UNIVERSITY *of* DELAWARE

Chapter 4

Diodes

IN THIS CHAPTER YOU WILL LEARN

1. The characteristics of the ideal diode and how to analyze and design circuits containing multiple ideal diodes together with resistors and dc sources to realize useful and interesting nonlinear functions.

2. The details of the *i*-*v* characteristic of the junction diode (which was derived in Chapter 3) and how to use it to analyze diode circuits operating in the various bias regions: forward, reverse, and breakdown.

3. A simple but effective model of the diode *i*-*v* characteristic in the forward direction; the constant-voltage-drop model.

IN THIS CHAPTER YOU WILL LEARN

4. A powerful technique for the application and modeling of the diode (and in later chapters, transistors): dc-biasing the diode and modeling its operation for small signals around the dc operating point by means of the small-signal model.

5. The use of a string of forward-biased diodes and of diodes operating in the breakdown region (zener diodes), to provide constant dc voltages (voltage regulators).

6. Application of the diode in the design of rectifier circuits, which convert ac voltages to dc as needed for powering electronic equipment.

7. A number of other practical and important applications of diodes.

4.1 THE IDEAL DIODE

The Ideal Diode

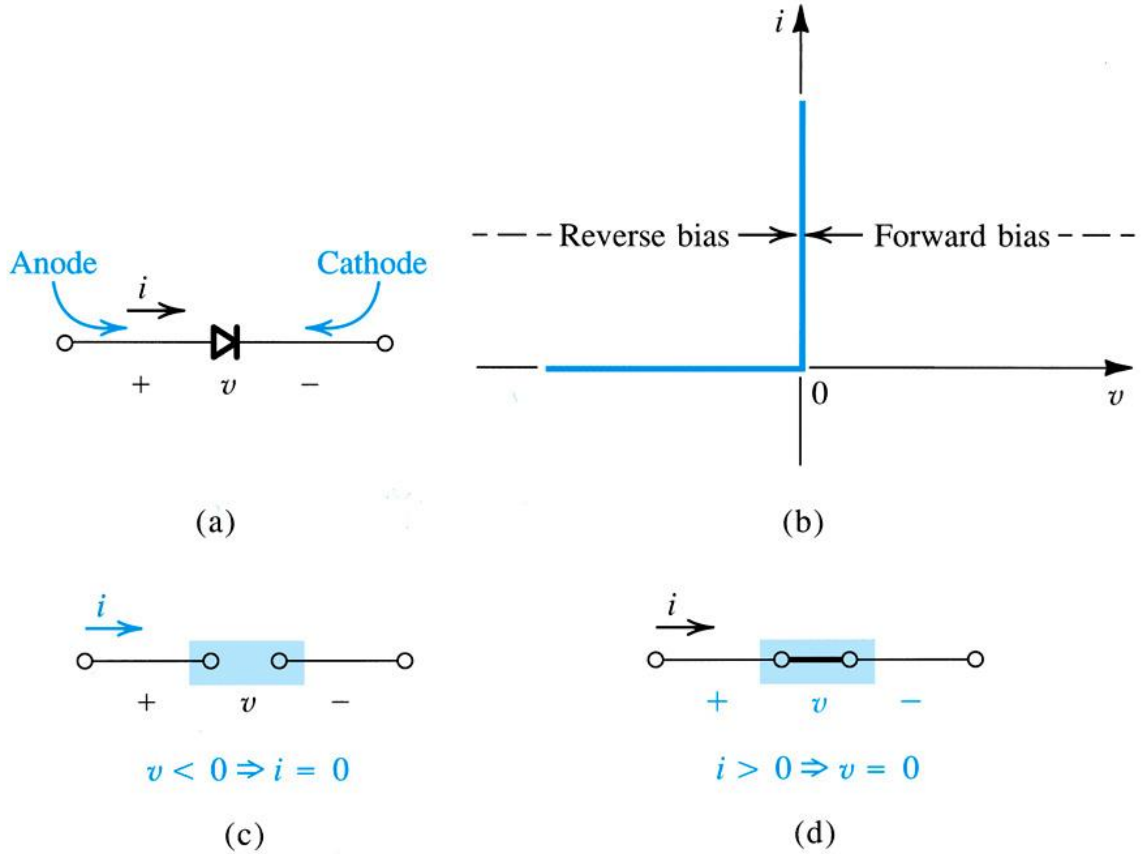

Figure 4.1 The ideal diode: (a) diode circuit symbol; (b) *i-v* characteristic; (c) equivalent circuit in the reverse direction; (d) equivalent circuit in the forward direction.

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Modes of Operation

- Forward Bias
  - Current limited by bias voltage and series resistance.
  - On, turned-on
- Reverse Bias
  - Voltage limited by bias voltage
  - Off, cut-off

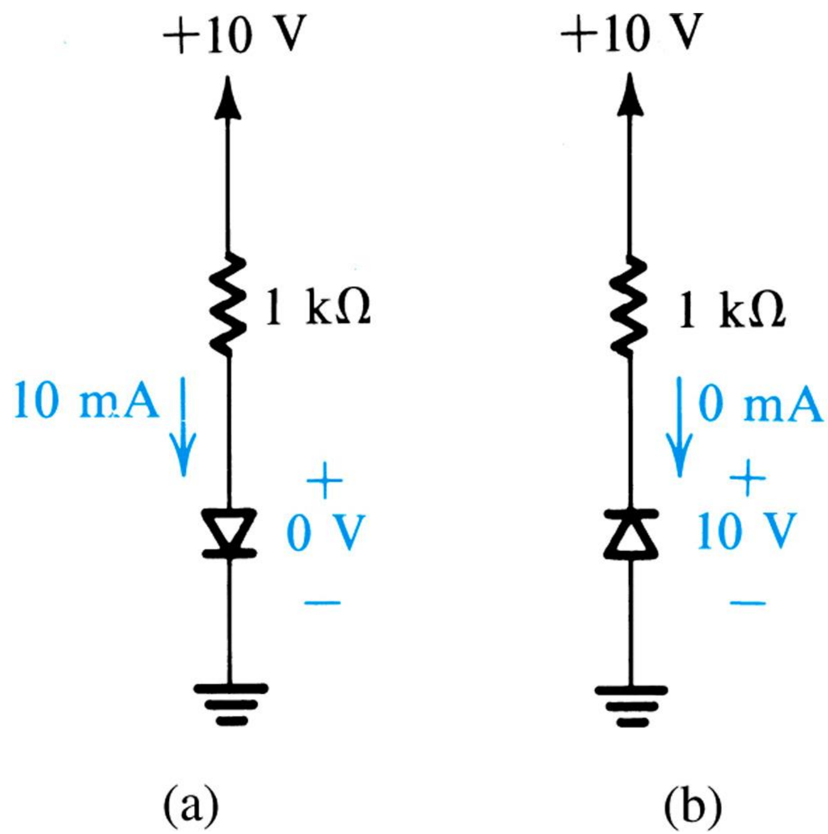

Figure 4.2 The two modes of operation of ideal diodes and the use of an external circuit to limit **(a)** the forward current and **(b)** the reverse voltage.

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Uses of Diodes

- Rectification
- Switching
- Logic
- Reference Voltages
- Limiting and clamping
- Generating and detecting optical signals

Rectification

A **rectifier** is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The process is known as **rectification**. Physically, rectifiers take a number of forms, including vacuum tube diodes, mercury-arc valves, solid-state diodes, silicon-controlled rectifiers and other silicon-based semiconductor switches. Historically, even synchronous electromechanical switches and motors have been used. Early radio receivers, called crystal radios, used a "cat's whisker" of fine wire pressing on a crystal of galena (lead sulfide) to serve as a point-contact rectifier or "crystal detector".

Rectifiers have many uses, but are often found serving as components of DC power supplies and high-voltage direct current power transmission systems. Rectification may serve in roles other than to generate direct current for use as a source of power. As noted, detectors of radio signals serve as rectifiers. In gas heating systems *flame rectification* is used to detect presence of flame.

http://en.wikipedia.org/wiki/Rectifier

Application: Rectifier Circuit

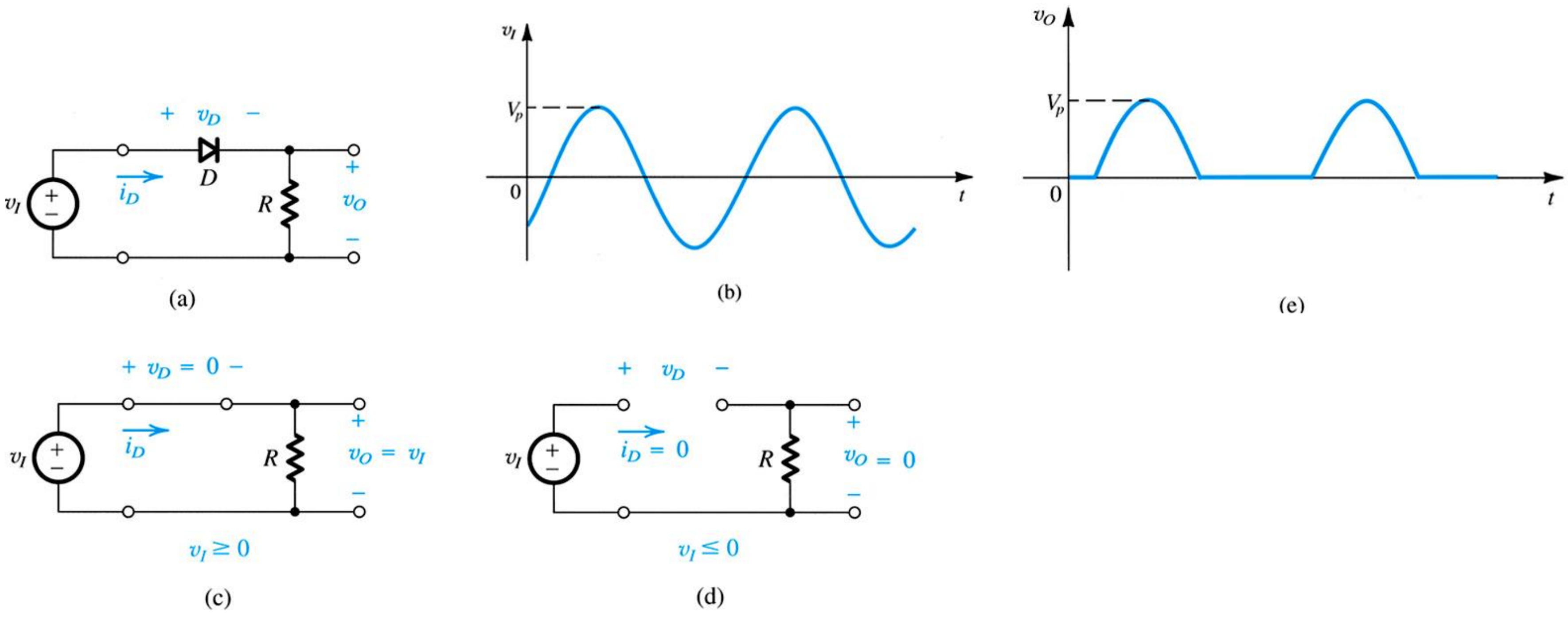

Figure 4.3 (a) Rectifier circuit. (b) Input waveform. (c) Equivalent circuit when $v_i \geq 0$. (d) Equivalent circuit when $v_i \leq 0$. (e) Output waveform.

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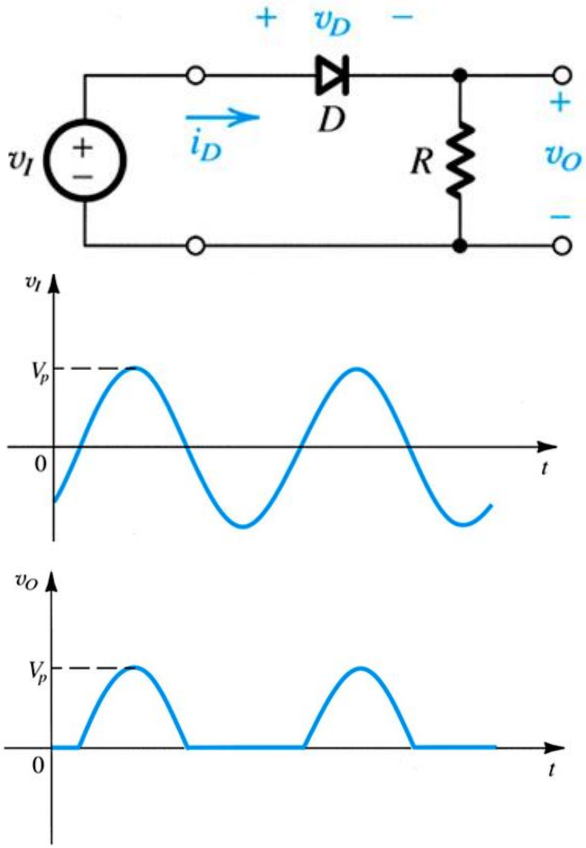
Rectifier Circuit



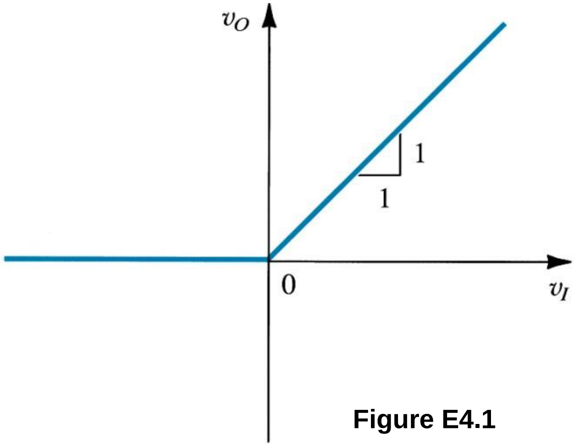


Figure E4.1

Transfer characteristic

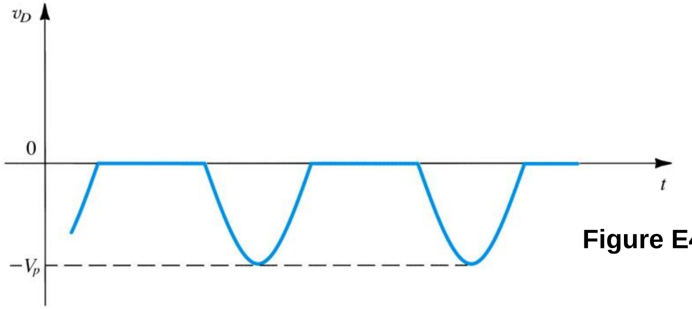


Figure E4.2

Voltage across the diode

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Example 4.1 (p. 180)

Figure 4.4 shows a circuit for charging a 12-V battery. If v_S is a sinusoid with 24-V peak amplitude, find the fraction of each cycle during which the diodes conduct. Also, find the peak value of the diode current and the maximum reverse-bias that appears across the diode.

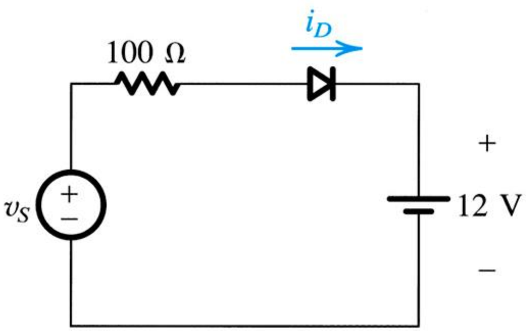
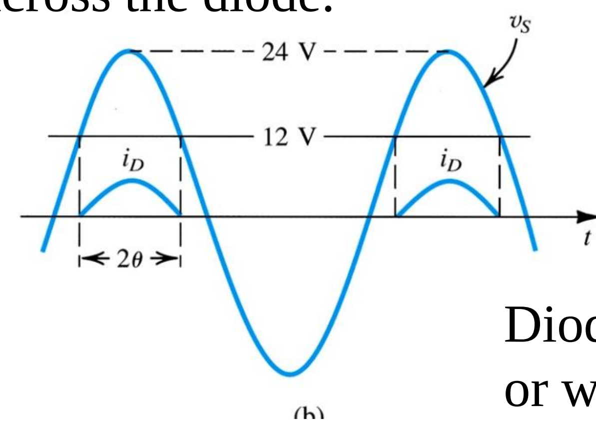
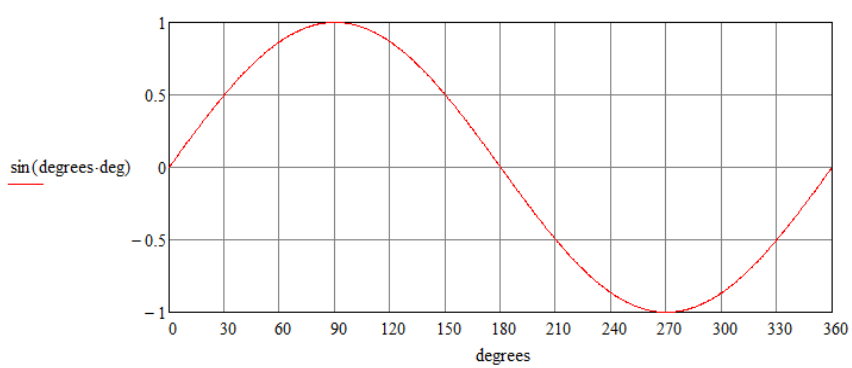


Figure 4.4 Circuit for Example 4.1.



$$v_S = 24 \sin \theta$$

Diode conducts when $v_S \geq 12$ V or when $\sin\theta \geq 0.5$.



$\sin\theta \geq 0.5$ when $30° \leq \theta \leq 150°$ so the diode is conducting $120°/360°$ or 1/3 of a cycle.

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Example 4.1 (p. 180)

Figure 4.4 shows a circuit for charging a 12-V battery. If v_S is a sinusoid with 24-V peak amplitude, find the fraction of each cycle during which the diodes conduct. Also, find the peak value of the diode current and the maximum reverse-bias that appears across the diode.

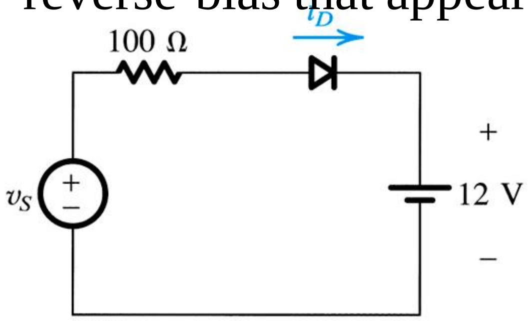
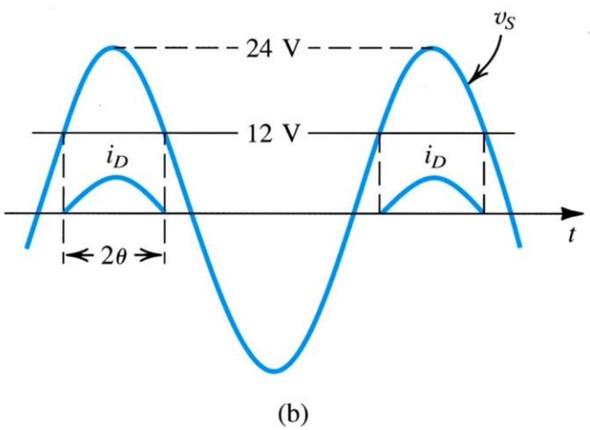


Figure 4.4 Circuit for Charging for Example 4.1.

$$v_S = 24 \sin \theta$$



Peak current is when v_S = 24 V

$$I_d = \frac{24\text{V} - 12\text{V}}{100\Omega} = 0.12\text{A}$$

The maximum reverse bias voltage is when v_S = -24 V so the total reverse voltage across the diode is 24 V + 12 V = 36 V

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Application: Diode Logic Gates

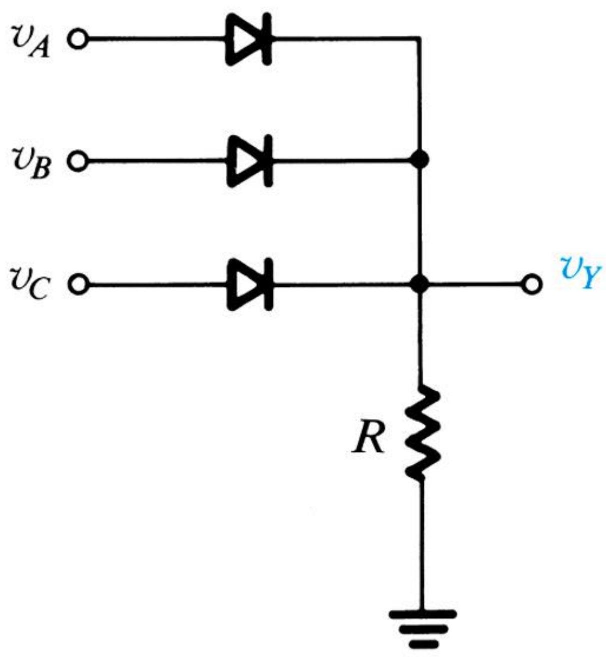

Figure 4.5 Diode logic gates: **(a)** OR gate;.

v_A	v_B	v_C	v_Y
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	1
…			
1	1	0	1
1	1	1	1

$$Y = A + B + C$$

logic OR function

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Application: Diode Logic Gates

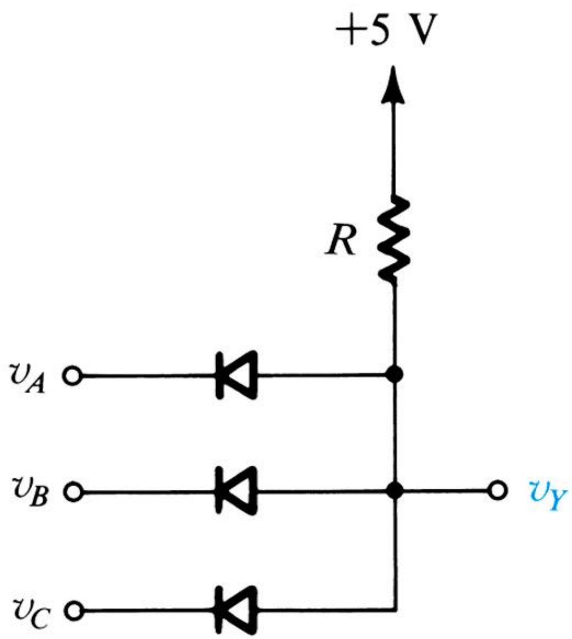

Figure 4.5 Diode logic gates: **(b)** AND gate (in a positive-logic system).

v_A	v_B	v_C	v_Y
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
…			
1	1	0	0
1	1	1	1

$$Y = A \cdot B \cdot C$$

logic AND function

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Example 4.2a

Assuming the diodes to be ideal, find the values of *I* and *V* in the circuits of Fig. 4.6.

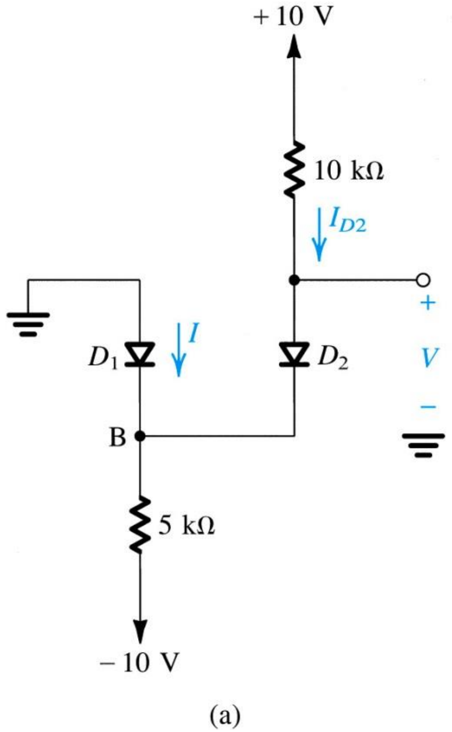

Figure 4.6 Circuits for Example 4.2.

Assume D_1 is conducting, then the voltage at node B is 0 V and D_2 is also conducting and the output voltage, $V = 0$ V.

$$I_{D2} = \frac{10\text{V}}{10\text{k}\Omega} = 1\text{mA}$$

$$I + I_{D2} = \frac{10\text{V}}{5\text{k}\Omega} = 2\text{mA}$$

$$I = 1\text{mA}$$

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Example 4.2b

Assuming the diodes to be ideal, find the values of I and V in the circuits of Fig. 4.6.

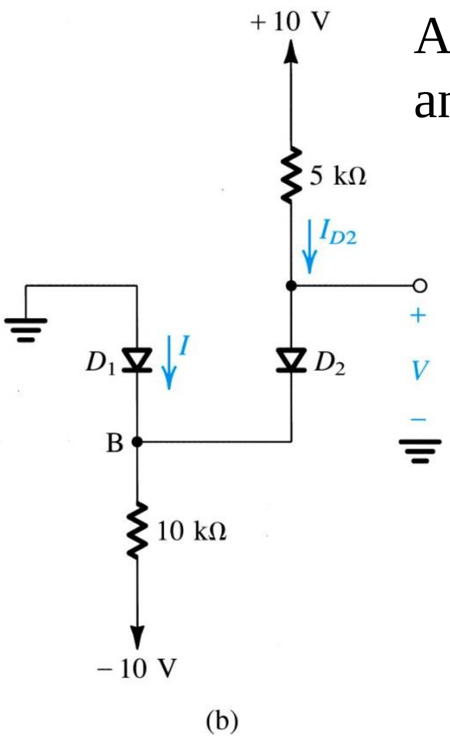

Figure 4.6 Circuits for Example 4.2.

Assume D_1 is conducting, then the voltage at node B is 0 V and D_2 is also conducting and the output voltage, $V = 0$ V.

$$I_{D2} = \frac{10\text{V}}{5\text{k}\Omega} = 2\text{mA}$$

$$I + I_{D2} = \frac{10\text{V}}{10\text{k}\Omega} = 1\text{mA} \qquad I = -1\text{mA}$$

Which can't be correct so D_1 can't be conducting, which means that the current, $I = 0$ A. The voltage at node B is

$$V = V_B = -10\text{V} + 20\text{V}\frac{10\text{k}\Omega}{15\text{k}\Omega} = 3.33\text{V}$$

$$I_{D2} = \frac{10\text{V} - 3.33\text{V}}{5\text{k}\Omega} = 1.33\text{mA}$$

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Exercise 4.4 (a-c)

Find the values of *I* and *V* in the circuits shown in Fig. E4.4

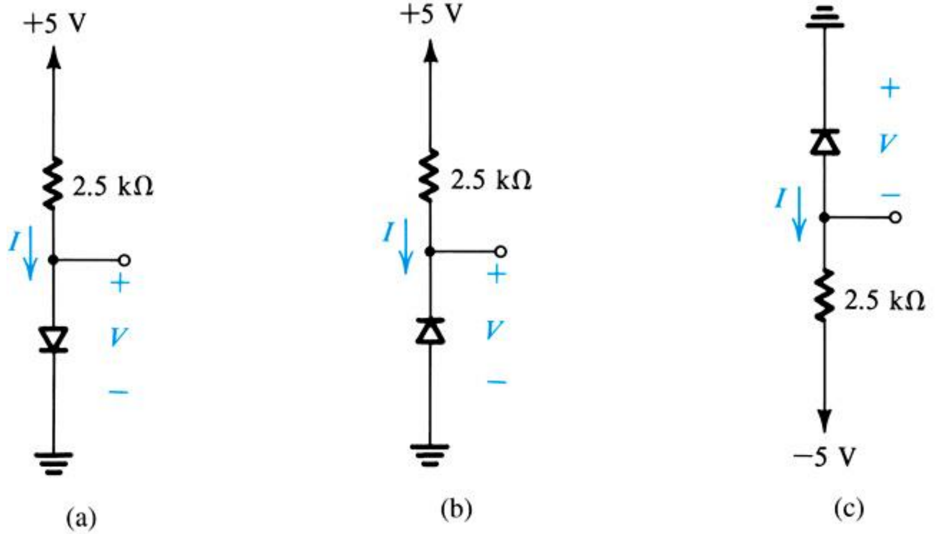

Figure E4.4

$$I = \frac{5\text{V}}{2.5\text{k}\Omega} = 2\text{mA}$$

$$V = 0\text{V}$$

$$I = 0\text{A}$$

$$V = +5\text{V}$$

$$I = 0\text{A}$$

$$V = -5\text{V}$$

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Exercise 4.4 (d-f)

Find the values of *I* and *V* in the circuits shown in Fig. E4.4

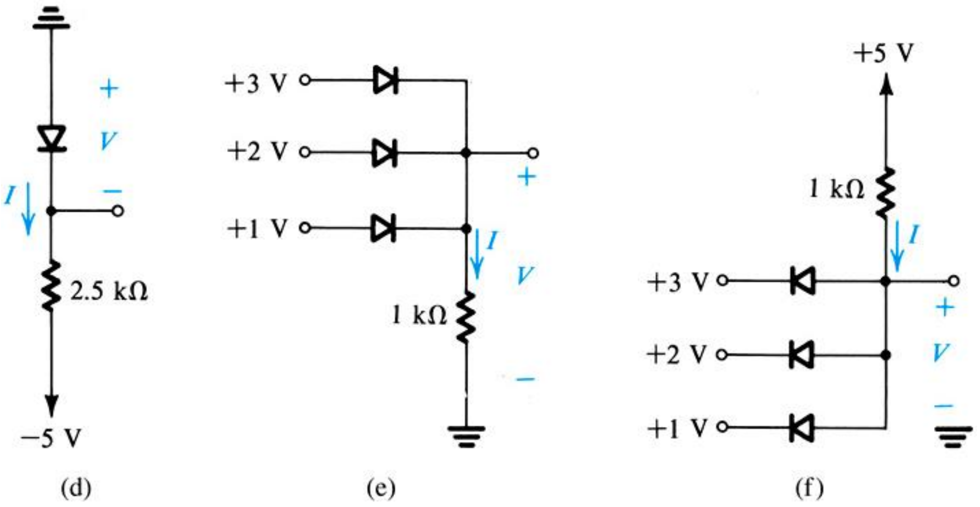

Figure E4.4

$$I = \frac{5\text{V}}{2.5\text{k}\Omega} = 2\text{mA}$$

$$V = 0\text{V}$$

$$I = \frac{3\text{V}}{1\text{k}\Omega} = 3\text{mA}$$

$$V = +3\text{V}$$

$$I = \frac{5\text{V} - 1\text{V}}{1\text{k}\Omega} = 4\text{mA}$$

$$V = +1\text{V}$$

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4.2 TERMINAL CHARACTERISTICS OF JUNCTION DIODES

i-v characteristic of a silicon junction diode

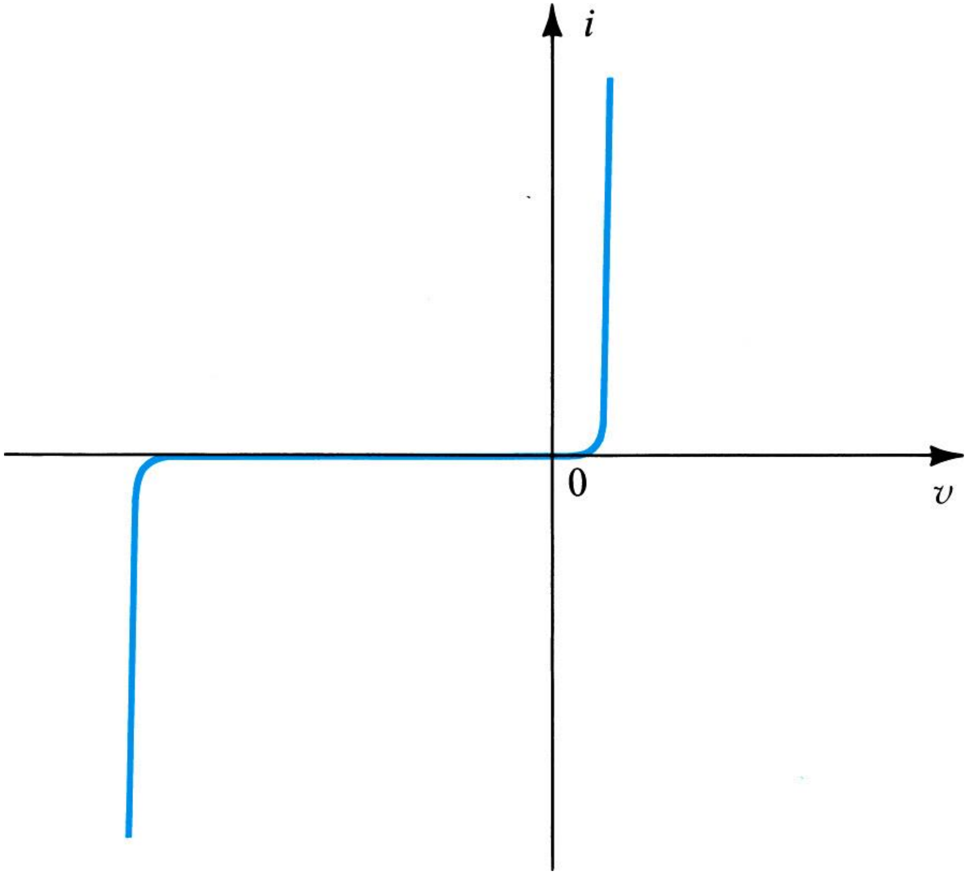

Figure 4.7 The *i-v* characteristics of a silicon junction diode.

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i-v characteristic of a silicon junction diode

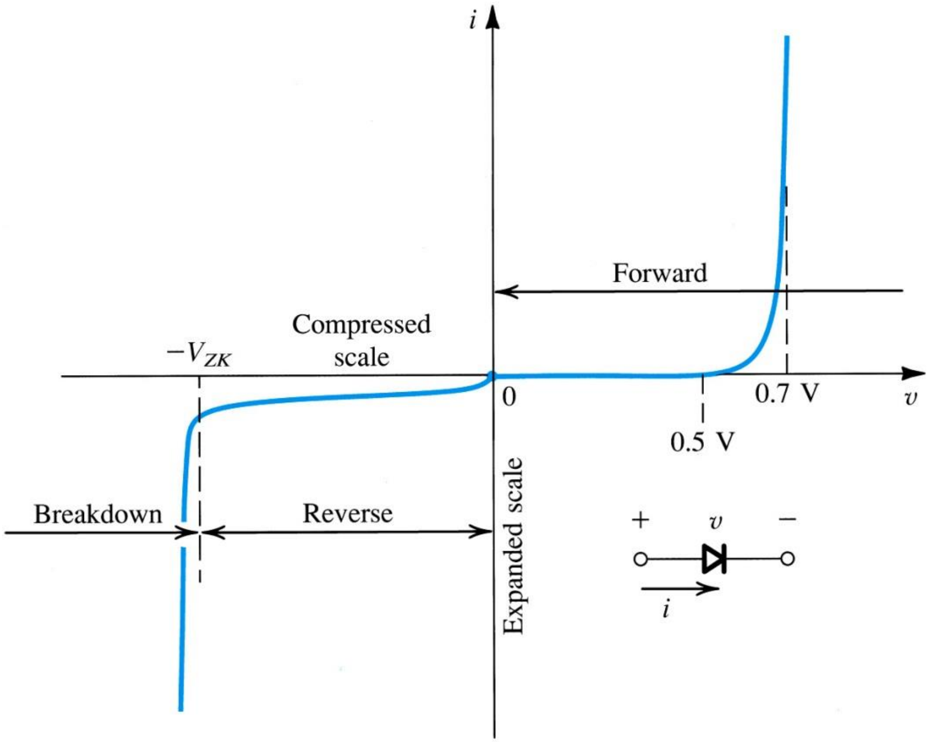

Figure 4.8 The diode *i*-*v* relationship with some scales expanded and others compressed in order to reveal details.

The characteristic curve consists of three distinct regions:

1 The forward-bias region, determined by $v > 0$

2. The reverse-bias region, determined by $v < 0$

3. The breakdown region, determined by $v < -V_{ZK}$

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The Forward-Bias Region

From Chapter 3: $I = Aqn_i{}^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)\left(e^{V/V_T} - 1\right)$

If we define the saturation current or scale current, I_S, as: $I_S = Aqn_i{}^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$

$$i = I_S\left(e^{v/V_T} - 1\right)$$

The current I_S is usually called the saturation current (for reasons that will become apparent shortly). Another name for I_S is the scale current. This name arises from the fact that I_S is directly proportional to the cross-sectional area of the diode. Thus doubling of the junction area results in a diode with double the value of I_S and, as the diode equation indicates, double the value of current *i* for a given forward voltage *v*. For "small-signal" diodes, which are small-size diodes intended for low-power applications, I_S is on the order of 10 fA. The value of I_S is, however, a very strong function of temperature. As a rule of thumb, I_S doubles in value for every 5°C rise in temperature.

The Forward-Bias Region

$$i = I_S\left(e^{v/V_T} - 1\right)$$

Where $V_T = \frac{kT}{q}$ is known as the thermal voltage

k is the Boltzmann constant [8.617×10^{-5} eV/K]
T is the temperature in Kelvin
q is the magnitude of the electrical charge on the electron [1.602×10^{-19} C]

$$V_T = 0.0862T \text{ mV}$$

At 20°C (293.15 K, 68°F, room temperature) $V_T = 25.3$ mV ≈ 25.0 mV

A slightly higher ambient temperature (25°C or so) is usually assumed for electronic equipment operating inside a cabinet. At this temperature, $V_T \sim 25.8$ mV. Nevertheless, for the sake of simplicity and to promote rapid circuit analysis, we shall use the more arithmetically convenient value of $V_T \sim 25$ mV throughout the rest of this book/class.

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The Forward-Bias Region

$$i = I_S\left(e^{v/V_T} - 1\right)$$

For case where $i \gg I_S$ the curve can be approximated by $i \simeq I_S e^{v/V_T}$

$$v = V_T \ln \frac{i}{I_S}$$

At diode voltage V_1 $\quad I_1 = I_S e^{V_1/V_T}$

At diode voltage V_2 $\quad I_2 = I_S e^{V_2/V_T}$

$$\frac{I_2}{I_1} = e^{(V_2 - V_1)/V_T}$$

$$V_2 - V_1 = V_T \ln \frac{I_2}{I_1} = 2.3 V_T \log \frac{I_2}{I_1}$$

This equation simply states that for a decade change in current, the diode voltage drop changes by 2.3 V_T which is approximately 60 mV. This also suggests that the diode i-v relationship is most conveniently plotted on semilog paper. Using the vertical, linear axis for v and the horizontal, log axis for i, one obtains a straight line with a slope of 60 mV per decade of current.

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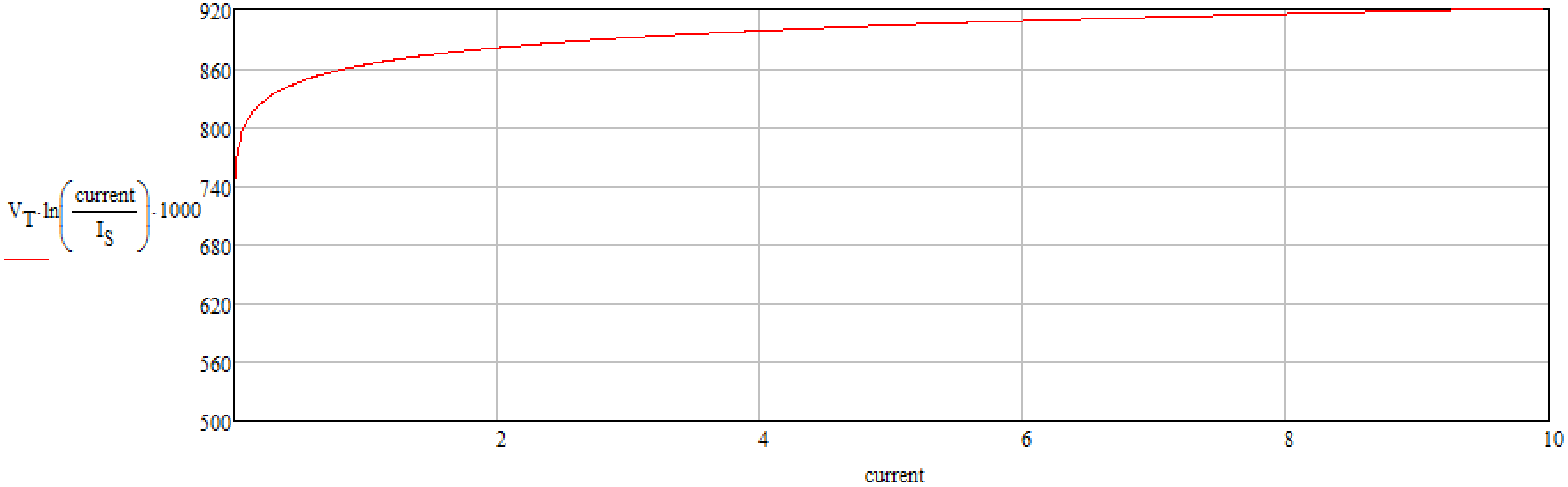
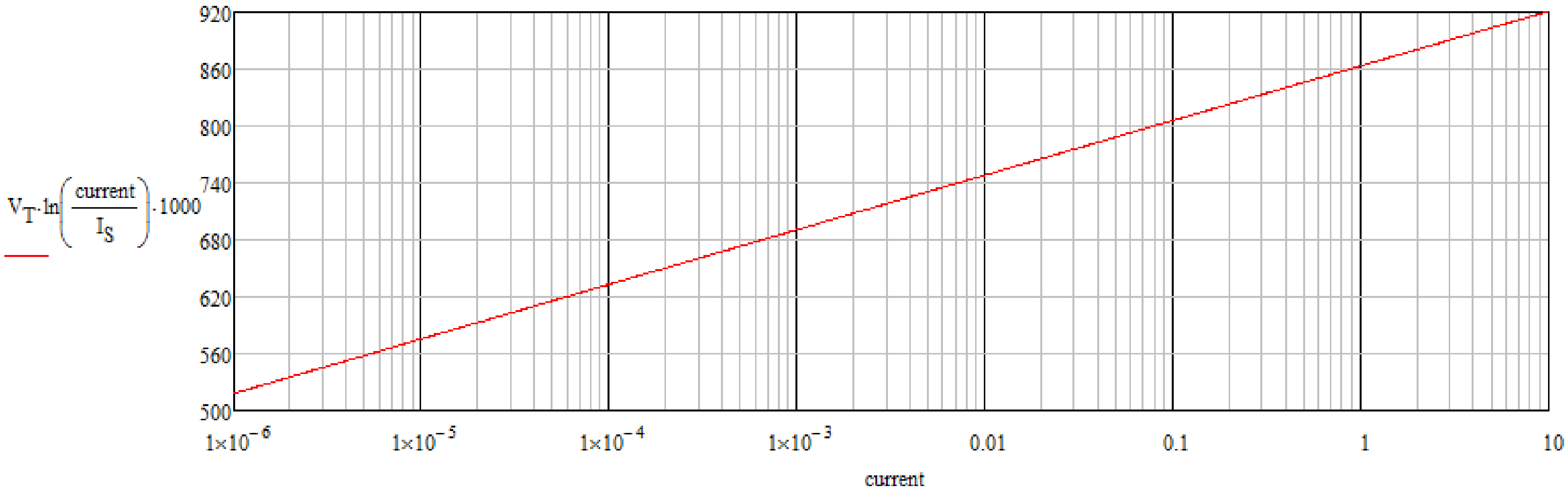
Linear, Semilog *v-i* Plot





Example 4.3

A silicon diode said to be a 1-mA device displays a forward voltage of 0.7 V at a current of 1 mA. Evaluate the junction scaling constant I_S. What scaling constants would apply for a 1-A diode of the same manufacture that conducts 1 A at 0.7 V?

$$i = I_S e^{v/V_T}$$

$$I_S = \frac{i}{e^{v/V_T}} = i e^{-v/V_T}$$

$$I_S := 1\text{mA} \cdot e^{\frac{-0.7\text{V}}{V_T}} = 0.691\,\text{fA}$$

$$I_S := 1\text{A} \cdot e^{\frac{-0.7\text{V}}{V_T}} = 691.44\,\text{fA}$$

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Forward Bias – Temperature Effects

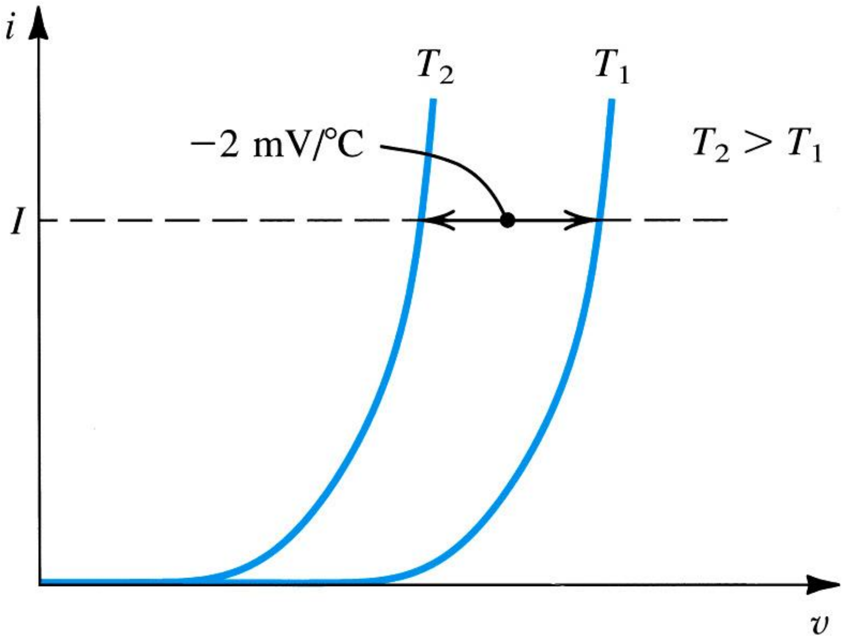

Figure 4.9 Temperature dependence of the diode forward characteristic. At a constant current, the voltage drop decreases by approximately 2 mV for every 1°C increase in temperature.

$$V_T = \frac{kT}{q} \qquad I_S = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$$

Since both I_S and V_T are functions of temperature, the forward *i-v* characteristic varies with temperature, as illustrated in Fig. 4.9. At a given constant diode current, the voltage drop across the diode decreases by approximately 2 mV for every 1°C increase in temperature. The change in diode voltage with temperature has been exploited in the design of electronic thermometers.

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The Reverse-Bias Region

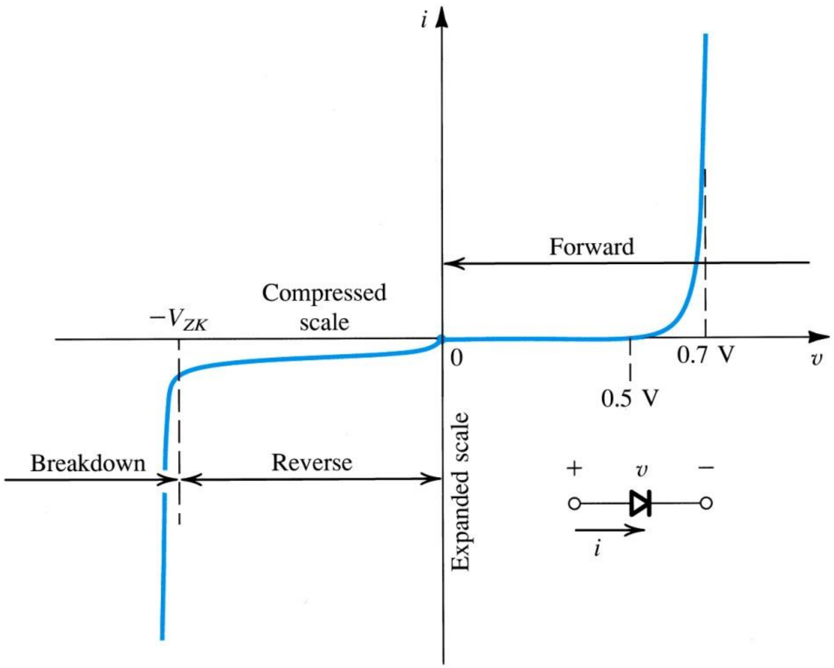

Figure 4.8 The diode *i*-*v* relationship with some scales expanded and others compressed in order to reveal details.

$$i = I_S\left(e^{v/V_T} - 1\right)$$

For case where $v > V_T$ and is negative the curve can be approximated by $i \simeq -I_S$

The current in the reverse direction is constant and equal to I_S. This constancy is the reason behind the term **saturation current**.

Real diodes exhibit reverse currents that, though quite small, are much larger than I_S. For instance, a small-signal diode whose I_S is on the order of 10^{-14} to 10^{-15} Amps could show a reverse current on the order of 1 nA. The rule of thumb for the temperature dependence of the reverse current is that it doubles for every 10°C rise in temperature.

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Reverse Current

NXP Semiconductors — Product data sheet

High-speed diodes — 1N4148; 1N4448

LIMITING VALUES

In accordance with the Absolute Maximum Rating System (IEC 60134).

SYMBOL	PARAMETER	CONDITIONS	MIN.	MAX.	UNIT
V_{RRM}	repetitive peak reverse voltage		–	100	V
V_R	continuous reverse voltage		–	100	V
I_F	continuous forward current	see Fig.2; note 1	–	200	mA
I_{FRM}	repetitive peak forward current		–	450	mA
I_{FSM}	non-repetitive peak forward current	square wave; T_j = 25 °C prior to surge; see Fig.4			
		t = 1 µs	–	4	A
		t = 1 ms	–	1	A
		t = 1 s	–	0.5	A
P_{tot}	total power dissipation	T_{amb} = 25 °C; note 1	–	500	mW
T_{stg}	storage temperature		−65	+200	°C
T_j	junction temperature		–	200	°C

Note

1. Device mounted on an FR4 printed-circuit board; lead length 10 mm.

ELECTRICAL CHARACTERISTICS

T_j = 25 °C unless otherwise specified.

SYMBOL	PARAMETER	CONDITIONS	MIN.	MAX.	UNIT
V_F	forward voltage	see Fig.3			
	1N4148	I_F = 10 mA	–	1	V
	1N4448	I_F = 5 mA	0.62	0.72	V
		I_F = 100 mA	–	1	V
I_R	reverse current	V_R = 20 V; see Fig.5		25	nA
		V_R = 20 V; T_j = 150 °C; see Fig.5	–	50	µA
I_R	reverse current; 1N4448	V_R = 20 V; T_j = 100 °C; see Fig.5	–	3	µA
C_d	diode capacitance	f = 1 MHz; V_R = 0 V; see Fig.6	–	4	pF
t_{rr}	reverse recovery time	when switched from I_F = 10 mA to I_R = 60 mA; R_L = 100 Ω; measured at I_R = 1 mA; see Fig.7	–	4	ns
V_{fr}	forward recovery voltage	when switched from I_F = 50 mA; t_r = 20 ns; see Fig.8	–	2.5	V

THERMAL CHARACTERISTICS

SYMBOL	PARAMETER	CONDITIONS	VALUE	UNIT
$R_{th(j\text{-}tp)}$	thermal resistance from junction to tie-point	lead length 10 mm	240	K/W
$R_{th(j\text{-}a)}$	thermal resistance from junction to ambient	lead length 10 mm; note 1	350	K/W

Note

1. Device mounted on a printed-circuit board without metallization pad.

2004 Aug 10 — 3

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1N4001 - 1N4007 — General Purpose Rectifiers

1N4001 - 1N4007
General Purpose Rectifiers

Features

- Low forward voltage drop.
- High surge current capability.

DO-41
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Absolute Maximum Ratings * T_A = 25°C unless otherwise noted

Symbol	Parameter	Value							Units
		4001	4002	4003	4004	4005	4006	4007	
V_{RRM}	Peak Repetitive Reverse Voltage	50	100	200	400	600	800	1000	V
$I_{F(AV)}$	Average Rectified Forward Current .375 " lead length @ T_A = 75°C	1.0							A
I_{FSM}	Non-Repetitive Peak Forward Surge Current 8.3ms Single Half-Sine-Wave	30							A
I^2t	Rating for Fusing (t<8.3ms)	3.7							A^2sec
T_{STG}	Storage Temperature Range	-55 to +175							°C
T_J	Operating Junction Temperature	-55 to +175							°C

* These ratings are limiting values above which the serviceability of any semiconductor device may by impaired.

Thermal Characteristics

Symbol	Parameter	Value	Units
P_D	Power Dissipation	3.0	W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	50	°C/W

Electrical Characteristics T_A = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_F	Forward Voltage @ 1.0A	1.1	V
I_{rr}	Maximum Full Load Reverse Current, Full Cycle T_A = 75°C	30	µA
I_R	Reverse Current @ Rated V_R T_A = 25°C / T_A = 100°C	5.0 / 50	µA / µA
C_T	Total Capacitance V_R = 4.0V, f = 1.0MHz	15	pF

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1N4001 - 1N4007 Rev. C2 — 1 — www.fairchildsemi.com

Exercise 4.9

The diode in the circuit of Fig. E4.9 is a large high-current device whose reverse leakage is reasonably independent of voltage. If $V = 1$ V at 20°C, find the value of V at 40°C and at 0°C.

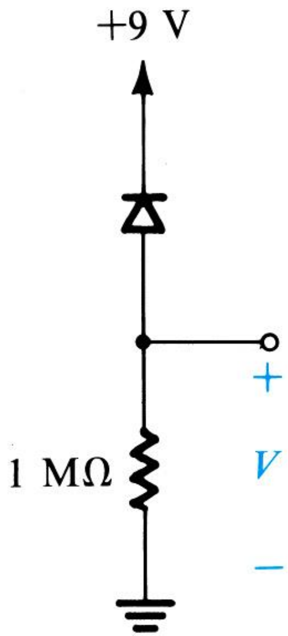

Figure E4.9

The rule of thumb for the temperature dependence of the reverse current is that it doubles for every 10°C rise in temperature.

40°C = 2 x 10°C increase $\rightarrow V = 4 \times 1$ V = 4V

0°C = 2 x 10°C decrease $\rightarrow V = \frac{1}{4} \times 1$ V = 0.25 V

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The Breakdown Region

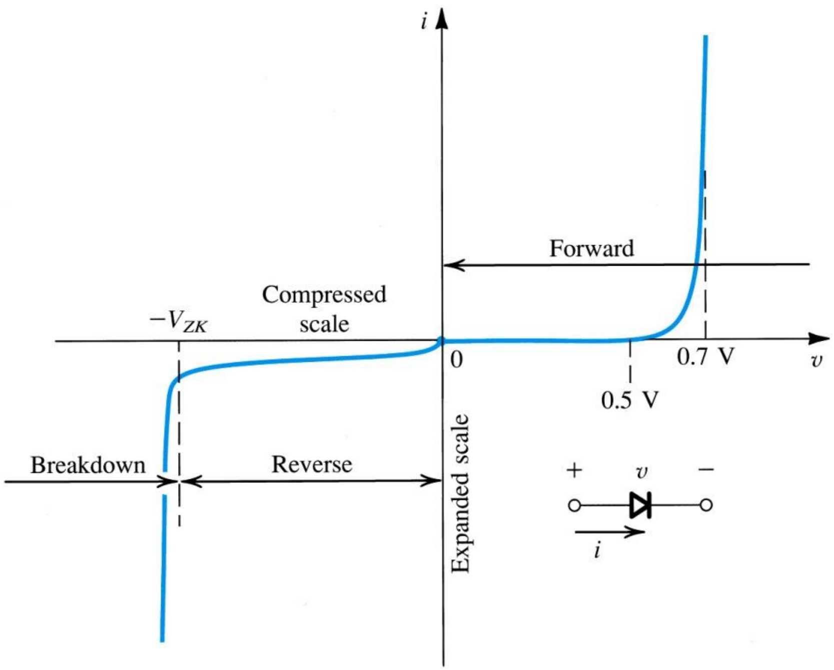

Figure 4.8 The diode *i*-*v* relationship with some scales expanded and others compressed in order to reveal details.

The breakdown region is entered when the magnitude of the reverse voltage exceeds a threshold value that is particular to a specific diode, called the **breakdown voltage**. This is the voltage at the "knee" of the *i*-*v* curve and designated as V_{ZK}.

The fact that the diode *i*-*v* characteristic in breakdown is almost a vertical line enables it to be used in voltage regulation.

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Homework #7

- Read Chapter 4
- Chapter 4 Problems:
  - 4.2*
  - 4.3*
  - 4.9*
  - 4.17*
  - 4.23*

*** Answers in Appendix L**

4.3 MODELING THE DIODE FORWARD CHARACTERISTIC

The Exponential Model

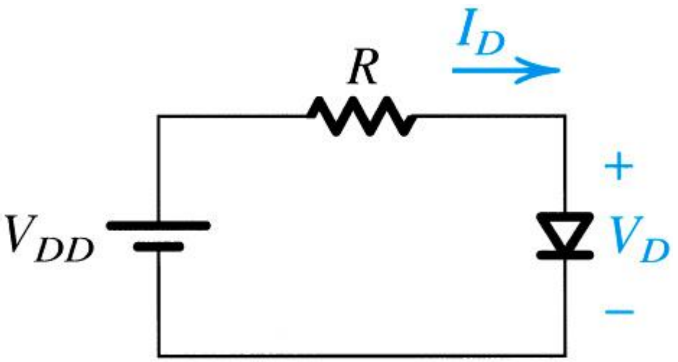

Figure 4.10 A simple circuit used to illustrate the analysis of circuits in which the diode is forward conducting.

Assuming that V_{DD} is greater than 0.5 V or so, the diode current will be much greater than I_S,

$$I_D = I_S\left(e^{V_D/V_T} - 1\right) \cong I_S e^{V_D/V_T}$$

and we can represent the diode *i*-*v* characteristic by the exponential relationship, resulting in

$$I_D = I_S e^{V_D/V_T}$$

From Kirchhoff's loop equation:

$$I_D = \frac{V_{DD} - V_D}{R}$$

If we know V_T, V_{DD}, and I_S we have 2 equations with 2 unknowns (I_D and V_D) which we can solve in two ways:

1. graphical analysis
2. iterative analysis

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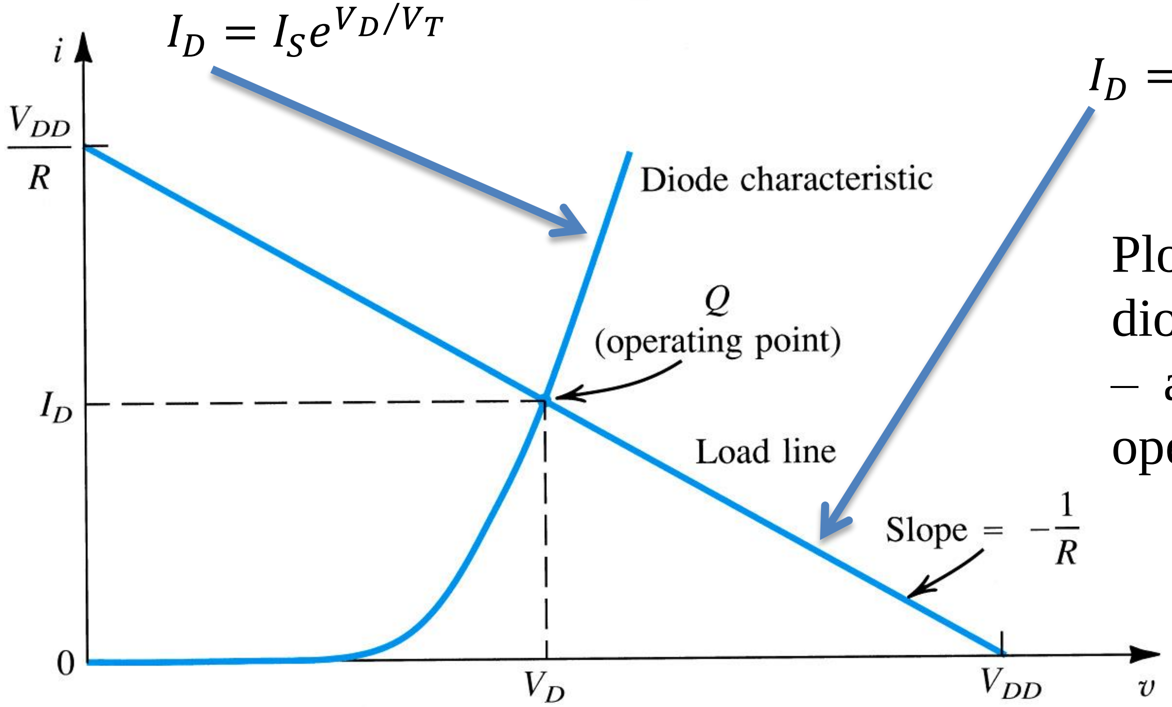
Graphical Analysis Using the Exponential Model

$$I_D = I_S e^{V_D/V_T}$$

$$I_D = \frac{V_{DD} - V_D}{R}$$



Plot the two *i*-*v* curves – the diode curve and the load line – and the intersection is the operating point (*Q*).

Figure 4.11 Graphical analysis of the circuit in Fig. 4.10 using the exponential diode model.

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Iterative Example 4.4 (p.192)

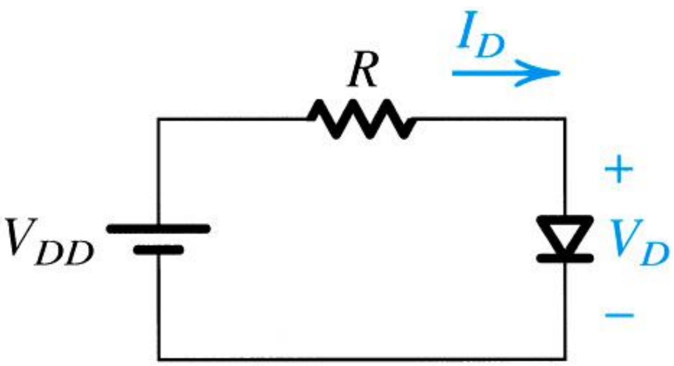

Figure 4.10 A simple circuit used to illustrate the analysis of circuits in which the diode is forward conducting.

Determine the current I_D and the diode voltage V_D for the circuit in Fig 4.10 with V_{DD} = 5 V and R = 1 kΩ. Assume that the diode has a current of 1 mA at a voltage of 0.7 V.

$$I_D = \frac{V_{DD} - V_D}{R} = \frac{5\text{V} - 0.7\text{V}}{1\text{k}\Omega} = 4.3\text{mA}$$

But 4.3 mA is 4.3x the 1 mA specification current

$$V_2 - V_1 = 2.3V_T \log\frac{I_2}{I_1}$$

$$V_2 = V_1 + 2.3V_T \log\frac{I_2}{I_1}$$

$$V_2 = 0.7V + 2.3(.025V)\log\frac{4.3\text{mA}}{1\text{mA}} = 0.736\text{V}$$

$$I_D = \frac{5\text{V} - 0.736\text{V}}{1\text{k}\Omega} = 4.264\text{mA}$$

$$V_2 = 0.736V + 2.3(.025V)\log\frac{4.264\text{mA}}{4.3\text{mA}} = 0.736\text{V}$$

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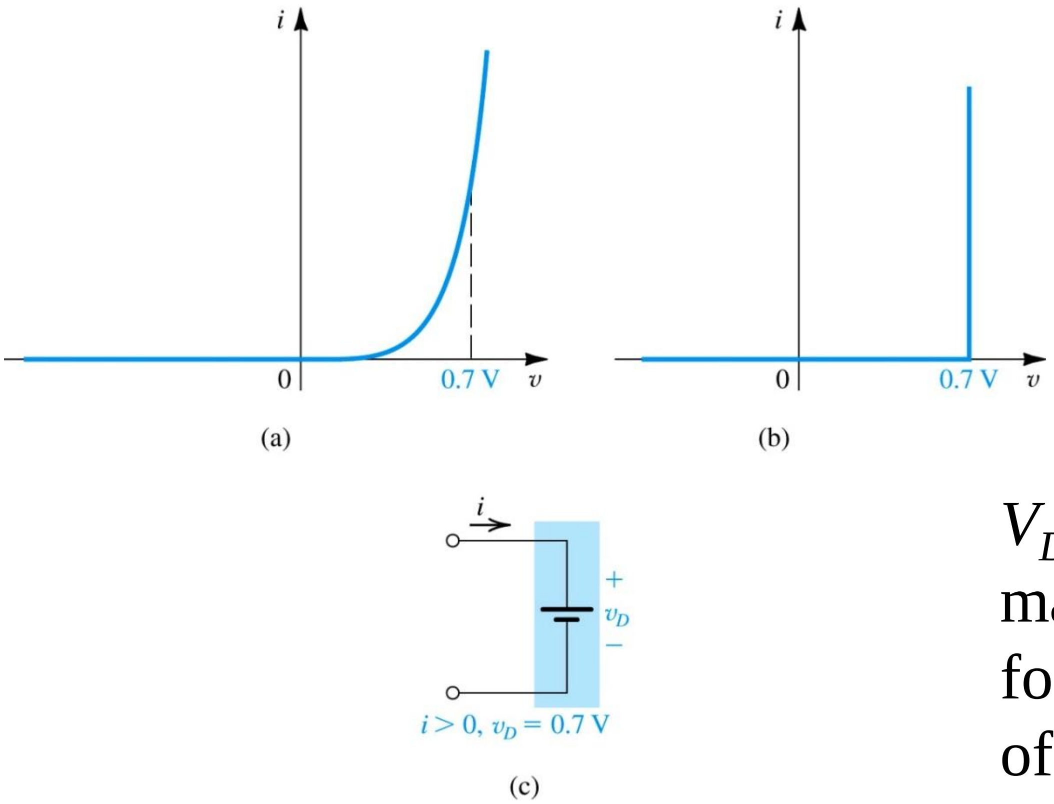
The Constant Voltage Drop Model



To speed up the circuit analysis we can use SPICE or approximate the diode as a constant voltage drop.

$$V_D = 0.7\ \text{V}$$

V_D depends on doping, material, and temperature and for Si is typically in the range of 0.6 to 0.8 V.

Figure 4.12 Development of the diode constant-voltage-drop model: **(a)** the exponential characteristic; **(b)** approximating the exponential characteristic by a constant voltage, usually about 0.7 V; **(c)** the resulting model of the forward–conducting diodes.

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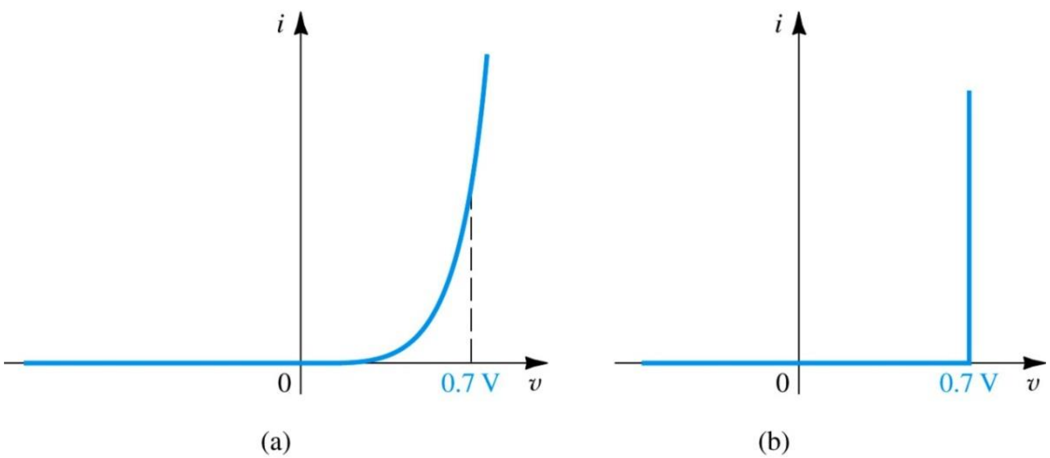
The Constant Voltage Drop Model



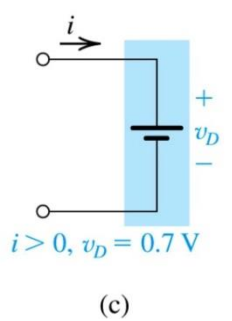


Figure 4.12 Development of the diode constant-voltage-drop model: **(a)** the exponential characteristic; **(b)** approximating the exponential characteristic by a constant voltage, usually about 0.7 V; **(c)** the resulting model of the forward–conducting diodes.

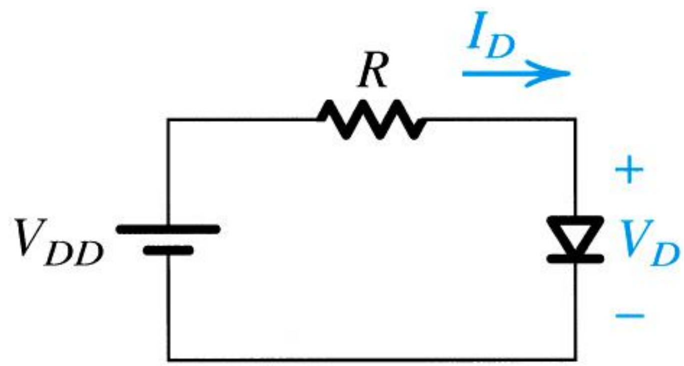


Figure 4.10 A simple circuit used to illustrate the analysis of circuits in which the diode is forward conducting.

Re-examining the circuit in Fig 4.10 yields:

$$I_D = \frac{V_{DD} - 0.7}{R} = \frac{(5 - 0.7)V}{1\text{k}\Omega}$$

$$I_D = 4.3 \text{ mA}$$

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Exercise 4.11

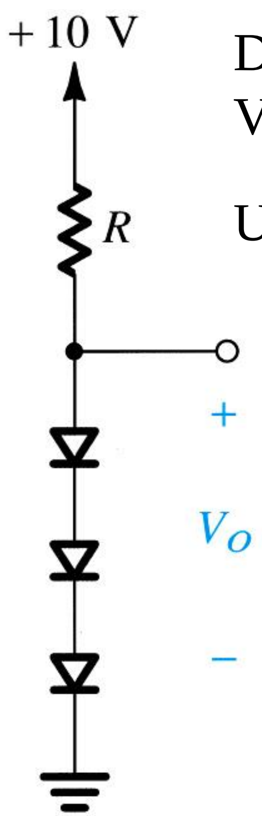

Figure E4.11

Design the circuit in Fig. E4.11 to provide an output voltage of 2.4 V. Assume that the diodes available have 0.7-V drop at 1 mA.

Use the iterative technique to find the current at V_D = 0.8 V.

$$V_2 - V_1 = 2.3V_T \log\frac{I_2}{I_1}$$

$$0.8V - 0.7V = 2.3(.025V)\log\frac{I_2}{1\text{mA}}$$

$$\frac{0.1\text{V}}{0.0575\text{V}} = \log\frac{I_2}{1\text{mA}} \qquad I_2 = 1\text{mA}\cdot 10^{1.739} = 54.83\text{mA}$$

$$R = \frac{V_{DD} - V_D}{I_D} = \frac{10\text{V} - 2.4\text{V}}{0.05483\text{A}} = 138.6\Omega$$

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The Small-Signal (AC) Model

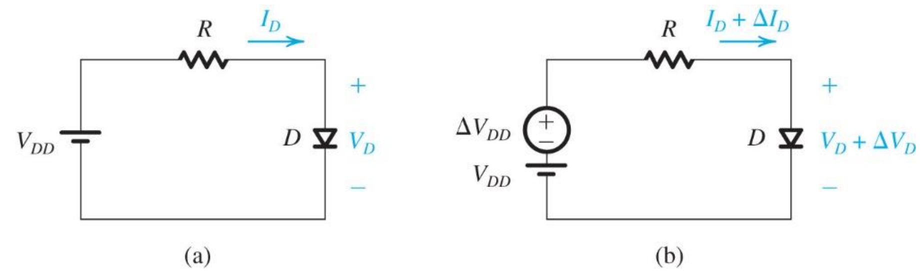

Figure 4.13 (a) A simple diode circuit; (b) the situation when V_{DD} changes by ΔV_{DD}.

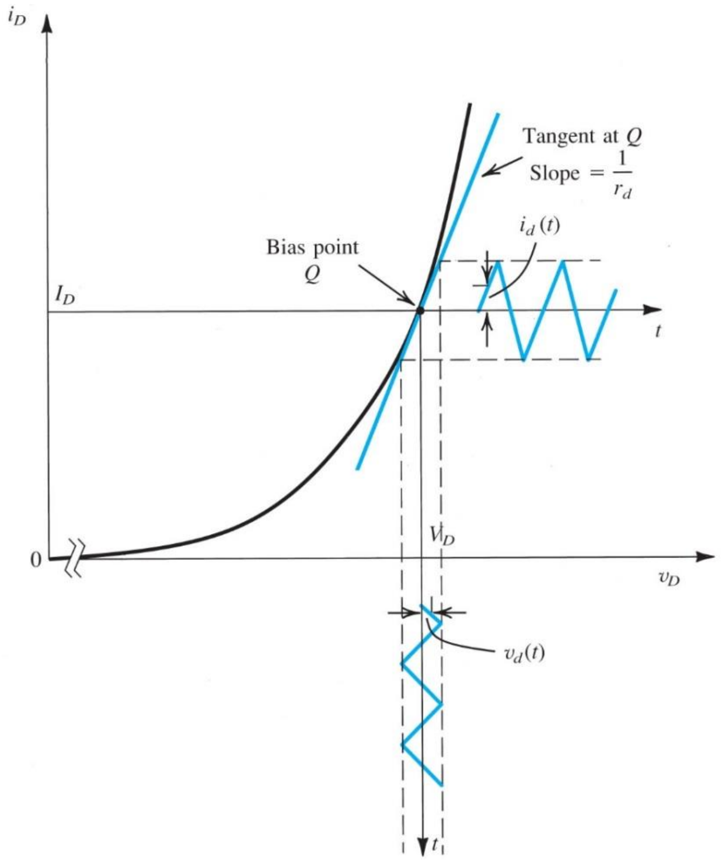

Figure 4.14 Development of the diode small-signal model.

There are applications in which a diode is biased to operate at a point on the forward *i*-*v* characteristic and a small ac signal is superimposed on the dc quantities. In this case we first solve for the dc operating point, *Q*, and then treat the diode as a resistor for the small ac signal.

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Quiescent

http://www.merriam-webster.com/dictionary/quiescent

1: marked by inactivity or repose : tranquilly at rest

2: causing no trouble or symptoms

From Chapter 1

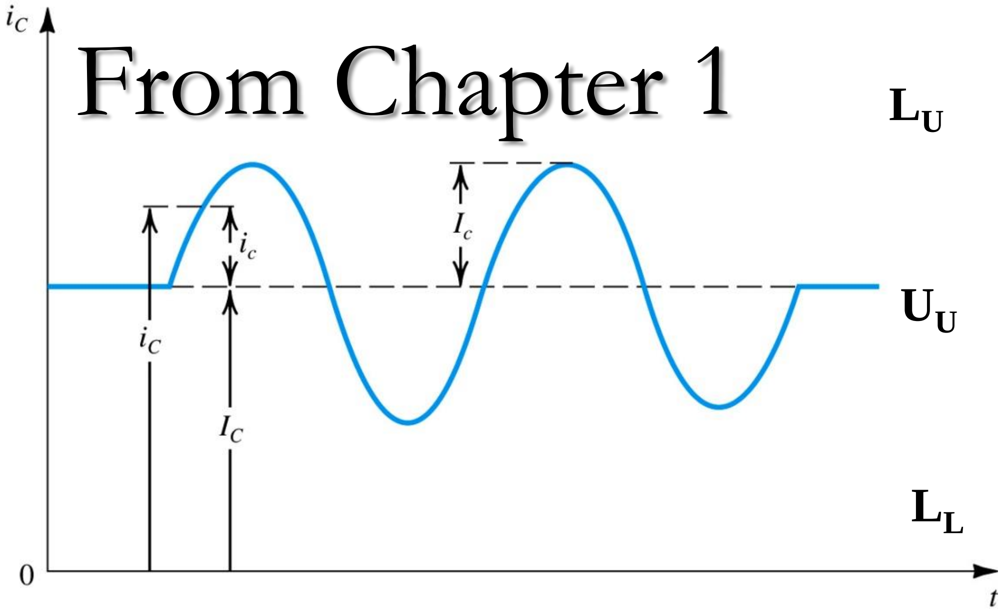

Figure 1.15 Symbol convention employed throughout the book.

Total instantaneous current

$$i_C(t) = I_C + i_c(t)$$

Signal current

$$i_c(t) = I_c \omega t$$

L_U Total instantaneous quantities are denoted by a lowercase symbol with uppercase subscript(s).

U_U Direct-current, (dc) quantities are denoted by a uppercase symbol with uppercase subscript(s).

L_L Incremental signal quantities are denoted by a lowercase symbol with lowercase subscript(s).

U_L If the signal is a sine wave, then its amplitude is denoted by an uppercase symbol with lowercase subscript(s).

U_{UU} Finally, power supply voltages and currents are denoted by an uppercase letter with a double-letter uppercase subscript.

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The Small-Signal (AC) Model

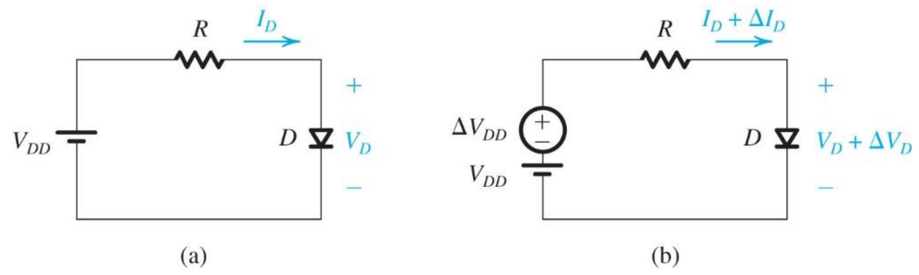

Figure 4.13 (a) A simple diode circuit; (b) the situation when V_{DD} changes by ΔV_{DD}.

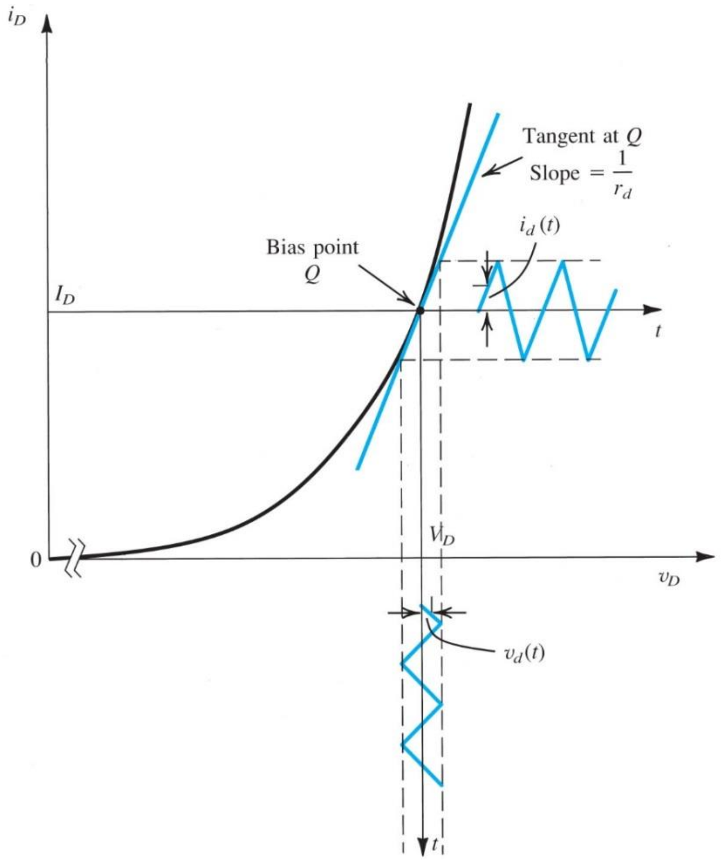

Figure 4.14 Development of the diode small-signal model.

With just the dc component (i.e. no small ac signal):

$$I_D = I_S e^{V_D/V_T}$$

Adding the small ac signal:

$$v_D(t) = V_D + v_d(t)$$

The total instantaneous diode current is then:

$$i_D = I_S e^{v_D/V_T} = I_S e^{(V_D+v_d)/V_T}$$

$$i_D = I_S e^{V_D/V_T} e^{v_d/V_T} = I_D e^{v_d/V_T}$$

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The Small-Signal (AC) Model

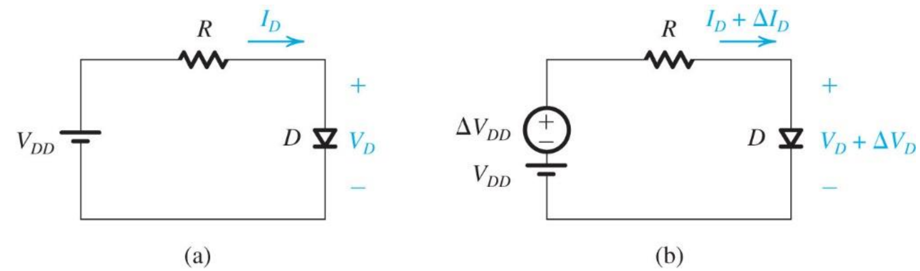

Figure 4.13 (a) A simple diode circuit; (b) the situation when V_{DD} changes by ΔV_{DD}.

The total instantaneous diode current is then:

$$i_D = I_D e^{v_d/V_T}$$

If $v_d(t)$ is small, i.e. much less than V_T:

$$i_D \simeq I_D\left(1 + \frac{v_d}{V_T}\right)$$

This is the **small-signal approximation.** It is valid for signals whose amplitudes are smaller than about 5 mV.

$$i_D = I_D + i_d \qquad \text{where} \qquad i_d = \frac{I_D}{V_T} v_d$$

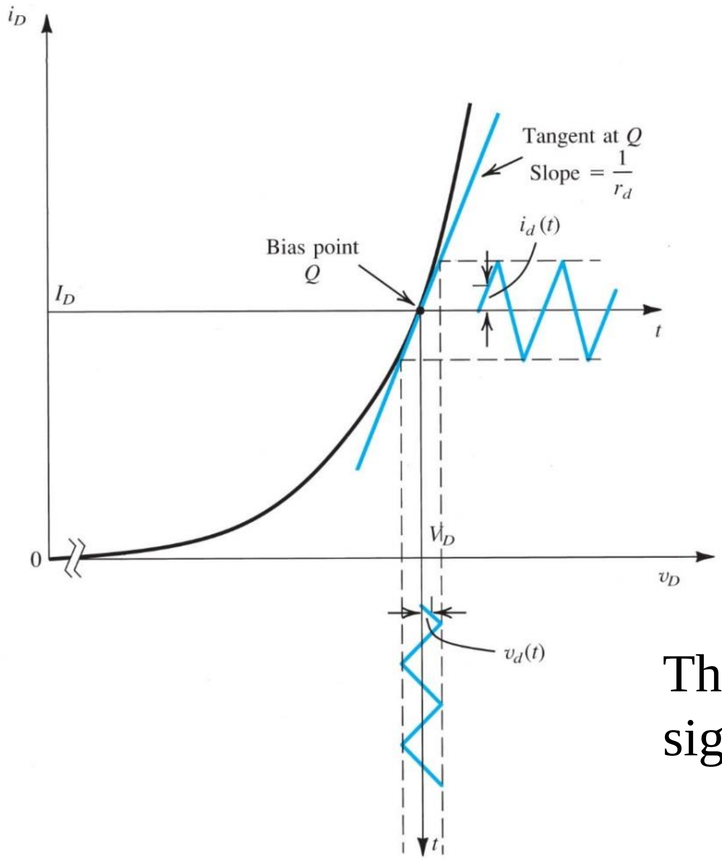

Figure 4.14 Development of the diode small-signal model.

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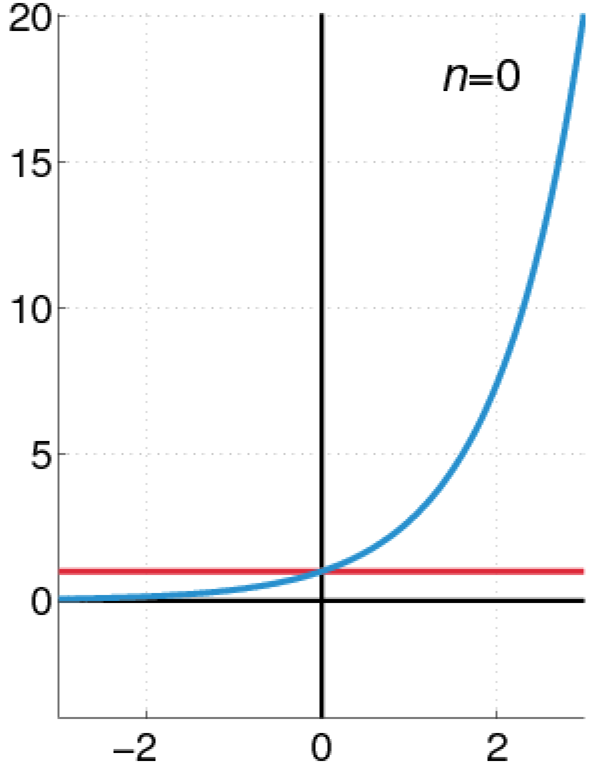
e^x Power Series Expansion



$$e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!} = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \cdots$$

$$e^x = \lim_{n \to \infty} \left(1 + \frac{x}{n}\right)^n$$

$$x = \frac{v_d}{V_T} \ll 1$$

For v_d = 5 mV, v_d / V_T = 0.2.
Thus the next term in the series expansion of the exponential will be $(0.2)^2/2 = 0.02$, a factor of 10 lower than the linear term we kept.

http://en.wikipedia.org/wiki/Exponential_function

The Small-Signal (AC) Model

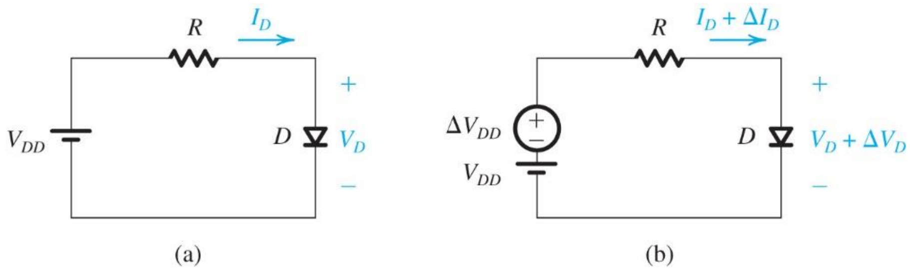


Figure 4.13 (a) A simple diode circuit; (b) the situation when V_{DD} changes by ΔV_{DD}.

The **small-signal approximation.**

$$i_D = I_D + i_d$$

where

$$i_d = \frac{I_D}{V_T} v_d$$

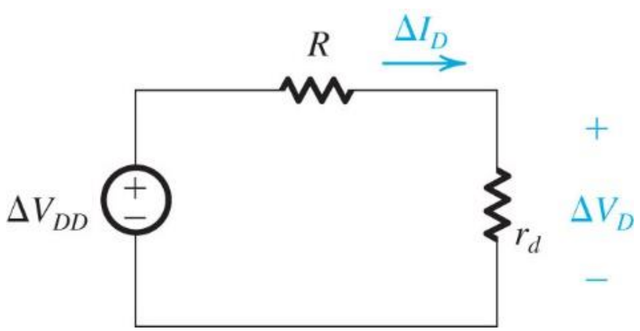


Figure 4.15 Circuit for determining the incremental quantities ΔI_D and ΔV_D for the circuit in Figure 4.13(b). Note that replacing the diode with its small-signal resistance r_d results in a linear circuit.

I_D/V_T is the **diode small-signal conductance** (mhos or Siemens)

V_T/I_D is the **diode small-signal resistance** or **incremental resistance** (ohms)

$$r_d = \frac{V_T}{I_D}$$

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Example 4.5

Consider the circuit shown in Fig. 4.16(a) for the case in which R = 10 kΩ. The power supply V has a dc value of 10 V on which is superimposed a 60-Hz sinusoid of 1-V peak amplitude. (This "signal" component of the power-supply voltage is an imperfection in the power-supply design. It is known as the power-supply ripple. More on this later.) Calculate both the dc voltage of the diode and the amplitude of the sine-wave signal appearing across it. Assume the diode to have a 0.7-V drop at 1-mA current.

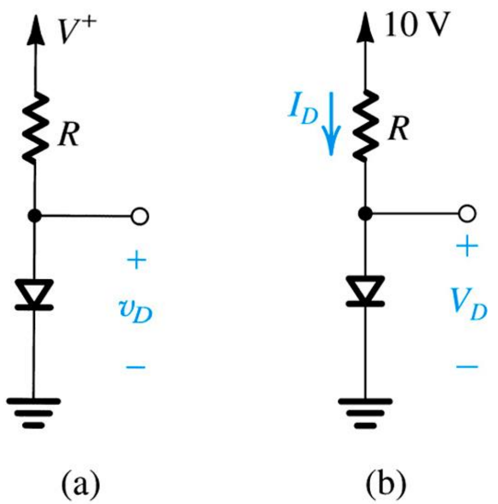

Figure 4.16 (a) Circuit for Example 4.5.

$$I_D = \frac{V_{DD} - V_D}{R} = \frac{10\text{V} - 0.7\text{V}}{10\text{k}\Omega} = 0.93\text{mA}$$

which is very close to 1 mA

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Example 4.5

Consider the circuit shown in Fig. 4.16(a) for the case in which R = 10 kΩ. The power supply V has a dc value of 10 V on which is superimposed a 60-Hz sinusoid of 1-V peak amplitude. (This "signal" component of the power-supply voltage is an imperfection in the power-supply design. It is known as the power-supply ripple. More on this later.) Calculate both the dc voltage of the diode and the amplitude of the sine-wave signal appearing across it. Assume the diode to have a 0.7-V drop at 1-mA current.

$$r_d = \frac{V_T}{I_D} = \frac{25\text{mV}}{0.93\text{mA}} = 26.9\Omega$$

$$v_{dpeak} = 1.0\,V\frac{r_d}{R + r_d} = 1.0\,V\frac{26.9\Omega}{10000\Omega + 26.9\Omega}$$

$$v_{dpeak} = 2.68\text{ mV}$$

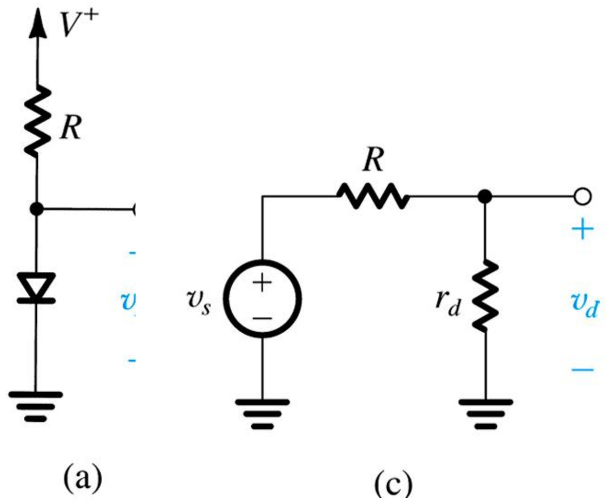

Figure 4.16 (a) Circuit for Example 4.5.

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Voltage Regulator Example 4.6

Consider the circuit shown in Fig 4.17. A string of three diodes is used to provide a constant voltage of about 2.1 V. We want to calculate the percentage change in this regulated voltage caused by (a) a ± 10% change in the power-supply voltage and (b) connection of a 1-kΩ load resistance.

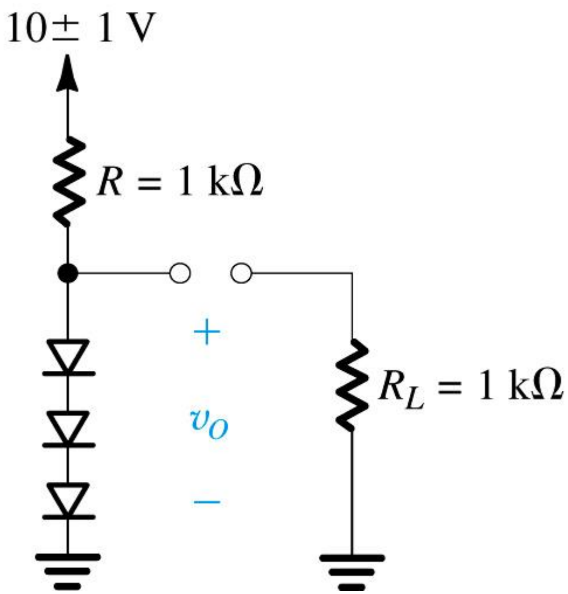

Figure 4.17 Circuit for Example 4.6.

with no load:

$$I_D = \frac{V_{DD} - V_D}{R} = \frac{10\text{V} - 2.1\text{V}}{1\text{k}\Omega} = 7.9\text{mA}$$

$$r_d = \frac{V_T}{I_D} = \frac{25\text{mV}}{7.9\text{mA}} = 3.165\Omega \text{ per diode}$$

$$r_{dtotal} = 9.5\Omega$$

$$v_{Op-p} = 2.0\ V\frac{r_{dtotal}}{R + r_{dtotal}} = 19.0\ mV$$

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Voltage Regulator Example 4.6

Consider the circuit shown in Fig 4.17. A string of three diodes is used to provide a constant voltage of about 2.1 V. We want to calculate the percentage change in this regulated voltage caused by (a) a ± 10% change in the power-supply voltage and (b) connection of a 1-kΩ load resistance.

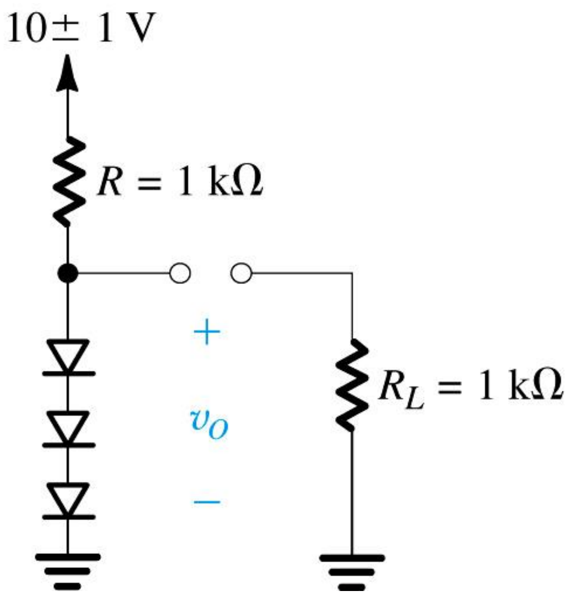

Figure 4.17 Circuit for Example 4.6.

with 1kΩ load: $I_L = \frac{v_O}{R_L} = \frac{2.1\text{V}}{1\text{k}\Omega} = 2.1\text{mA}$

with no load: $I_D = 7.9\text{mA}$

with 1kΩ load: $I_D = 7.9\text{mA} - 2.1\text{mA} = 5.8\text{mA}$

$$r_d = \frac{V_T}{I_D} = \frac{25\text{mV}}{5.8\text{mA}} = 4.31\Omega \text{ per diode} \qquad r_{dtotal} = 12.9\Omega$$

$$v_{dp-p} = 2.0\,V\frac{r_{dtotal}}{R + r_{dtotal}} = 25.0\text{ m}V$$

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Exercise 4.15

Design the circuit of Fig. E4.15 so that V_O = 3 V when I_L = 0, and V_O changes by 20 mV per 1 mA of load current.

(a) Use the small-signal model of the diode to find the value of R.

$$r_{dtotal} = \frac{\Delta V_O}{\Delta I_D} = \frac{20\text{mV}}{1\text{mA}} = 20\Omega \qquad r_d = \frac{r_{dtotal}}{4} = 5\Omega$$

$$I_D = \frac{V_T}{r_d} = \frac{25\text{mV}}{5\Omega} = 5\text{mA} \qquad R = \frac{V_{CC} - V_O}{I_D} = \frac{12\text{V}}{5\text{mA}} = 2.4\text{k}\Omega$$

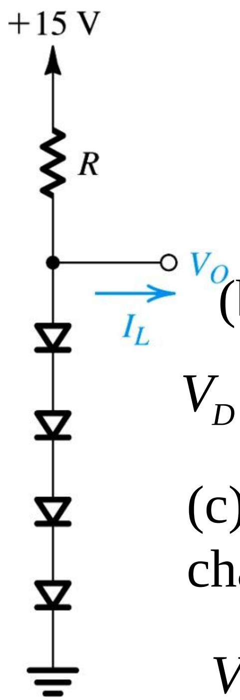

Figure E4.15

(b) Specify the value of I_S of each of the diodes.

$$V_D = \frac{3\text{V}}{4} = 750\text{mV} \qquad i_D = I_S e^{V/V_T} \Rightarrow I_S = \frac{i_D}{e^{V_D/V_T}} = \frac{5\text{mA}}{e^{750\text{mV}/25\text{mV}}} = 4.679\times10^{-16}\,\text{A}$$

(c) For this design, use the diode exponential model to determine the actual change in V_O when a current I_L = 1 mA is drawn from the regulator.

$$V_D = V_T \ln\left(\frac{I_D}{I_S}\right) = 25\text{mV}\times\ln\left(\frac{5\text{mA} - 1\text{mA}}{4.679\times10^{-16}\,\text{A}}\right) = 0.7444\text{V}$$

$$\Delta V_O = 3\text{V} - 4V_D = 3\text{V} - 4(0.7444\text{V}) = 0.0223\text{V}$$

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4.4 OPERATION IN THE REVERSE BREAKDOWN REGION - ZENER DIODES

Breakdown Region – Zener Diodes

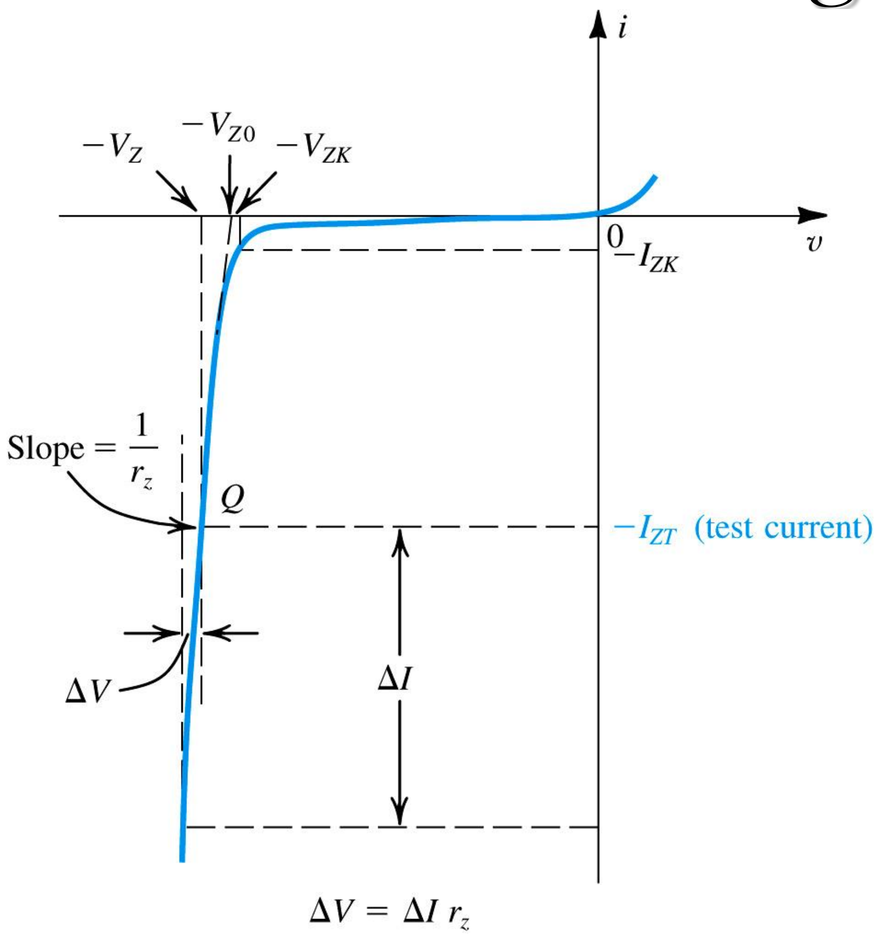

Figure 4.19 The diode *i*–*v* characteristic with the breakdown region shown in some detail.

For currents greater than the knee current I_{ZK} (specified on the data sheet of the zener diode), the *i*-*v* characteristic is almost a straight line. The manufacturer usually specifies the voltage across the zener diode V_Z at a specified test current, I_{ZT}. We have Indicated these parameters in Fig. 4.19 as the coordinates of the point labeled *Q*. Thus a 6.8-V zener diode will exhibit a 6.8-V drop at a specified test current of, say, 10 mA.

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Breakdown Region – Zener Diodes

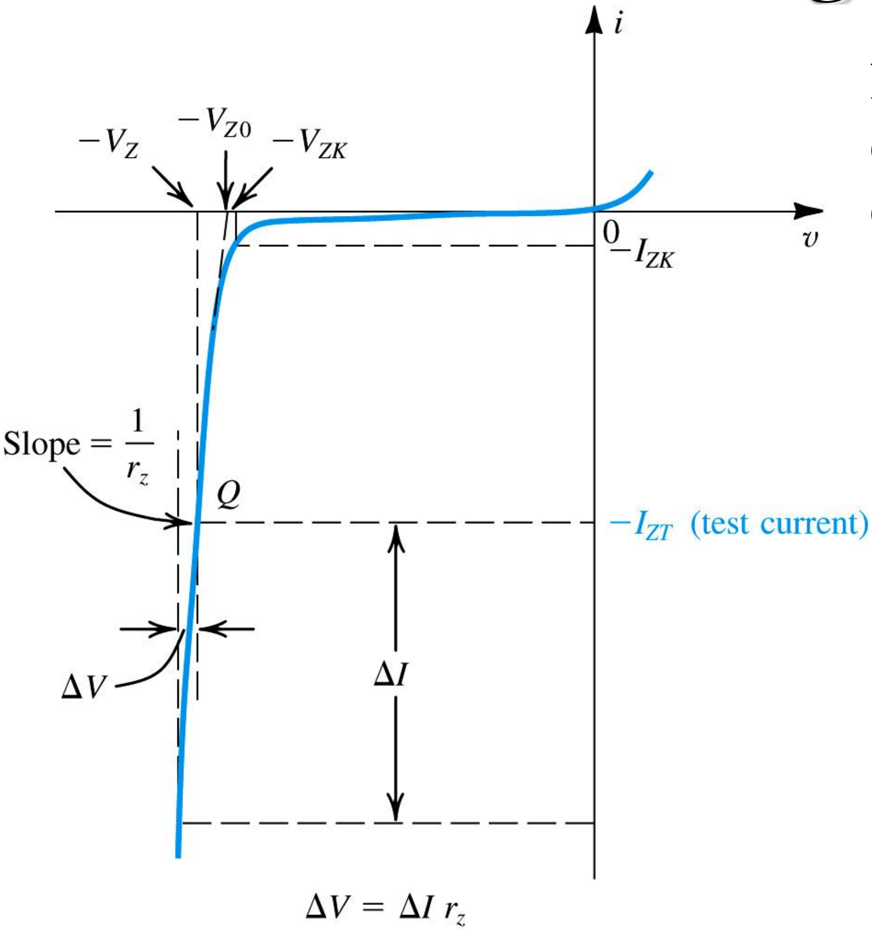

Figure 4.19 The diode *i*–*v* characteristic with the breakdown region shown in some detail.

Figure 4.19 shows that corresponding to current change ΔI the zener voltage changes by ΔV, which is related to ΔI by

$$\Delta V = r_z \Delta I$$

where r_z is the inverse of the slope of the almost-linear *i*-*v* curve at point *Q*. Resistance r_z is the **incremental resistance** of the zener diode at operating point *Q*. It is also known as the **dynamic resistance** of the zener, and its value is specified on the device data sheet. Typically, r_z is in the range of a few ohms to a few tens of ohms.

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Table 8. Characteristics per type

T_j = 25 °C unless otherwise specified.

Type number	Working voltage V_Z (V)[1] at I_{test}	Test current I_{test} (mA)	Differential resistance r_{dif} (Ω) at I_{test}	Differential resistance r_{dif} (Ω) at I_Z	I_Z (mA)	Reverse current I_R (μA)	V_R (V)	Working current I_Z (mA)	Non-repetitive peak reverse current I_{ZSM} (mA)[2]
	Nom		Max	Max		Max		Max	Max
1N4728A	3.3	76	10	400	1	100	1	276	1380
1N4729A	3.6	69	10	400	1	100	1	252	1260
1N4730A	3.9	64	9	400	1	50	1	234	1190
1N4731A	4.3	58	9	400	1	10	1	217	1070
1N4732A	4.7	53	8	500	1	10	1	193	970
1N4733A	5.1	49	7	550	1	10	1	178	890
1N4734A	5.6	45	5	600	1	10	2	162	810
1N4735A	6.2	41	2	700	1	10	3	146	730
1N4736A	6.8	37	3.5	700	1	10	4	133	660
1N4737A	7.5	34	4	700	0.5	10	5	121	605
1N4738A	8.2	31	4.5	700	0.5	10	6	110	550
1N4739A	9.1	28	5	700	0.5	10	7	100	500
1N4740A	10	25	7	700	0.25	10	7.6	91	454
1N4741A	11	23	8	700	0.25	5	8.4	83	414
1N4742A	12	21	9	700	0.25	5	9.1	76	380
1N4743A	13	19	10	700	0.25	5	9.9	69	344
1N4744A	15	17	14	700	0.25	5	11.4	61	304
1N4745A	16	15.5	16	700	0.25	5	12.2	57	285
1N4746A	18	14	20	750	0.25	5	13.7	50	250
1N4747A	20	12.5	22	750	0.25	5	15.2	45	225
1N4748A	22	11.5	23	750	0.25	5	16.7	41	205
1N4749A	24	10.5	25	750	0.25	5	18.2	38	190

[1] V_Z is measured with device at thermal equilibrium while held in clips at 10 mm from body in still air at 25 °C.

[2] Half square wave or equivalent sine wave pulse 1/120 second duration superimposed on I_{test}.

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DIODES INCORPORATED

Electrical Characteristics

@T_A = 25°C unless otherwise specified

Type Number	Nominal Zener Voltage (Note 3) V_Z @ I_{ZT} (V)	Test Current I_{ZT} (mA)	Maximum Zener Impedance (Note 4) Z_{ZT} @ I_{ZT} (Ω)	Z_{ZK} @ I_{ZK} (Ω)	I_{ZK} (mA)	Maximum Reverse Leakage Current I_R (μA)	@ V_R (V)	Max Surge Current 8.3ms I_{ZS} (mA)	Temperature Coefficient @ I_{ZT} %/°C
1N4728A	3.3	76	10	400	1.0	100	1.0	1380	-0.08 to -0.05
1N4729A	3.6	69	10	400	1.0	100	1.0	1260	-0.08 to -0.05
1N4730A	3.9	64	9.0	400	1.0	50	1.0	1190	-0.07 to -0.02
1N4731A	4.3	58	9.0	400	1.0	10	1.0	1070	-0.07 to -0.01
1N4732A	4.7	53	8.0	500	1.0	10	1.0	970	-0.03 to +0.04
1N4733A	5.1	49	7.0	550	1.0	10	1.0	890	-0.01 to +0.04
1N4734A	5.6	45	5.0	600	1.0	10	2.0	810	0 to +0.045
1N4735A	6.2	41	2.0	700	1.0	10	3.0	730	+0.01 to +0.055
1N4736A	6.8	37	3.5	700	1.0	10	4.0	660	+0.015 to +0.06
1N4737A	7.5	34	4.0	700	0.5	10	5.0	605	+0.02 to +0.065
1N4738A	8.2	31	4.5	700	0.5	10	6.0	550	0.03 to 0.07
1N4739A	9.1	28	5.0	700	0.5	10	7.0	500	0.035 to 0.075
1N4740A	10	25	7.0	700	0.25	10	7.6	454	0.04 to 0.08
1N4741A	11	23	8.0	700	0.25	5.0	8.4	414	0.045 to 0.08
1N4742A	12	21	9.0	700	0.25	5.0	9.1	380	0.045 to 0.085
1N4743A	13	19	10	700	0.25	5.0	9.9	344	0.05 to 0.085
1N4744A	15	17	14	700	0.25	5.0	11.4	304	0.055 to 0.09
1N4745A	16	15.5	16	700	0.25	5.0	12.2	285	0.055 to 0.09
1N4746A	18	14	20	750	0.25	5.0	13.7	250	0.06 to 0.09
1N4747A	20	12.5	22	750	0.25	5.0	15.2	225	0.06 to 0.09
1N4748A	22	11.5	23	750	0.25	5.0	16.7	205	0.06 to 0.095
1N4749A	24	10.5	25	750	0.25	5.0	18.2	190	0.06 to 0.095
1N4750A	27	9.5	35	750	0.25	5.0	20.6	170	0.06 to 0.095
1N4751A	30	8.5	40	1000	0.25	5.0	22.8	150	0.06 to 0.095
1N4752A	33	7.5	45	1000	0.25	5.0	25.1	135	0.06 to 0.095
1N4753A	36	7.0	50	1000	0.25	5.0	27.4	125	0.06 to 0.095
1N4754A	39	6.5	60	1000	0.25	5.0	29.7	115	0.06 to 0.095
1N4755A	43	6.0	70	1500	0.25	5.0	32.7	110	0.06 to 0.095
1N4756A	47	5.5	80	1500	0.25	5.0	35.8	95	0.06 to 0.095
1N4757A	51	5.0	95	1500	0.25	5.0	38.8	90	0.06 to 0.095
1N4758A	56	4.5	110	2000	0.25	5.0	42.6	80	0.06 to 0.095
1N4759A	62	4.0	125	2000	0.25	5.0	47.1	70	0.06 to 0.095
1N4760A	68	3.7	150	2000	0.25	5.0	51.7	65	0.06 to 0.095
1N4761A	75	3.3	175	2000	0.25	5.0	56.0	60	0.06 to 0.095

Notes:
3. Measured under thermal equilibrium and dc (I_{ZT}) test conditions.
4. The Zener impedance is derived from the 60 Hz ac voltage which results when an ac current having an rms value equal to 10% of the Zener current (I_{ZT} or I_{ZK}) is superimposed on I_{ZT} or I_{ZK}. Zener impedance is measured at two points to insure a sharp knee on the breakdown curve and to eliminate unstable units.

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The Zener Diode Symbol and Model

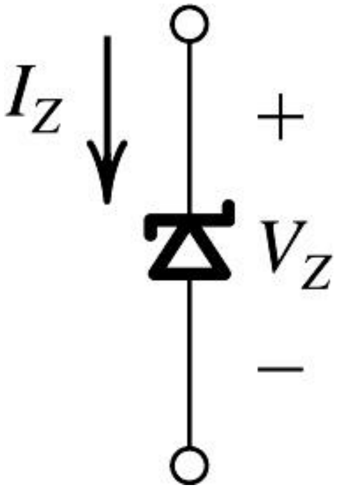

Figure 4.18 Circuit symbol for a zener diode.

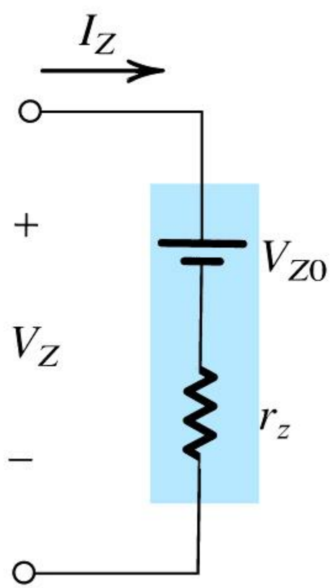

Figure 4.20 Model for the zener diode.

The almost-linear *i*-*v* characteristic of the zener diode suggests that the device can be modeled as indicated in Fig. 4.20. Here V_{Z0} denotes the point at which the straight line of slope $1/r_z$ intersects the voltage axis. Although V_{Z0} is shown in Fig. 4.19 to be slightly different from the knee voltage V_{ZK}, in practice their values are almost equal. The equivalent circuit model of Fig. 4.20 can be analytically described by

$$V_Z = V_{Z0} + r_z I_Z$$

and it applies for $I_Z > I_{ZK}$ and, obviously, $V_Z > V_{Z0}$.

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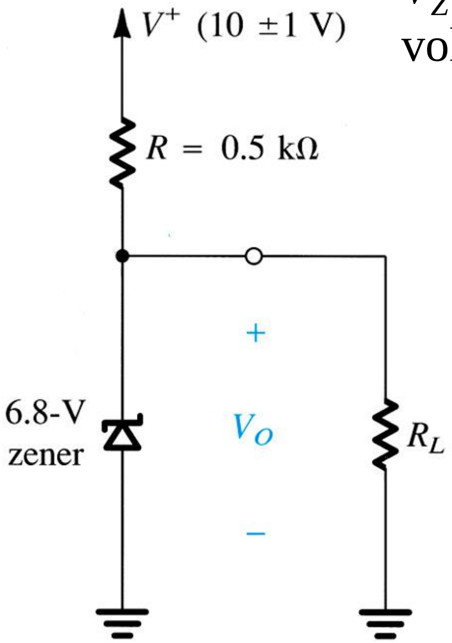
Use as a Shunt Regulator (Example 4.7)



(a)

Figure 4.21 (a) Circuit for Example 4.7.

The 6.8-V zener diode in the circuit of Fig. 4.21(a) is specified to have V_Z = 6.8 V at I_Z = 5 mA, r_z = 20 Ω, and I_{ZK} = 0.2 mA. The supply voltage V^+ is nominally 10 V but can vary by ± 1 V.

(a) Find V_O with no load and with V^+ at its nominal value.

(b) Find the change in V_O resulting from the ± 1-V change In V^+. Note that $(\Delta V_O/\Delta V^+)$, usually expressed in mV/V, is known as **line regulation**.

(c) Find the change in V_O resulting from connecting a load resistance R_L that draws a current I_L = 1 mA, and hence find the **load regulation** $(\Delta V_O/\Delta I_L)$ in mV/mA.

(d) Find the change in V_O when R_L = 2 kΩ.

(e) Find the change in V_O when R_L = 0.5 kΩ.

(f) What is the minimum value of R_L for which the diode still operates in the breakdown region?

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Use as a Shunt Regulator (Example 4.7)

The 6.8-V zener diode in the circuit of Fig. 4.21(a) is specified to have $V_Z = 6.8$ V at $I_Z = 5$ mA, $r_z = 20\ \Omega$, and $I_{ZK} = 0.2$ mA. The supply voltage V^+ is nominally 10 V but can vary by ± 1 V.

(a) Find V_O with no load and with V^+ at its nominal value.

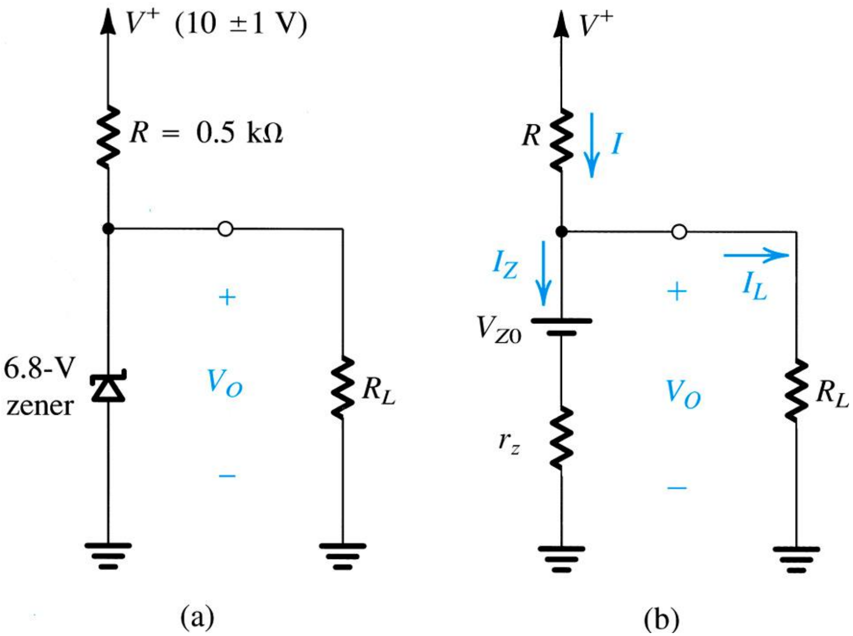

Figure 4.21 (a) Circuit for Example 4.7. **(b)** The circuit with the zener diode replaced with its equivalent circuit model.

$$V_Z = V_{Z0} + r_z I_Z$$

$$V_{Z0} = V_Z - r_z I_Z = 6.8 - (20)(.005) = 6.7\text{V}$$

$$I_Z = \frac{V^+ - V_{Z0}}{R + r_z} = \frac{10V - 6.7V}{500 + 20} = 6.35\text{mA}$$

$$V_O = V_{Z0} + r_z I_Z = 6.7 + (20)(.00635)$$
$$= 6.83\text{V}$$

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Use as a Shunt Regulator (Example 4.7)

The 6.8-V zener diode in the circuit of Fig. 4.21(a) is specified to have $V_Z = 6.8$ V at $I_Z = 5$ mA, $r_z = 20\ \Omega$, and $I_{ZK} = 0.2$ mA. The supply voltage V^+ is nominally 10 V but can vary by ± 1 V.

(b) Find the change in V_O resulting from the ± 1-V change In V^+. Note that $(\Delta V_O/\Delta V^+)$, usually expressed in mV/V, is known as **line regulation**.

$$\Delta V_O = \Delta V^+ \frac{r_z}{R + r_z} = \pm 1 \frac{20}{520} = \pm 38.5\text{mV}$$

the **line regulation** in mV/V is 38.5 mV/V

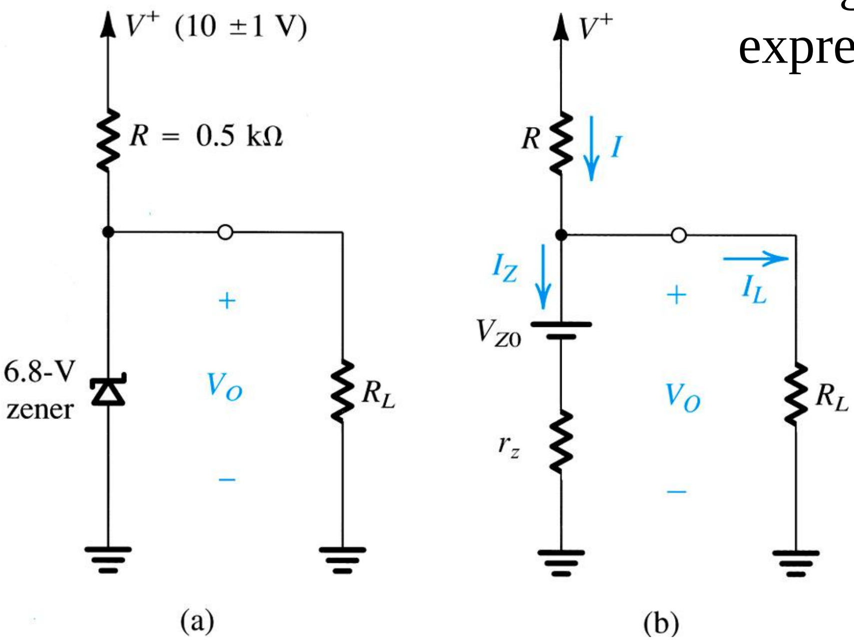

Figure 4.21 (a) Circuit for Example 4.7. **(b)** The circuit with the zener diode replaced with its equivalent circuit model.

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Use as a Shunt Regulator (Example 4.7)

The 6.8-V zener diode in the circuit of Fig. 4.21(a) is specified to have $V_Z = 6.8$ V at $I_Z = 5$ mA, $r_z = 20\ \Omega$, and $I_{ZK} = 0.2$ mA. The supply voltage V^+ is nominally 10 V but can vary by ± 1 V.

(c) Find the change in V_O resulting from connecting a load resistance R_L that draws a current $I_L = 1$ mA, and hence find the **load regulation** ($\Delta V_O / \Delta I_L$) in mV/mA.

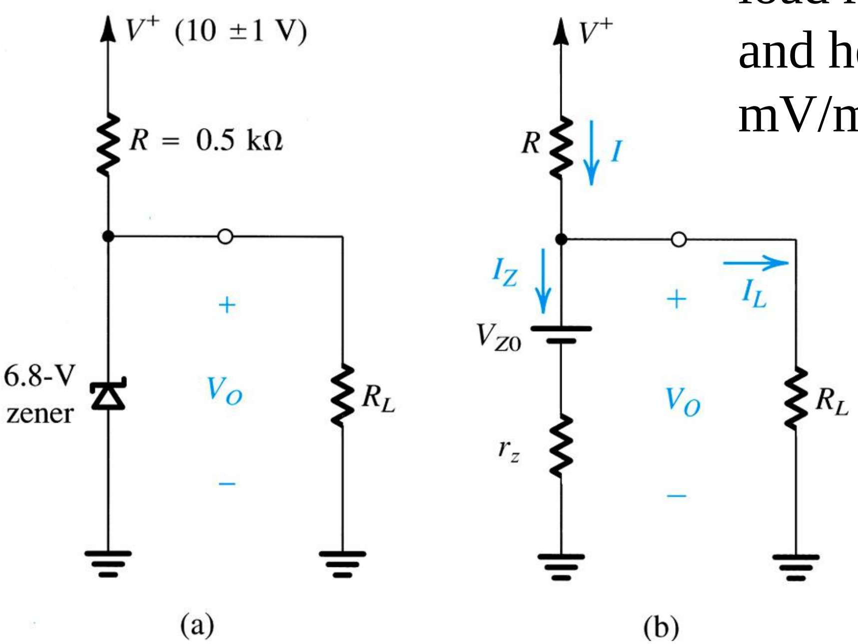

Figure 4.21 (a) Circuit for Example 4.7. **(b)** The circuit with the zener diode replaced with its equivalent circuit model.

$$\Delta V_O = r_z \Delta I_Z = 20 \times -.001 = -20\text{mV}$$

the **load regulation** in mV/mA is -20 mV/mA

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Use as a Shunt Regulator (Example 4.7)

The 6.8-V zener diode in the circuit of Fig. 4.21(a) is specified to have V_Z = 6.8 V at I_Z = 5 mA, r_z = 20 Ω, and I_{ZK} = 0.2 mA. The supply voltage V^+ is nominally 10 V but can vary by ± 1 V.

(d) Find the change in V_O when R_L = 2 kΩ.

$$I_L = \frac{6.8\text{V}}{2000\Omega} = 3.4\text{mA}$$

$$\Delta V_O = r_z \Delta I_Z = 20 \times -.0034 = -68\text{mV}$$

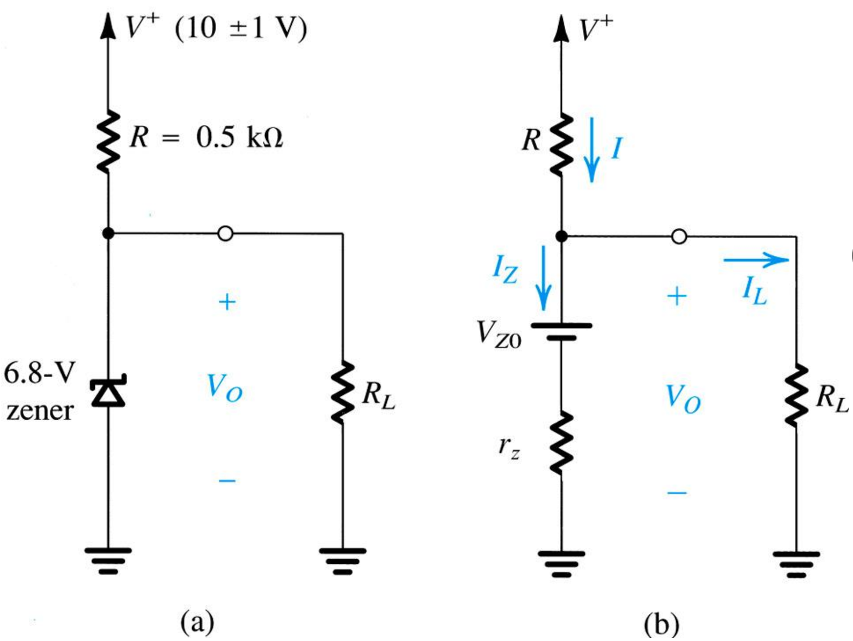

Figure 4.21 (a) Circuit for Example 4.7. **(b)** The circuit with the zener diode replaced with its equivalent circuit model.

(e) Find the change in V_O when R_L = 0.5 kΩ.

$$I_L = \frac{6.8\text{V}}{500\Omega} = 13.6\text{mA}$$

But I_Z = 6.4 mA so the zener must be cut-off !

$$V_O = 10\text{V}\frac{500\Omega}{1000\Omega} = 5\text{V}$$

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Use as a Shunt Regulator (Example 4.7)

The 6.8-V zener diode in the circuit of Fig. 4.21(a) is specified to have $V_Z = 6.8$ V at $I_Z = 5$ mA, $r_z = 20\ \Omega$, and $I_{ZK} = 0.2$ mA. The supply voltage V^+ is nominally 10 V but can vary by ± 1 V.

(f) What is the minimum value of R_L for which the diode still operates in the breakdown region?

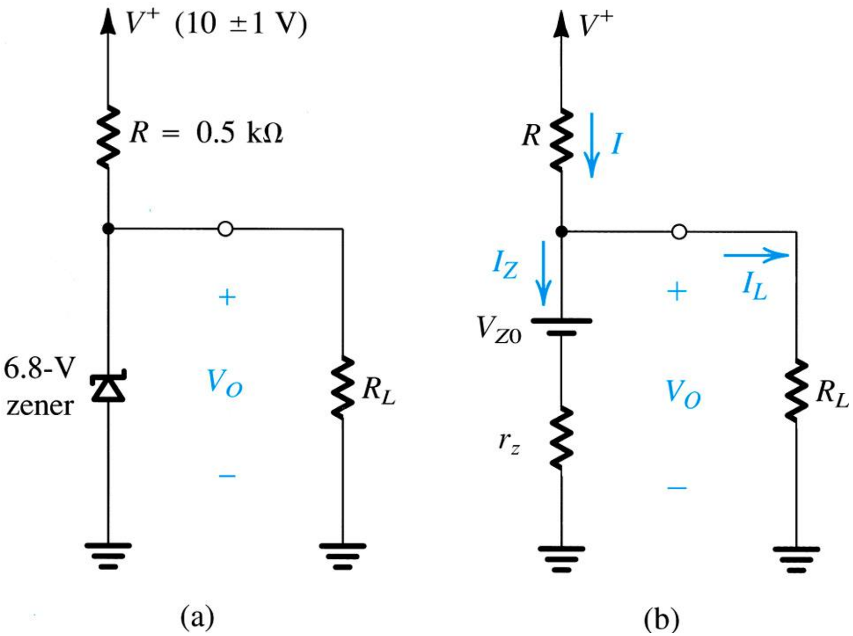

Figure 4.21 (a) Circuit for Example 4.7. **(b)** The circuit with the zener diode replaced with its equivalent circuit model.

$$I_Z = I_{ZK} = 0.2\text{mA}$$

$$V_Z = V_{ZK} = 6.7\text{V}$$

Worst case $V^+ = 9$ V.

$$I = \frac{9 - 6.7\text{V}}{500\Omega} = 4.6\text{mA}$$

$$I_L = I - I_Z = 4.6\text{mA} - 0.2\text{mA} = 4.4\text{mA}$$

$$R_L = \frac{V_O}{I_L} = \frac{6.7\text{V}}{4.4\text{mA}} = 1523\Omega$$

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Temperature Effects

The dependence of the zener voltage V_Z on temperature is specified in terms of its **temperature coefficient TC**, or **temco**, which is usually expressed in mV/°C. Zener diodes whose V_Z are lower than about 5 V exhibit a negative TC while zeners with higher voltages exhibit a positive TC.

A commonly used technique to obtain a reference voltage with a low TC is to use a forward biased diode (-2 mV/°C) in series with a reverse biased zener (~2mV /°C).

End 3/13/2018 lecture

4.5 RECTIFIER CIRCUITS

Rectifier Circuits

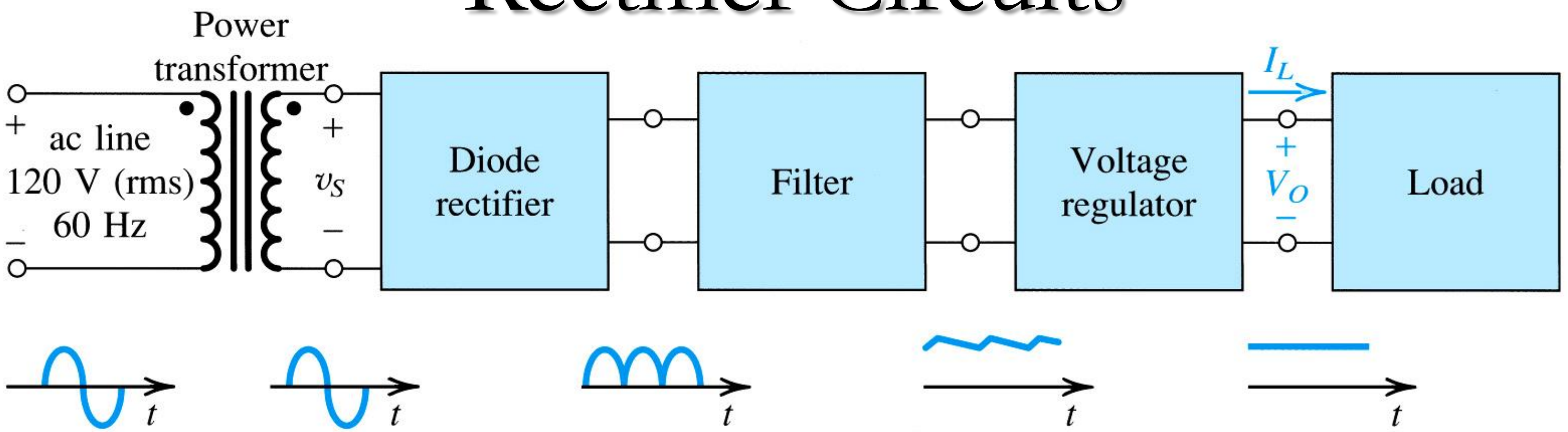

Figure 4.22 Block diagram of a dc power supply.

- Power transformer
  - Primary (N_1) and secondary (N_2) windings

    $$v_S = 120\frac{N_2}{N_1}\mathrm{V_{rms}}$$
  - Isolates electronics
- Diode Rectifier
  - Converts AC to DC
  - Half-Wave
  - Full-Wave

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Half-Wave Rectifier

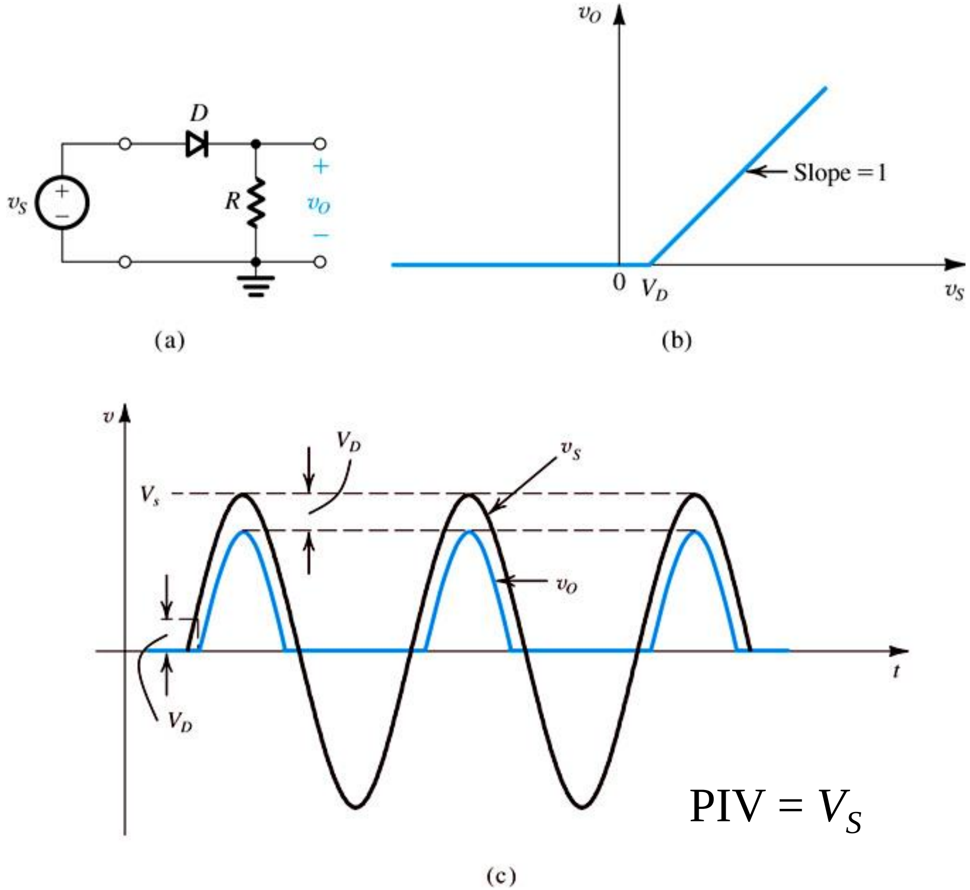

Figure 4.23 (a) Half-wave rectifier. **(b)** Transfer characteristic of the rectifier circuit. **(c)** Input and output waveforms.

Using a constant voltage drop model

$$v_O = 0;\ v_S < V_D$$

$$v_O = v_S - V_D;\ v_S \geq V_D$$

In selecting diodes for rectifier design, two important parameters must be specified: the current-handling capability required of the diode, determined by the largest current the diode is expected to conduct, and the **peak inverse voltage** (PIV) that the diode must be able to withstand without breakdown. determined by the largest reverse voltage that is expected to appear across the diode.

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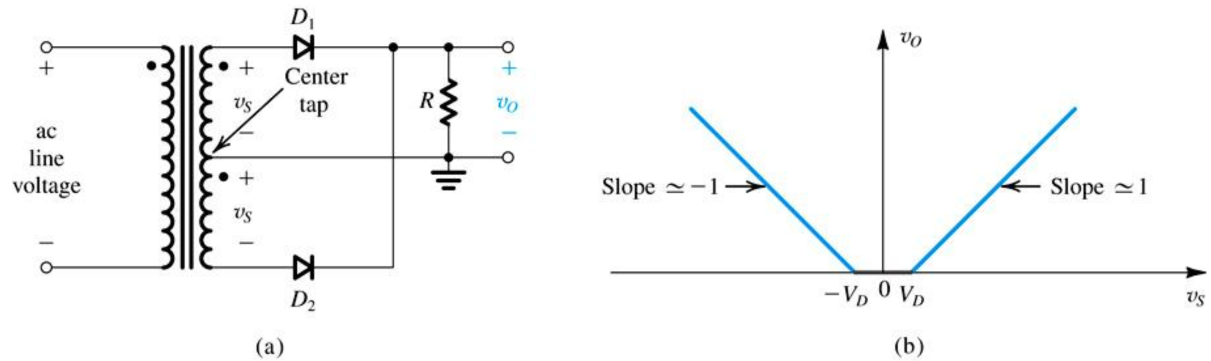
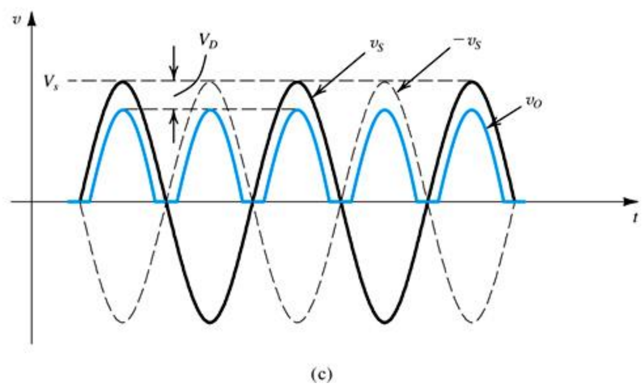
Full-Wave Rectifier using a Center-Tapped Transformer



Center-tapped transformer generates two outputs 180° out of phase



$$\text{PIV} = 2V_S - V_D$$

Figure 4.24 Full-wave rectifier utilizing a transformer with a center-tapped secondary winding: **(a)** circuit; **(b)** transfer characteristic assuming a constant-voltage-drop model for the diodes; **(c)** input and output waveforms.

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Bridge Full-Wave Rectifier

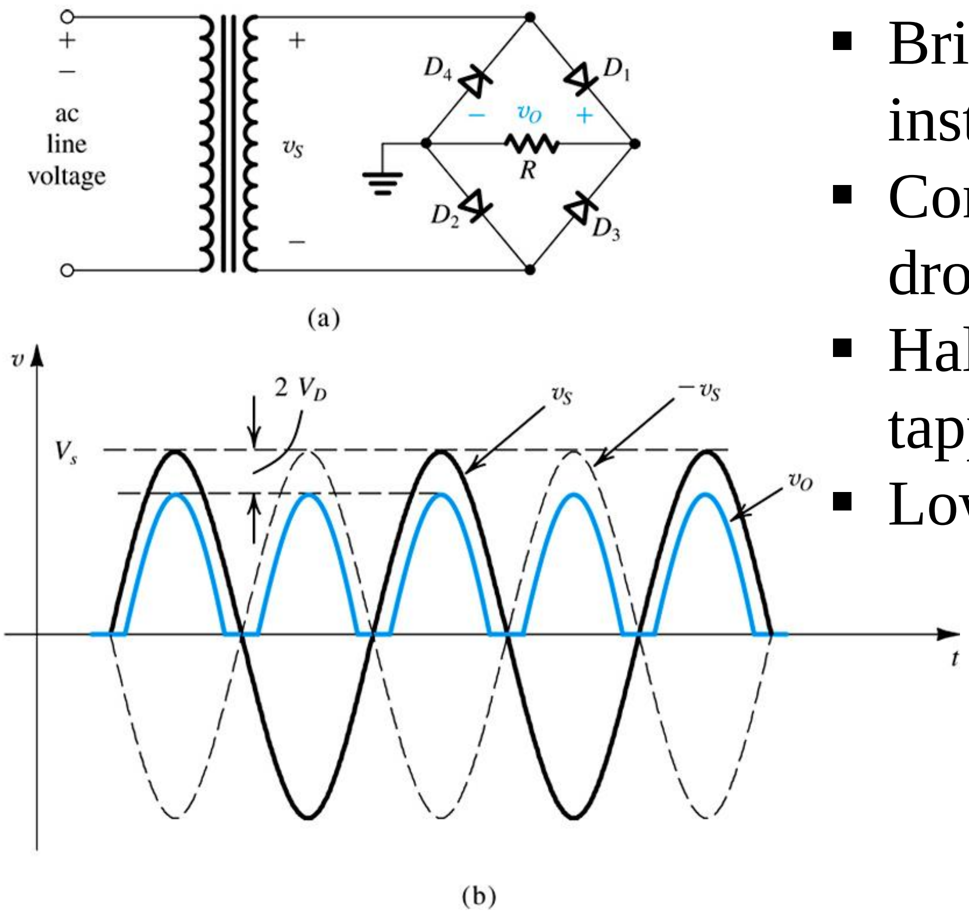

Figure 4.25 The bridge rectifier: **(a)** circuit; **(b)** input and output waveforms.

- Bridge rectifier requires 4 diodes instead of 2
- Conduction paths have two diode drops
- Half as many windings as a center-tapped transformer
- Lower peak inverse voltage

$$PIV = V_S - V_D$$

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The Half-Wave Rectifier with a Filter Capacitor

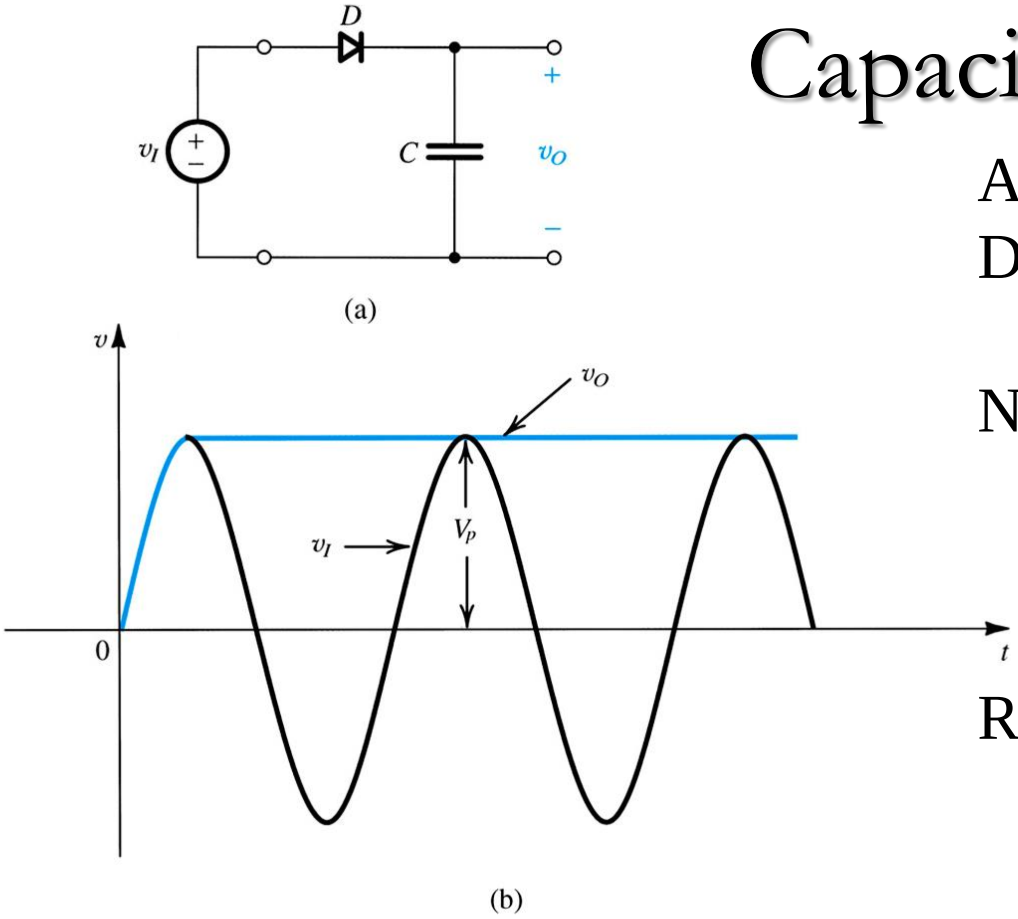

Figure 4.26 (a) A simple circuit used to illustrate the effect of a filter capacitor. **(b)** Input and output waveforms assuming an ideal diode. Note that the circuit provides a dc voltage equal to the peak of the input sine wave. The circuit is therefore known as a *peak rectifier* or a *peak detector*.

Assume an ideal diode.

Diode is only forward biased for the first ¼ cycle.

No load so there is no way for the capacitor to discharge.

Results in $v_O = V_p$ and is known as a **peak rectifier** or **peak detector**.

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Half-Wave Rectifier with a Load

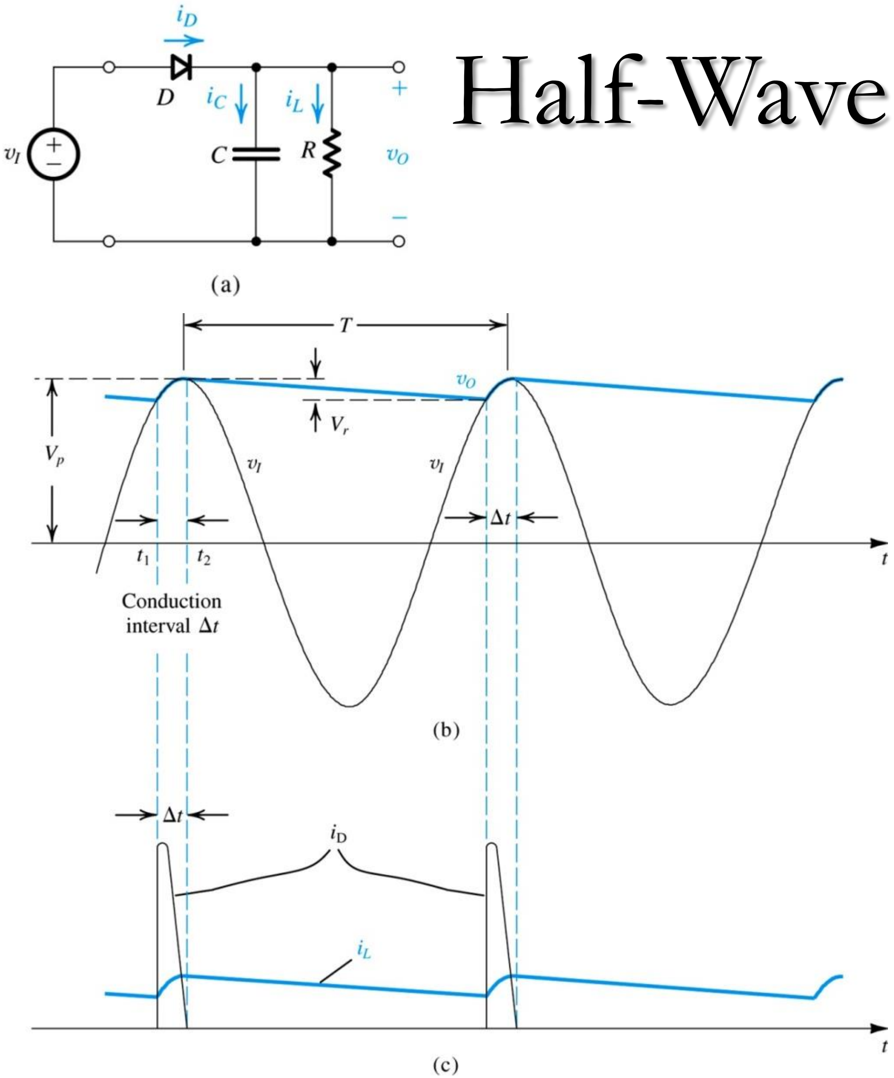

Figure 4.27 Voltage and current waveforms in the peak-rectifier circuit with $CR \gg T$. The diode is assumed ideal.

Assume an ideal diode.

Diode is only forward biased for a brief period in each cycle.

The capacitor charges during forward conduction and then discharges through the load resistor.

Choose a capacitor such that

$$\tau_{RC} \gg T$$

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Half-Wave Rectifier with a Load

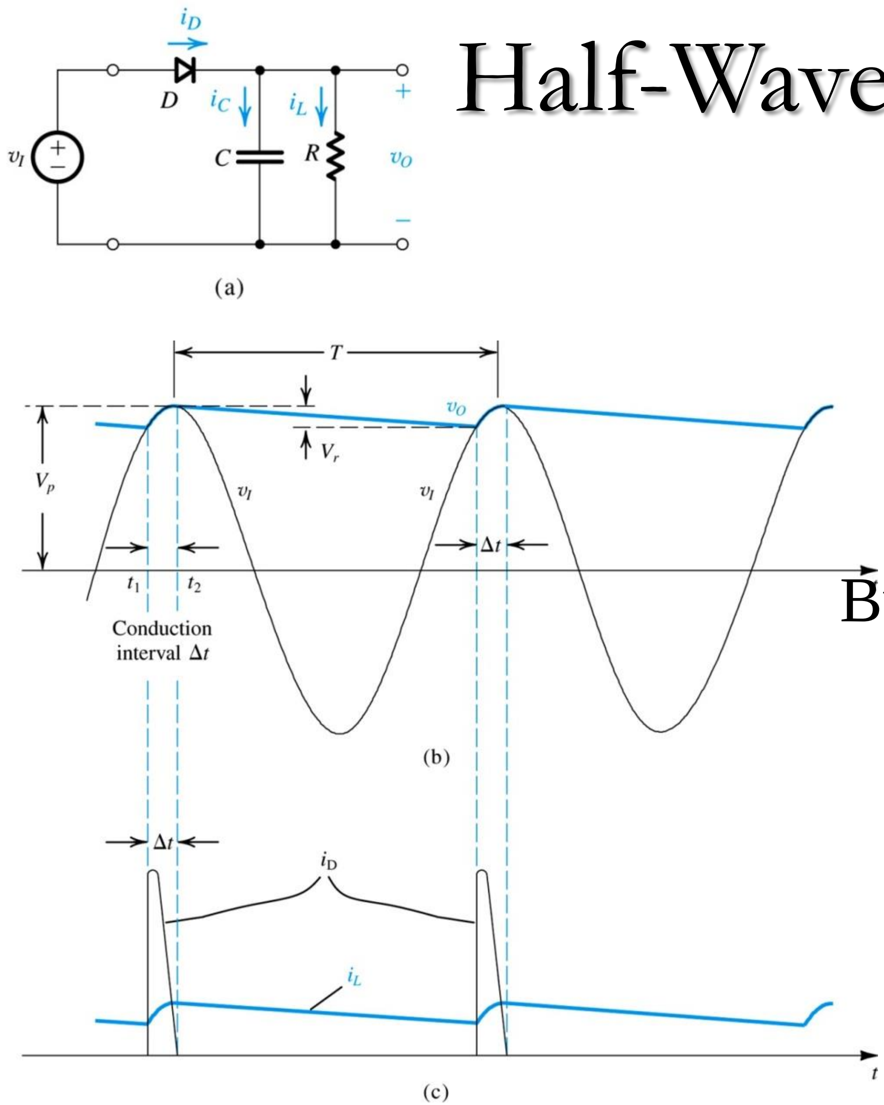

Figure 4.27 Voltage and current waveforms in the peak-rectifier circuit with $CR \gg T$. The diode is assumed ideal.

During the diode-off interval:

$$v_O = V_P e^{-t/RC}$$

At the end of the discharge

$$V_P - V_r \cong V_P e^{-T/RC}$$

But RC $\gg T$ so $e^{-T/RC} \cong 1 - T/RC$

$$V_r \cong V_P \frac{T}{RC}$$

Therefore, to keep the **ripple voltage**, V_r, low we need to select a capacitor such that $RC \gg T$.

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Half-Wave Rectifier with a Load

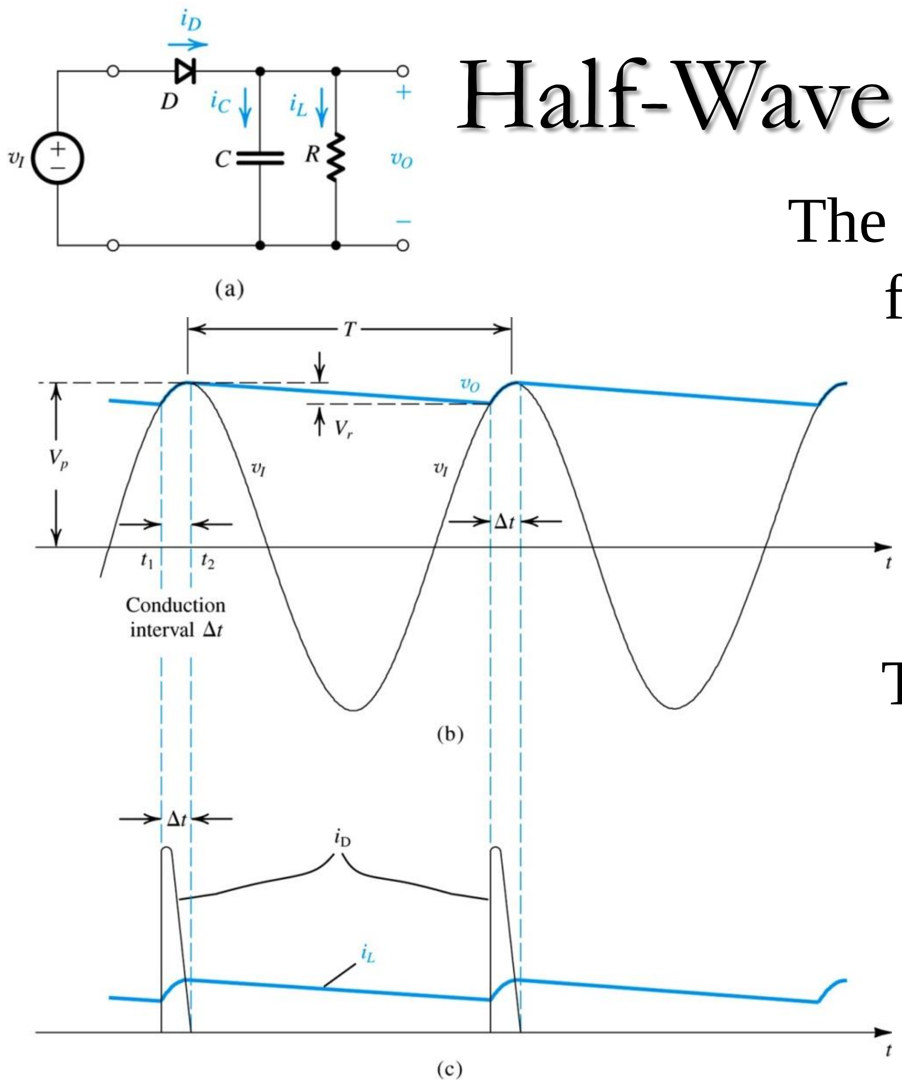

Figure 4.27 Voltage and current waveforms in the peak-rectifier circuit with $CR \gg T$. The diode is assumed ideal.

The ripple voltage in terms of the frequency is

$$V_r = \frac{V_P}{fRC}$$

The DC component of the load current is

$$I_L = \frac{V_P}{R} \quad \text{so} \quad V_r = \frac{I_L}{fC}$$

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Half-Wave Rectifier with a Load

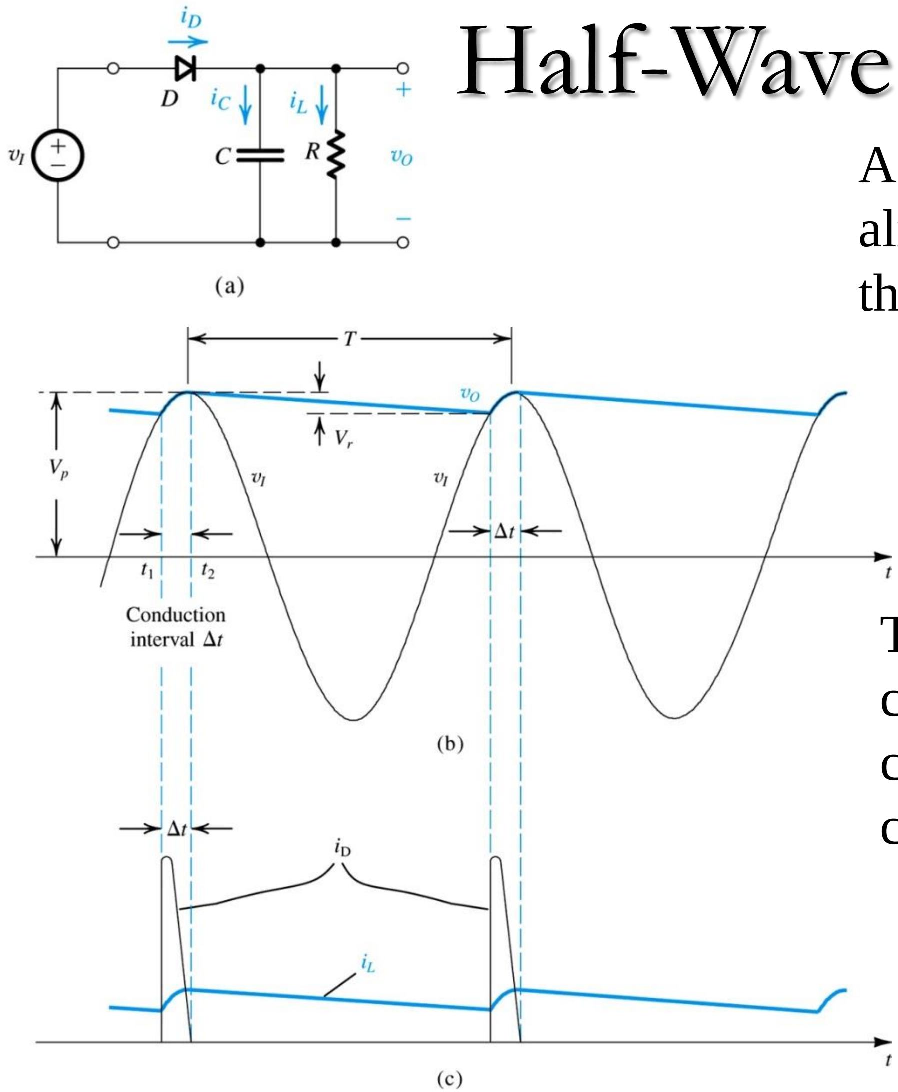

Figure 4.27 Voltage and current waveforms in the peak-rectifier circuit with $CR \gg T$. The diode is assumed ideal.

Assuming that diode conduction ceases almost at the peak of v_I, we can determine the **conduction interval** Δt from

$$V_P \cos(\omega \Delta t) \cong V_P - V_r$$

Using the small angle approximation

$$\omega \Delta t = \sqrt[2]{2V_r/V_P}$$

To determine the average and peak diode current during conduction we equate the charge that the diode supplies to the capacitor (see p. 217).

$$I_{Dav} = I_L\left(1 + \pi\sqrt{2V_P/V_r}\right)$$

$$I_{Dmax} = I_L\left(1 + 2\pi\sqrt{2V_P/V_r}\right)$$

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Full-Wave Peak Rectifier

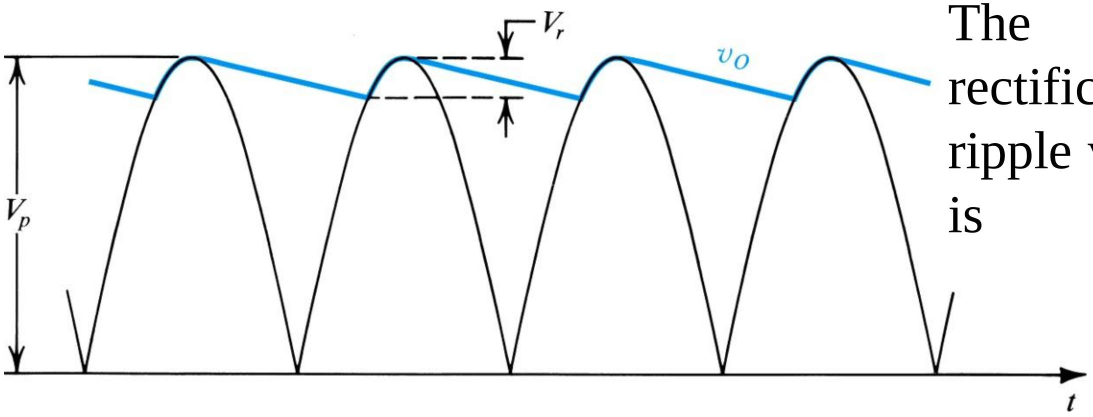

Figure 4.28 Waveforms in the full-wave peak rectifier.

The period in the half-wave rectification is replaced by $T/2$. The ripple voltage in terms of the frequency is

$$V_r = \frac{V_P}{2fRC}$$

$$\omega\Delta t = \sqrt[2]{2V_r/V_P}$$

$$I_{\mathrm{Dav}} = I_L\left(1 + \pi\sqrt{V_P/2V_r}\right)$$

$$I_{\mathrm{Dmax}} = I_L\left(1 + 2\pi\sqrt{V_P/2V_r}\right)$$

Comparing these expressions with the corresponding ones for the half-wave case, we note that for the same values of V_P, f, R, and V_r (and thus the same I_L), we need a capacitor half the size of that required in the half-wave rectifier. Also, the current in each diode in the full-wave rectifier is approximately half that which flows in the diode of the half-wave circuit.

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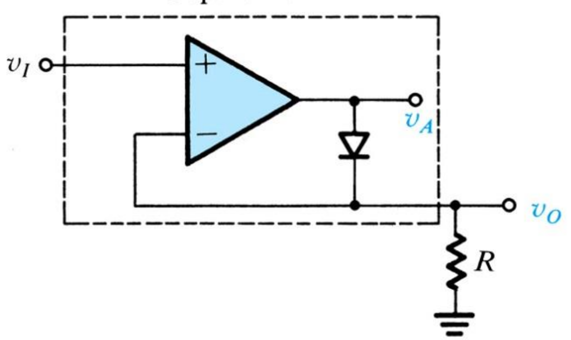
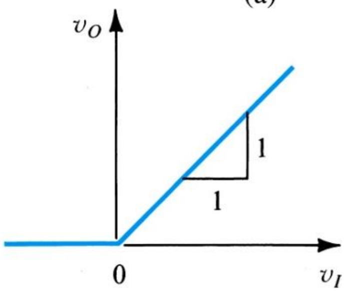
Precision Half-Wave Rectifier, the "Superdiode"



(a)



(b)

Figure 4.29 (a)The "superdiode" precision half-wave rectifier and (b) its almost-ideal transfer characteristic. Note that when $v_I > 0$ and the diode conducts, the op amp supplies the load current, and the source is conveniently buffered, an added advantage. Not shown are the op-amp power supplies.

The rectifier circuits studied thus far suffer from having one or two diode drops in the signal paths. Thus these circuits work well only when the signal to be rectified is much larger than the voltage drop of a conducting diode (0.7 V or so). In such a case. the details of the diode forward characteristics or the exact value of the diode voltage do not play a prominent role in determining circuit performance.

Figure 4.29(a) shows a precision half-wave rectifier circuit consisting of a diode placed in the negative-feedback path of an op amp. with *R* being the rectifier load resistance. The combination of diode and op amp, shown in the dotted box in Fig. 4.29(a), is appropriately referred to as a "superdiode."

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4.6 LIMITING AND CLAMPING CIRCUITS

The Limiter Circuit

Figure 4.30 shows the general transfer characteristic of a double limiter circuit.

$$v_O = Kv_I \quad \text{if} \quad L_-/K \le v_I \le L_+/K$$

$$v_O = L_+ \quad \text{if} \quad v_I > L_+/K$$

$$v_O = L_- \quad \text{if} \quad v_I < L_-/K$$

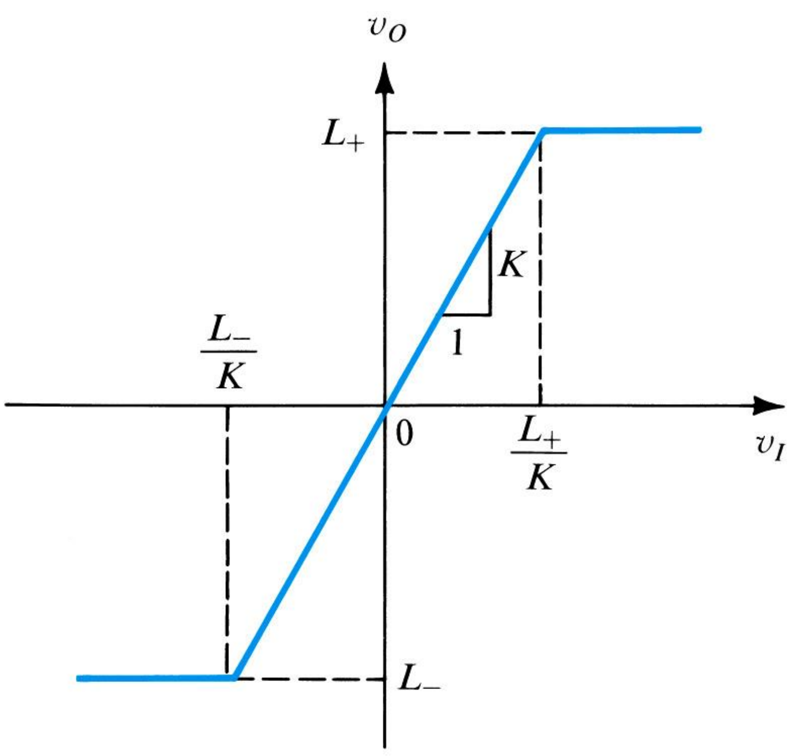

Figure 4.30 General transfer characteristic for a limiter circuit.

Although in general K can be greater than 1, the circuits discussed in this section have $K \le$ I and are known as **passive limiters**.

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Results of a Double Limiter, or Clipper Circuit

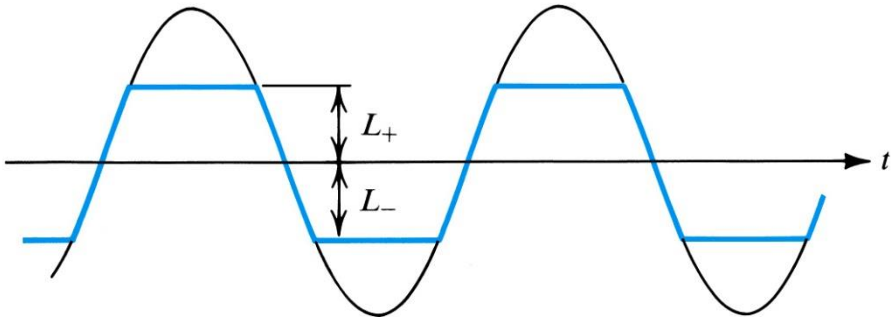

Figure 4.31 Applying a sine wave to a limiter can result in clipping off its two peaks.

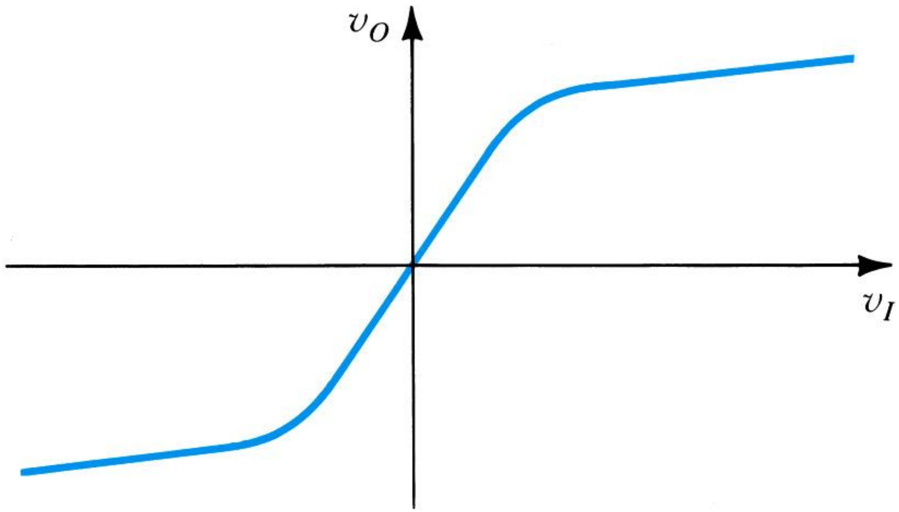

Figure 4.32 Soft limiting.

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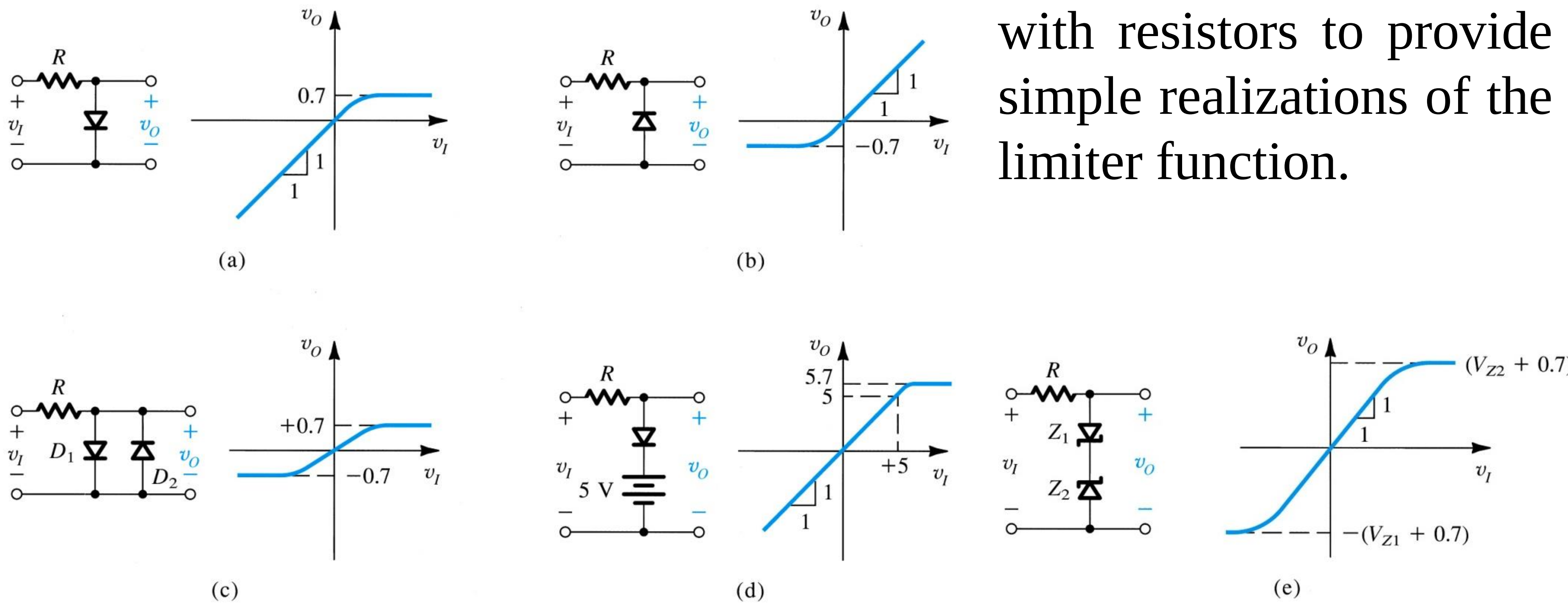
Basic Limiting Circuits



Diodes can be combined with resistors to provide simple realizations of the limiter function.

Figure 4.33 A variety of basic limiting circuits.

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Exercise 4.26

Assuming the diodes to be ideal, describe the transfer characteristic of the circuit shown in Fig. E4.26.

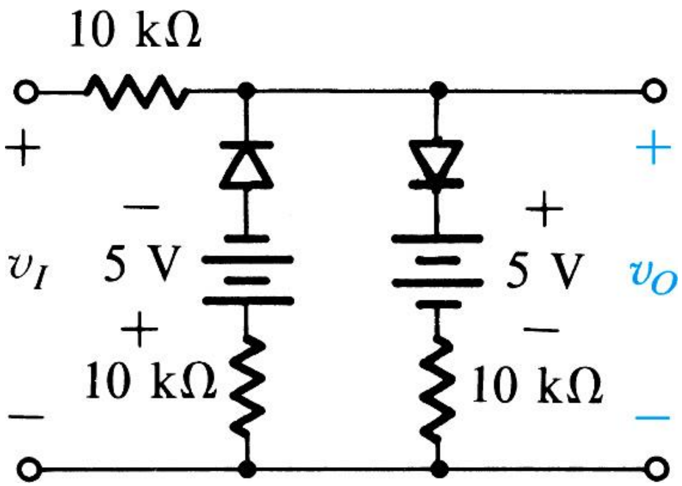
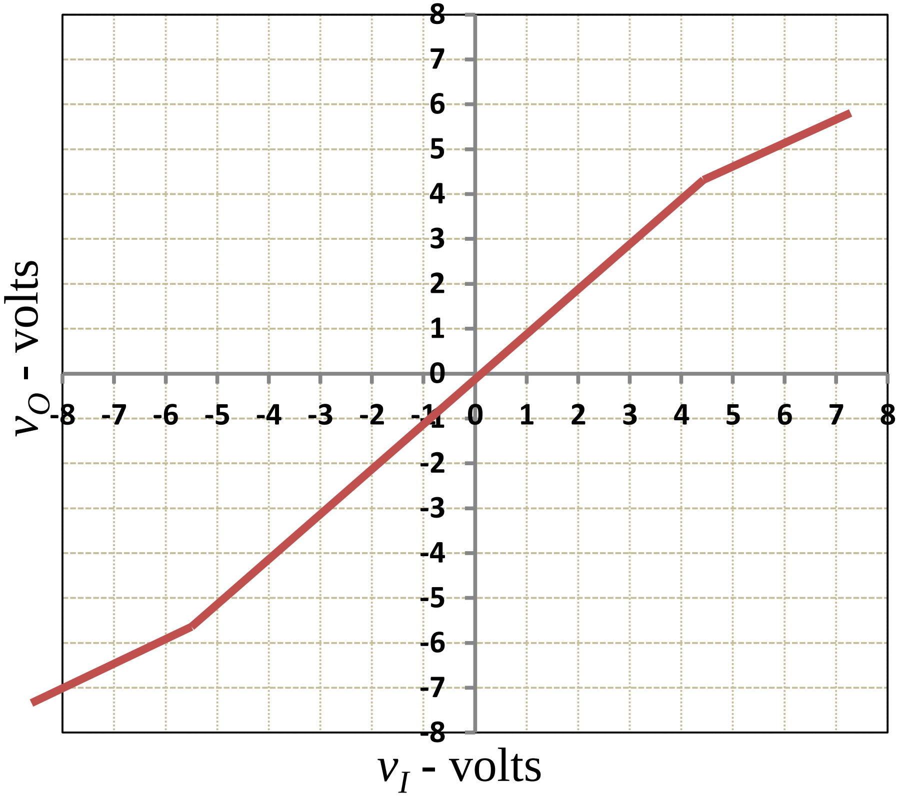


Figure E4.26



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The Clamped Capacitor or DC Restorer

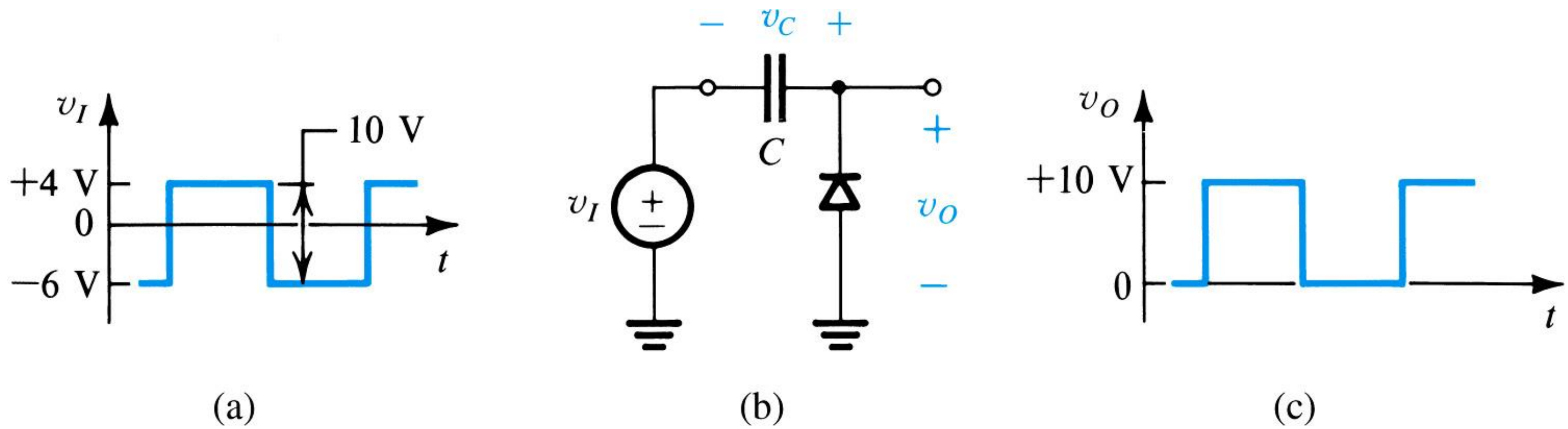

Figure 4.34 The clamped capacitor or dc restorer with a square-wave input and no load.

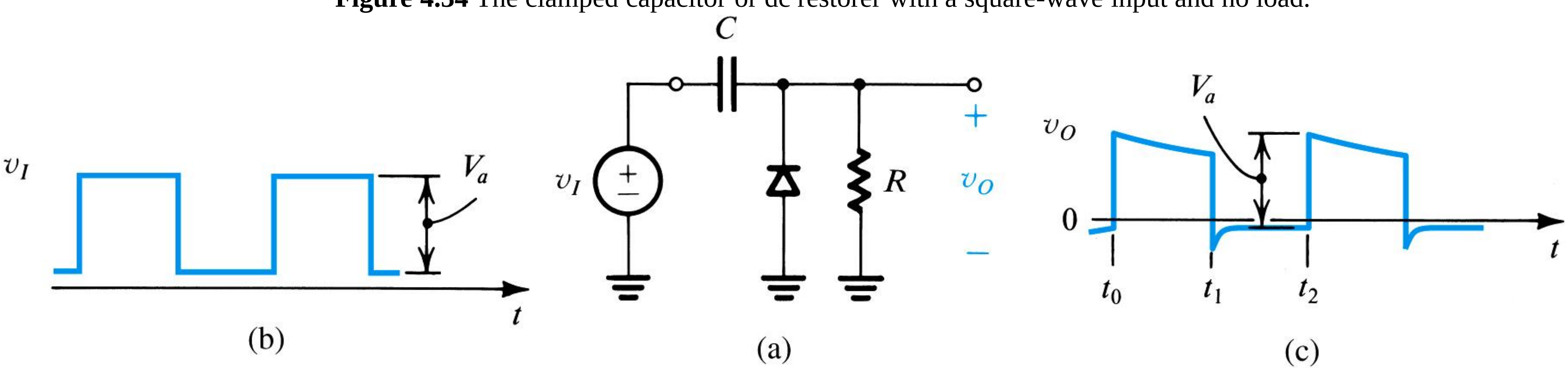

Figure 4.35 The clamped capacitor with a load resistance *R*.

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The Voltage Doubler (Lab #4)

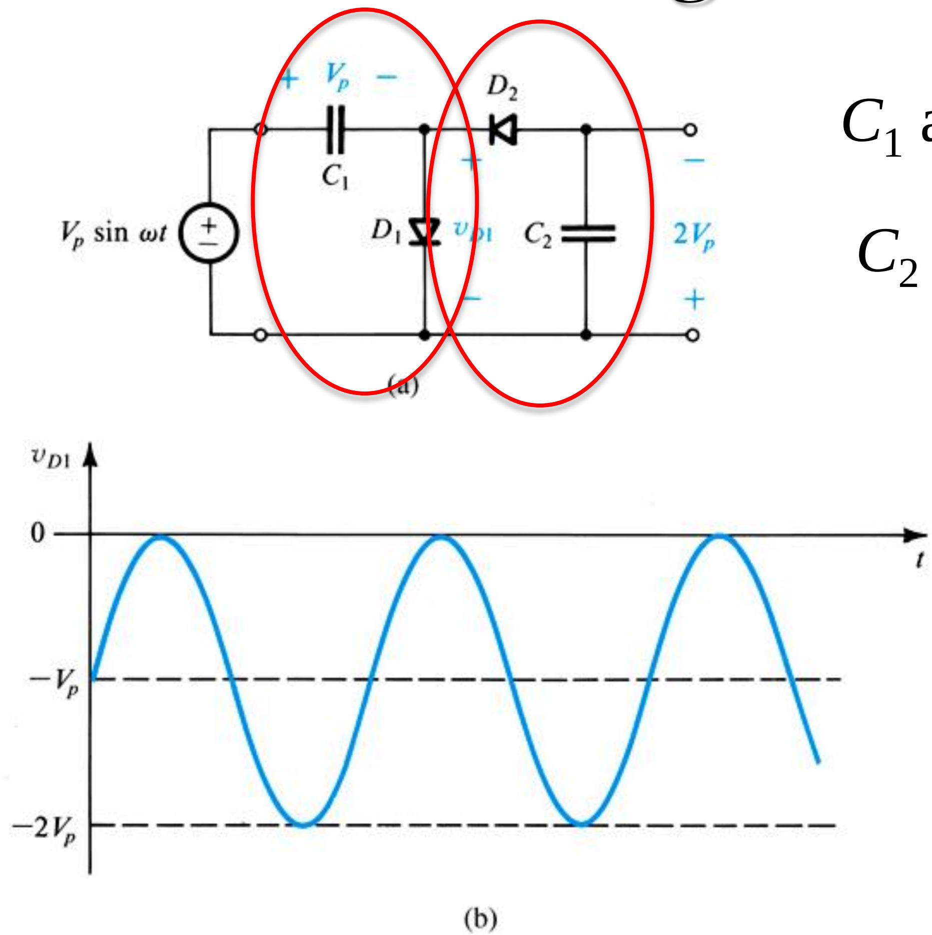

Figure 4.36 Voltage doubler: **(a)** circuit; **(b)** waveform of the voltage across D_1.

C_1 and D_1 form a clamped capacitor

C_2 and D_2 form a peak rectifier

When excited by a sinusoid of amplitude V_P the clamping section provides the voltage waveform shown, assuming ideal diodes.

Note that while the positive peaks are clamped to 0 V, the negative peak reaches - $2V_P$.

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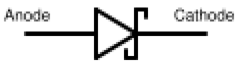
Homework #8

- Finish reading Chapter 4
- Chapter 4 Problems:
  - 4.35*
  - 4.59*
  - 4.62
  - 4.70
  - 4.72
  - 4.87

*** Answers in Appendix L**

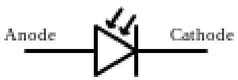
4.7 SPECIAL DIODE TYPES

Special Diode Types

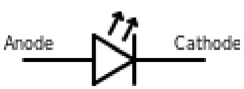


- The Schottky-Barrier Diode (SBD)
  - Uses metal-semiconductor junctions
    - Faster (only majority carriers) and lower voltage drop

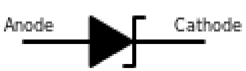
- Varactors
  - Voltage-variable capacitor (used for tuning frequency)



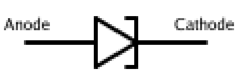
- Photodiodes/Solar Cells (Lab #3)
  - Convert photons to current



- Light-Emitting Diodes (LEDs), Laser Diodes (Lab #3)
  - Convert current to photons



- Zener Diode



- Tunnel Diode

Diode symbols from https://en.wikipedia.org/wiki/Diode

Summary

- In the forward direction, the ideal diode conducts any current forced by the external circuit while displaying a zero voltage drop. The ideal diode does not conduct in the reverse direction; any applied voltage appears as reverse bias across the diode.
- The unidirectional-current-flow property makes the diode useful in the design of rectifier circuits.
- The forward conduction of practical silicon-junction diodes is accurately characterized by the relationship $i = I_S e^{v/V_T}$.
- A silicon diode conducts a negligible current until the forward voltage is at least 0.5 V. Then the current increases rapidly, with the voltage drop increasing by 60 mV for every decade of current change.

Microelectronic Circuits, Seventh Edition - Sedra/Smith
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Summary

- In many applications, a conducting diode is modeled as having a constant voltage drop, usually approximately 0.7 V.
- A diode biased to operate at a dc current ID has a small-signal resistance $r_d = V_T / I_D$.
- Rectifiers convert ac voltages into unipolar voltages. Half-wave rectifiers do this by passing the voltage in half of each cycle and blocking the opposite-polarity voltage in the other half of the cycle. Full-wave rectifiers accomplish the task by passing the voltage in half of each cycle and inverting the voltage in the other half-cycle.
- The bridge-rectifier circuit is the preferred full-wave rectifier configuration.

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Summary

- The variation of the output waveform of the rectifier is reduced considerably by connecting a capacitor C across the output load resistance R. The resulting circuit is the peak rectifier. The output waveform then consists of a dc voltage almost equal to the peak of the input sine wave, V_p, on which is superimposed a ripple component of frequency $2f$ (in the full-wave case) and of peak-to-peak amplitude $V_r = V_p/2fCR$. To reduce this ripple voltage further, a voltage regulator is employed.
- Combination of diodes, resistors, and possibly reference voltages can be used to design voltage limiters that prevent one or both extremities of the output wave form from going beyond predetermined values, the limiting level(s).

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Summary

- Applying a time-varying waveform to a circuit consisting of a capacitor in series with a diode and taking the output across the diode provides a clamping function. Specifically, depending on the polarity of the diode, either the positive or negative peaks of the signal will be clamped to the voltage at the other terminal of the diode (usually ground). In this way the output waveform has a nonzero average or dc component, and the circuit is known as a dc restorer.
- By cascading a clamping circuit with a peak-rectifier circuit, a voltage doubler is realized.

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