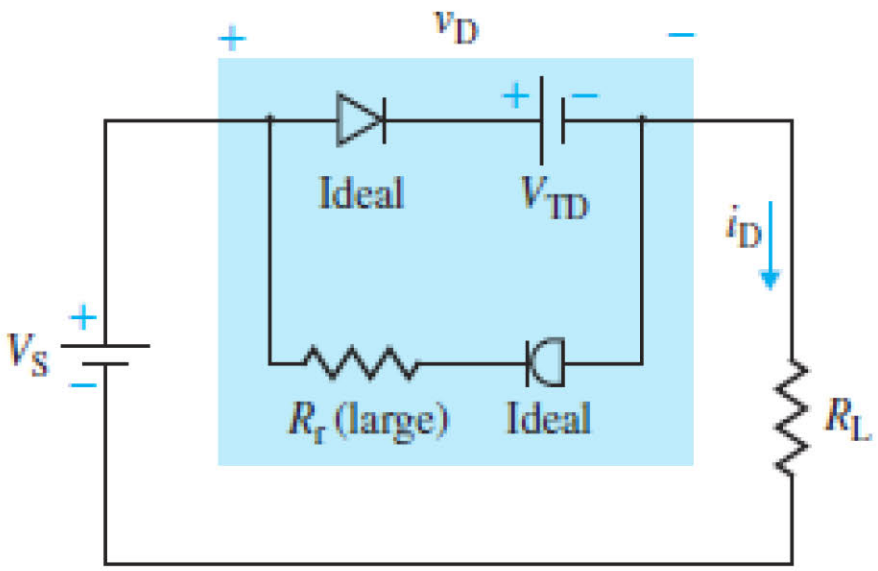
- **Constant-Drop DC Model**

$$v_D = \begin{cases} v_{TD} & for\ v_D \geq V_{TD} \\ 0 & for\ v_D < V_{TD} \end{cases}$$

$$i_D = \frac{V_S - V_{TD}}{R_L}$$



(a) *Q*-point



(b) Circuit model

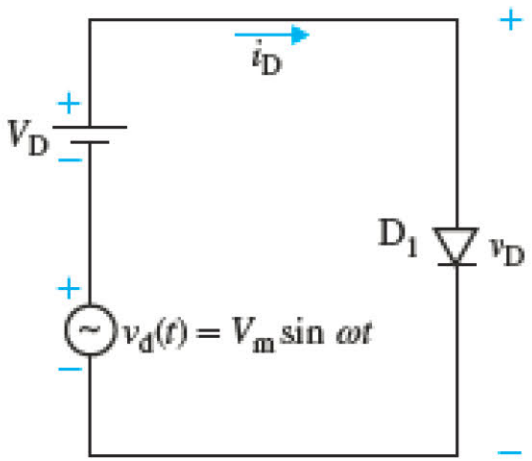
Low-Frequency Small-Signal Model

- Under small-signal conditions, the diode characteristic around the Q-point is approximated by a straight line and modeled by a resistance called the *dynamic resistance* or *AC resistance* or *small-signal resistance* r_d, which is defined by:

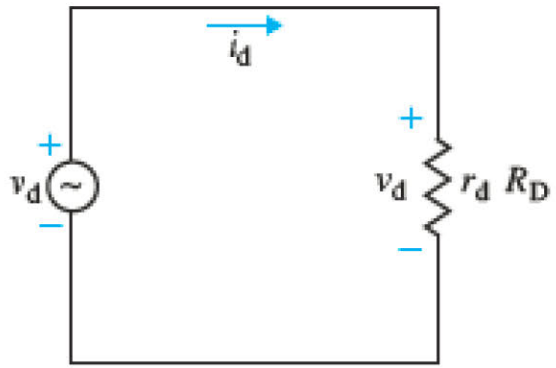
$$\frac{1}{r_d} = g_d = \frac{\Delta i_D}{\Delta v_D}\Big|_{at\ Q-point}$$

where g_d is the *small-signal diode transconductance*

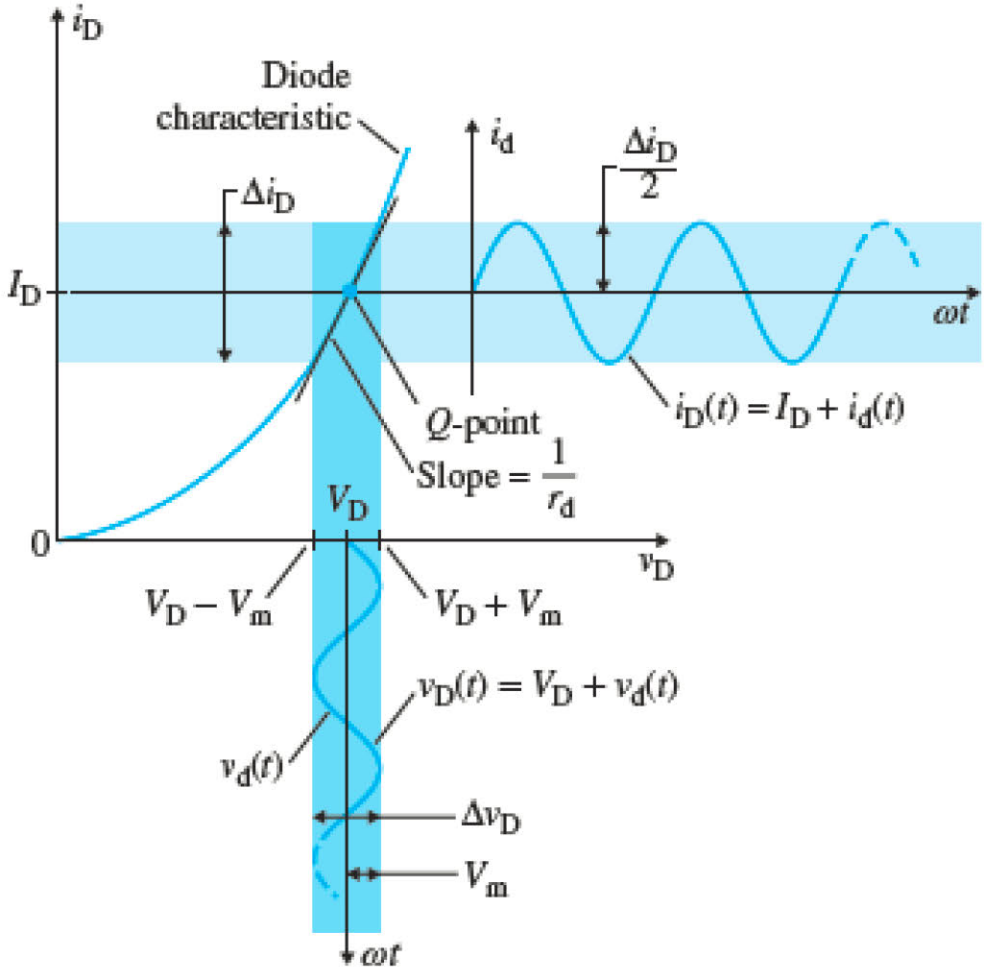
Low-Frequency Small-Signal Model



(a) Circuit



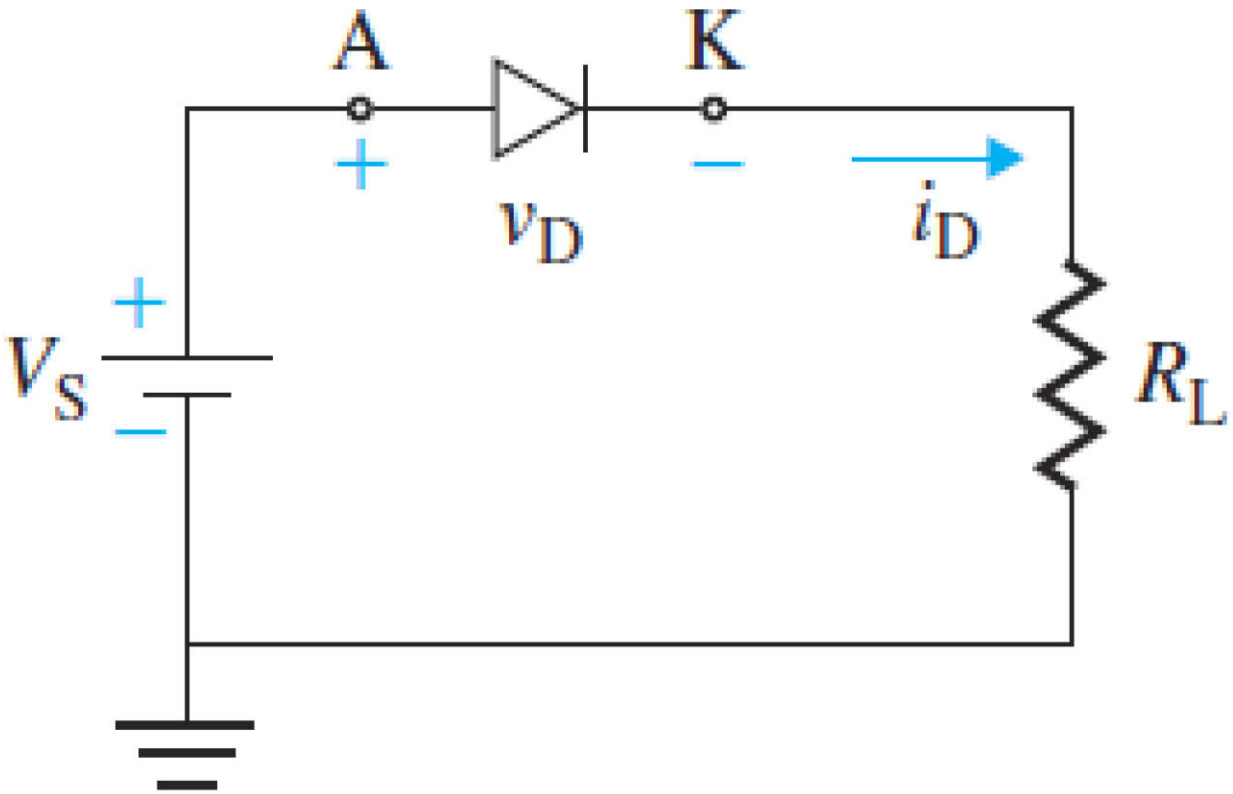
(c) AC model



(b) Outputs v_D and i_D

Analysis of Practical Diode Circuits

$$V_S = v_D + R_L i_D$$



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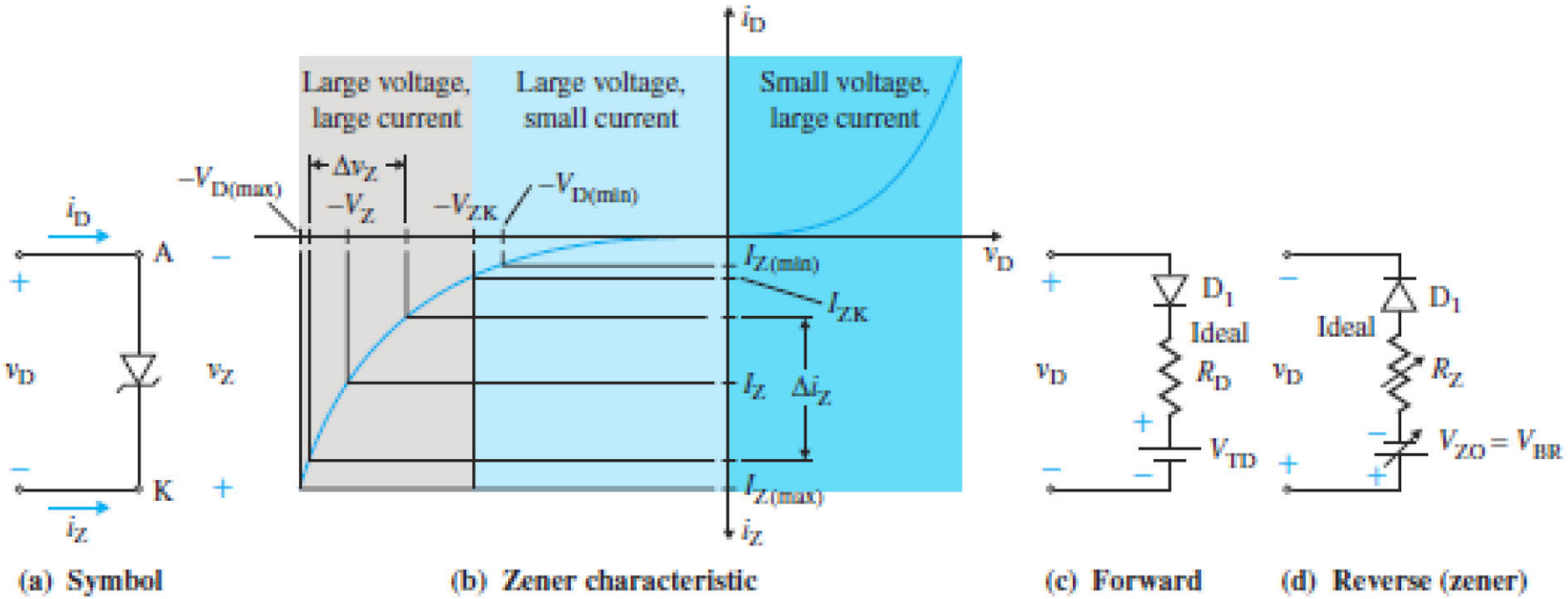
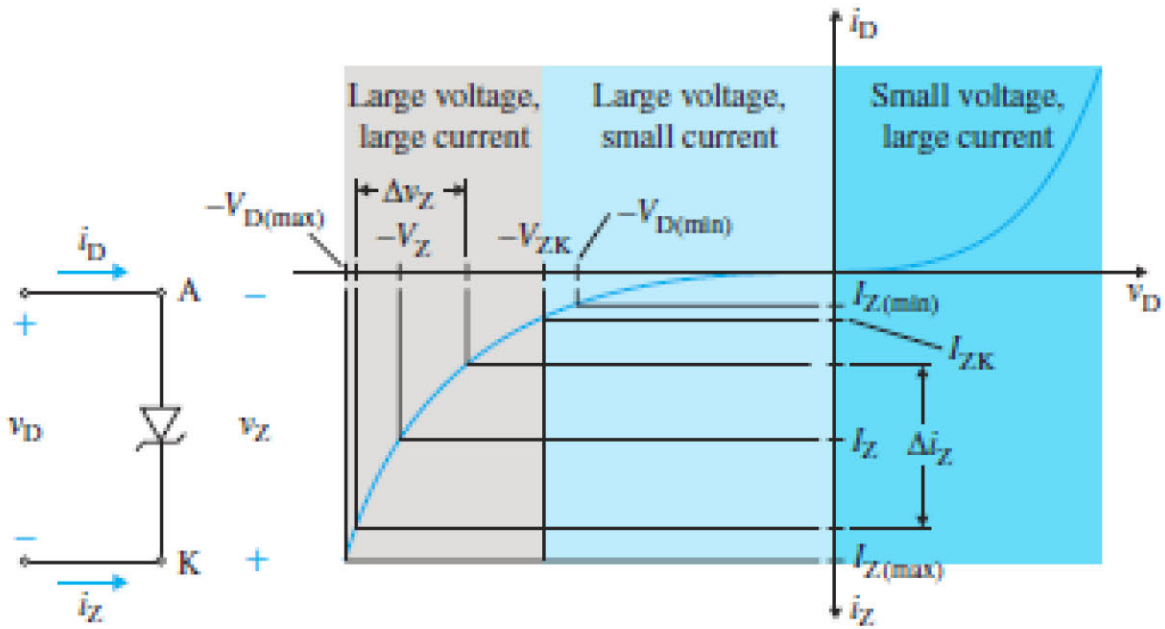
Zener Diodes

- If the reverse voltage of a diode exceeds a specific voltage called the *breakdown voltage*, the diode operates in the breakdown region.
- In this region, the reverse diode current increases rapidly.

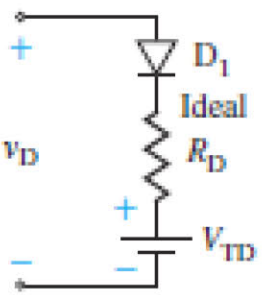


Zener Diodes

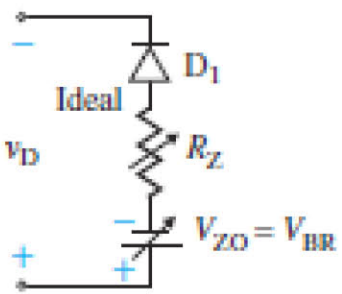
- The diode voltage remains almost constant and is practically independent of the diode current.
- A diode especially designed to have a steep characteristic in the breakdown region is called a *zener diode.*



(a) Symbol (b) Zener characteristic

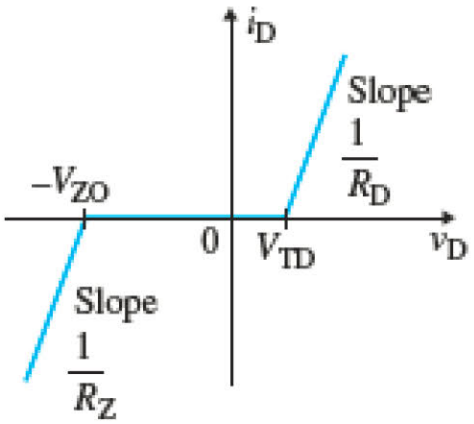


(c) Forward

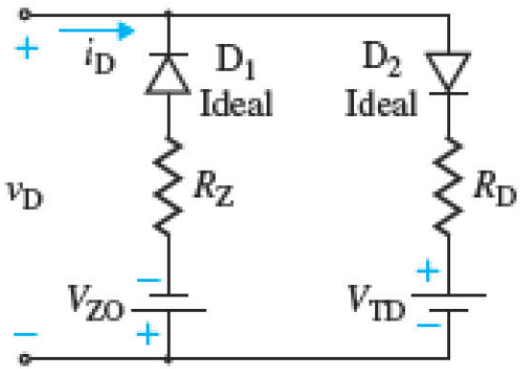


(d) Reverse (zener)

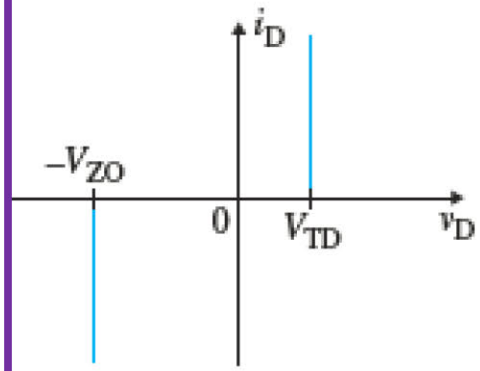
Zener Limiters



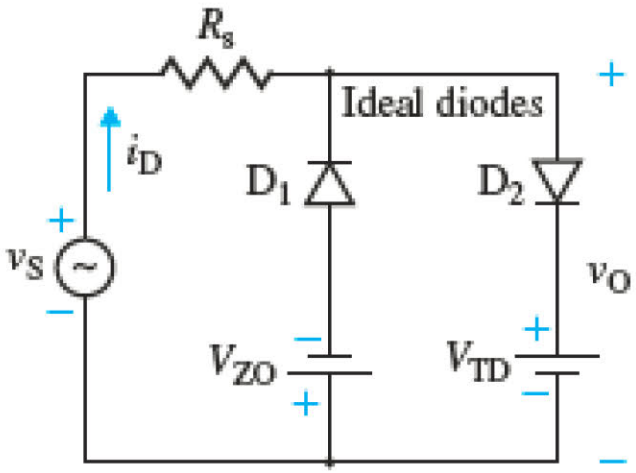
(a) Approximate characteristic



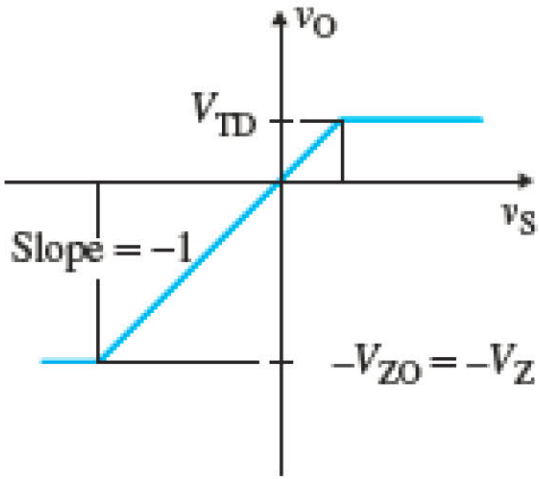
(b) Model



(c) Ideal zener characteristic



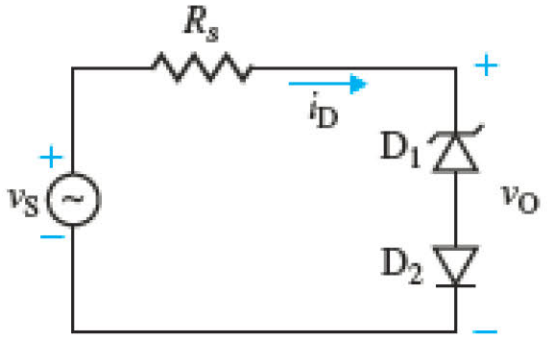
(a) Model



(b) Transfer characteristic

Temperature Effects on Zener Diodes

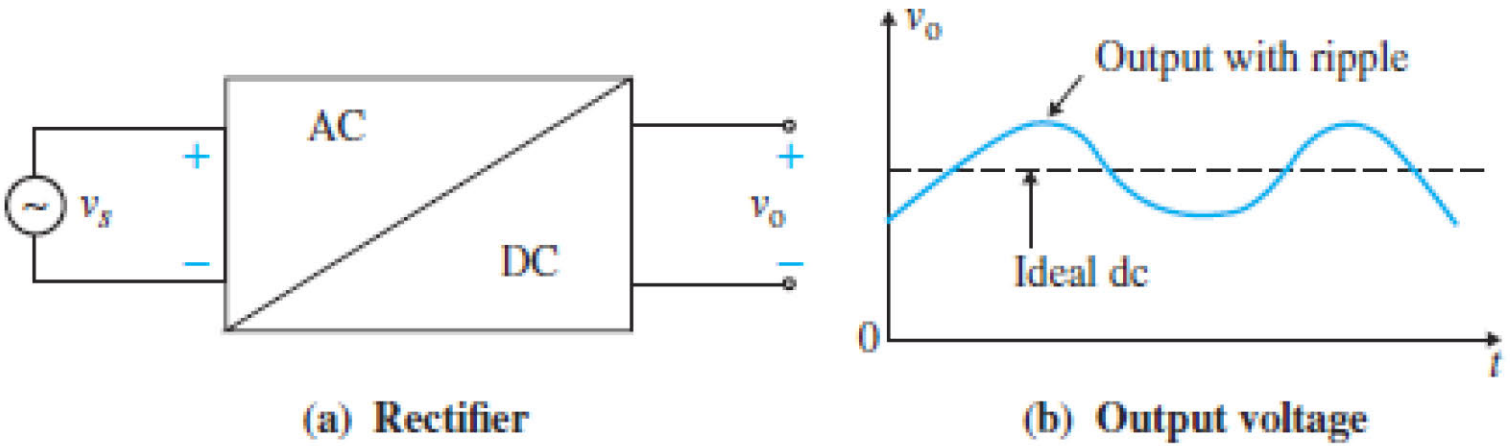
- Any change in junction temperature generally changes the zener voltage V_Z.
- The temperature coefficient is approximately +2 mV/°C, which is the same as but opposite that of a forward-biased diode.
- However, if a zener diode is connected in series with a forward-biased diode, the temperature coefficients of the two diodes tend to cancel each other.



Diode Rectifiers

- A rectifier that converts an AC voltage to a unidirectional voltage is used as a DC power supply for many electronic circuits.

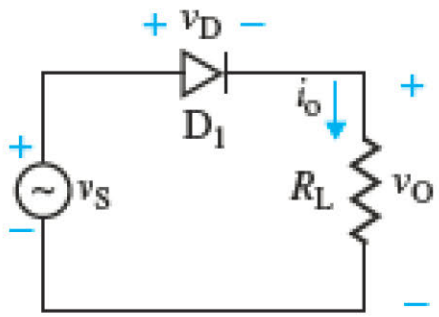
- A rectifier is also called an *AC–DC converter*.



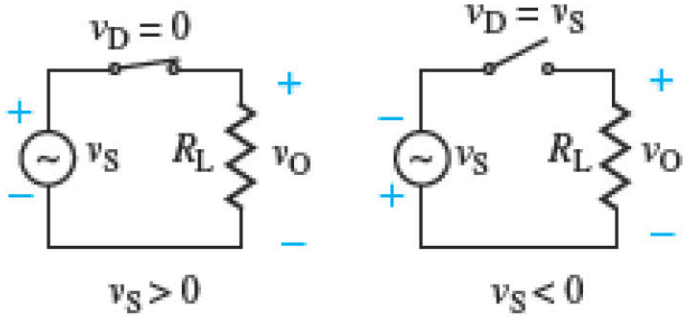
(a) Rectifier (b) Output voltage

Single-Phase Half-Wave Rectifiers

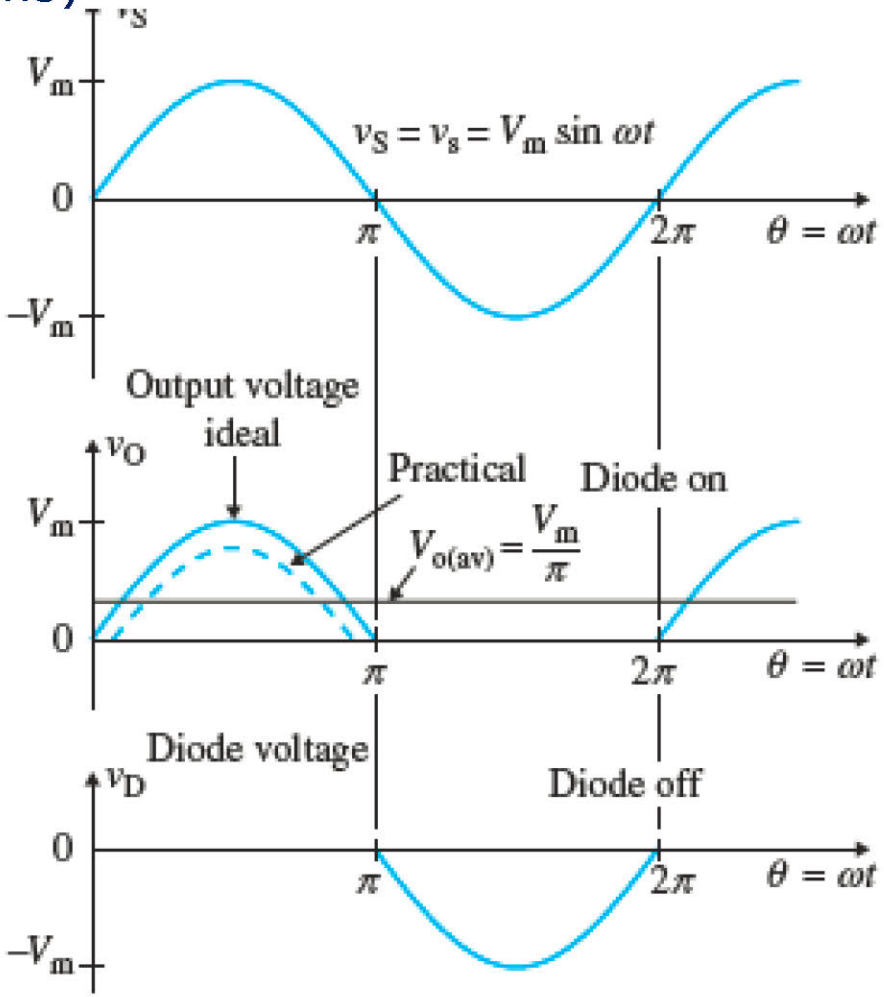
- $V_{o(av)}$, $I_{o(av)}$, $V_{o(rms)}$, $I_{o(rms)}$



(a) Circuit

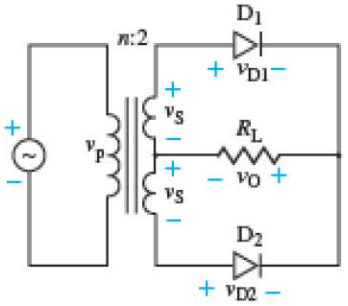


(b) Equivalent circuits

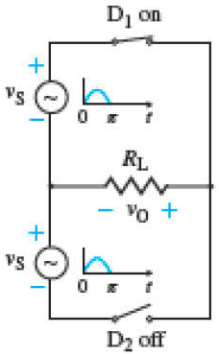


Single-Phase Full-Wave Center-Tapped Rectifier

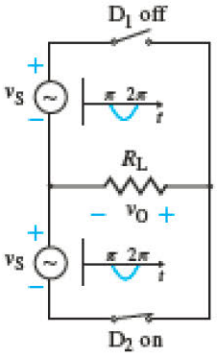
- For a half-wave rectifier, the average (or DC) voltage is only 0.318 V_m. A full-wave rectifier has double this output voltage, and it is constructed by combining two half-wave rectifiers.



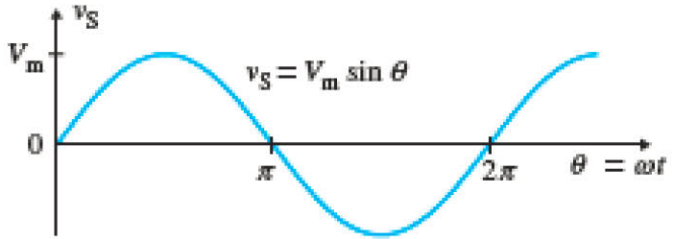
(a) Circuit

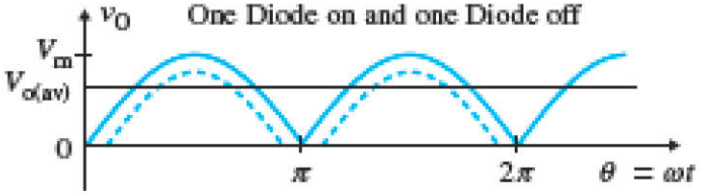


(b) Equivalent circuit for $v_S > 0$



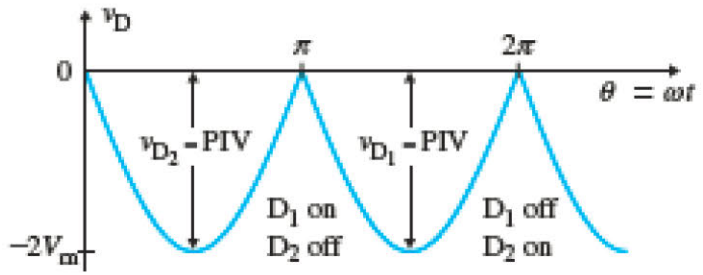
(c) Equivalent circuit for $v_S < 0$

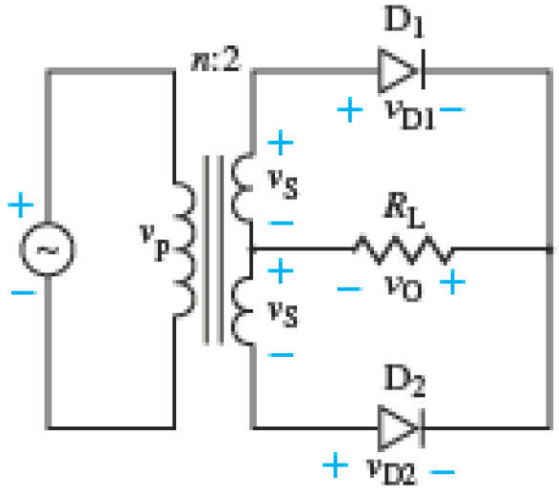




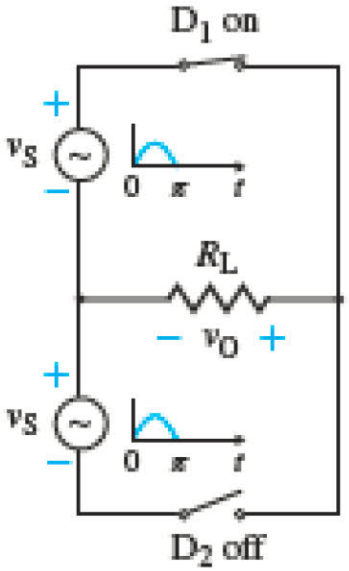
$v_{D_1} = -2v_S$ $\quad v_{D_1} = 0$

$v_{D_2} = 0$ $\quad v_{D_2} = -2v_S$

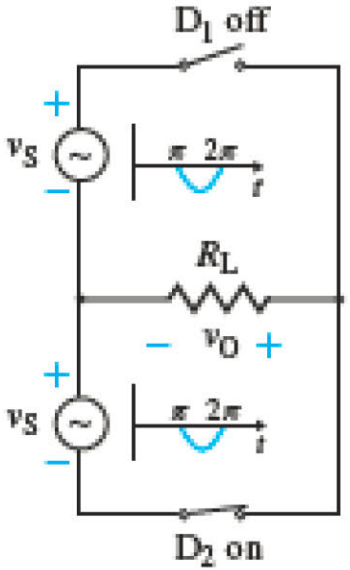




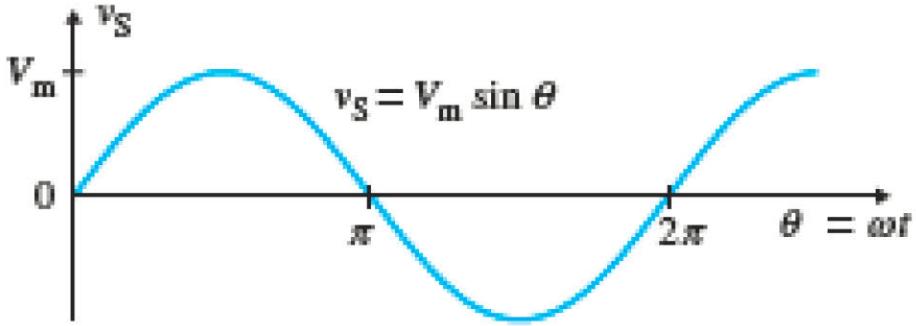
(a) Circuit

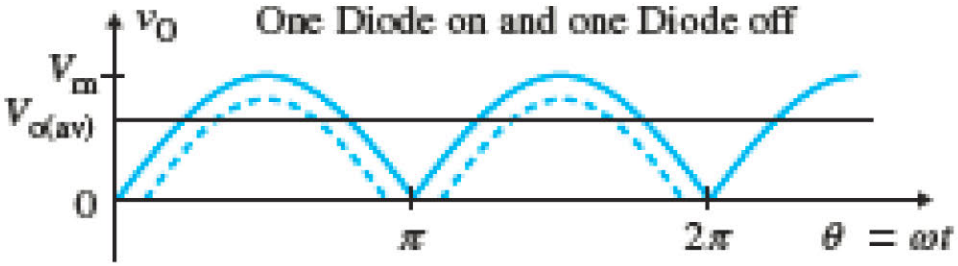


(b) Equivalent circuit for $v_S > 0$



(c) Equivalent circuit for $v_S < 0$

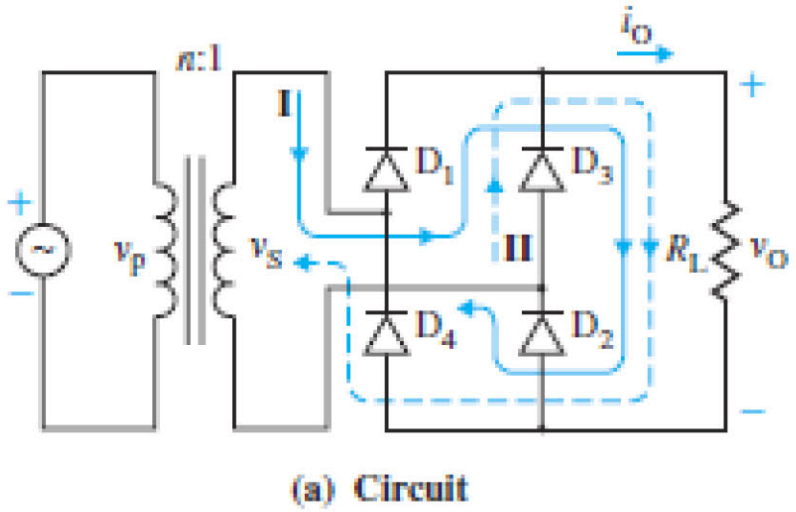




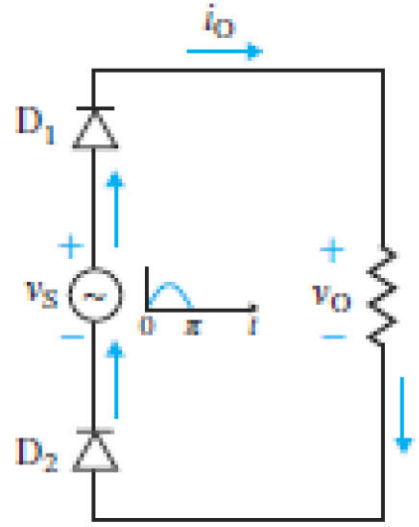
$v_{D_1} = -2v_S$ $\quad$ $v_{D_1} = 0$

$v_{D_2} = 0$ $\quad$ $v_{D_2} = -2v_S$

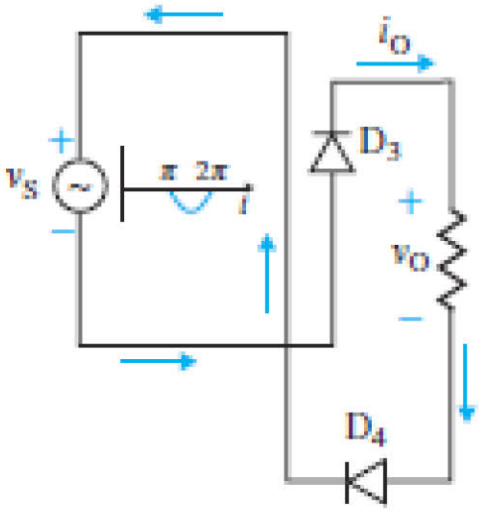
Single-Phase Full-Wave Bridge Rectifier



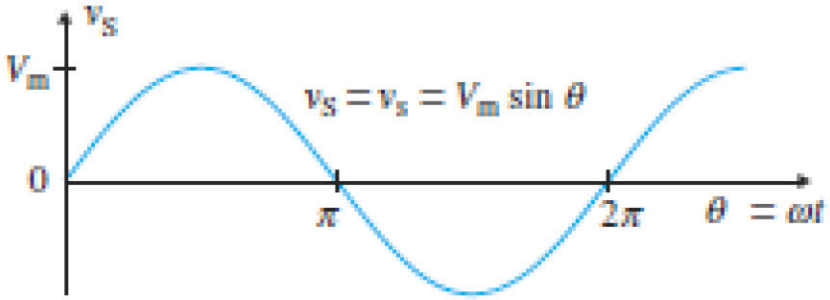
(a) Circuit

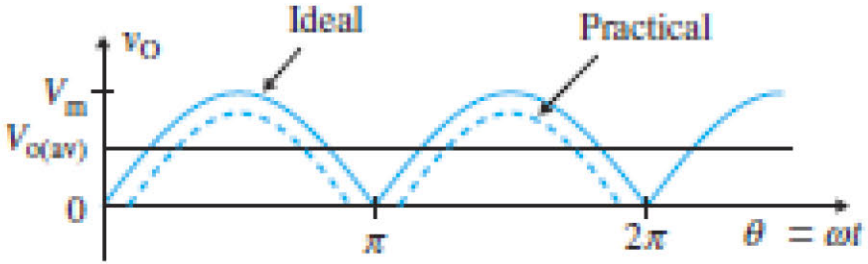


(b) Equivalent circuit for $v_s > 0$



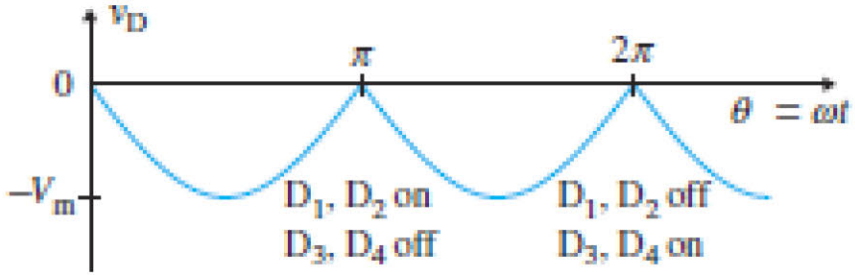
(c) Equivalent circuit for $v_s < 0$





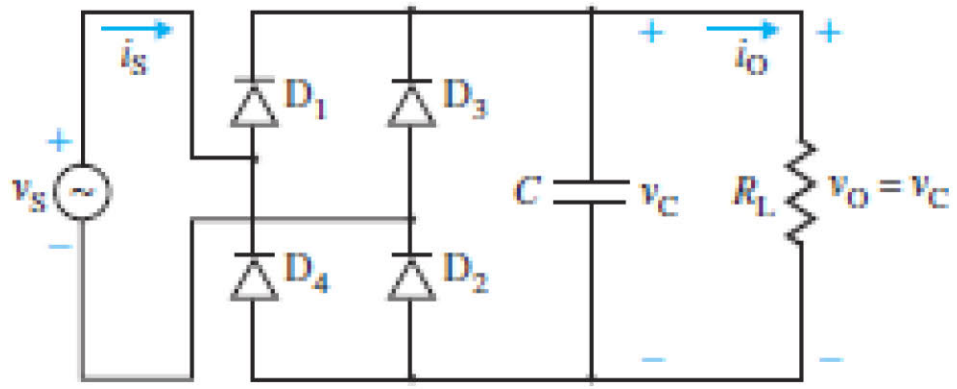
$v_{D_1} = -v_S$ $\quad$ $v_{D_1} = 0$

$v_{D_2} = 0$ $\quad$ $v_{D_2} = -v_S$

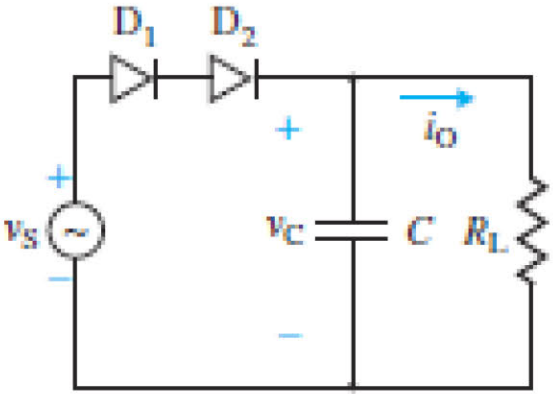


C Filters

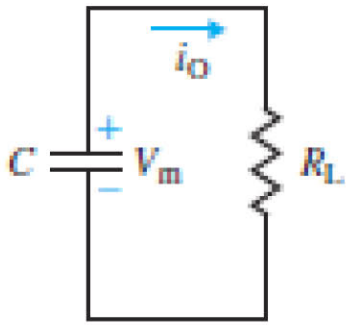
- A capacitor C can be connected across the load to maintain a continuous output voltage v_O.



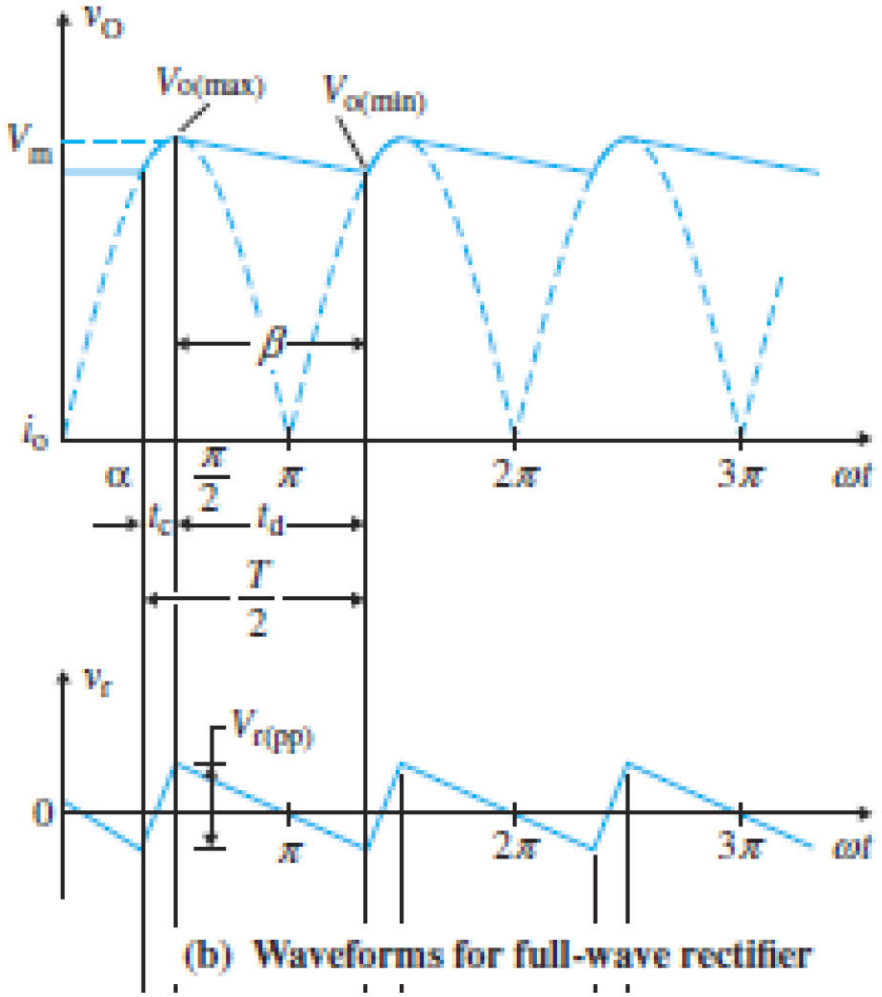
(a) Circuit



(c) Charging



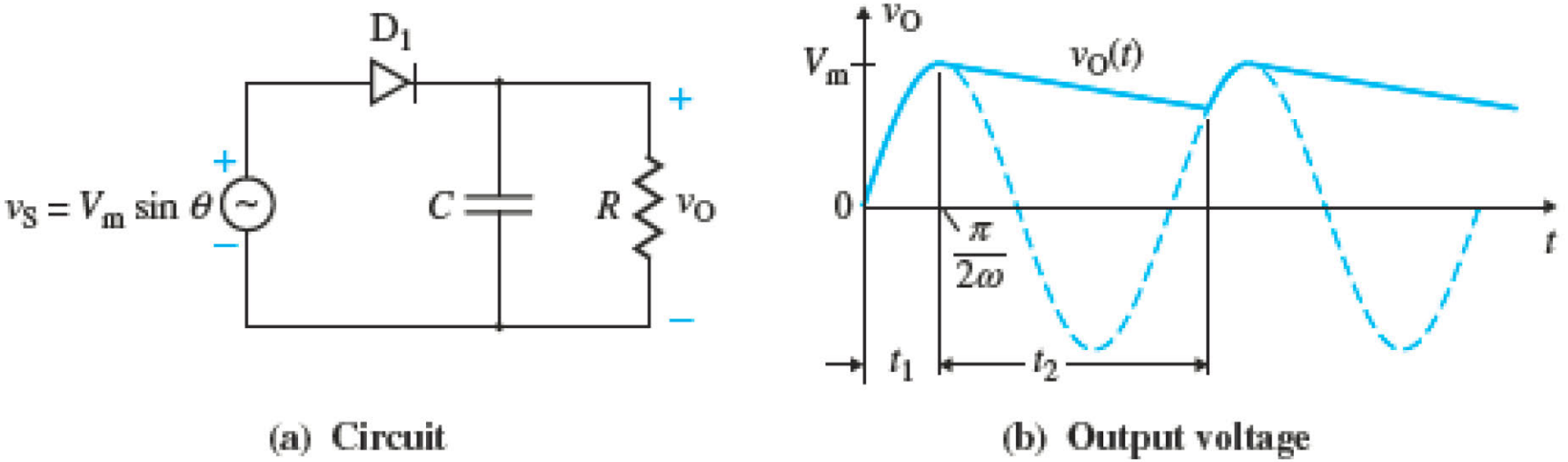
(d) Discharging



(b) Waveforms for full-wave rectifier

Diode Peak Detectors and Demodulators

- Slope *S*
- Peak slope
- Peak slope S_D of the detector



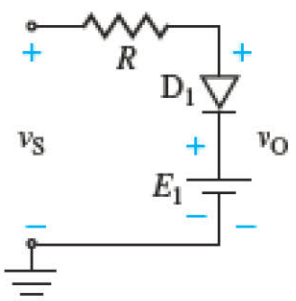
(a) Circuit

(b) Output voltage

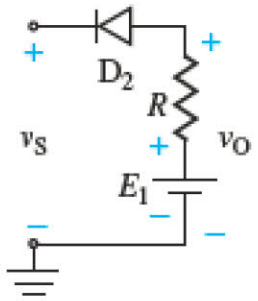
Ideal Diode Clippers

- A clipper is a limiting circuit; it is basically an extension of the half-wave rectifier.
- The output of a clipper circuit looks as if a portion of the output signal was cut off (clipped).
- A clipper in which the diode is connected across the output terminals is known as a *parallel clipper* because the diode is in parallel (or shunt) with the load.

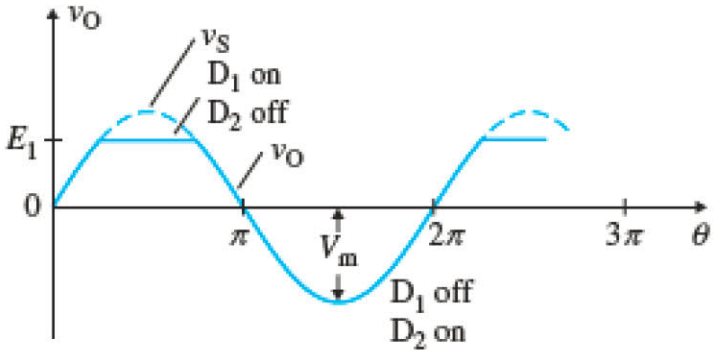
Ideal Diode Clippers



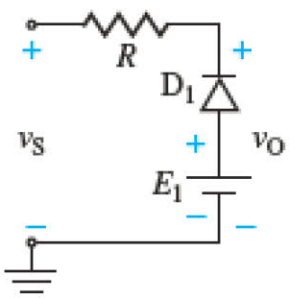
(a)



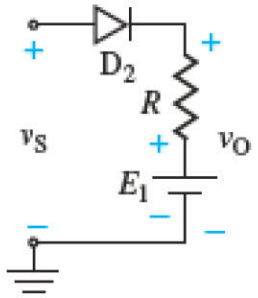
(b)



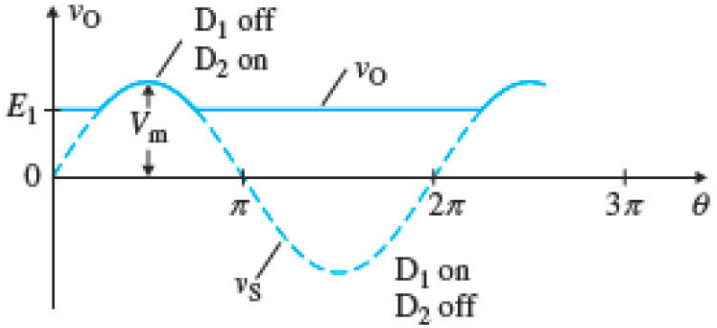
(c) Output voltage



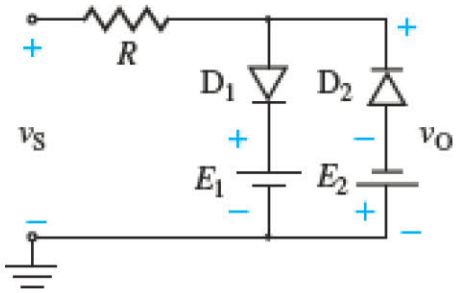
(d)



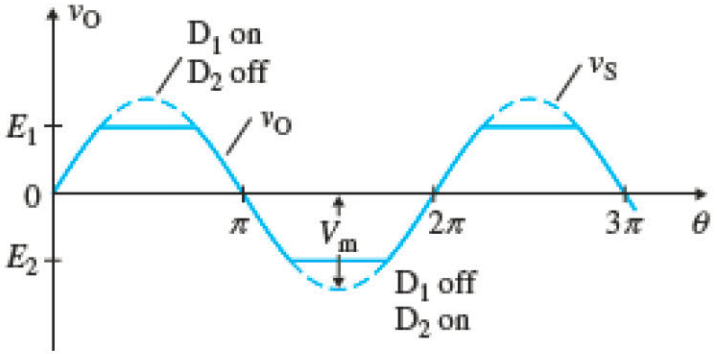
(e)



(f) Output voltage



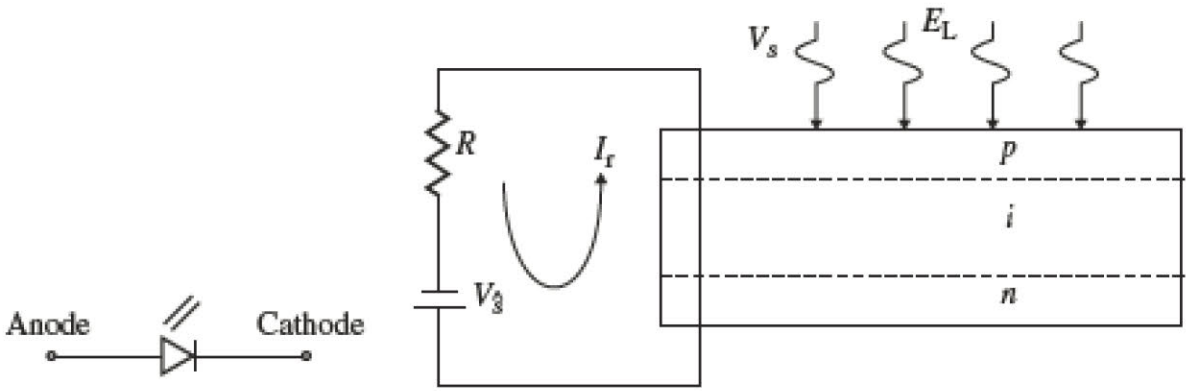
(g)



(h) Output voltage

Photodiodes

- Similar to regular semiconductor diodes except they are capable of converting light into either current or voltage and are designed to operate in reverse bias.
- The photodiodes use a *p–i–n* junction rather than a *pn* junction.
- Designed to operate in reverse bias.
- The device contains a *pn* junction, and an intrinsic (undoped) layer between the *n* and *p* layers, to increase the speed of response.

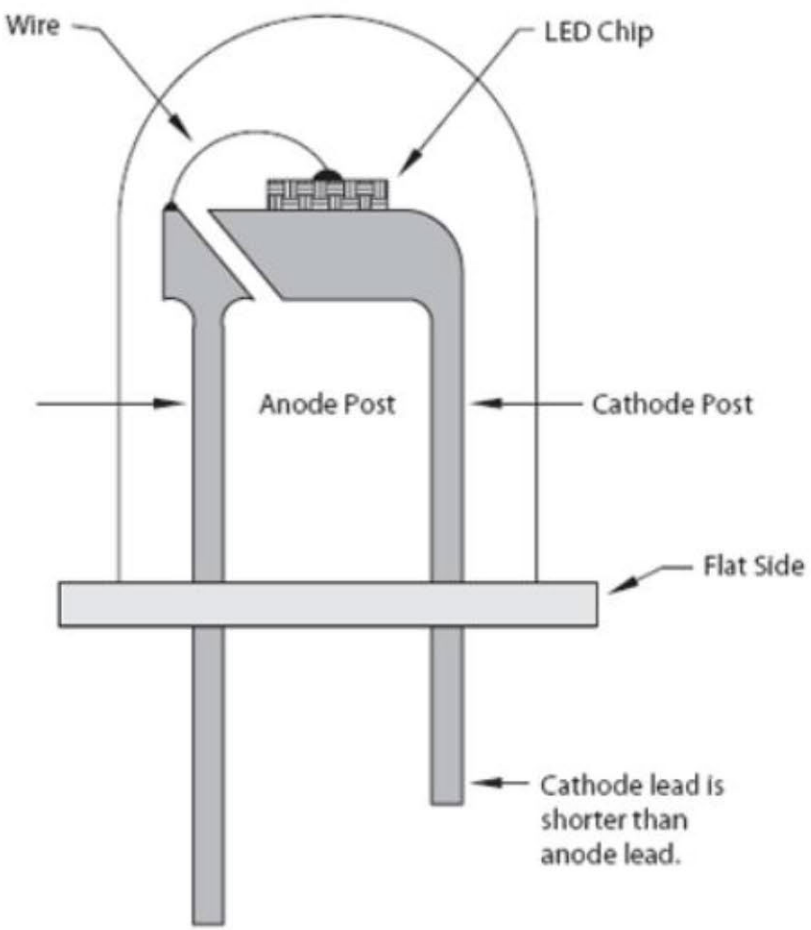


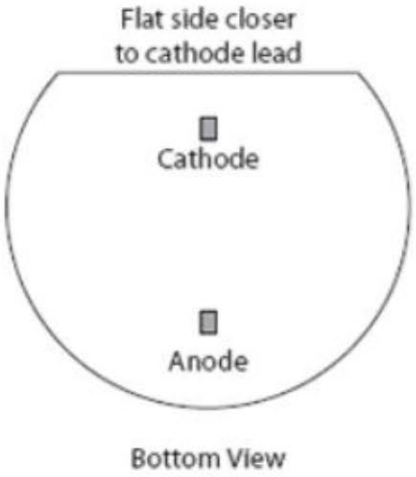
(a) Symbol (b) Schematic

Pins of Photodiodes

When used in a circuit, the LED generally operates with a current of about 20 mA (0.020 A) or less.

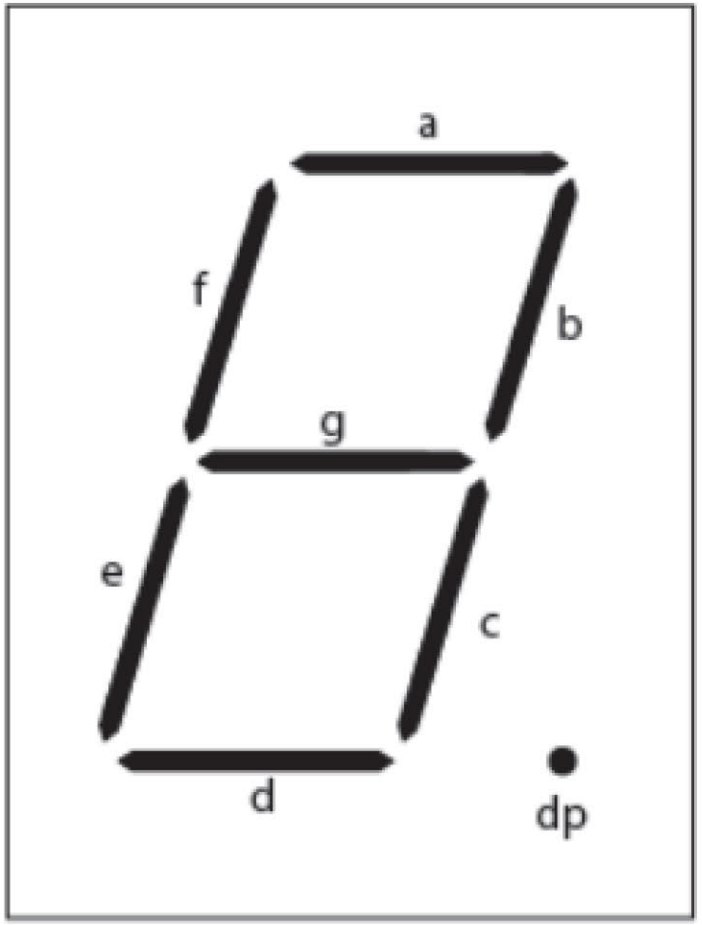
Identifying the leads of an LED



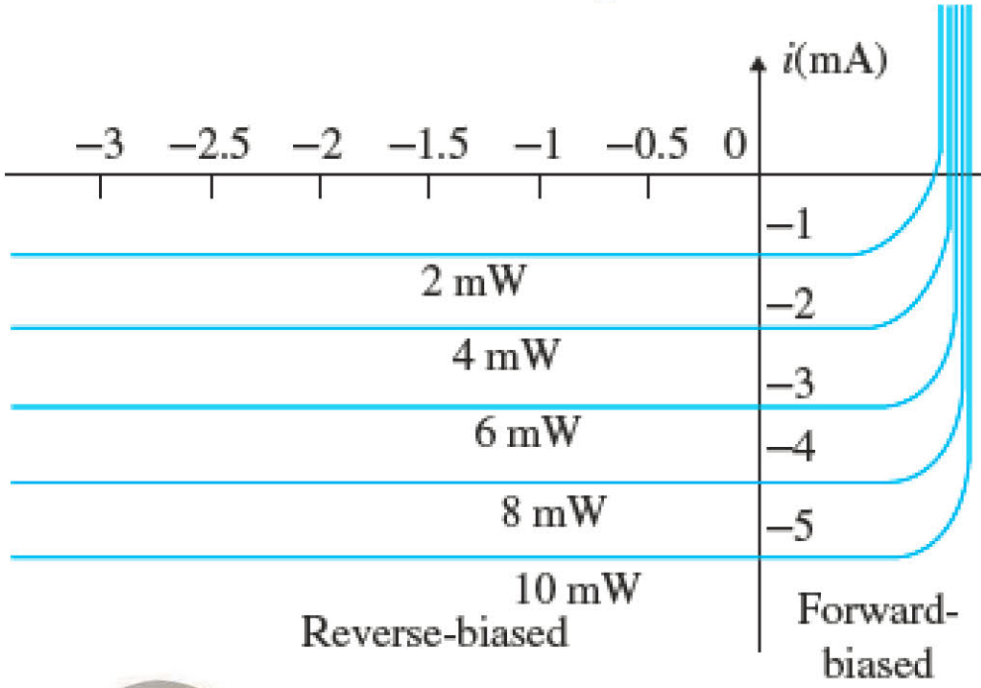


7 Segment

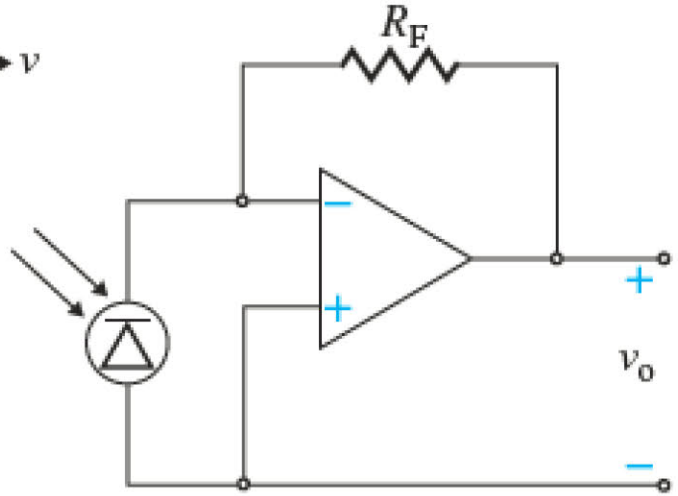
Seven-segment display



Typical current–voltage characteristics of a photodiode and photodetector



(a) *v–i* characteristics



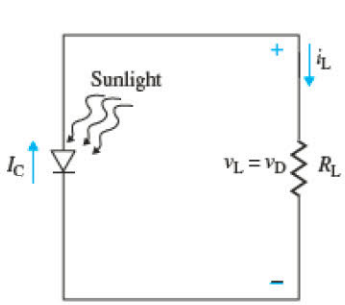
(b) Photodetector

Types of Photodiode

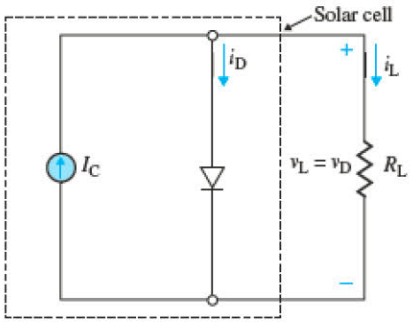
- **PN photodiode**
- **PIN photodiode:** Collects the light photons more efficiently than the more standard PN photodiode, and also offers a lower capacitance.
- **Avalanche photodiode:** Used in areas of low light.
  - Offers very high levels of gain, but it has high levels of noise.
- **Schottky photodiode:** Schottky photodiode technology is based upon the Schottky diode.
  - Has a small diode capacitance, and it offers a very high-speed capability.
  - It is used in high-bandwidth communication systems.

Photovoltaic Cells

- The photovoltaic cells are similar to photodiodes except they have larger areas and they are operated in the forward-bias condition.
- **Photovoltaic:** Photovoltaic (PV) materials and devices convert sunlight into electrical energy, and PV cells are commonly known as solar cells.
- **Photovoltaic Cells:** PV cells are the building blocks of all PV systems because they are the devices that convert sunlight into electricity.

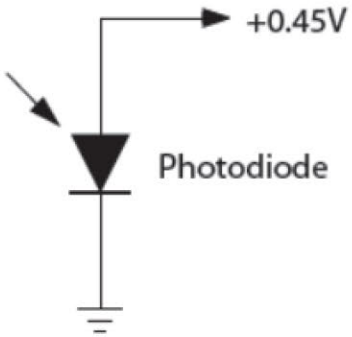


(a) Solar cell



(b) Current source model

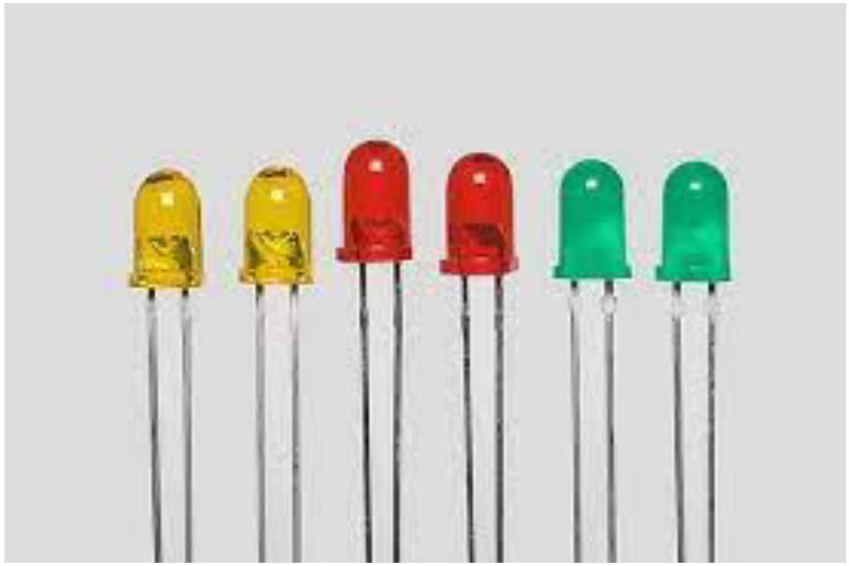
Photodiode used as a photovoltaic device



Light-Emitting Diodes

- Light-emitting diodes (LEDs) are a specialized type of *pn* junction diode which is made from a very thin layer of fairly heavily doped semiconductor material.

- The LEDs convert electrical energy into electromagnetic radiation and produce either visible or infrared light when subjected to an electric current, as a result of electroluminescence.



Power Rating

- The power dissipation of a diode is found from:

$$P_D = I_D V_D$$

- Power diodes are normally mounted on a heat sink.
- The function of the heat sink is to dissipate heat on the ambient.
- In practice, power dissipation is limited to the value that corresponds to the permissible diode current.