Diodes and Applications

- Diodes and Applications
- 2–1 Diode Operation
- 2–2 Voltage-Current (V-I) Characteristics
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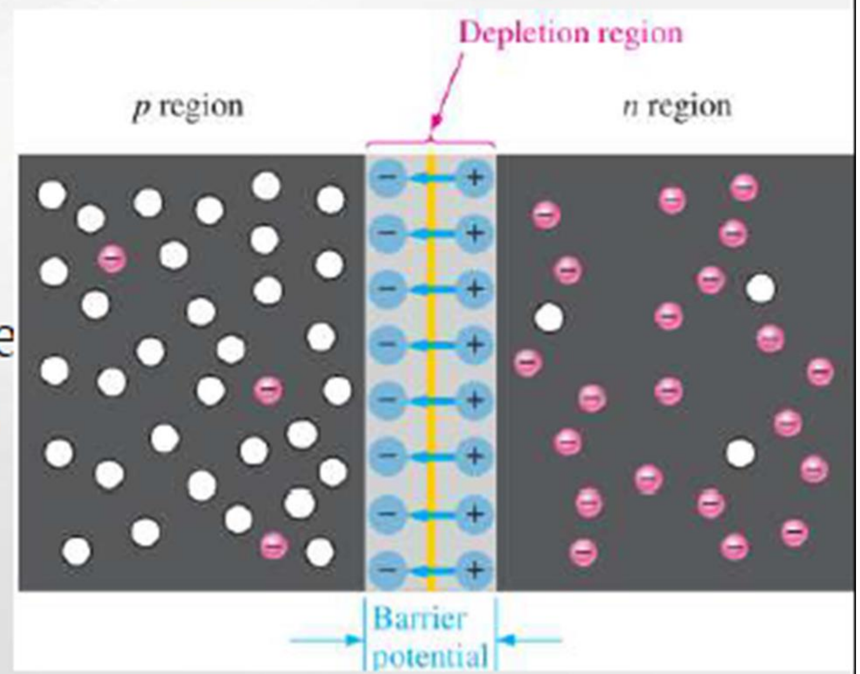
THE *PN* JUNCTION

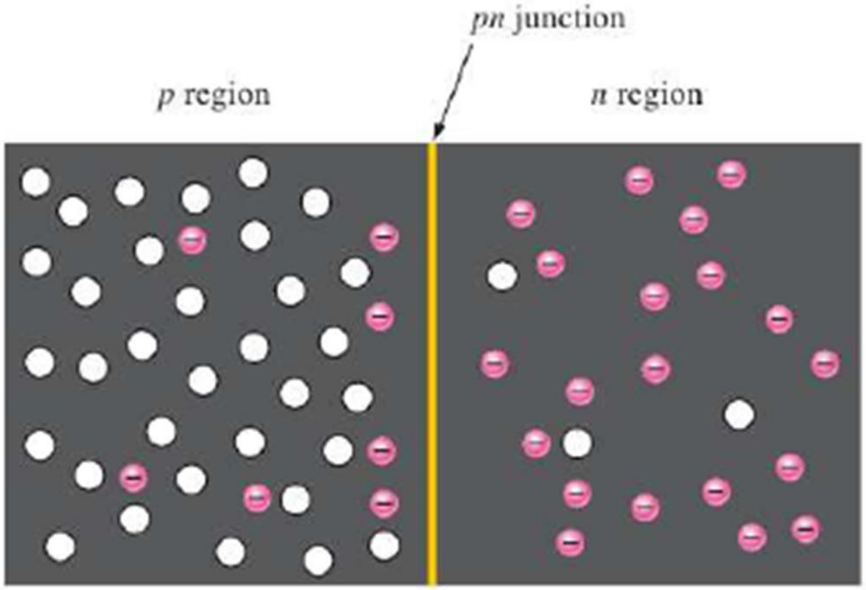
- When you take a block of silicon and dope part of it with a trivalent impurity and the other part with a pentavalent impurity, a boundary called the pn junction is formed between the resulting p-type and n-type portions. The pn junction is the basis for diodes, certain transistors, solar cells, and other devices, as you will learn later.

Formation of the Depletion Region

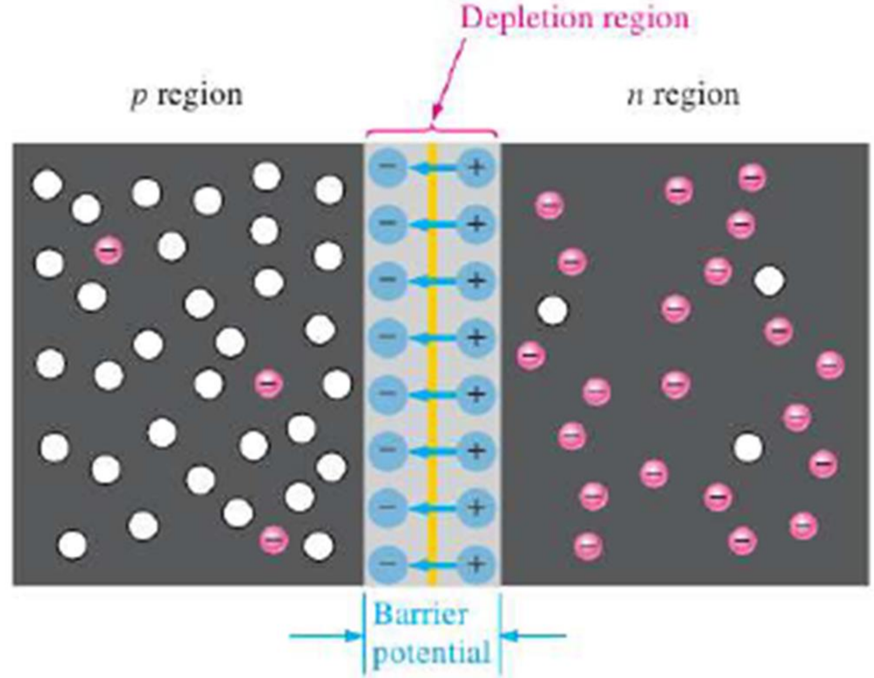
- When the pn junction is formed, the *n* region loses free electrons as they diffuse across the junction.
- The *p* region loses holes as the electrons and holes combine.
- The term depletion refers to the fact that the region near the pn junction is depleted of charge carriers (electrons and holes) due to diffusion across the junction.



Formation of the Depletion Region



(a) The basic silicon structure at the instant of junction formation showing only the majority and minority carriers. 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.

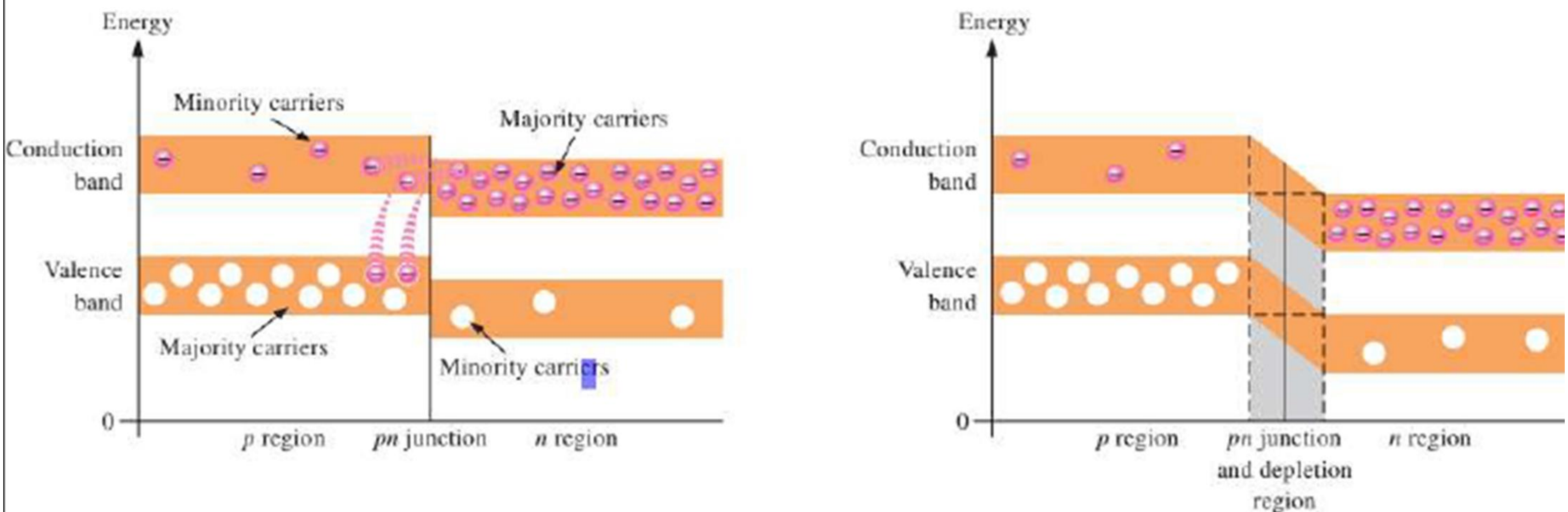


(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion. The blue arrows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

Formation of the Depletion Region

- External energy must be applied to get the electrons to move across the barrier of the electric field in the depletion region.
- The potential difference of the electric field across the depletion region is the amount of voltage required to move electrons through the electric field. This potential difference is called the barrier potential and is expressed in volts.
- The typical barrier potential is approximately 0.7 V for silicon and 0.3 V for germanium at 25° C.

Energy Diagram of the *PN* Junction

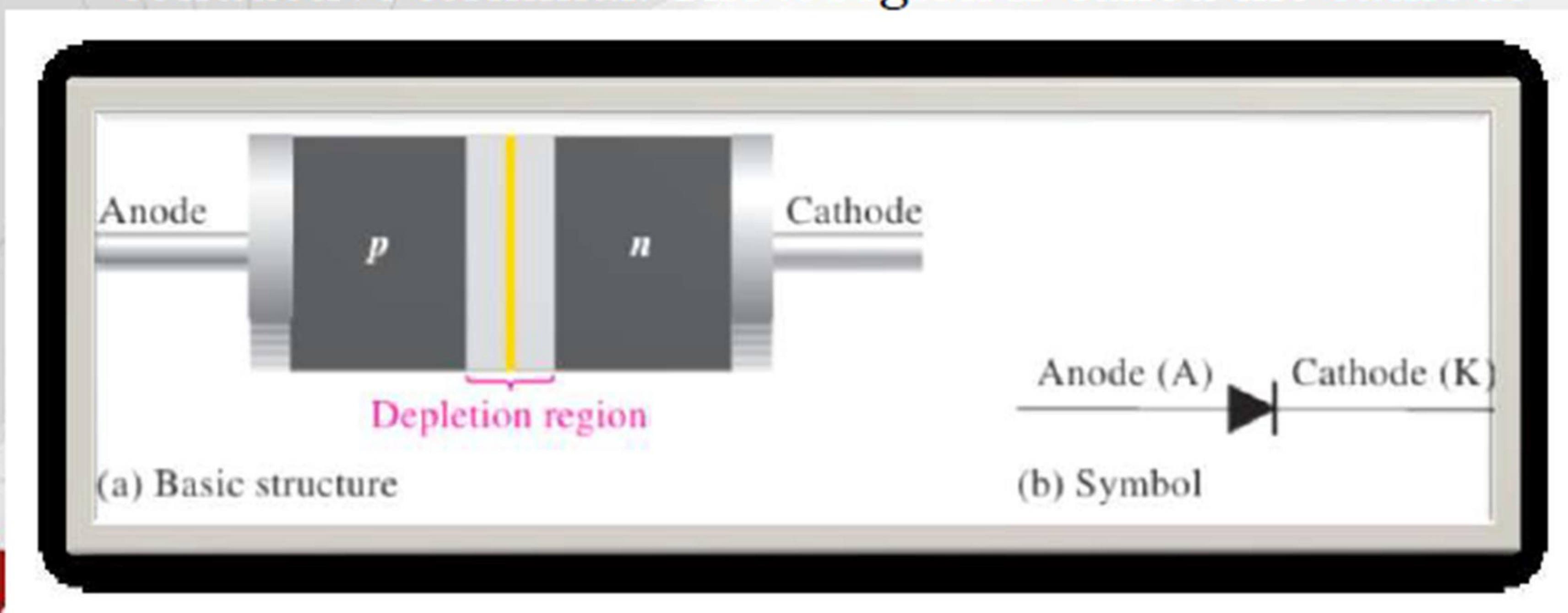


(a) At the instant of junction formation

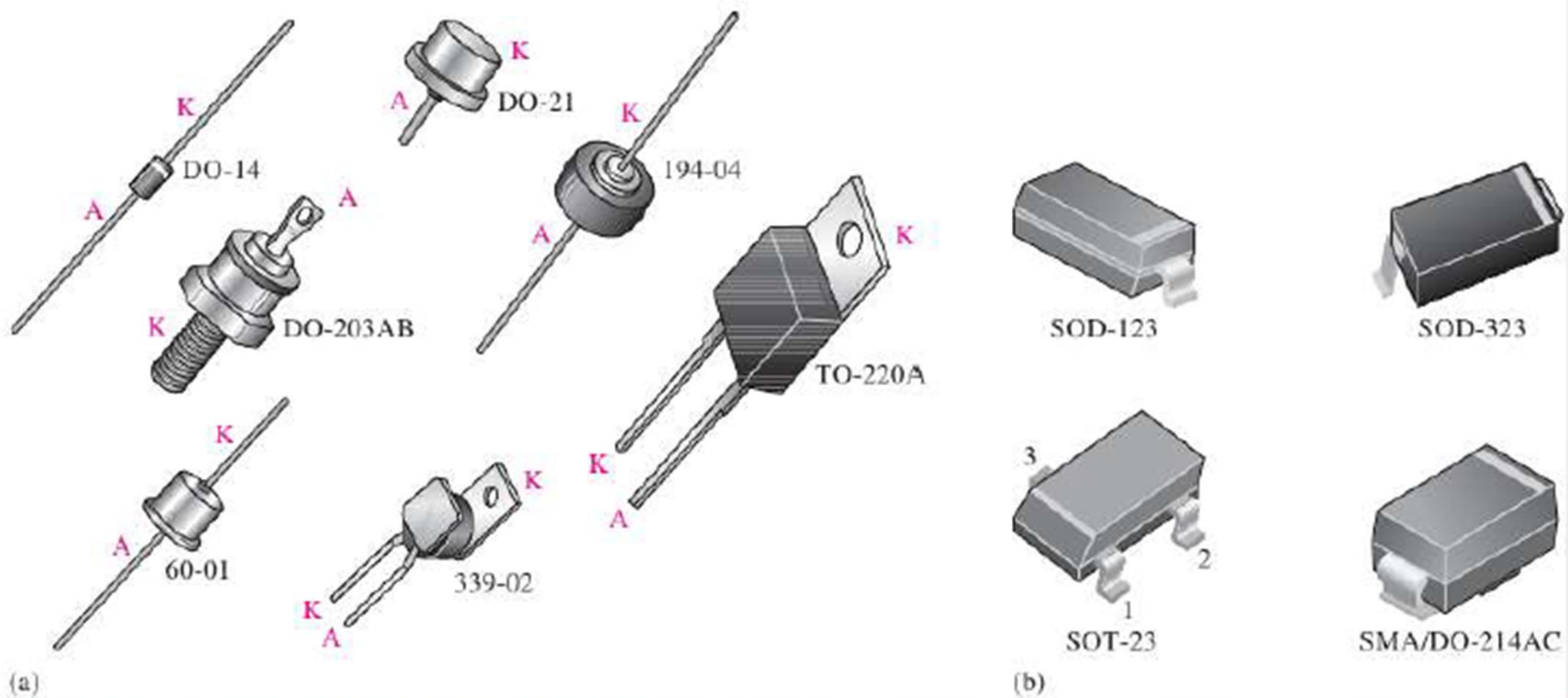
(b) At equilibrium

2–1 Diode Operation

- A diode is made from a small piece of semiconductor material, usually silicon, in which half is doped as a p region and half is doped as an n region with a pn junction and depletion region in between.
- The *p* region is called the anode and is connected to a conductive terminal. The *n* region is called the cathode

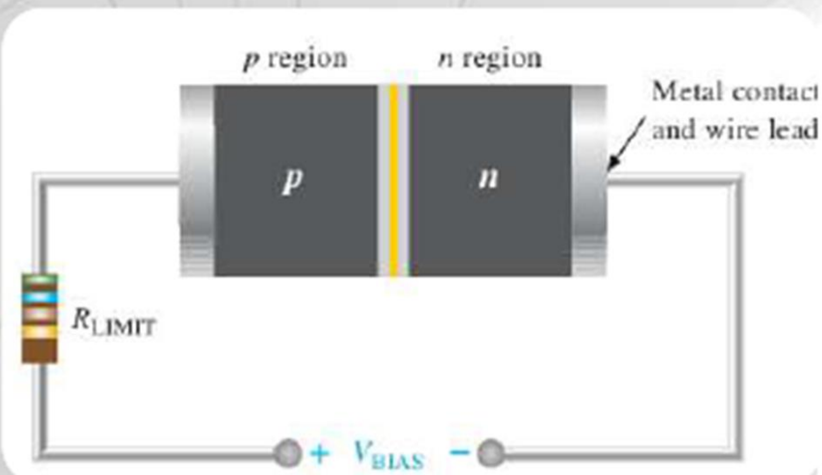


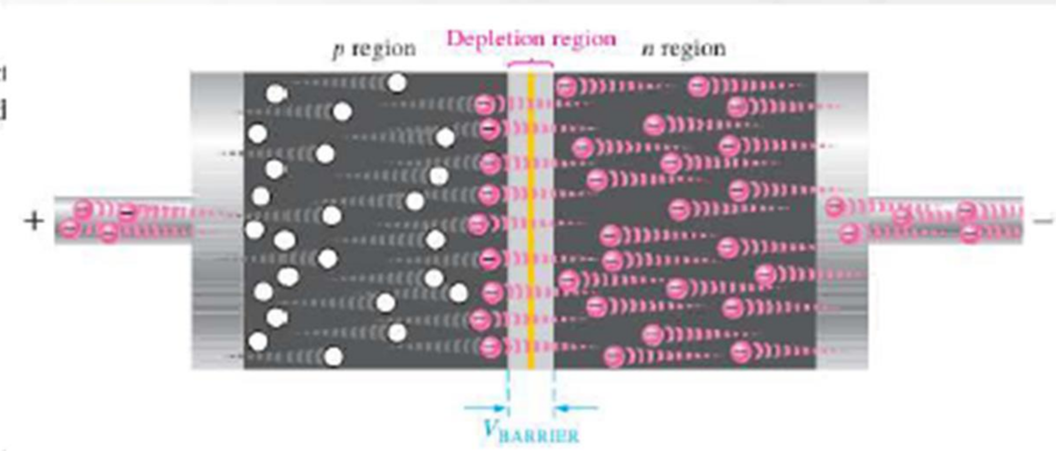
Typical diode packages



BIASING THE *PN* JUNCTION

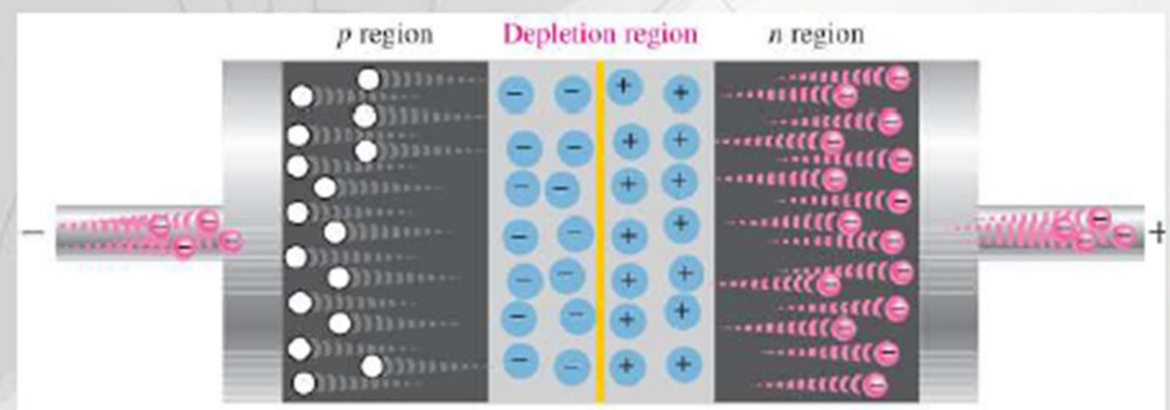
- Forward Bias
  - Forward bias is the condition that permits current through a *pn* junction

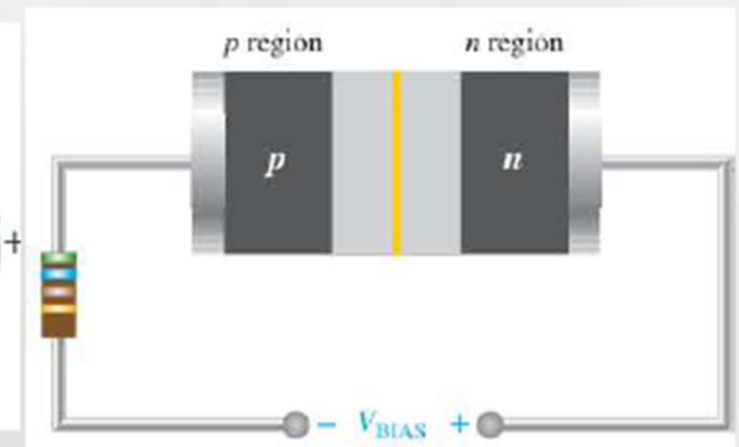




BIASING THE *PN* JUNCTION

- Reverse Bias
  - Reverse bias is the condition that prevents current through the *pn* junction
  - Reverse current is a very small current produced by minority carries during reverse bias





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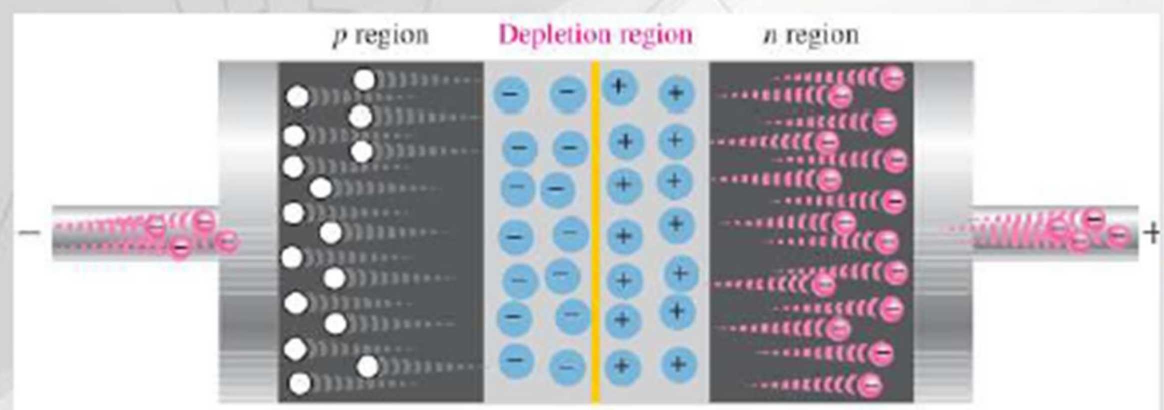
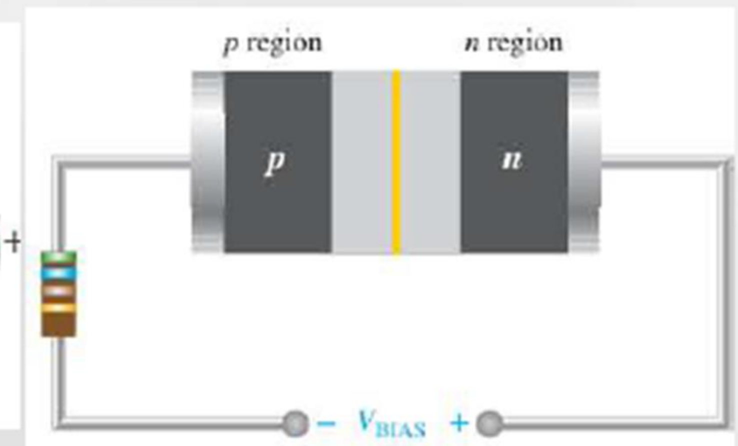
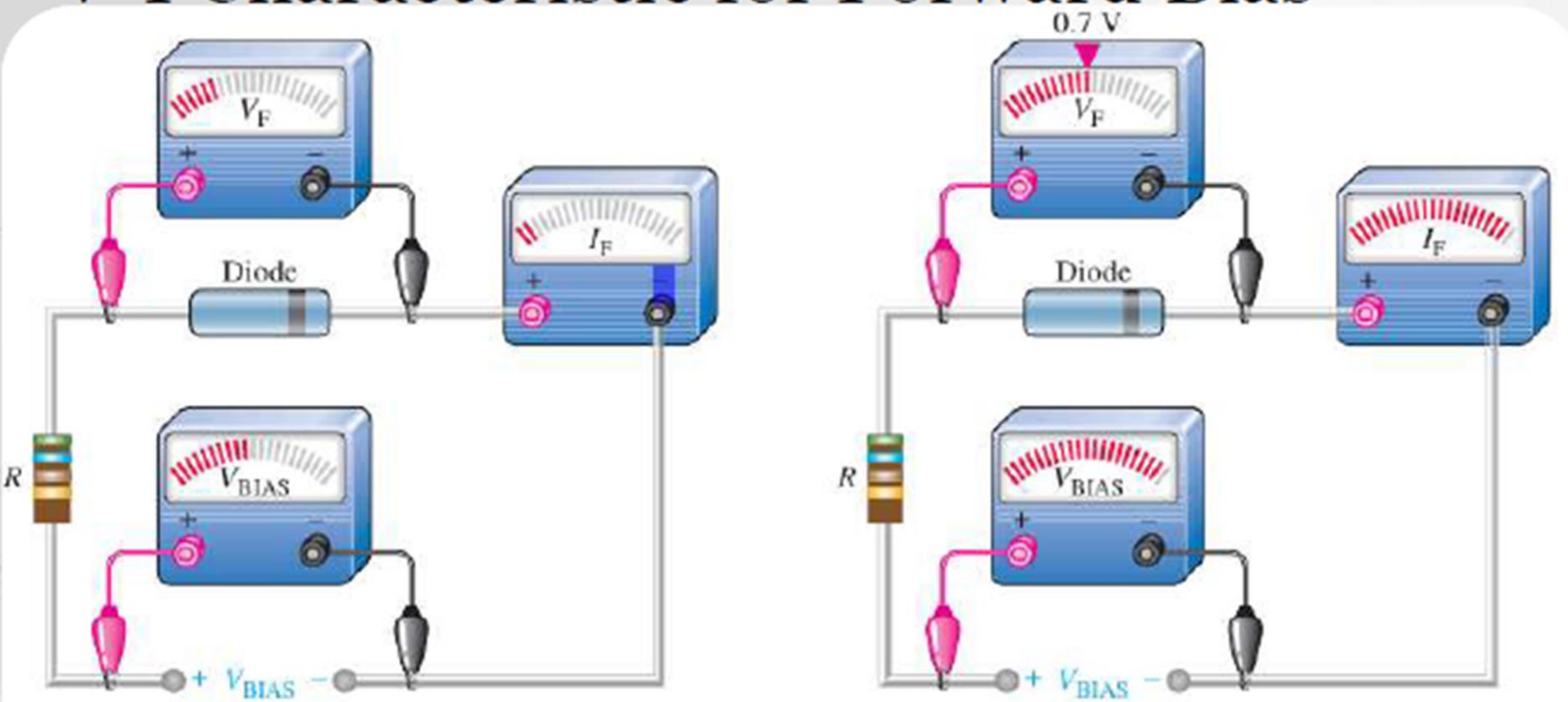




2–2 VOLTAGE-CURRENT CHARACTERISTIC OF A DIODE

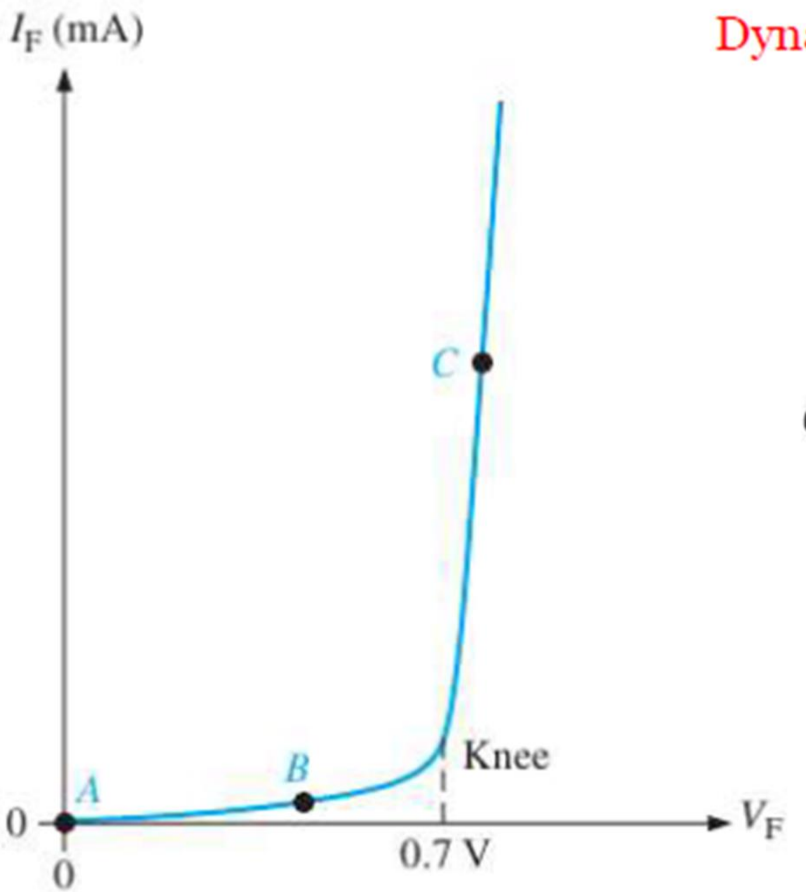
- V-I Characteristic for Forward Bias



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

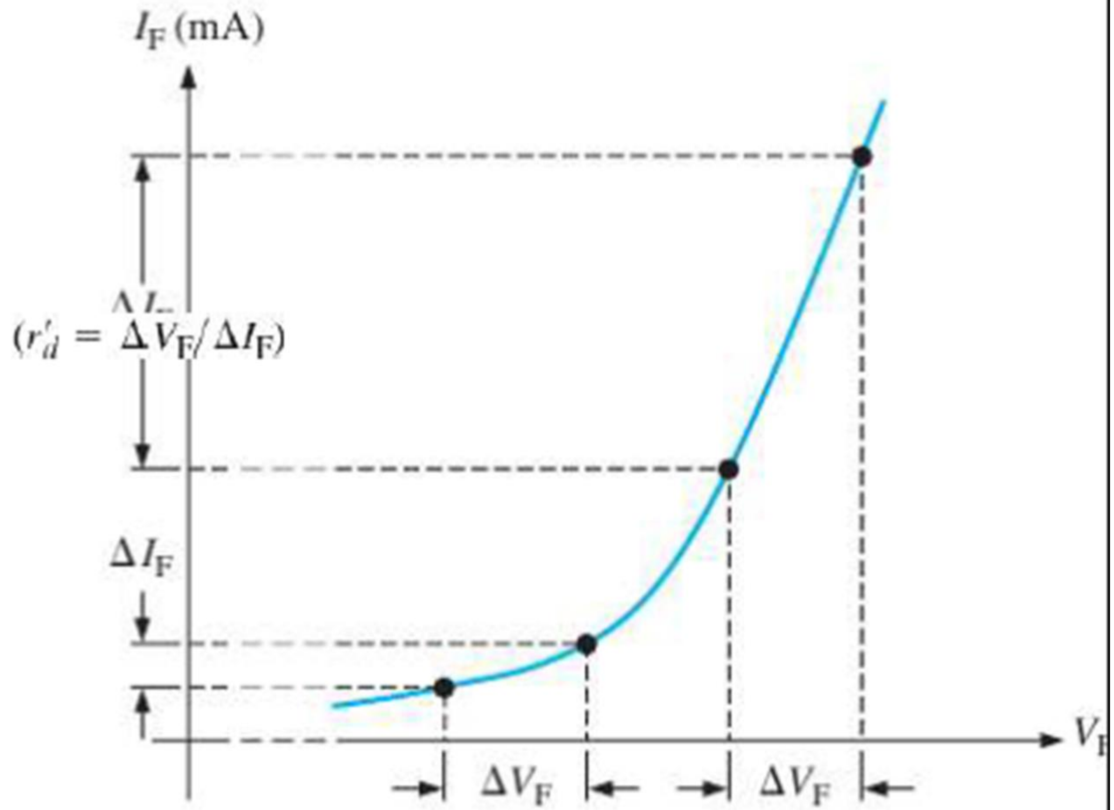
(b) Forward voltage reaches and remains nearly constant at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

V-I Characteristic for Forward Bias



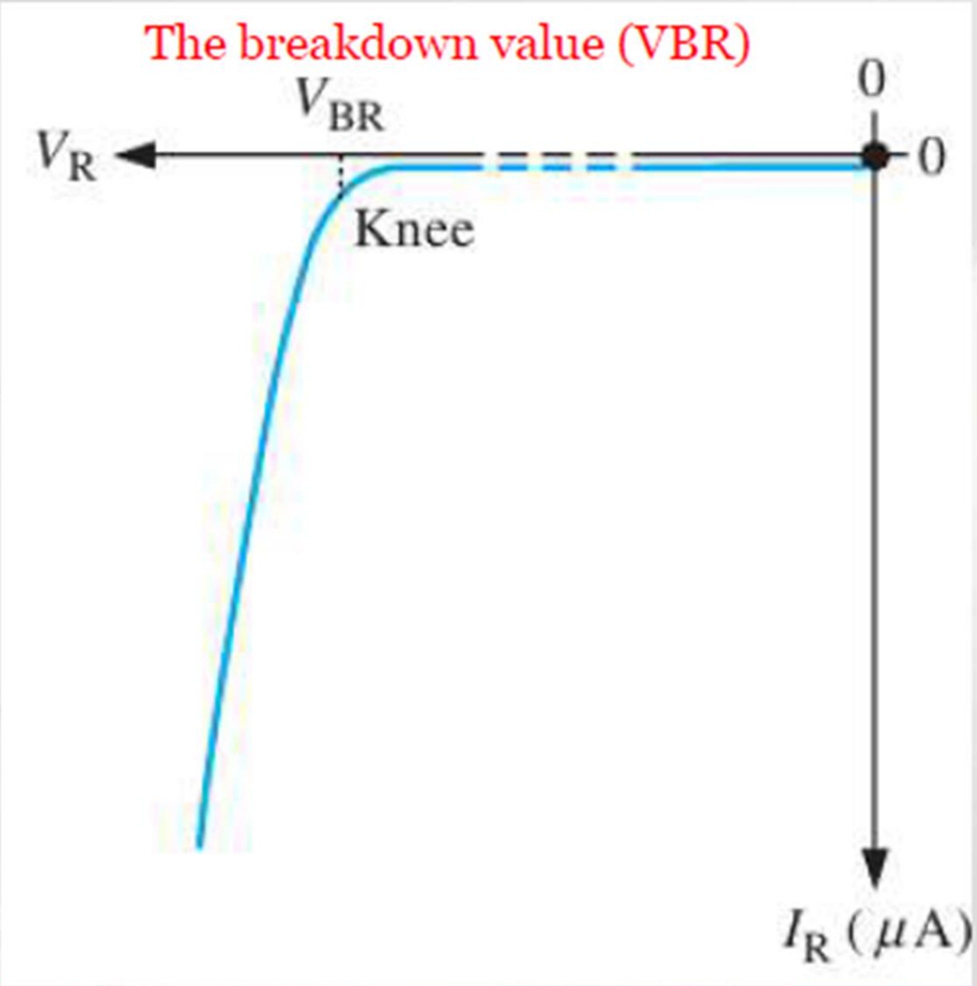
(a) *V-I* characteristic curve for forward bias.

Dynamic Resistance $(r'_d = \Delta V_F / \Delta I_F)$



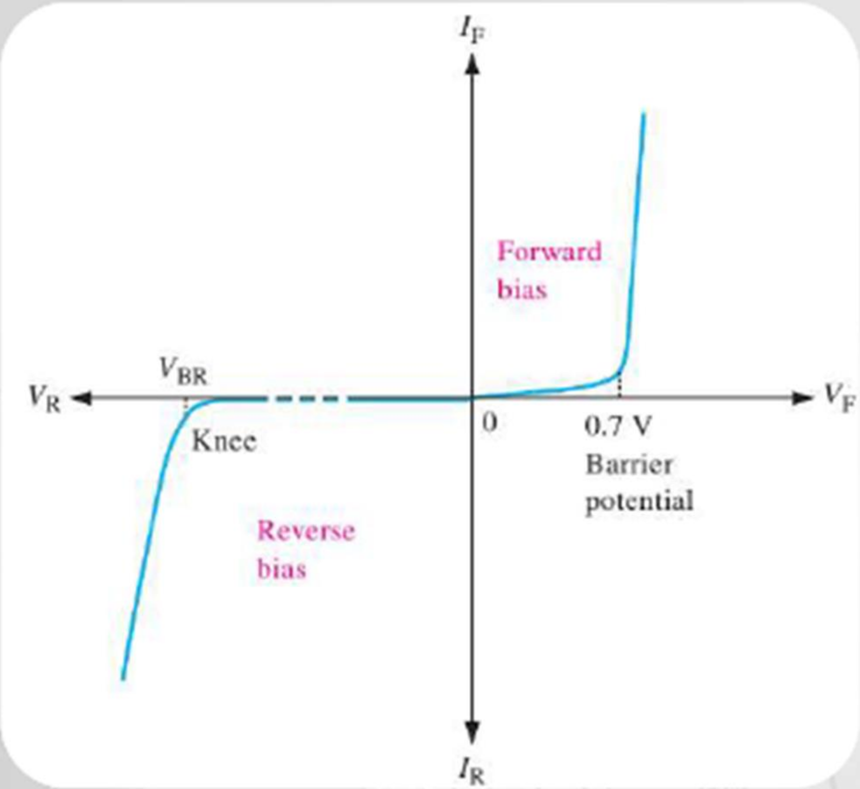
(b) Expanded view of a portion of the curve in part (a).
The dynamic resistance r'_d decreases as you move

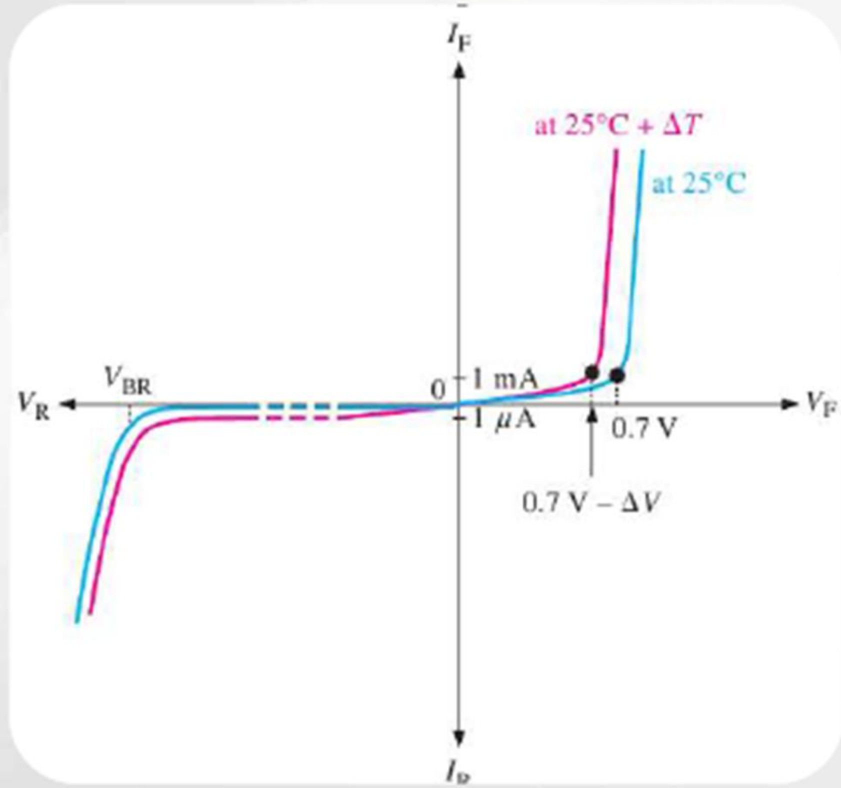
V-I Characteristic for Reverse Bias



- A typical rectifier diode (the most widely used type) has a breakdown voltage of greater than 50 V.
- Some specialized diodes have a breakdown voltage that is only 5 V

The Complete V-I Characteristic Curve





The blue curve is at room temperature and the red curve is at an elevated temperature

The barrier potential decreases by 2 mV for each degree increase in temperature

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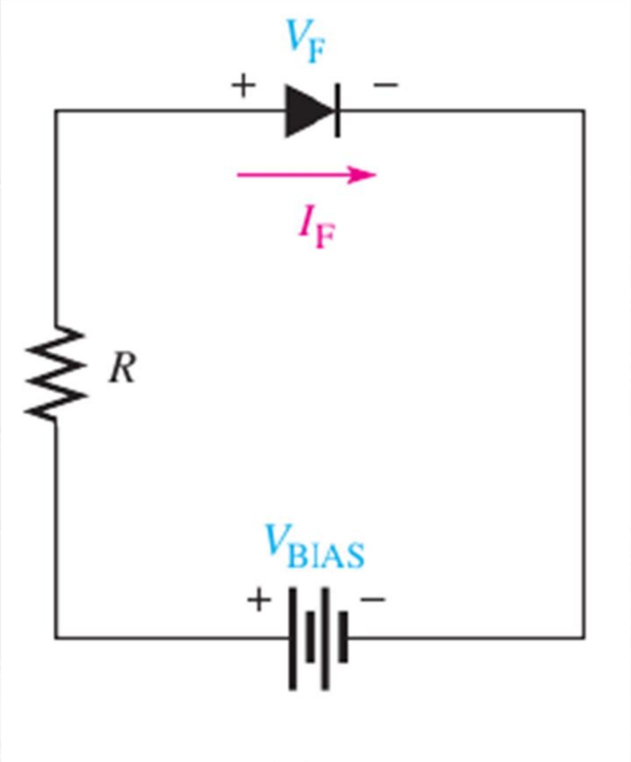
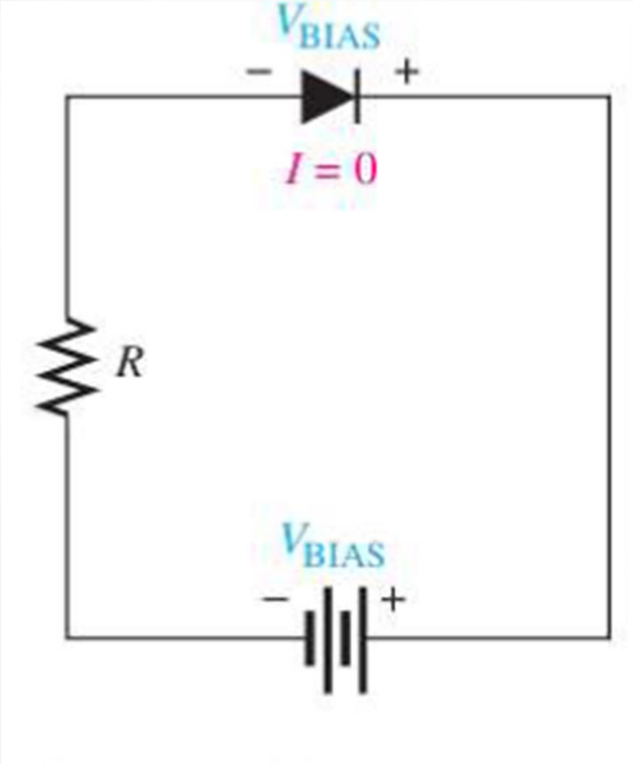
2–3 DIODE MODELS

- Forward-Bias



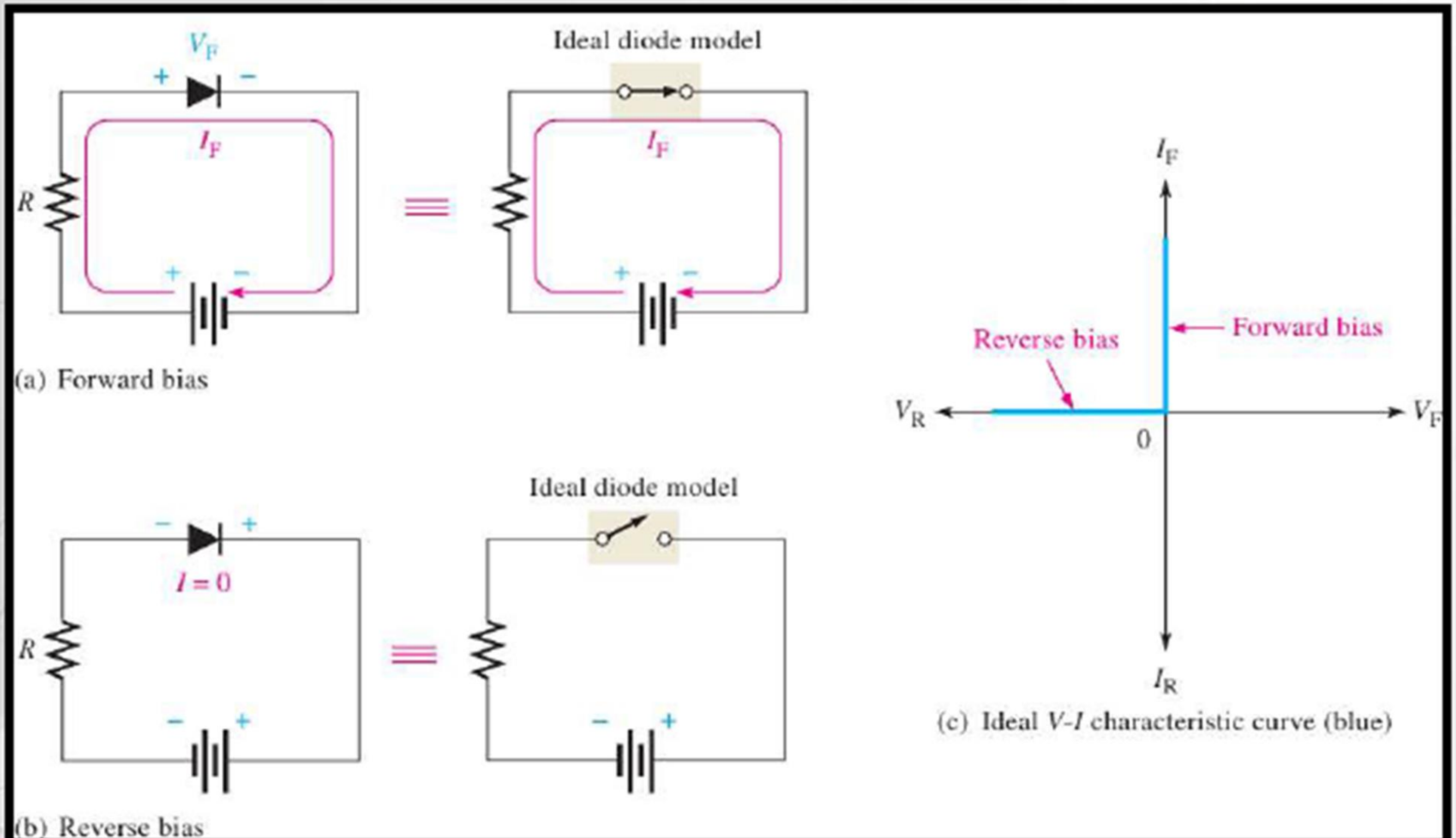
(a) Forward bias

- Reverse-Bias

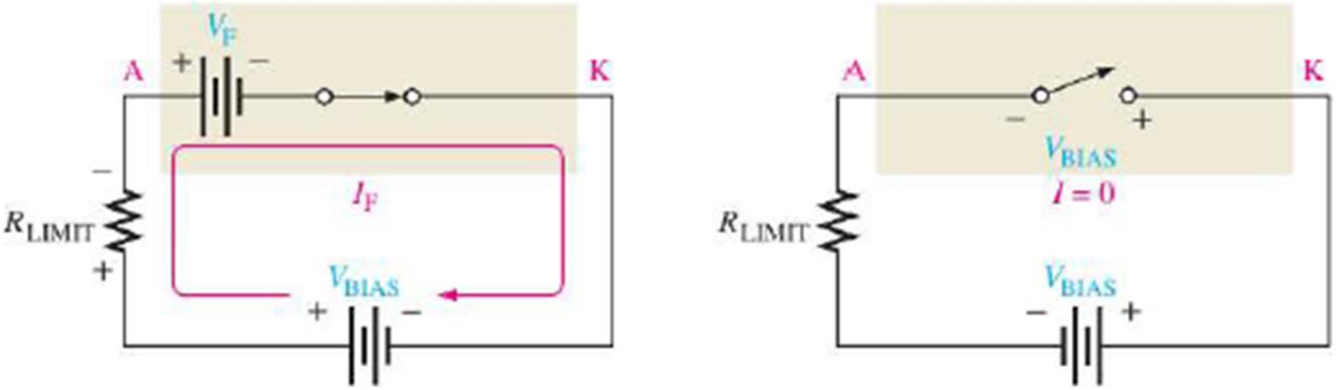


(b) Reverse bias

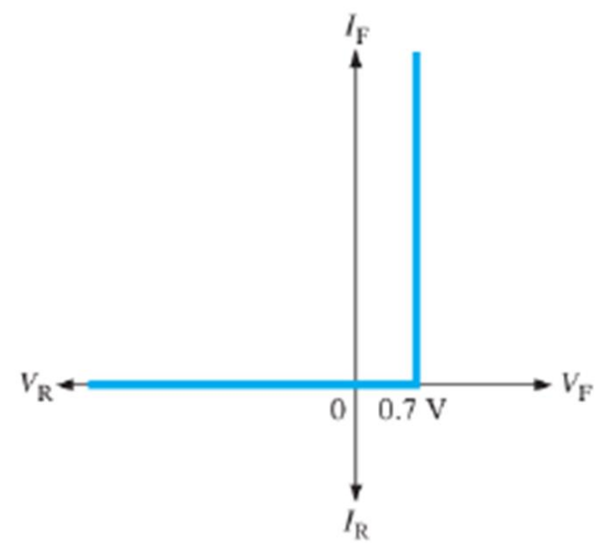
Diode Approximations (The Ideal Diode Mode)



The Practical Diode Model



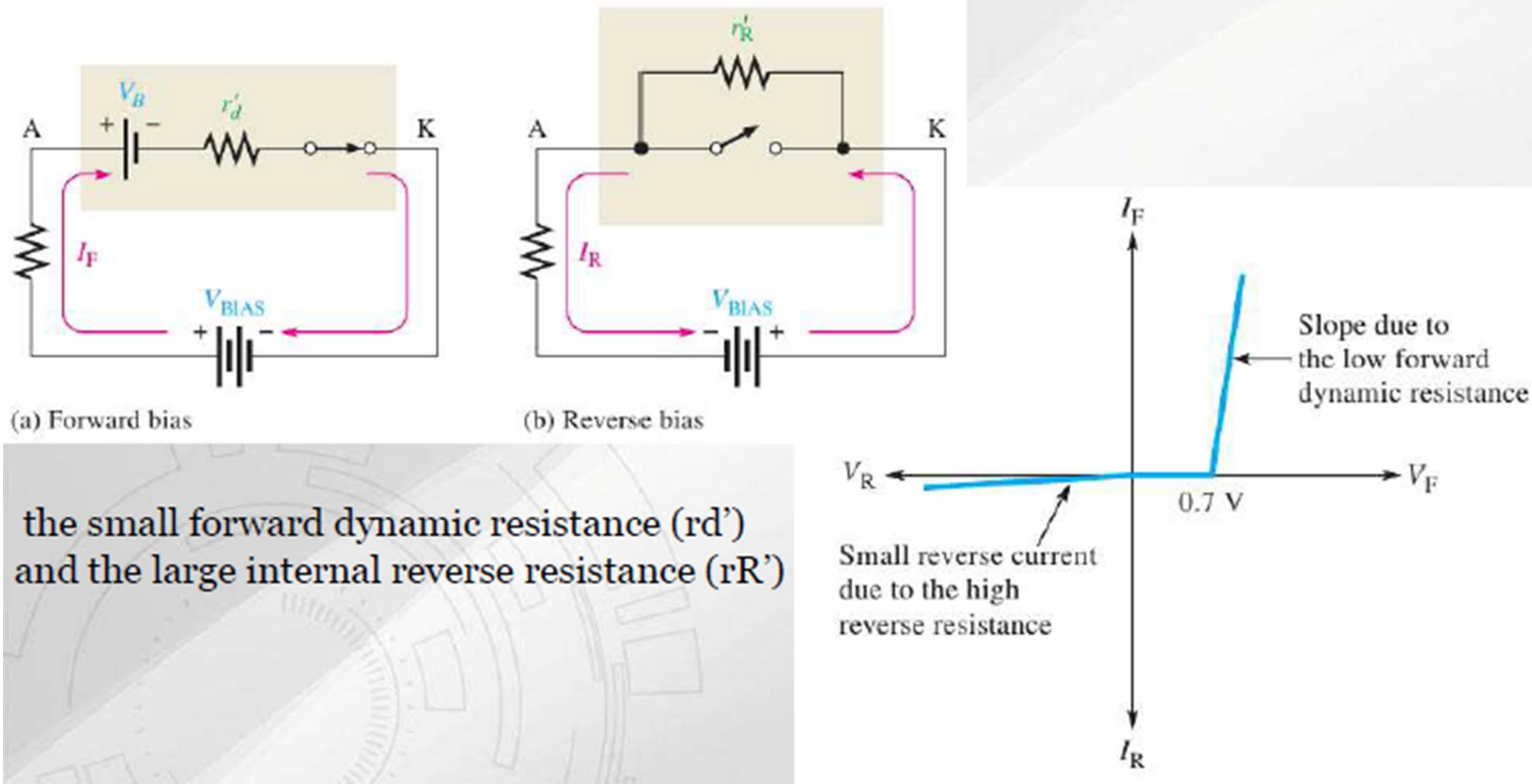
(a) Forward bias (b) Reverse bias



(c) Characteristic curve (silicon)

The practical model includes the barrier potential. When the diode is forward-biased, it is equivalent to a closed switch in series with a small equivalent voltage source (VF) equal to the barrier potential (0.7 V) with the positive side toward the anode

The Complete Diode Model

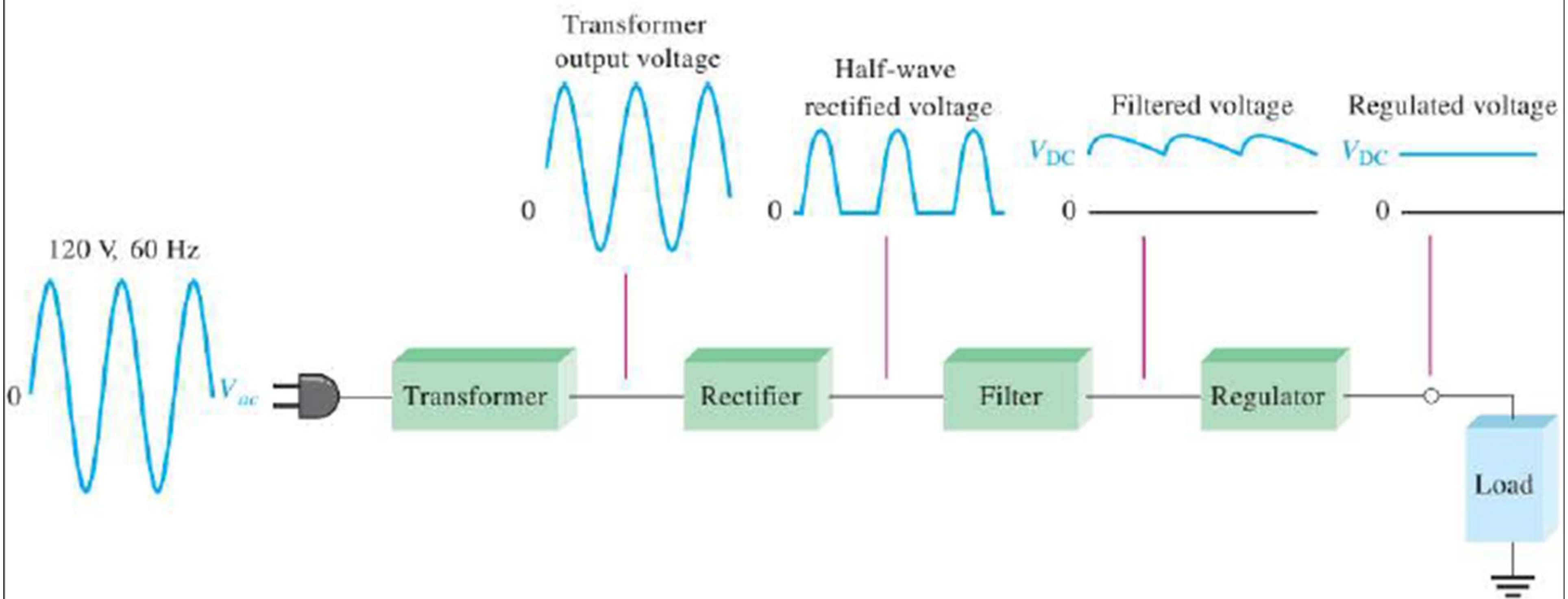


(c) V-I characteristic curve

the small forward dynamic resistance (rd')
and the large internal reverse resistance (rR')

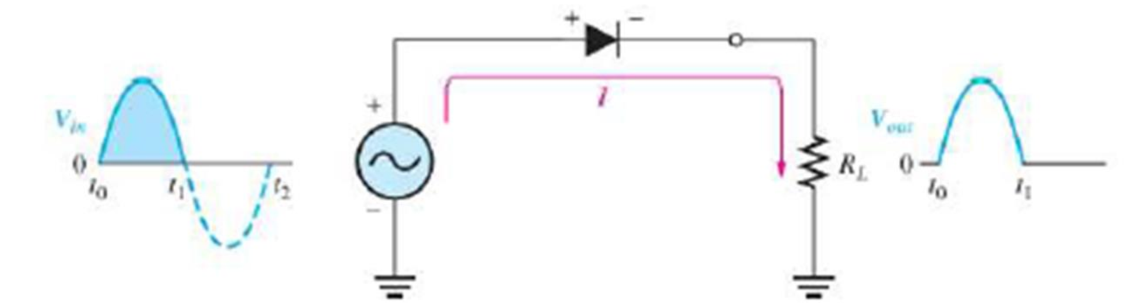
2–4 HALF-WAVE RECTIFIERS

The Basic DC Power Supply

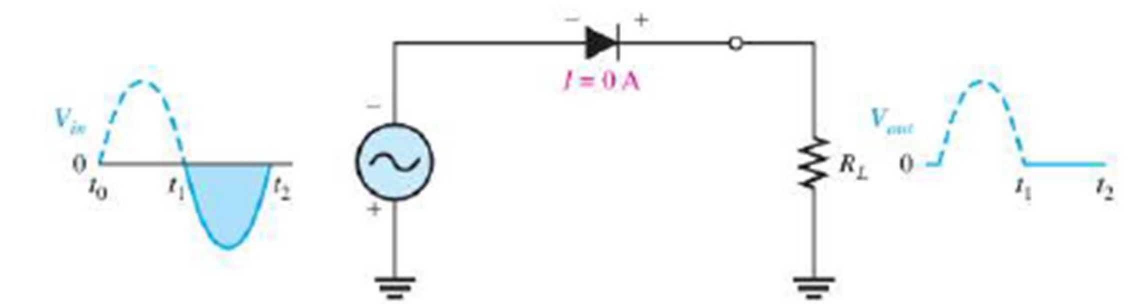


(a) Complete power supply with transformer, rectifier, filter, and regulator

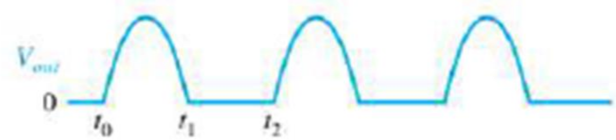
Half-Wave Rectifier Operation



(a) During the positive alternation of the 60 Hz input voltage, the output voltage looks like the positive half of the input voltage. The current path is through ground back to the source.



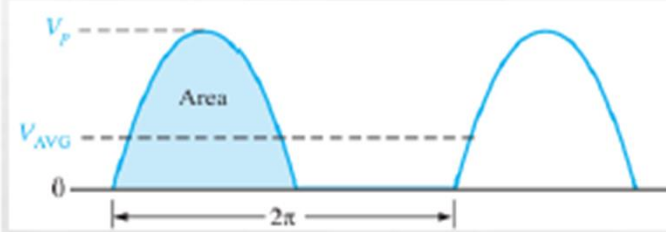
(b) During the negative alternation of the input voltage, the current is 0, so the output voltage is also 0.



(c) 60 Hz half-wave output voltage for three input cycles

Average Value of the Half-Wave Output Voltage

$$\boxed{V_{AVG} = \frac{V_p}{\pi}}$$



EXAMPLE 2-2

EXAMPLE 2–2 What is the average value of the half-wave rectified voltage in Figure 2–22?

▶ FIGURE 2–22

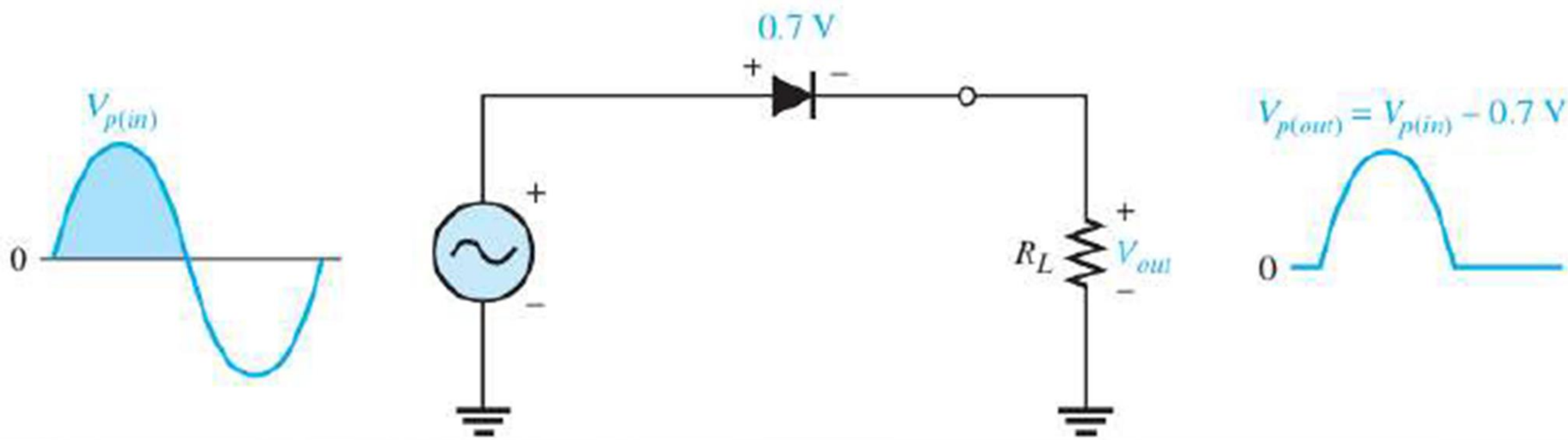
Solution

$$V_{AVG} = \frac{V_p}{\pi} = \frac{50\text{ V}}{\pi} = \mathbf{15.9\text{ V}}$$

Notice that V_{AVG} is 31.8% of V_p.

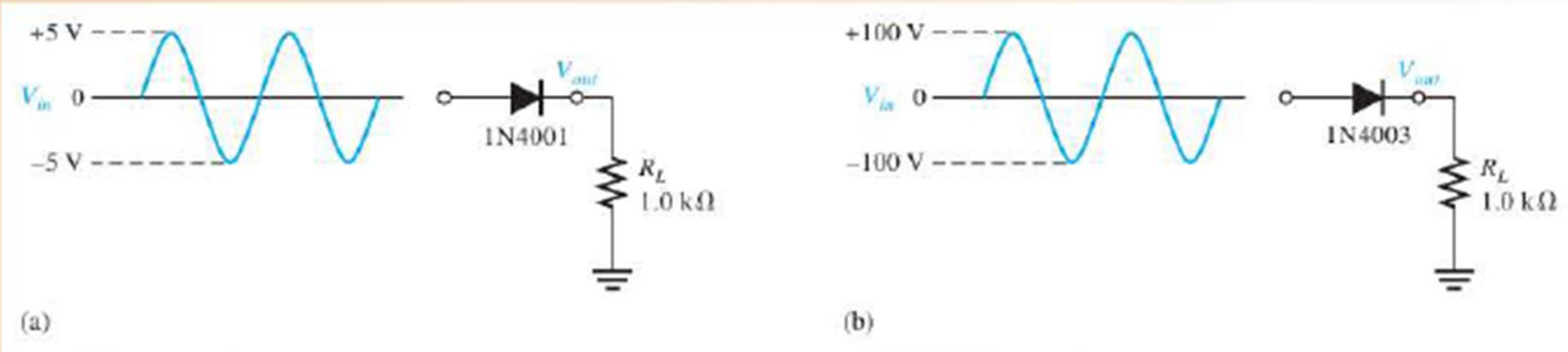
Effect of the Barrier Potential on the Half-Wave Rectifier Output

$$V_{p(out)} = V_{p(in)} - 0.7\text{ V}$$



EXAMPLE 2-3

EXAMPLE 2–3 Draw the output voltages of each rectifier for the indicated input voltages, as shown in Figure 2–24. The 1N4001 and 1N4003 are specific rectifier diodes.



▲ **FIGURE 2–24**

Solution The peak output voltage for circuit (a) is

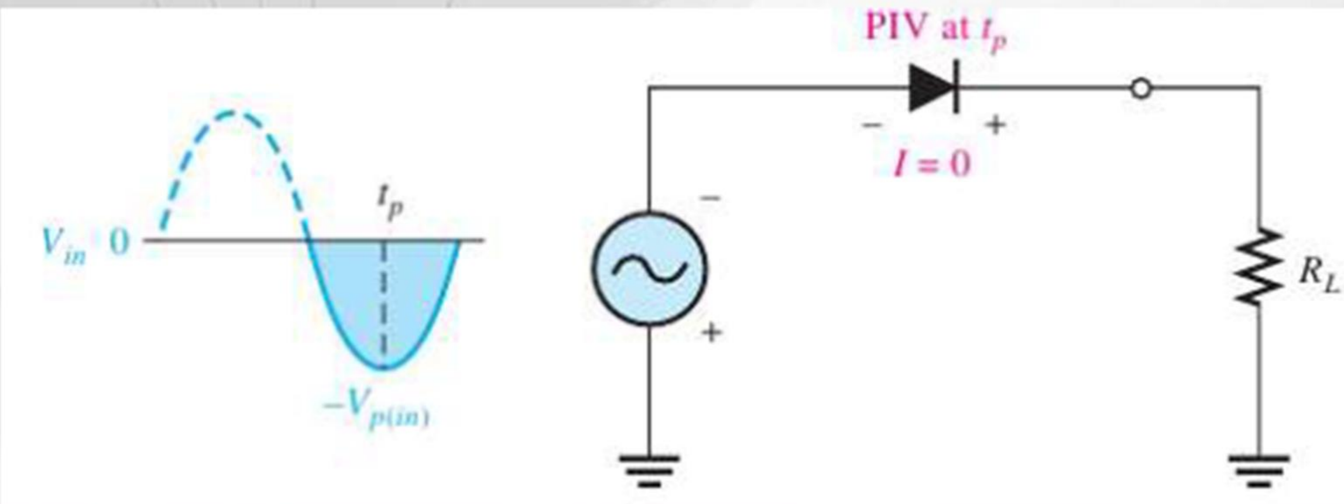
$$V_{p(out)} = V_{p(in)} - 0.7\text{ V} = 5\text{ V} - 0.7\text{ V} = \mathbf{4.30\text{ V}}$$

The peak output voltage for circuit (b) is

$$V_{p(out)} = V_{p(in)} - 0.7\text{ V} = 100\text{ V} - 0.7\text{ V} = \mathbf{99.3\text{ V}}$$

Peak Inverse Voltage (PIV)

- The peak inverse voltage (PIV) equals the peak value of the input voltage, and the diode must be capable of withstanding this amount of repetitive reverse voltage

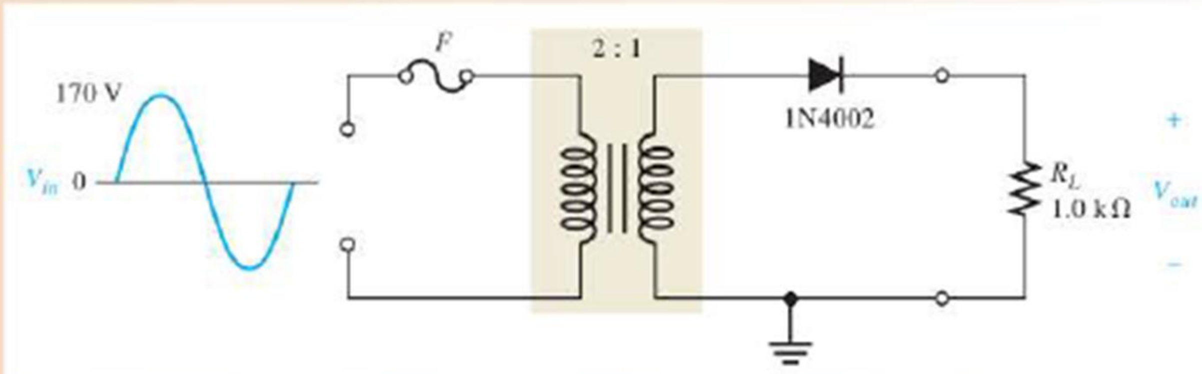


$$\boxed{\mathbf{PIV} = V_{p(in)}}$$

EXAMPLE 2-4

EXAMPLE 2–4 Determine the peak value of the output voltage for Figure 2–28 if the turns ratio is 0.5.

► FIGURE 2–28



Solution

$$V_{p(pri)} = V_{p(in)} = 170\text{ V}$$

The peak secondary voltage is

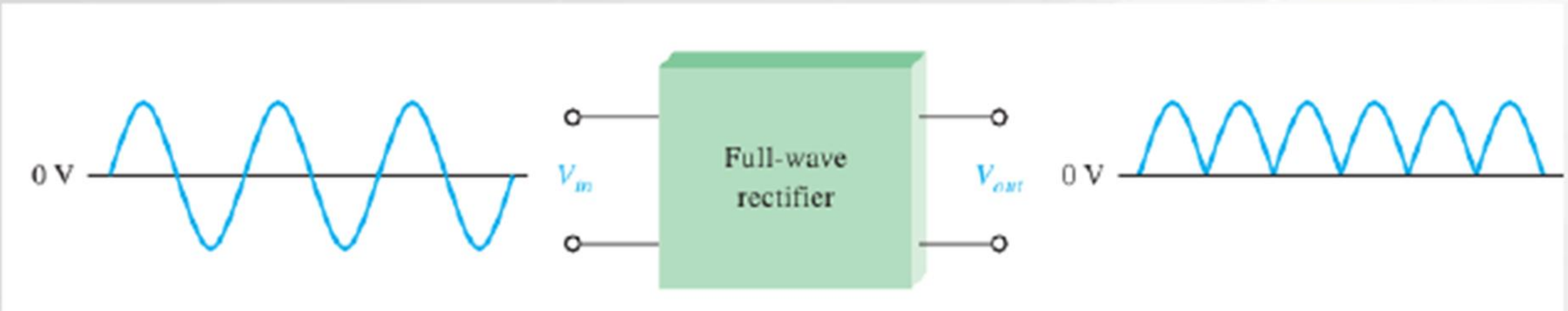
$$V_{p(sec)} = nV_{p(pri)} = 0.5(170\text{ V}) = 85\text{ V}$$

The rectified peak output voltage is

$$V_{p(out)} = V_{p(sec)} - 0.7\text{ V} = 85\text{ V} - 0.7\text{ V} = \mathbf{84.3\text{ V}}$$

where $V_{p(sec)}$ is the input to the rectifier.

2–5 FULL-WAVE RECTIFIERS



$$\boxed{V_{AVG} = \frac{2V_p}{\pi}}$$

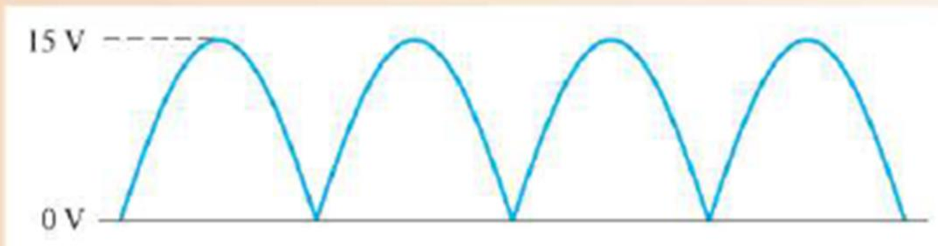
VAVG is approximately 63.7% of Vp for a full-wave rectified voltage.

EXAMPLE 2-5

EXAMPLE 2–5

Find the average value of the full-wave rectified voltage in Figure 2–30.

▶ **FIGURE 2–30**



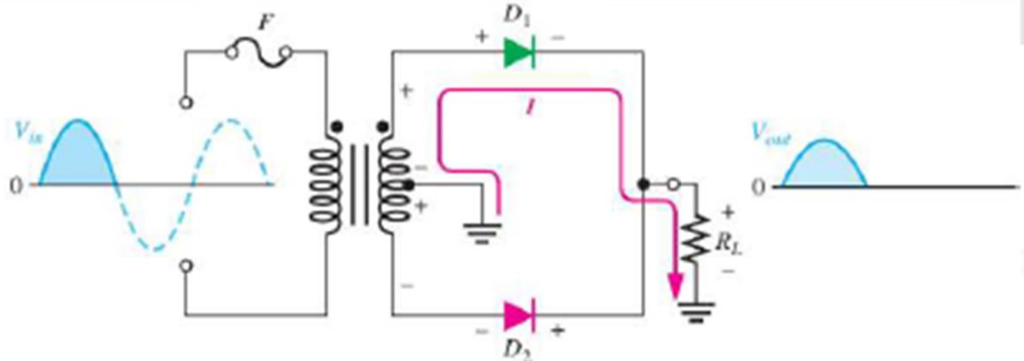
Solution

$$V_{AVG} = \frac{2V_p}{\pi} = \frac{2(15\text{ V})}{\pi} = \mathbf{9.55\ V}$$

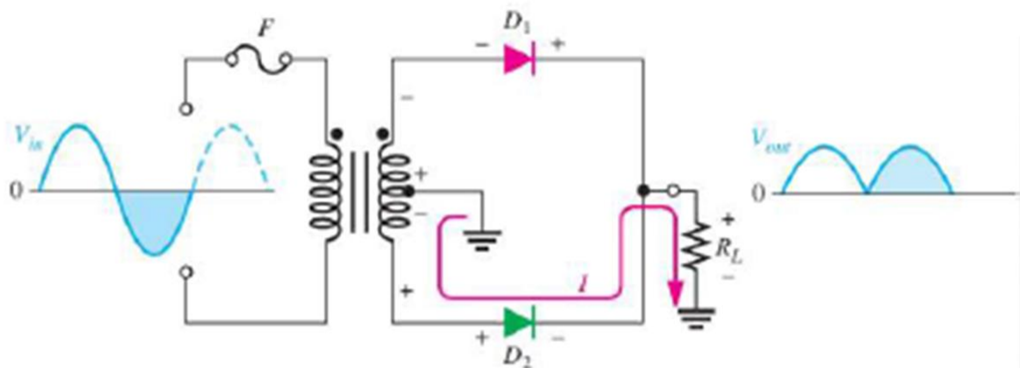
V_{AVG} is 63.7% of V_p.

Related Problem Find the average value of the full-wave rectified voltage if its peak is 155 V.

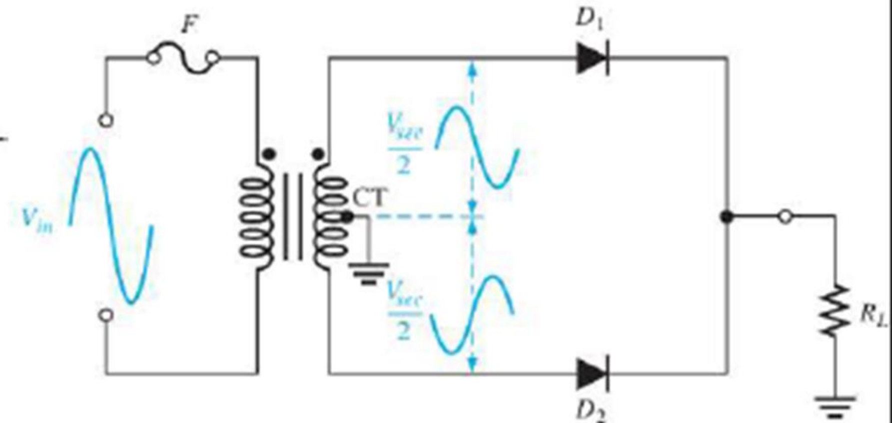
Center-Tapped Full-Wave Rectifier Operation



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

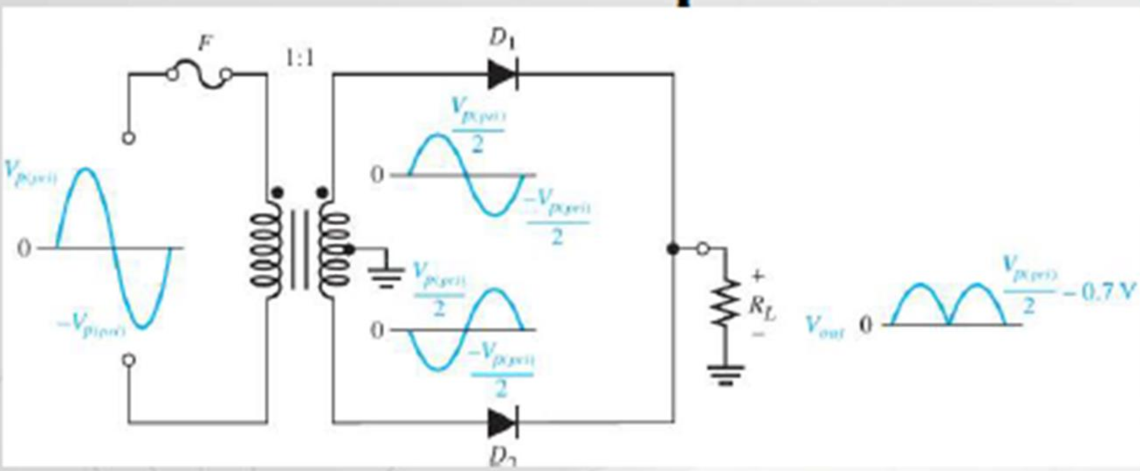


(b) During negative half-cycles, D_2 is forward-biased and D_1 is reverse-biased.

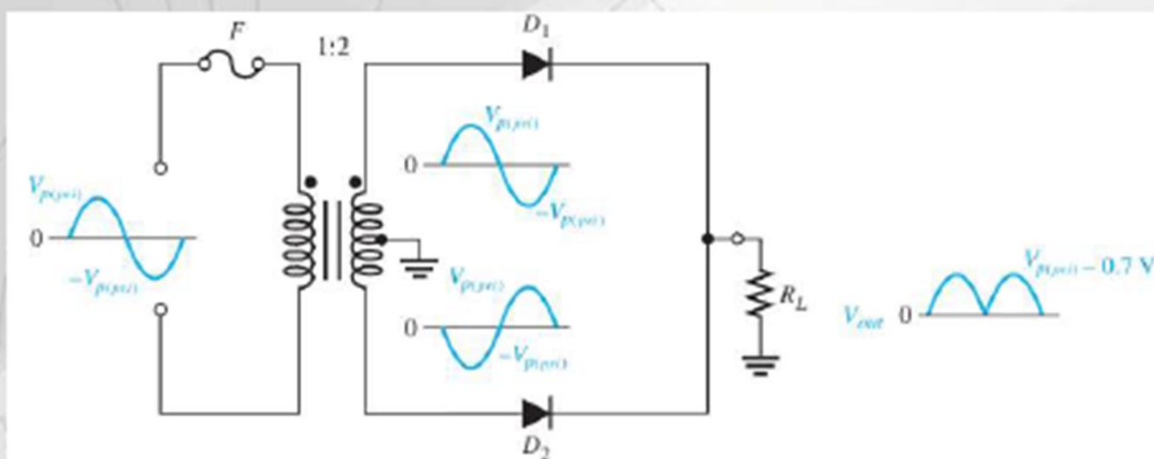


A center-tapped full-wave rectifier.

Effect of the Turns Ratio on the Output Voltage

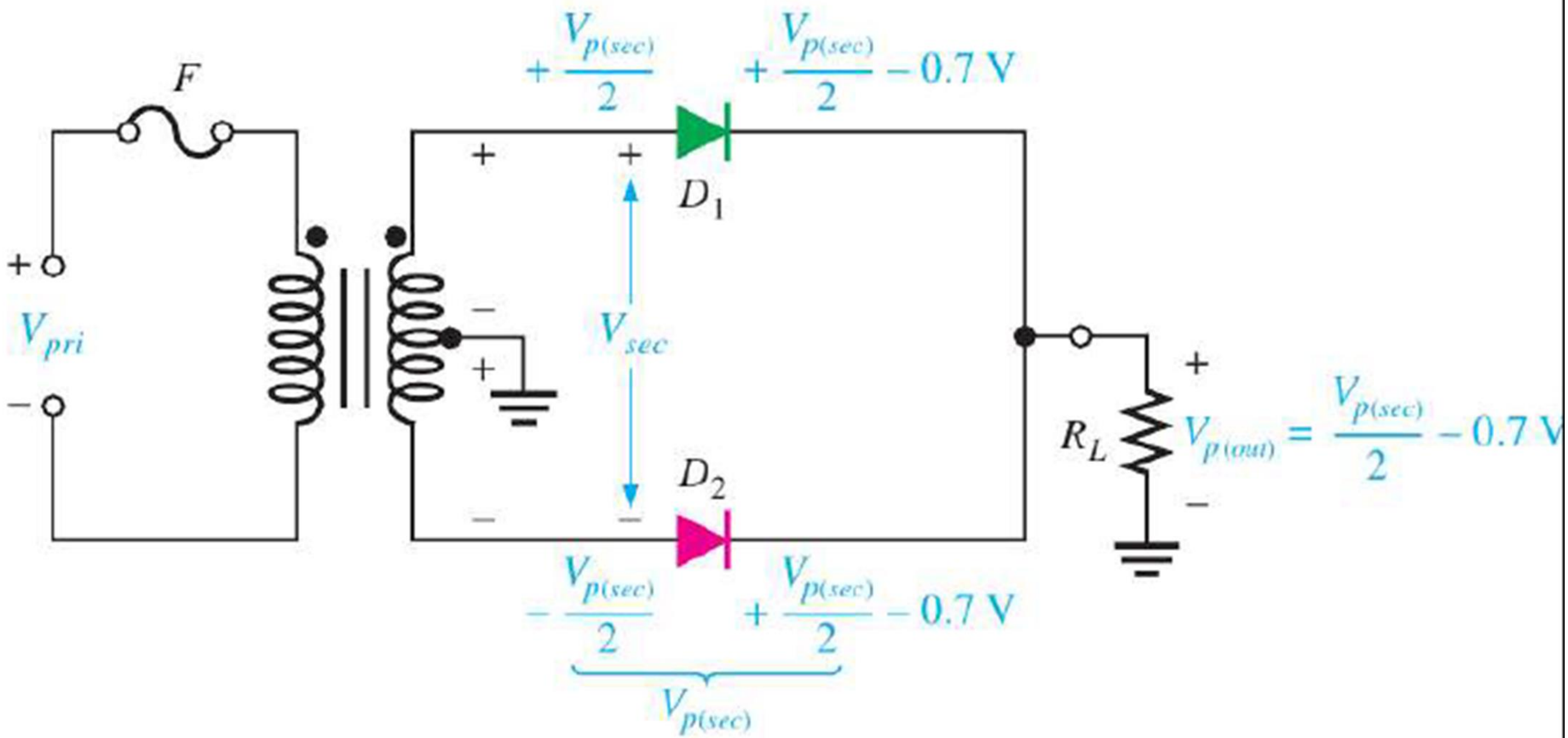


Center-tapped full-wave rectifier with a transformer turns ratio of 1. Vp(pri) is the peak value of the primary voltage.



Center-tapped full-wave rectifier with a transformer turns ratio of 2.

Peak Inverse Voltage (full-wave rectifier)

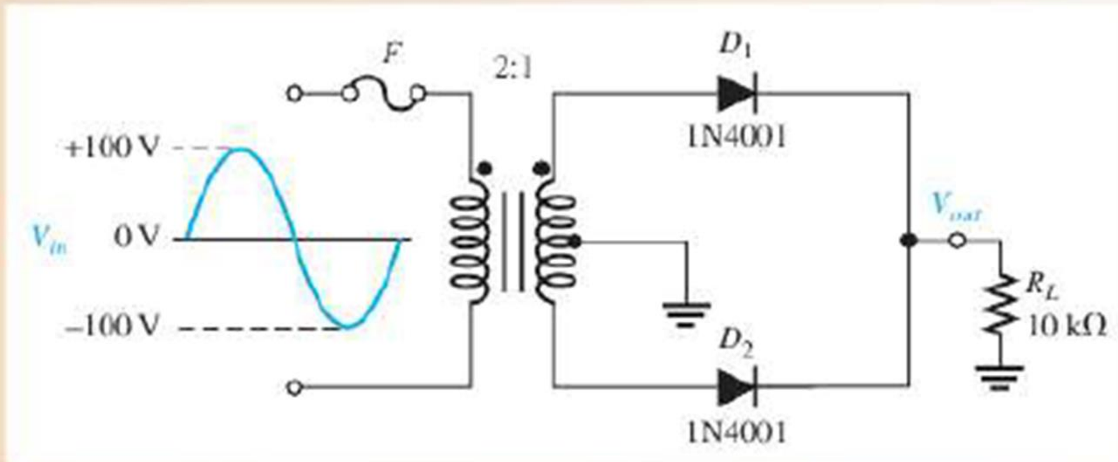


EXAMPLE 2–6

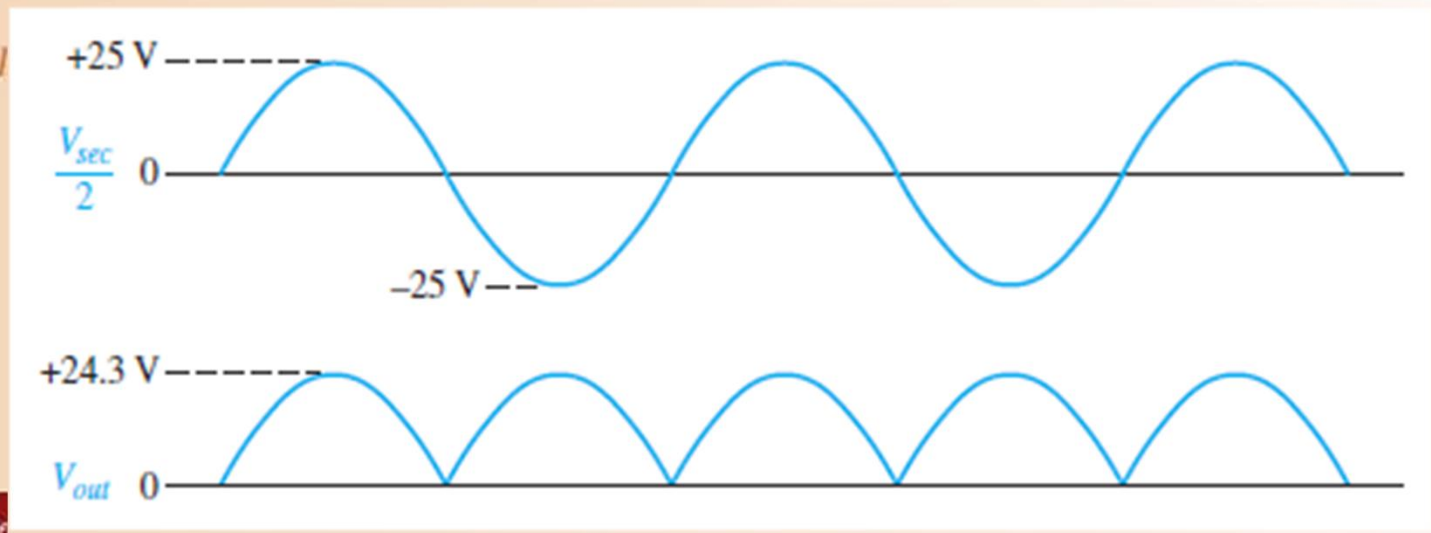
(a) Show the voltage waveforms across each half of the secondary winding and across R_L when a 100 V peak sine wave is applied to the primary winding in Figure 2–36.

(b) What minimum PIV rating must the diodes have?

FIGURE 2–36



Sol



1. The

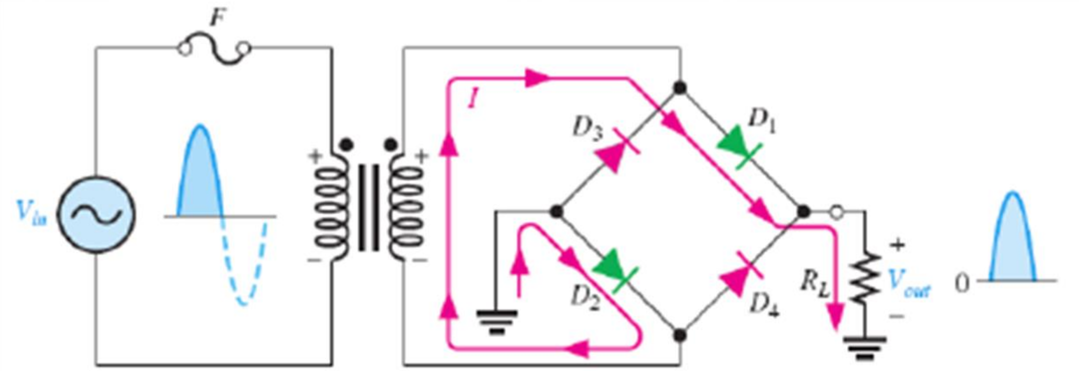
iode.

Bridge Full-Wave Rectifier Operation

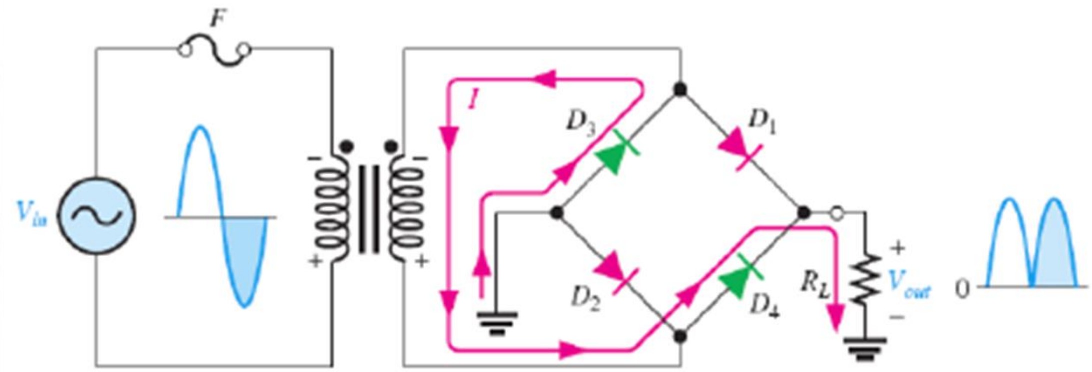
The **bridge rectifier uses four diodes connected as shown in Figure 2–38.**

• When the input cycle is positive diodes D1 and D2 are forward-biased , and diodes D3 and D4 are reverse-biased.

•When the input cycle is negative diodes D3 and D4 are forward biased, and D1 and D2 are reverse-biased

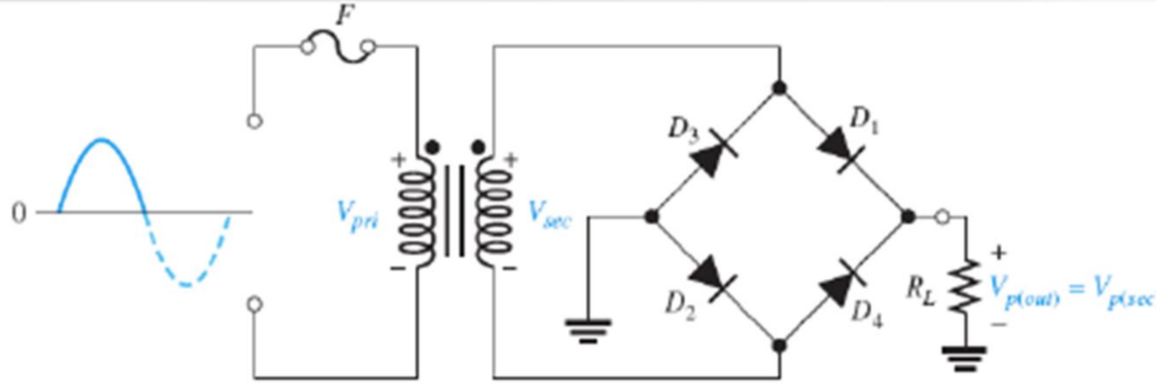


(a) During the positive half-cycle of the input, D_1 and D_2 are forward-biased and conduct current. D_3 and D_4 are reverse-biased.



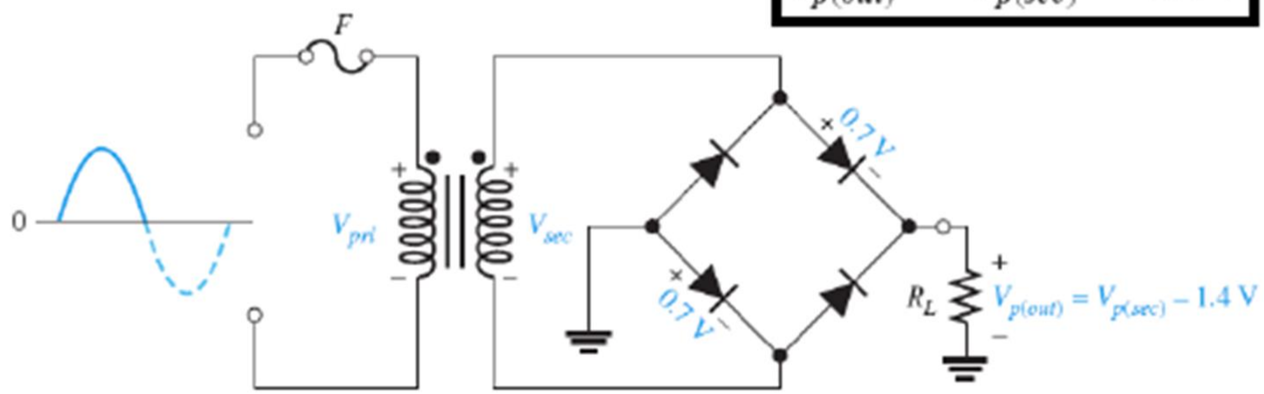
(b) During the negative half-cycle of the input, D_3 and D_4 are forward-biased and conduct current. D_1 and D_2 are reverse-biased.

Bridge Output Voltage



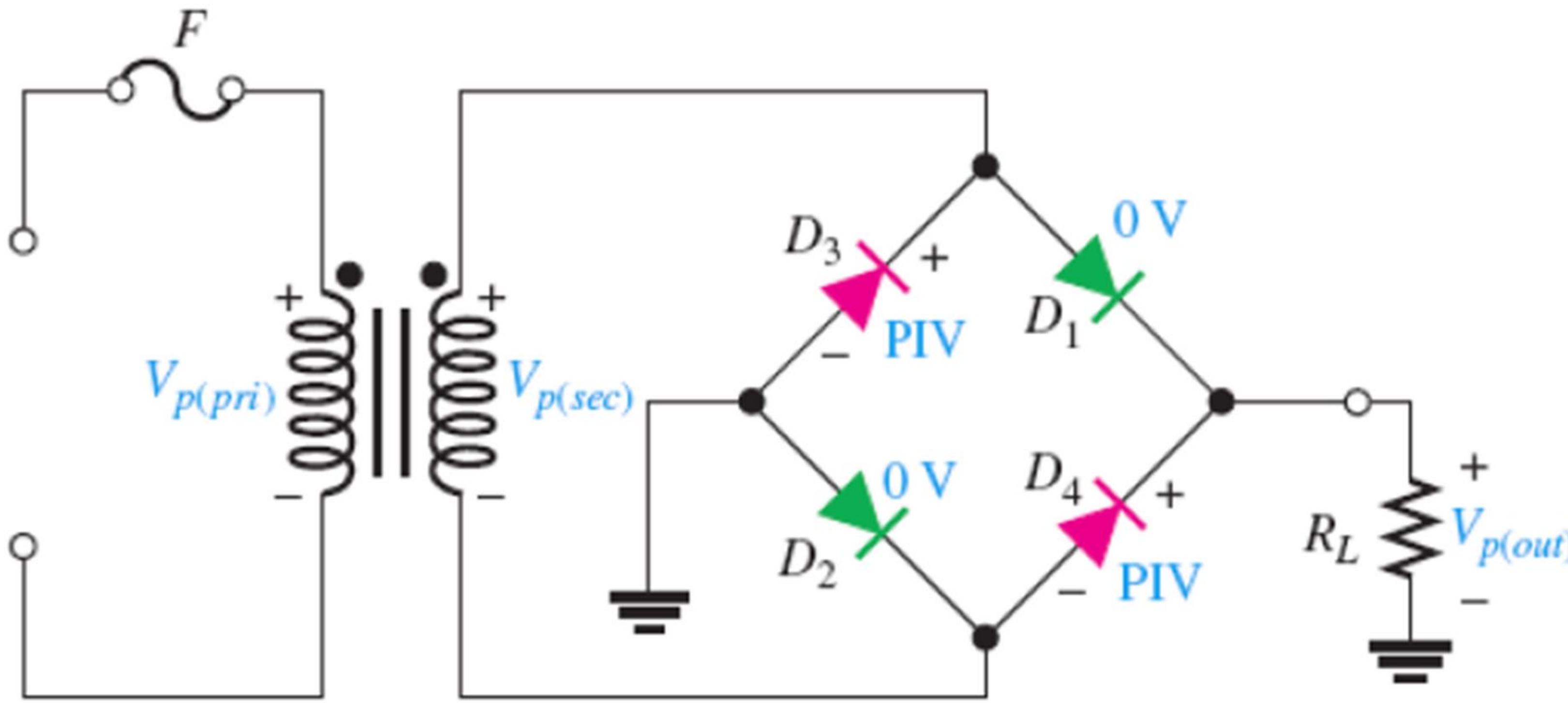
(a) Ideal diodes

$$\boxed{V_{p(out)} = V_{p(sec)} - 1.4\text{ V}}$$



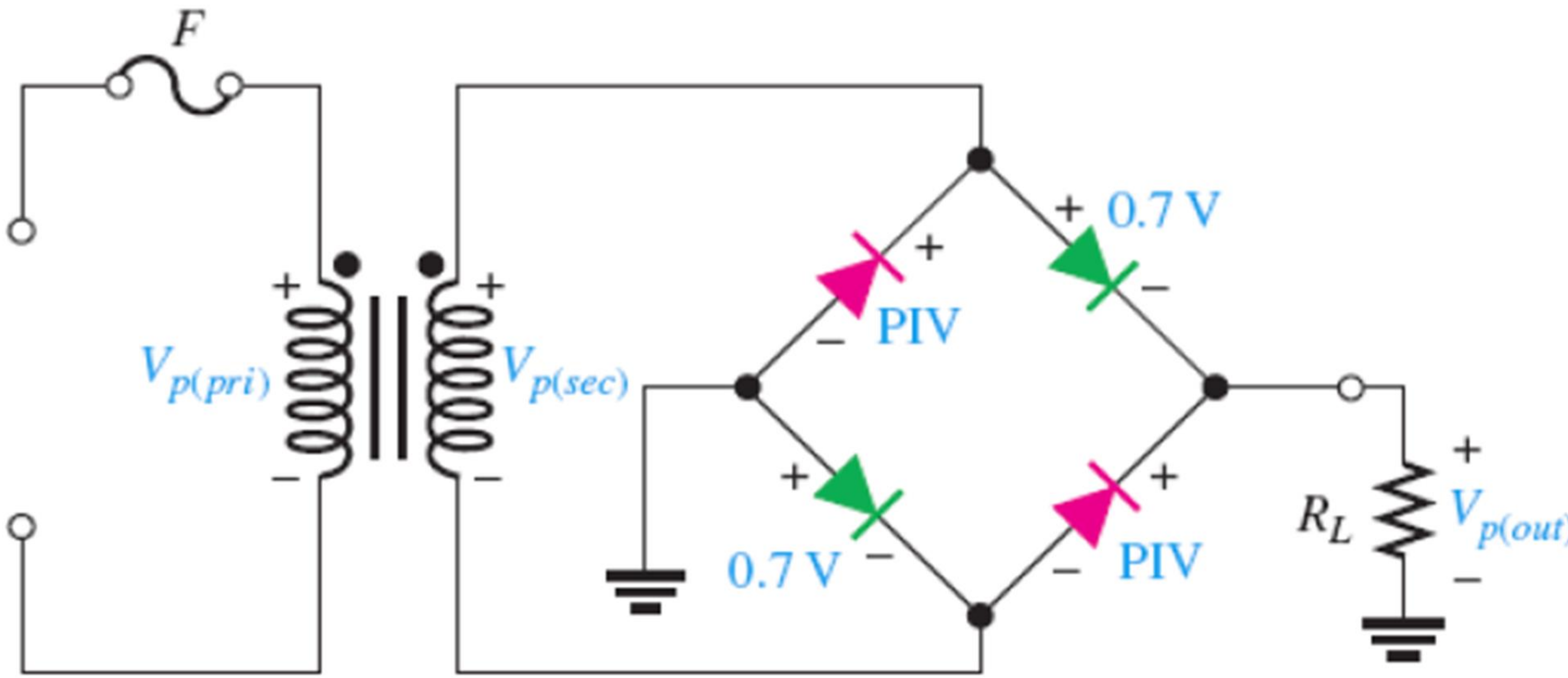
(b) Practical diodes (Diode drops included)

Peak Inverse Voltage
(Bridge Full-Wave Rectifier)



(a) For the ideal diode model (forward-biased diodes D_1 and D_2 are shown in green), PIV = $V_{p(out)}$.

Peak Inverse Voltage
(Bridge Full-Wave Rectifier

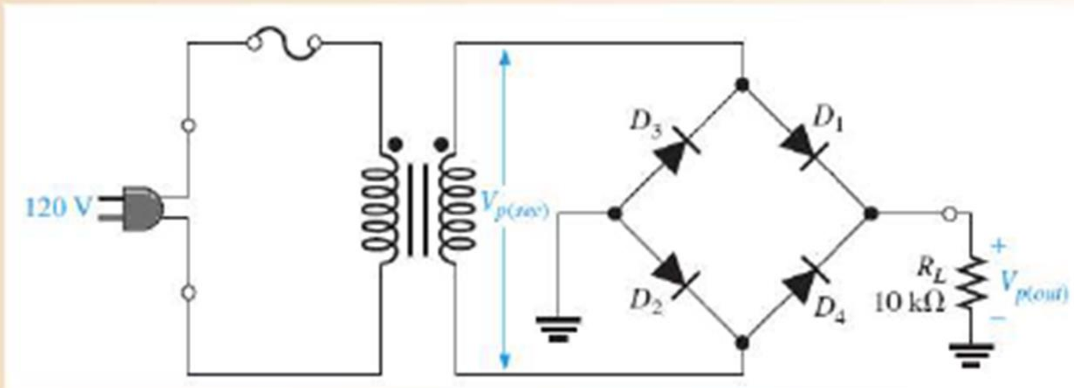


(b) For the practical diode model (forward-biased diodes D_1 and D_2 are shown in green), PIV = $V_{p(out)}$ + 0.7 V.

Example 2-7

EXAMPLE 2–7 Determine the peak output voltage for the bridge rectifier in Figure 2–41. Assuming the practical model, what PIV rating is required for the diodes? The transformer is specified to have a 12 V rms secondary voltage for the standard 120 V across the primary.

FIGURE 2–41



Solution The peak output voltage (taking into account the two diode drops) is

$$V_{p(sec)} = 1.414V_{rms} = 1.414(12\text{ V}) \cong 17\text{ V}$$

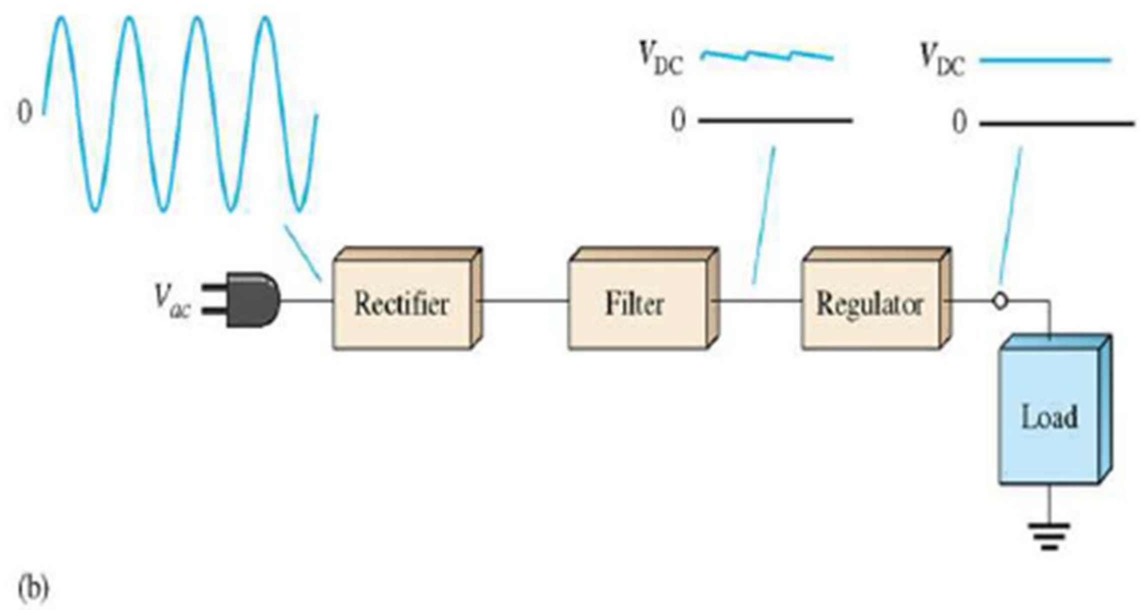
$$V_{p(out)} = V_{p(sec)} - 1.4\text{ V} = 17\text{ V} - 1.4\text{ V} = \mathbf{15.6\text{ V}}$$

The PIV rating for each diode is

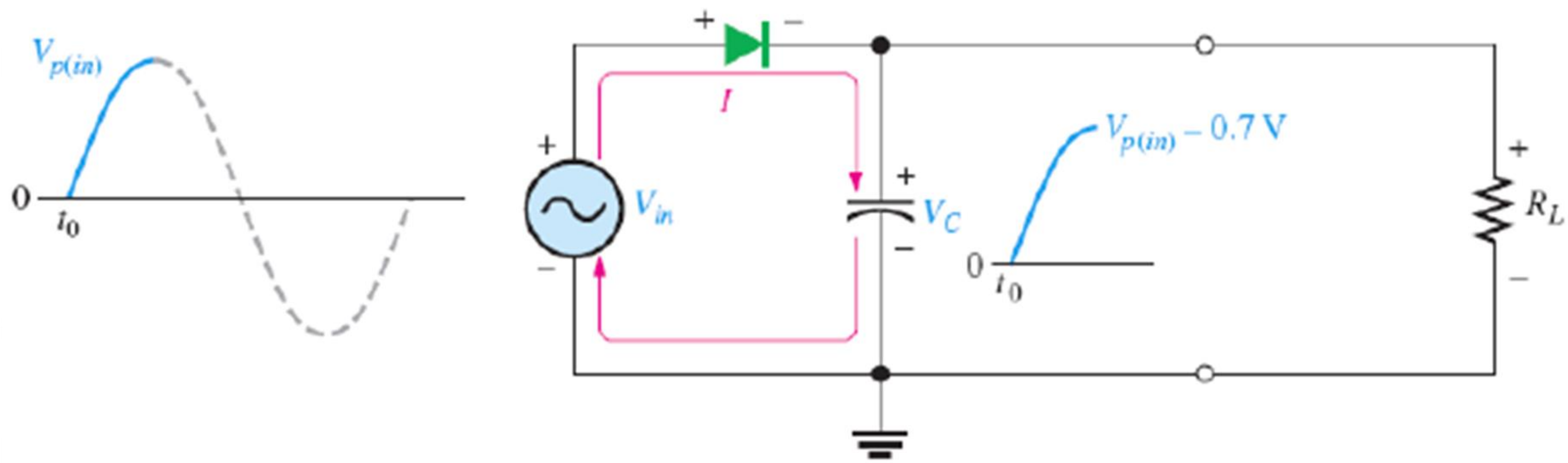
$$\text{PIV} = V_{p(out)} + 0.7\text{ V} = 15.6\text{ V} + 0.7\text{ V} = \mathbf{16.3\text{ V}}$$

2–6 POWER SUPPLY FILTERS AND REGULATORS

- A power supply filter ideally eliminates the fluctuations in the output voltage of a halfwave or full-wave rectifier and produces a constant-level dc voltage.



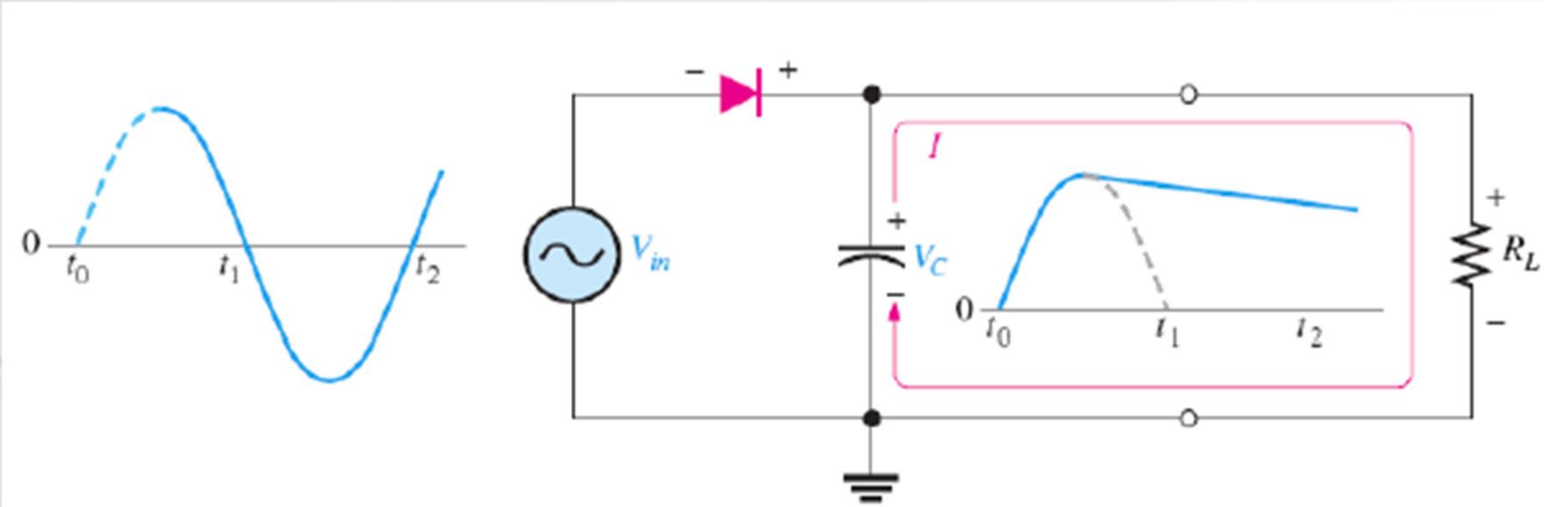
Capacitor-Input Filter



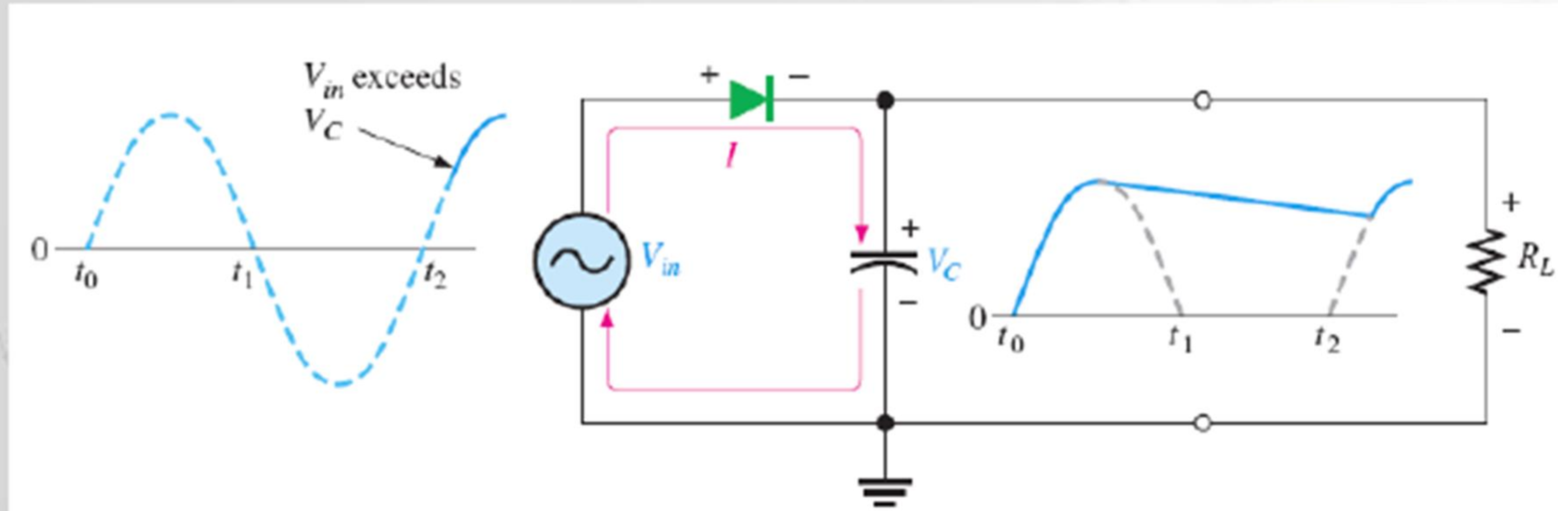
(a) Initial charging of the capacitor (diode is forward-biased) happens only once when power is turned on.

During the positive first quarter-cycle of the input, the diode is forward-biased, allowing the capacitor to charge to within 0.7 V of the input peak.

Capacitor-Input Filter

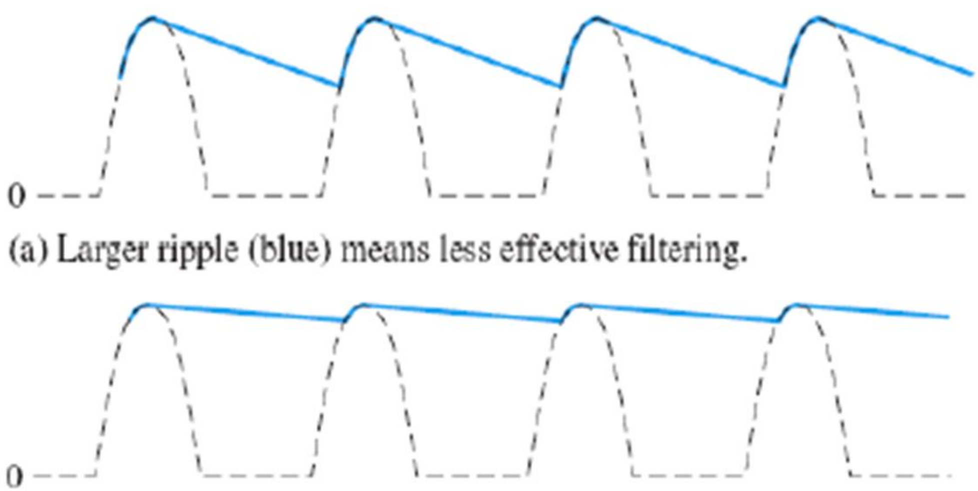


When the input begins to decrease below its peak, as shown in part (b), the capacitor retains its charge and the diode becomes reverse-biased because the cathode is more positive than the anode. During the remaining part of the cycle, the capacitor can discharge only through the load resistance at a rate determined by the *RLC time constant*



During the first quarter of the next cycle, as illustrated in part (c), the diode will again become forward-biased when the input voltage exceeds the capacitor voltage by approximately 0.7 V.

Ripple Voltage



(a) Larger ripple (blue) means less effective filtering.

(b) Smaller ripple means more effective filtering. Generally, the larger the capacitor value, the smaller the ripple for the same input and load.

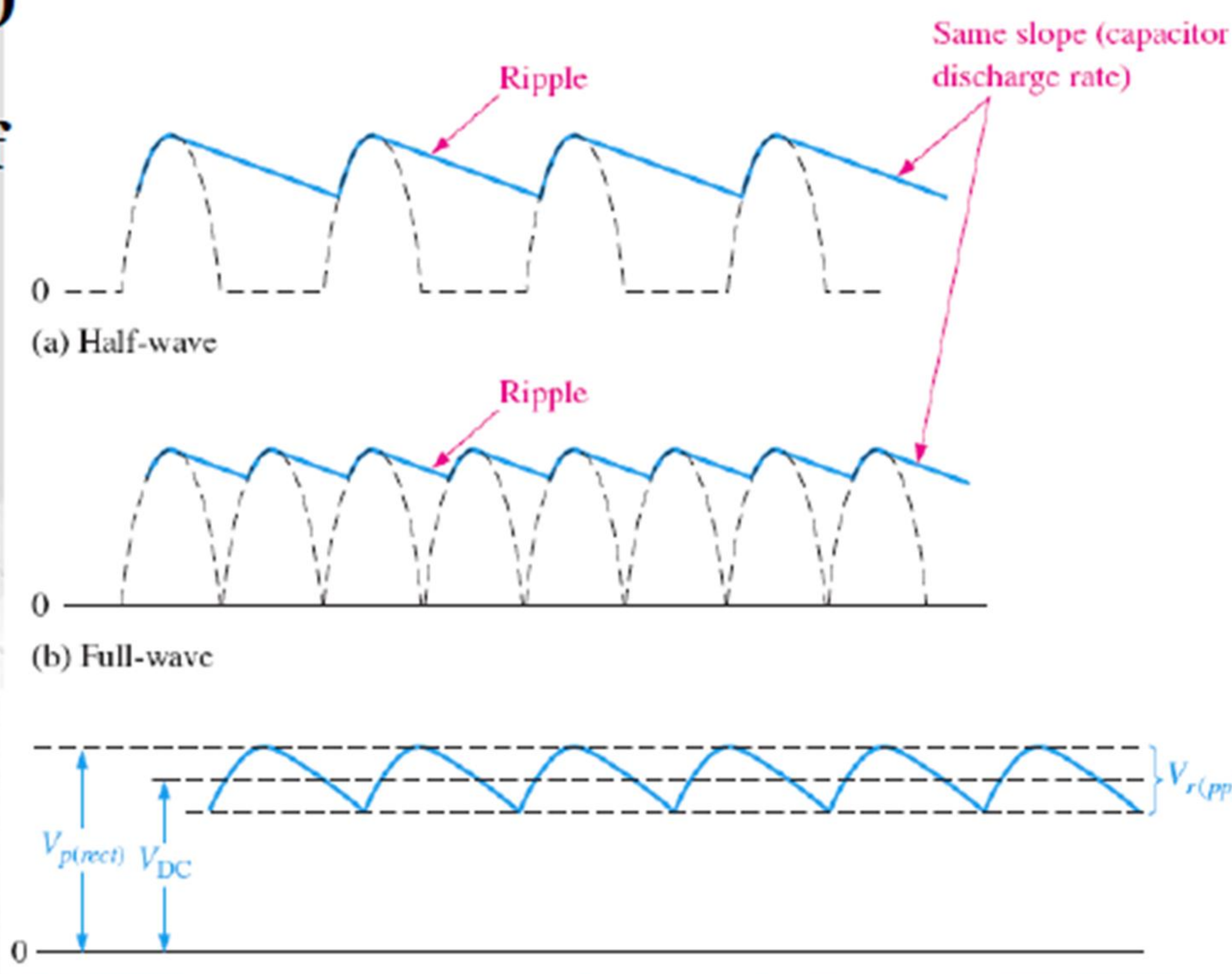
As you have seen, the capacitor quickly charges at the beginning of a cycle and slowly discharges through *RL* after the positive peak of the input voltage (when the diode is reverse-biased). The variation in the capacitor voltage due to the charging and discharging is called the **ripple voltage.** Generally, ripple is undesirable; thus, the smaller the ripple, the better the filtering action

Ripple Factor

The **ripple factor (r) is an indication of the effectiveness of the filter and** is defined as

$$r = \frac{V_{r(pp)}}{V_{DC}}$$

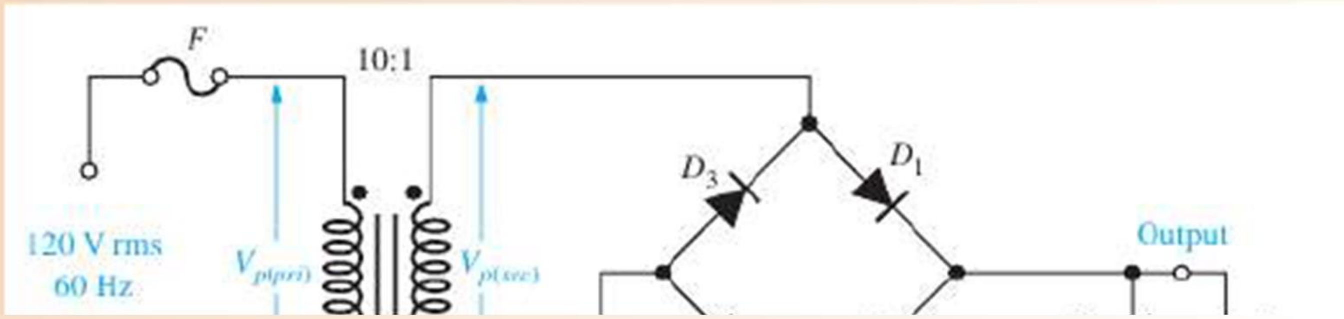
Notice :
if RL or C increases, the ripple voltage decreases and the dc voltage increases.



Example 2-8

EXAMPLE 2–8 Determine the ripple factor for the filtered bridge rectifier with a load as indicated in Figure 2–48.

FIGURE 2–48



The frequency of a full-wave rectified voltage is 120 Hz. The approximate peak-to-peak ripple voltage at the output is

$$V_{r(pp)} \cong \left(\frac{1}{fR_LC}\right)V_{p(rect)} = \left(\frac{1}{(120\text{ Hz})(220\ \Omega)(1000\ \mu\text{F})}\right)15.6\text{ V} = 0.591\text{ V}$$

The approximate dc value of the output voltage is determined as follows:

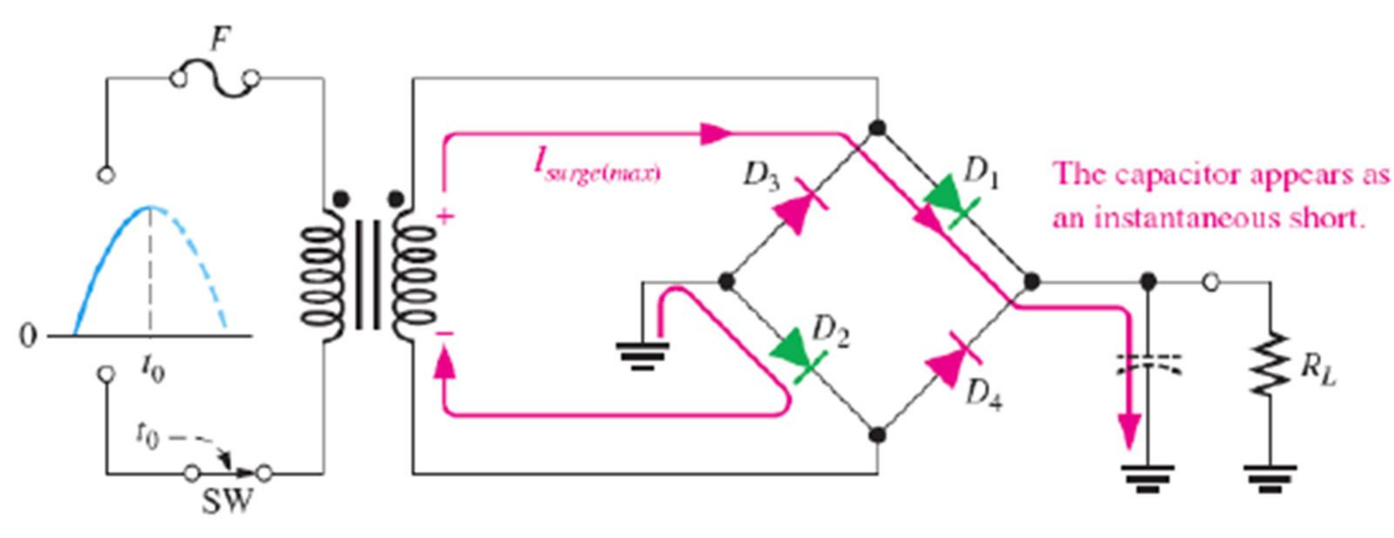
$$V_{DC} = \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)} = \left(1 - \frac{1}{(240\text{ Hz})(220\ \Omega)(1000\ \mu\text{F})}\right)15.6\text{ V} = 15.3\text{ V}$$

The resulting ripple factor is

$$r = \frac{V_{r(pp)}}{V_{DC}} = \frac{0.591\text{ V}}{15.3\text{ V}} = 0.039$$

The percent ripple is 3.9%.

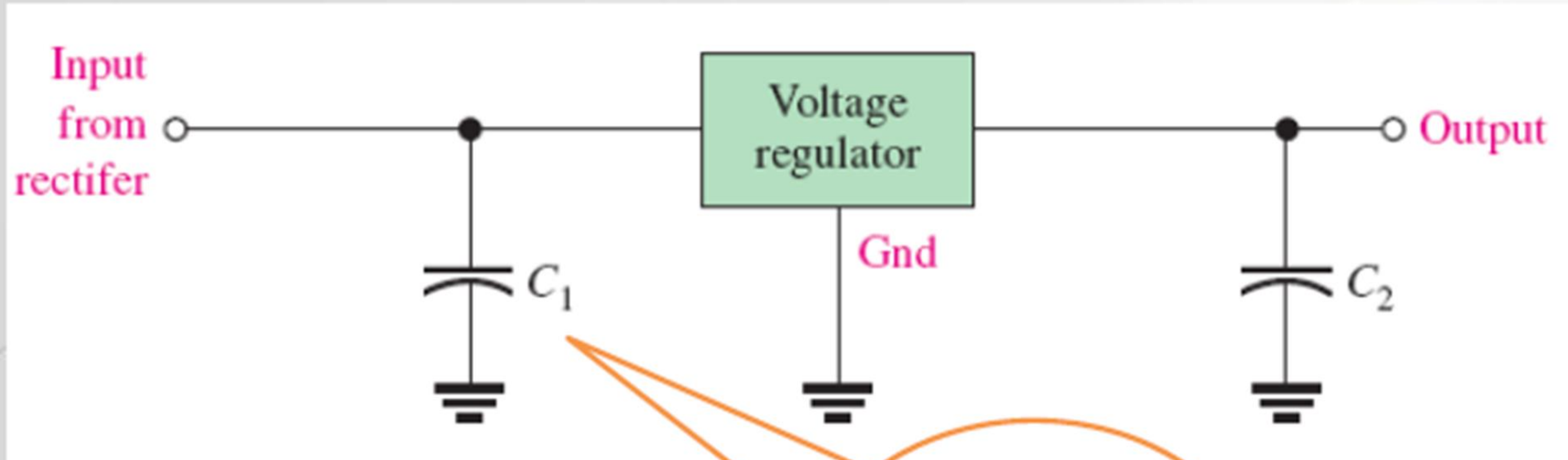
Surge Current in the Capacitor-Input Filter



$$I_{pri} = \frac{P_{in}}{120\ \text{V}}$$

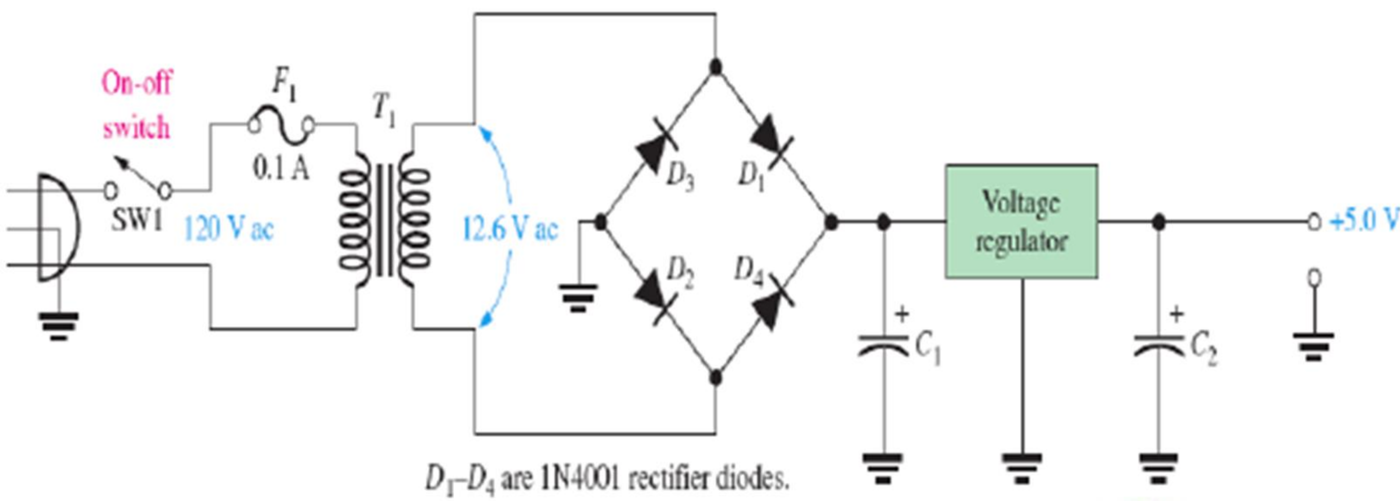
Problem: At the instant the switch is closed, voltage is connected to the bridge and the uncharged capacitor appears as a short
Solve: A slow-blow type fuse is generally used to protect the surge current that initially occurs when power is first turned on.

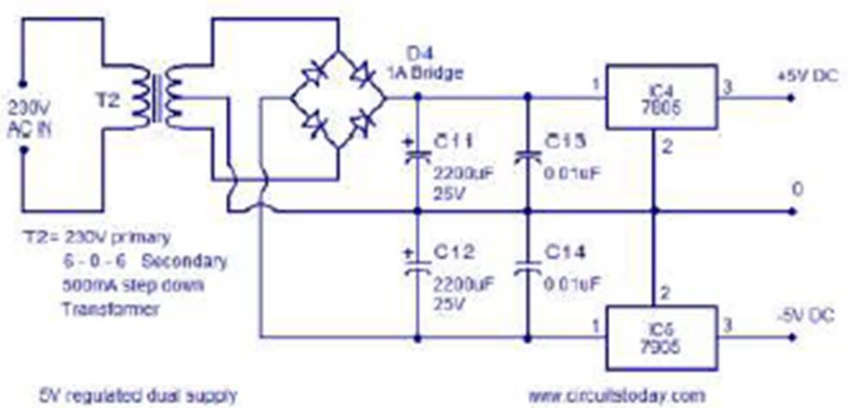
Voltage Regulators



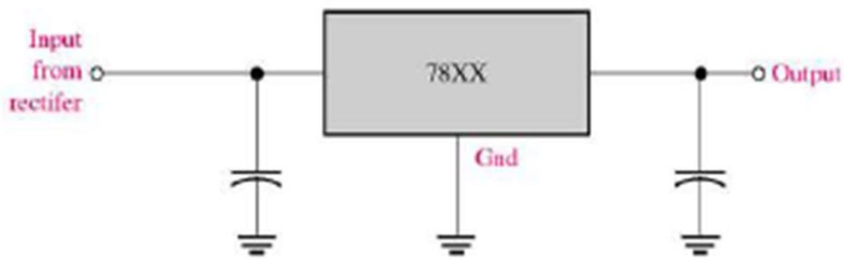
typically
0.1 mF to
1.0 mF

Regulated power supply





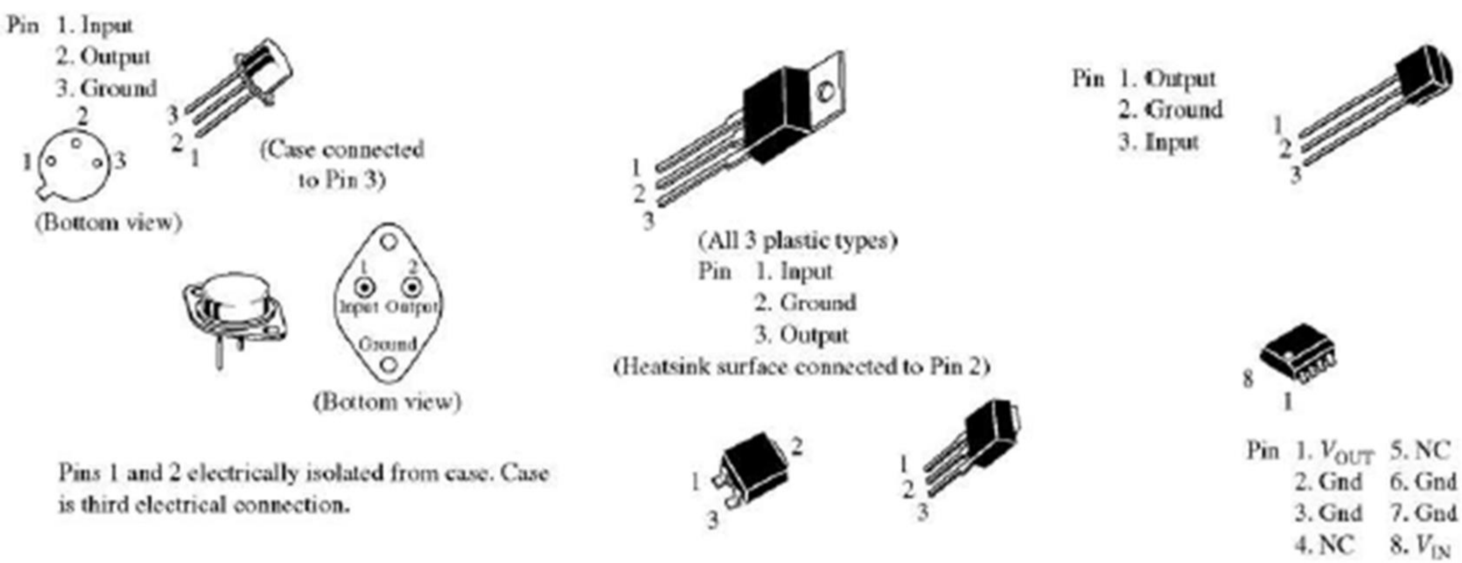
IC Regulators



(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

Percent Regulation

- Line regulation
  - Specifies how much change occurs in the output voltage for a given change in the input voltage

$$\text{Line regulation} = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}}\right)100\%$$

- Load regulation
  - Specifies how much change occurs in the output voltage over a certain range of load current value

$$\text{Load regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\%$$

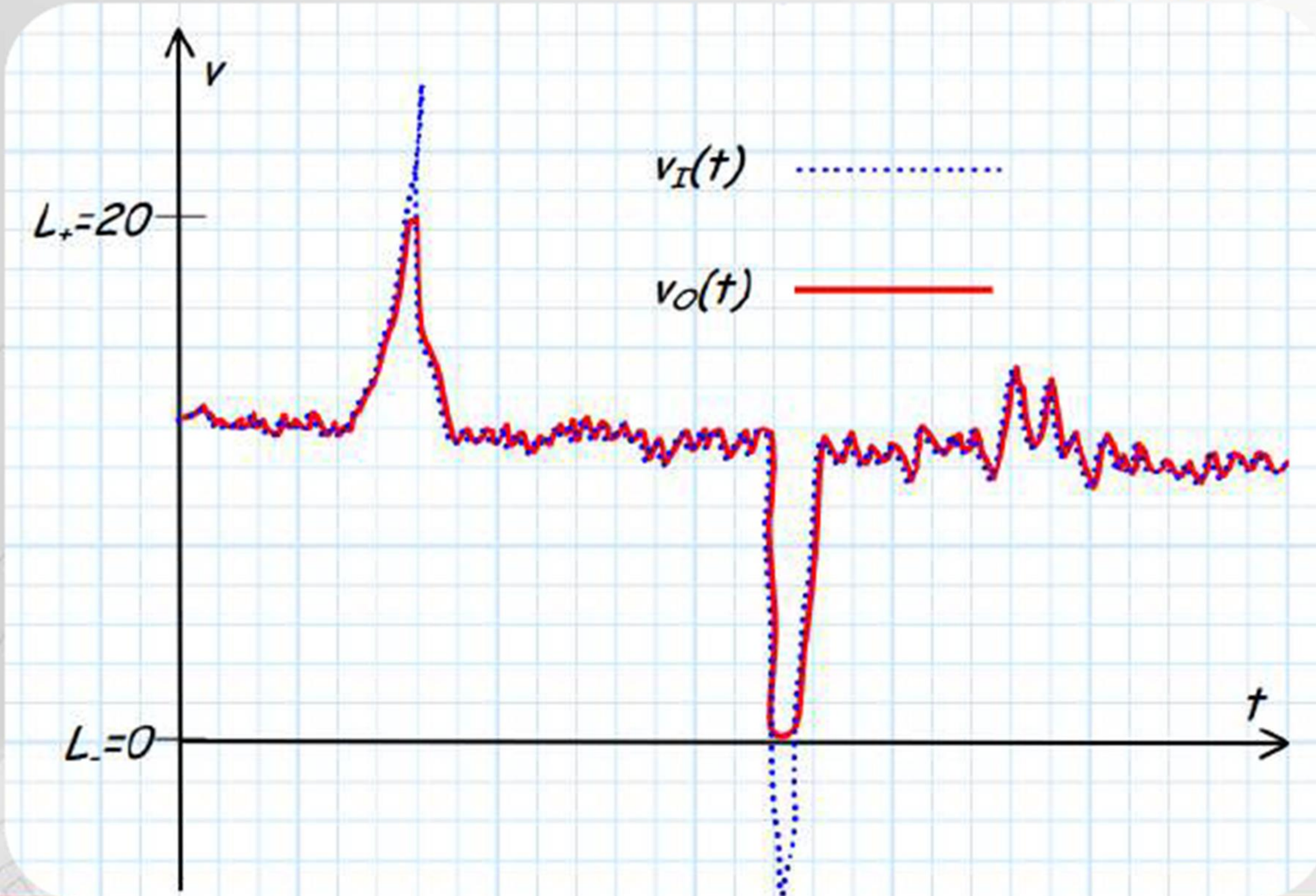
Example 2-9

EXAMPLE 2–9 A certain 7805 regulator has a measured no-load output voltage of 5.18 V and a full-load output of 5.15 V. What is the load regulation expressed as a percentage?

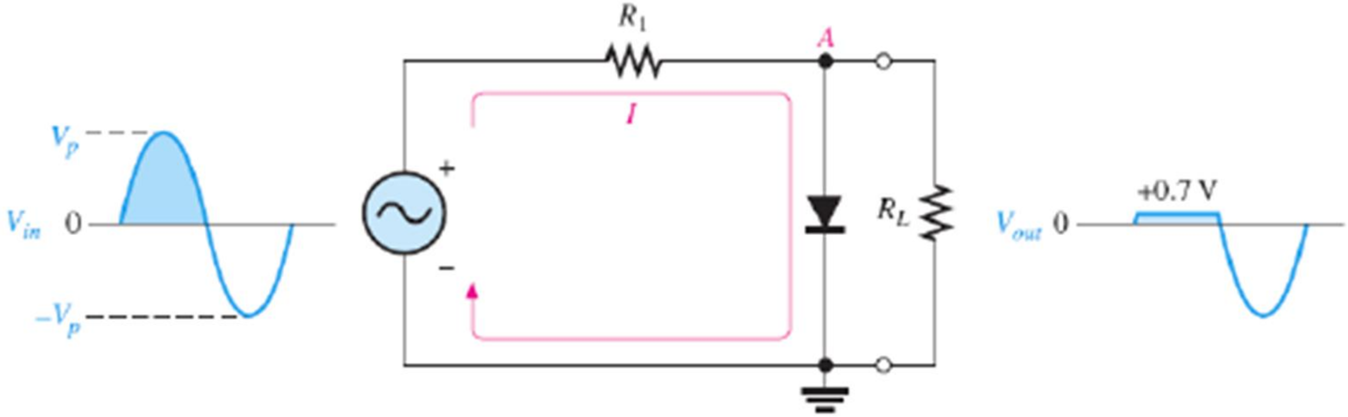
Solution $$\text{Load regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\% = \left(\frac{5.18\text{ V} - 5.15\text{ V}}{5.15\text{ V}}\right)100\% = \mathbf{0.58\%}$$

2–7 DIODE LIMITERS AND CLAMPERS

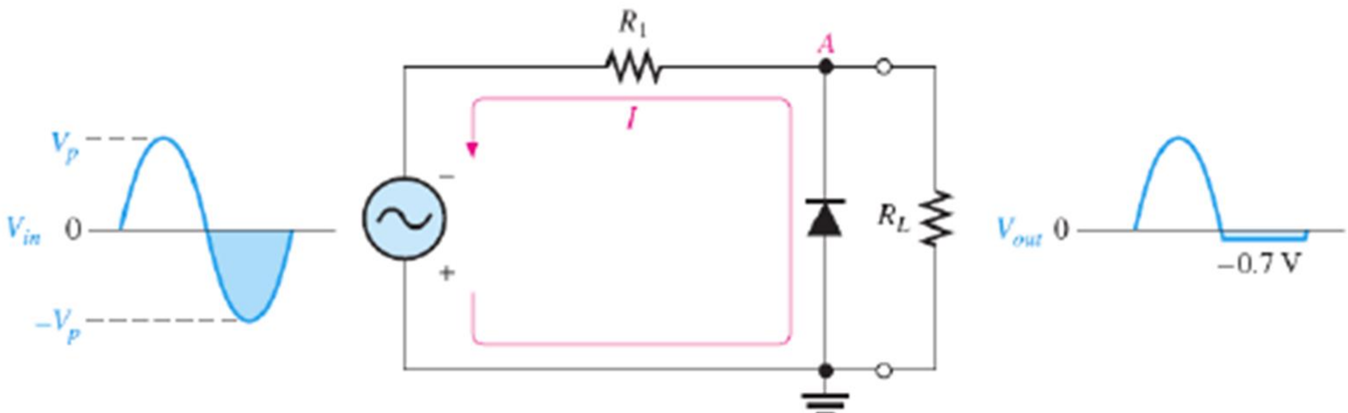
Diode Limiters or clipper



Diode Limiters or clipper



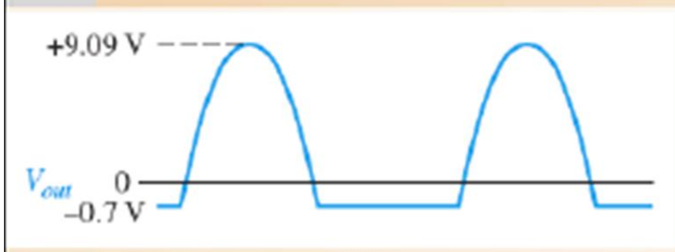
(a) Limiting of the positive alternation. The diode is forward-biased during the positive alternation (above 0.7 V) and reverse-biased during the negative alternation.

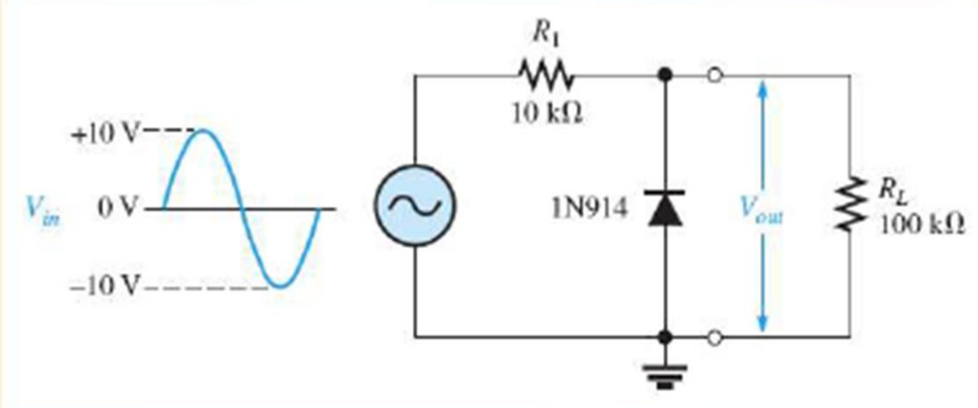


(b) Limiting of the negative alternation. The diode is forward-biased during the negative alternation (below −0.7 V) and reverse-biased during the positive alternation.

Example 2-10

EXAMPLE 2–10 What would you expect to see displayed on an oscilloscope connected across R_L in the limiter shown in Figure 2–53?



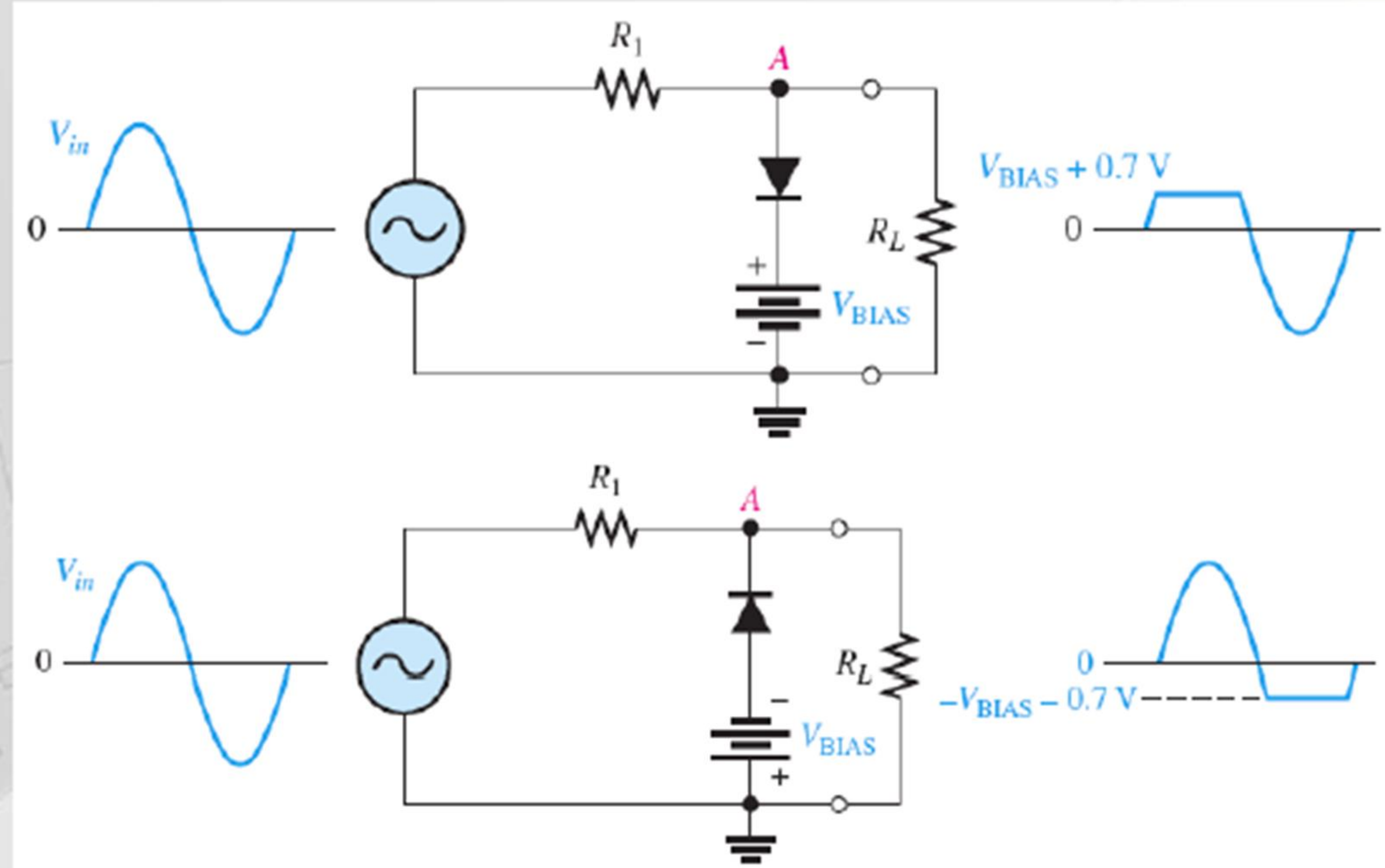


▶ FIGURE 2–53

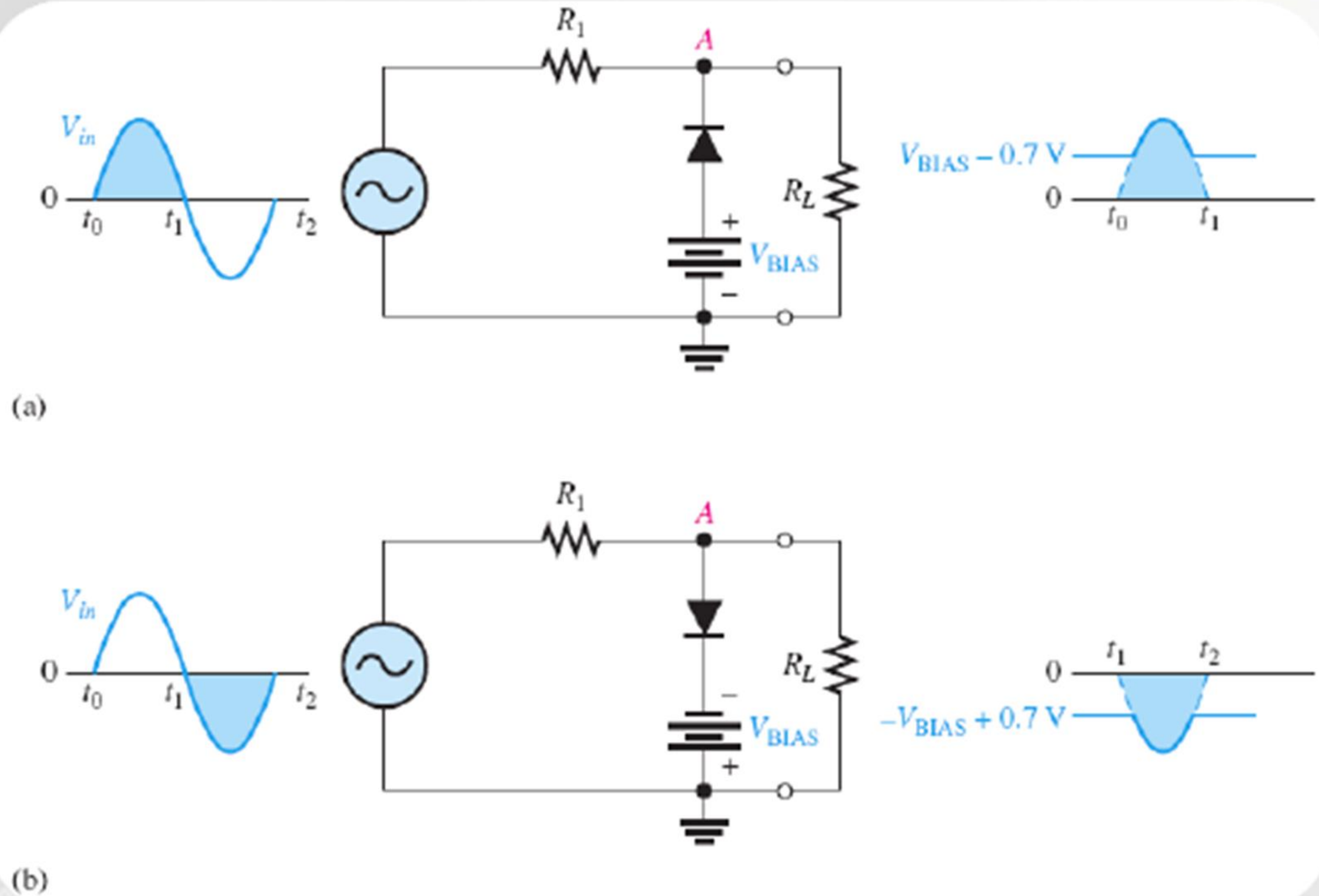
Solution The diode is forward-biased and conducts when the input voltage goes below −0.7 V. So, for the negative limiter, determine the peak output voltage across R_L by the following equation:

$$V_{p(out)} = \left(\frac{R_L}{R_1 + R_L}\right)V_{p(in)} = \left(\frac{100\ \text{k}\Omega}{110\ \text{k}\Omega}\right)10\ \text{V} = 9.09\ \text{V}$$

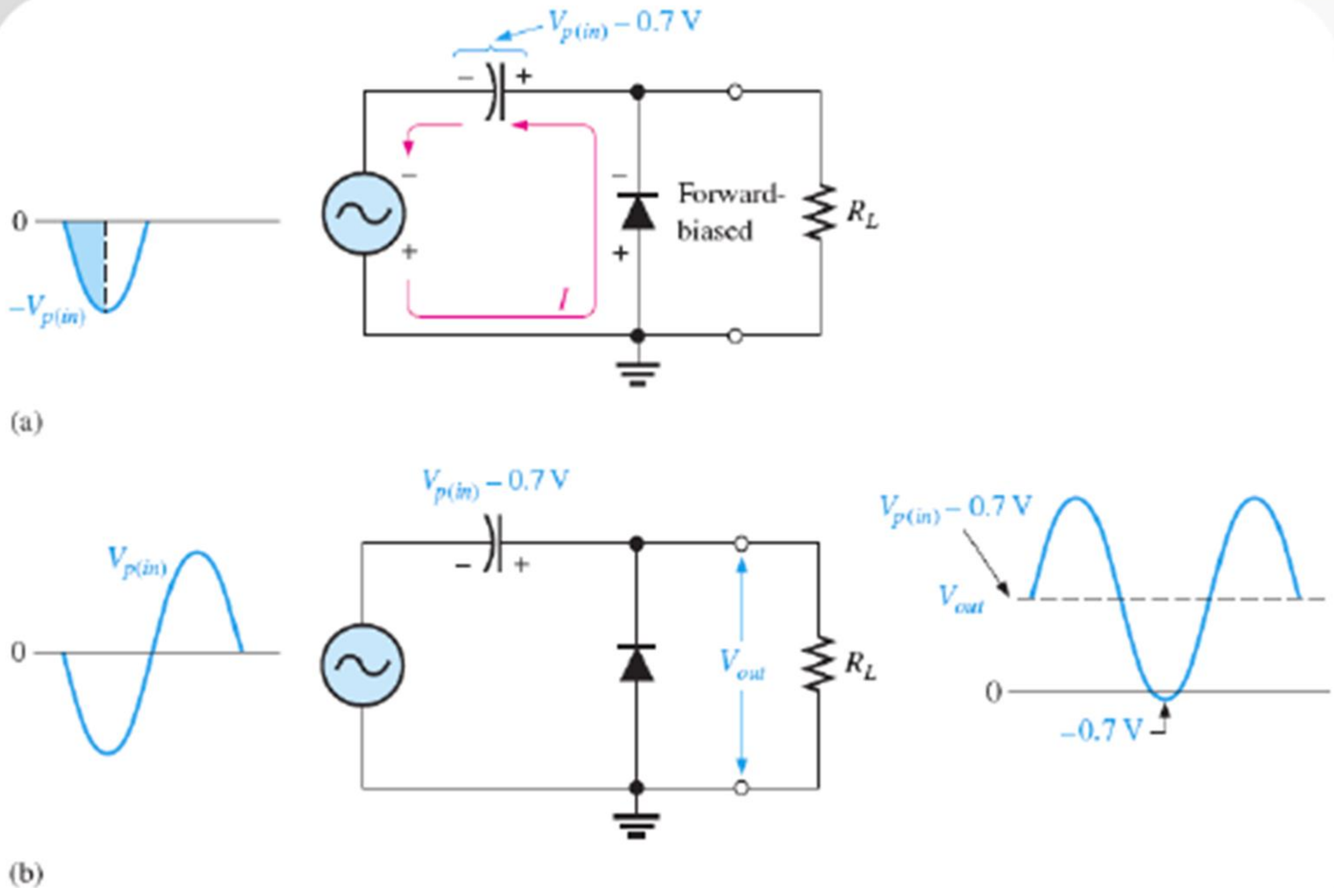
Biased Limiters



Biased Limiters



Diode Clampers



2–9 THE DIODE DATASHEET

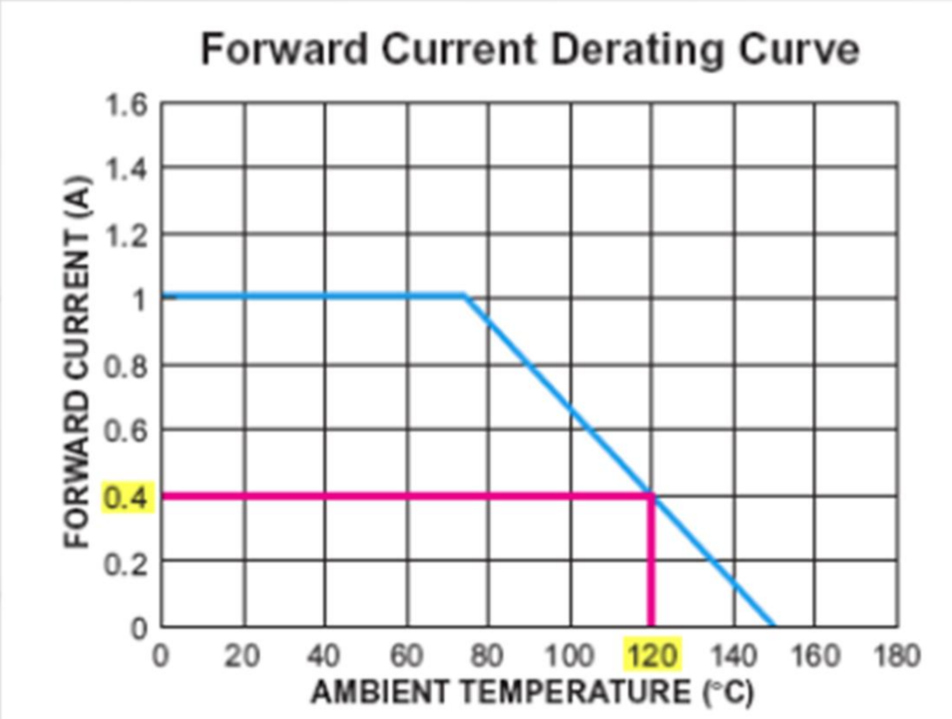
Maximum Ratings and Electrical Characteristics @T_A = 25°C unless otherwise specified

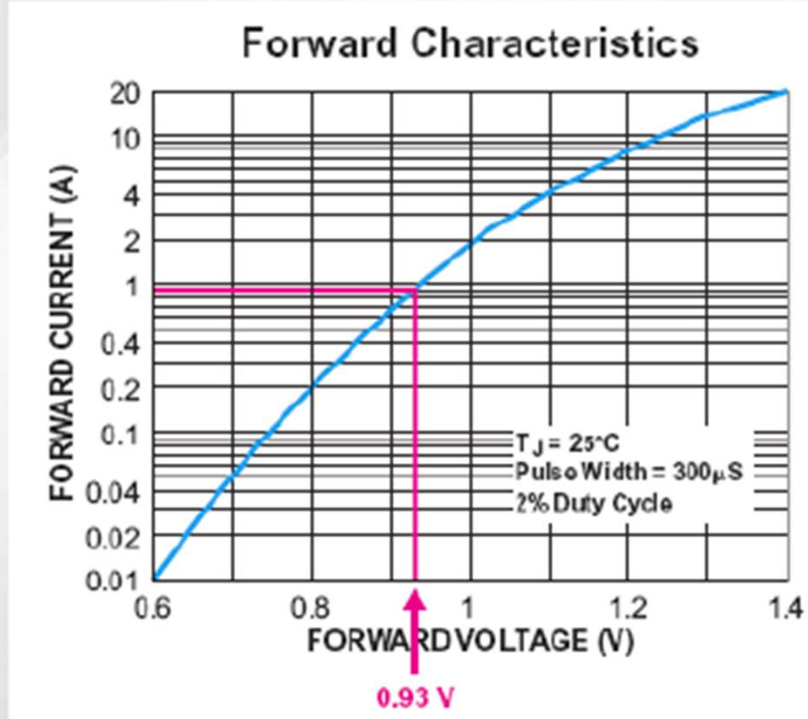
Single phase, half wave, 60Hz, resistive or inductive load.
For capacitive load, derate current by 20%.

Characteristic	Symbol	1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	50	100	200	400	600	800	1000	V
RMS Reverse Voltage	$V_{R(RMS)}$	35	70	140	280	420	560	700	V
Average Rectified Output Current (Note 1) @ T_A = 75°C	I_O	1.0							A
Non-Repetitive Peak Forward Surge Current 8.3ms single half sine-wave superimposed on rated load	I_{FSM}	30							A
Forward Voltage @ I_F = 1.0A	V_{FM}	1.0							V
Peak Reverse Current @T_A = 25°C at Rated DC Blocking Voltage @ T_A = 100°C	I_{RM}	5.0 50							µA
Typical Junction Capacitance (Note 2)	C_j	15				8			pF
Typical Thermal Resistance Junction to Ambient	$R_{\theta JA}$	100							K/W
Maximum DC Blocking Voltage Temperature	T_A	+150							°C
Operating and Storage Temperature Range	T_J, T_{STG}	-65 to +150							°C

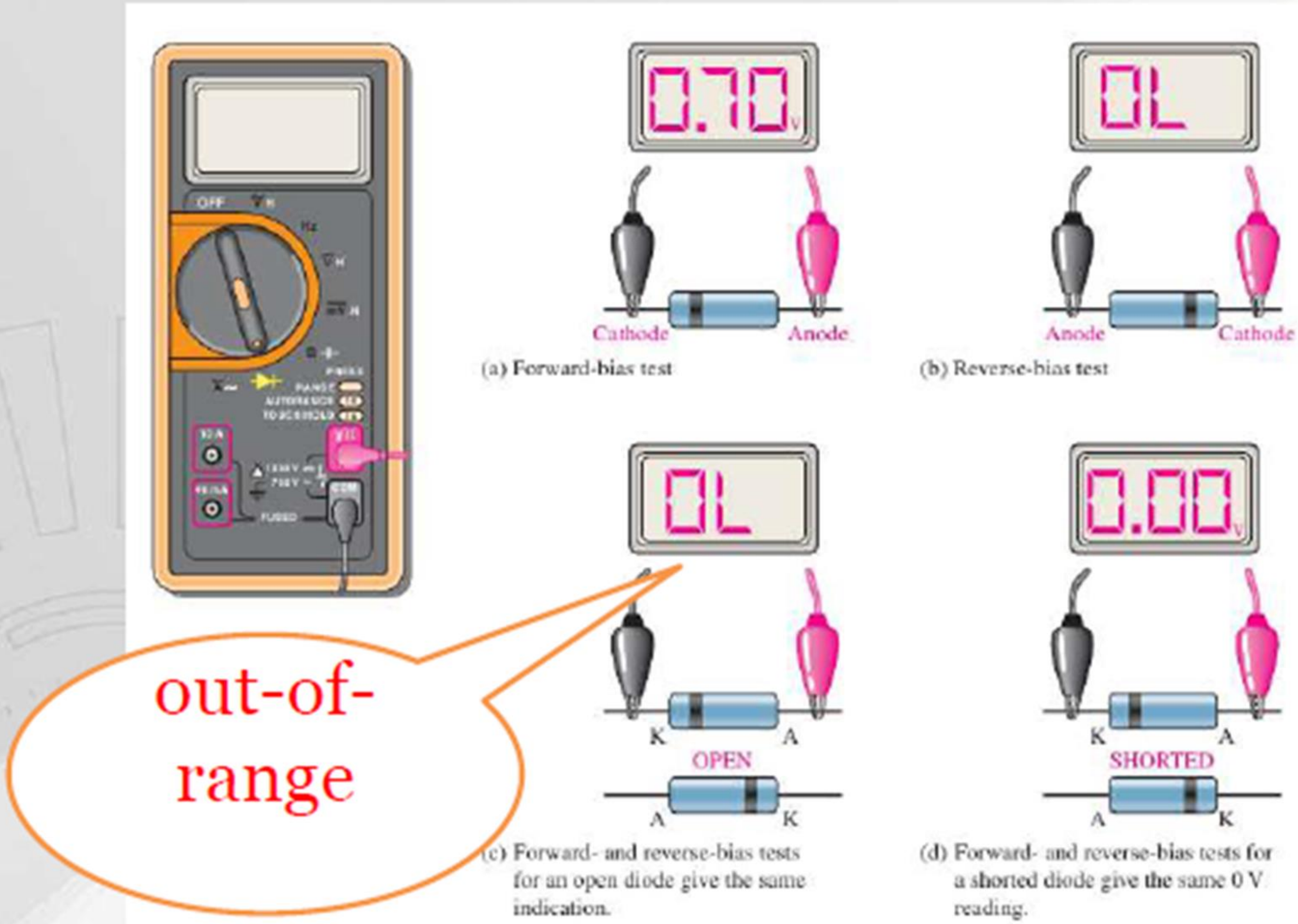
Notes:
1. Leads maintained at ambient temperature at a distance of 9.5mm from the case.
2. Measured at 1.0 MHz and applied reverse voltage of 4.0V DC.
3. EU Directive 2002/95/EC (RoHS). All applicable RoHS exemptions applied, see EU Directive 2002/95/EC Annex Notes.

2–9 THE DIODE DATASHEET





2–10 TROUBLESHOOTING



(a) Forward-bias test

(b) Reverse-bias test

(c) Forward- and reverse-bias tests for an open diode give the same indication.

(d) Forward- and reverse-bias tests for a shorted diode give the same 0 V reading.

Effect of an Open Diode in a Half-Wave Rectifier