Diodes

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Linear Passive Components
Resistor, inductor and Capacitor

Let us review some of their properties:

1. They may store energy or may convert it into heat.
2. They are LINEAR – the current through them is proportional to applied voltage across their terminals.
3. Their parameter values like resistance, capacitance and inductance does not change with value of applied voltage or current passing through them. In that sense their values are STATIC.

DIODE

In comparison, a DIODE is completely different than R, L and C:

1. It does not store energy. A very small amount of energy is converted into heat.
2. It is NON-LINEAR, i.e. current through diode is not linearly proportional to voltage across its terminals.
3. Its so called “resistance” is DYNAMIC in nature and its value changes based on “point of operation” on its I-V curve.

Actual DIODE Terminal Characteristics

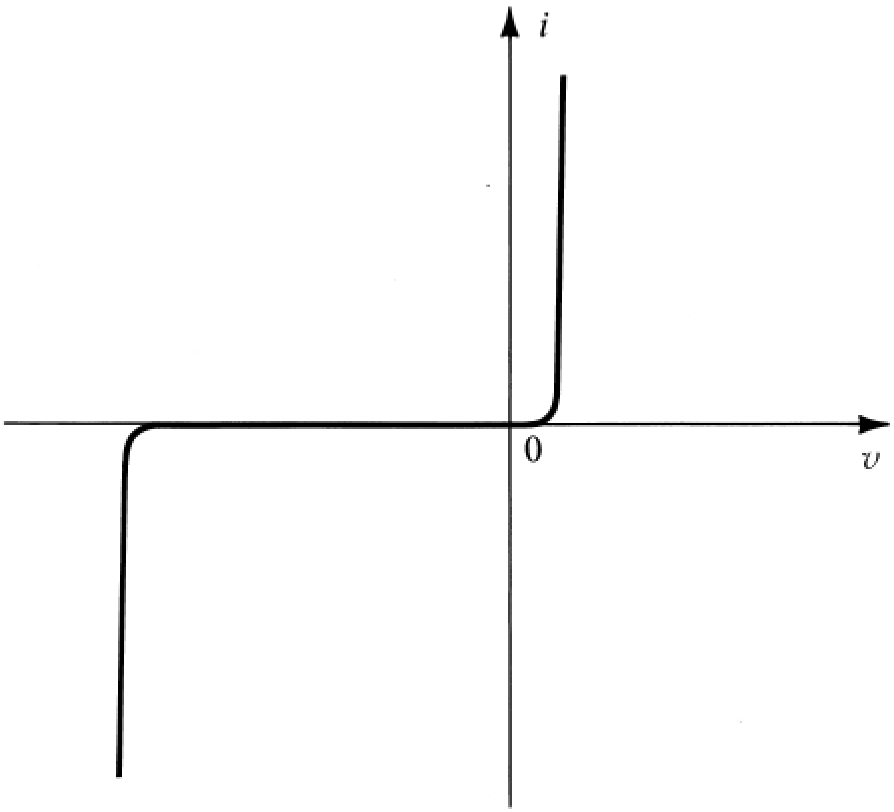

FIGURE 2.7 The i–v characteristic of a silicon junction diode.

For v> 0V, forward bias region, exponential curve

For v< 0V, reverse bias region, virtually open circuit or very high resistance.

For Vi< V_{zk}, breakdown region, constant voltage source.

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Converting Non-linear Diode Characteristics into simpler Linear Models..

1. There is a need for rapid analysis of diode based circuits which will quickly tell the designer whether the diode in the given circuit will be conducting or not and if yes, then approx. how much current will be there.
2. Such need created simpler linear models which approximated the actual diode behavior with an acceptable level of error say + or -5 %.
3. The designer first analyzed the circuit using approximate models. If found workable then detailed analysis was used for solving for currents.

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IDEAL DIODE
(behaves like a switch)

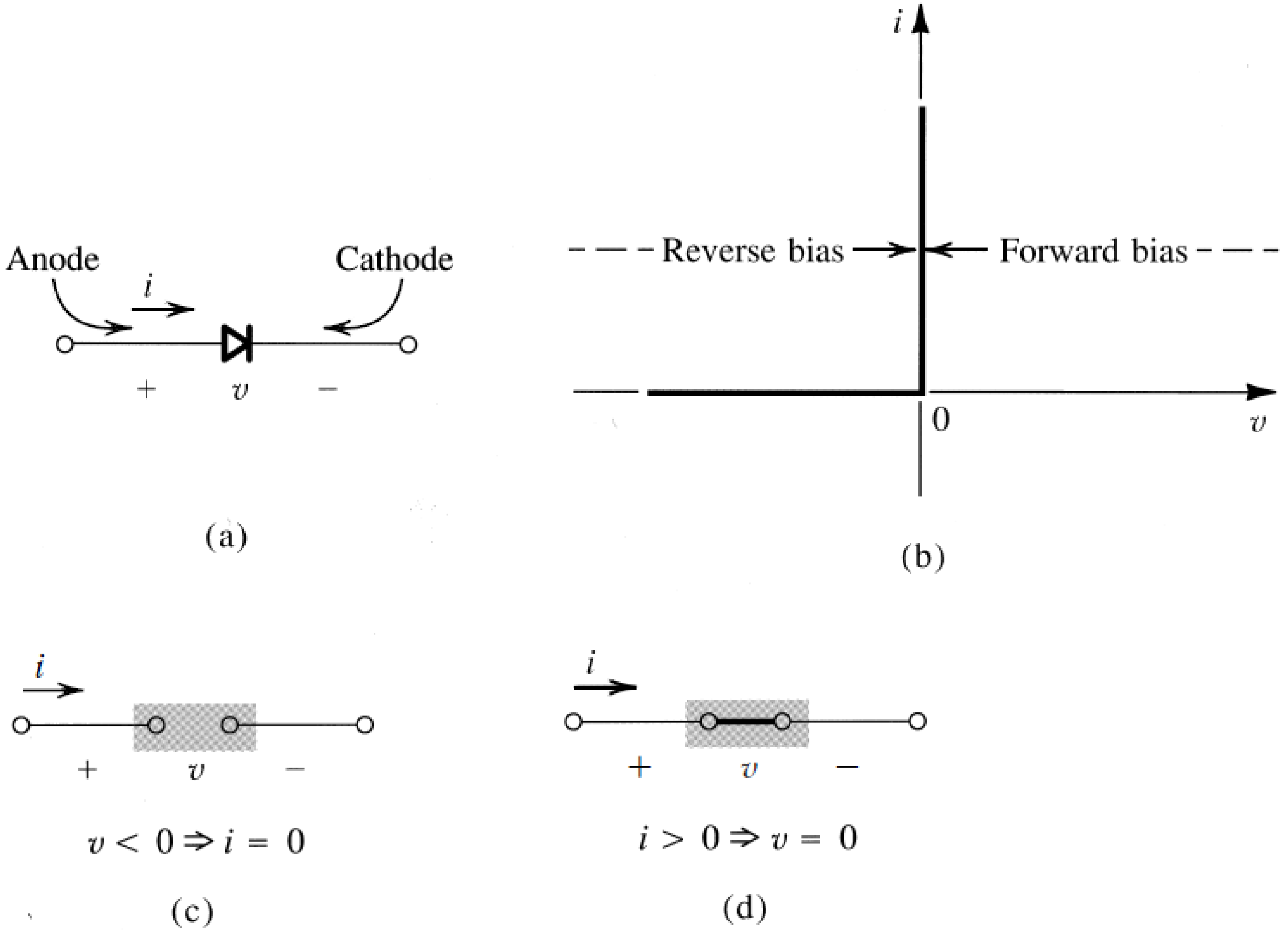

FIGURE 2.1 The ideal diode: (a) diode circuit symbol; (b) i–v characteristic; (c) equivalent cir reverse direction; (d) equivalent circuit in the forward direction.

- **In forward direction the diode behaves like a short circuit or the resistance is ZERO.**
- **In reverse direction it behaves like an open circuit or the resistance is INFINITY.**

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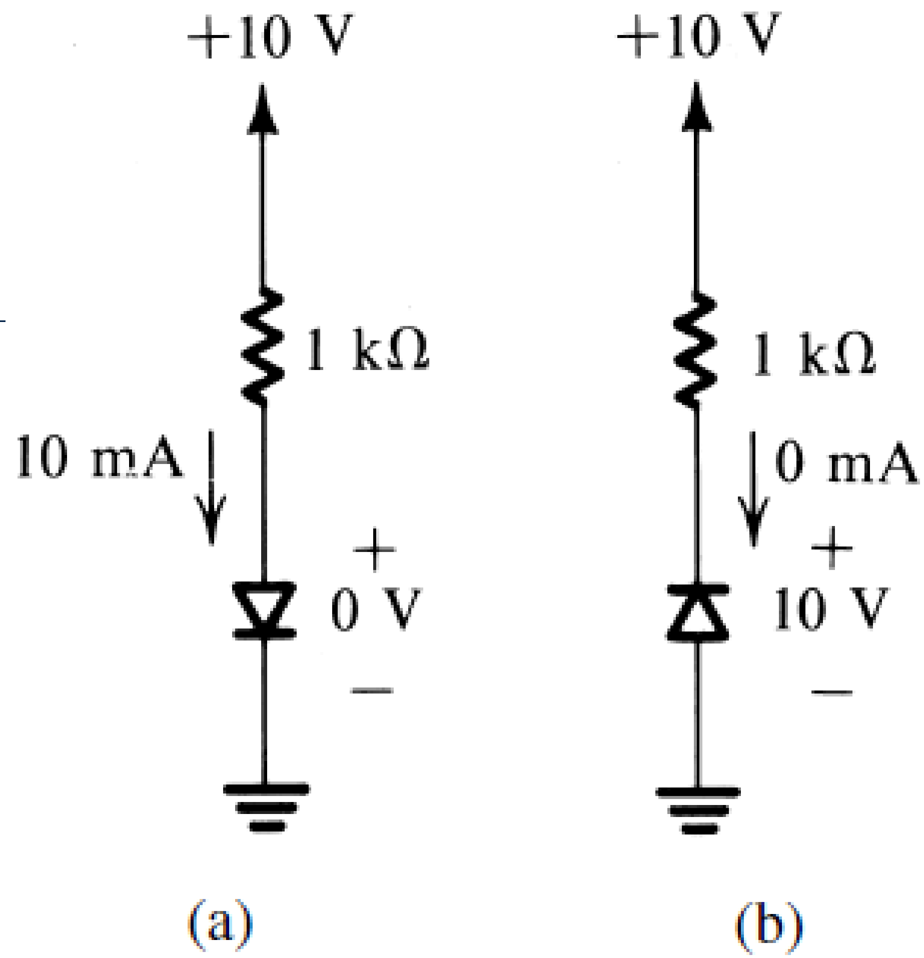

FIGURE 2.2 The two modes of operation of ideal diodes and the use of an external circuit to limit the forward current (a) and the reverse voltage (b).

(a) In forward direction, the voltage across diode is 0 and all of 10V appears across 1K so current is 10 mA.

(b) In reverse direction, since the resistance is infinity, all the 10V appears across diode, there is 0V across the 1K resistor and the current is ZERO.

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IDEAL DIODE as a RECTIFIER (converts AC into DC)

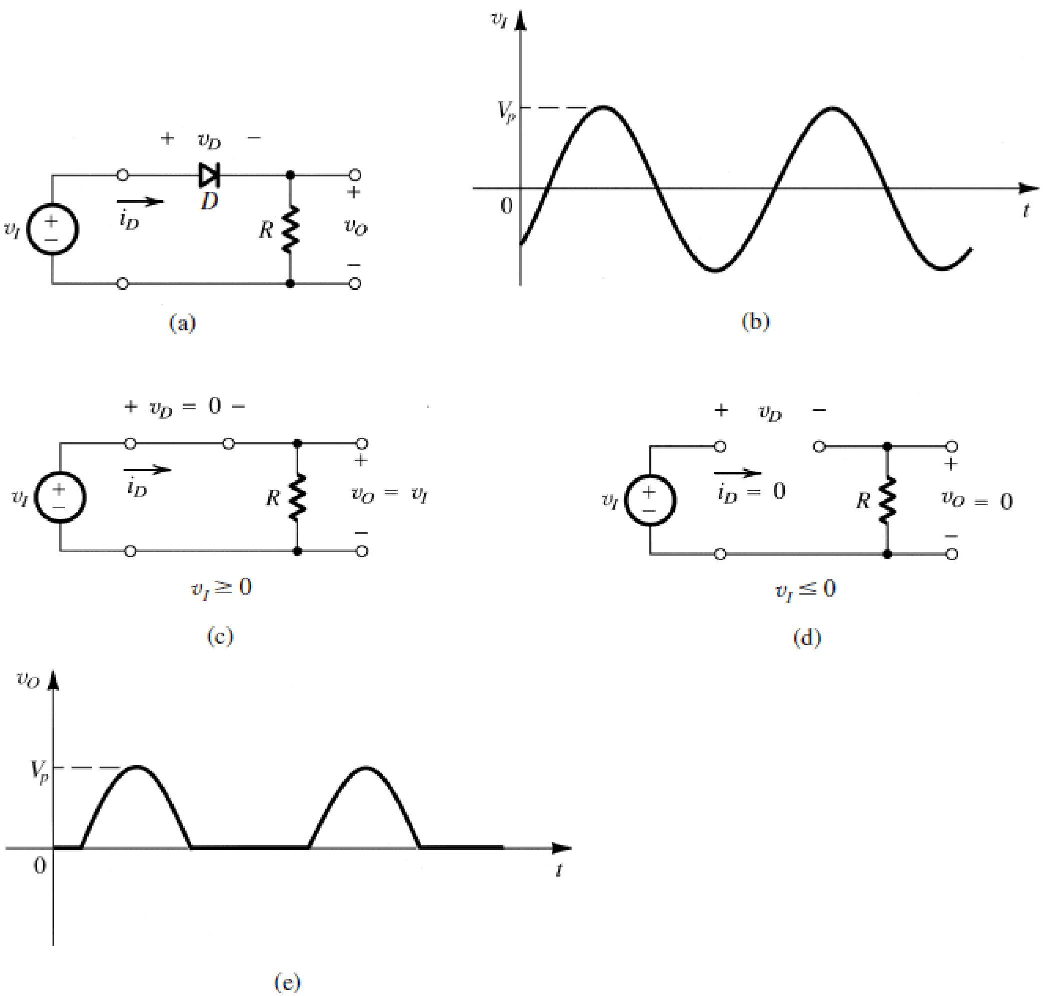

FIGURE 2.3 (**a**) Rectifier circuit. (**b**) Input waveform. (**c**) Equivalent circuit when $v_I \geq 0$. (**d**) Equivalent circuit when $v_I \leq 0$. (**e**) Output waveform.

- **During positive half cycle, the diode is forward biased and connects load R to source. Hence all of source voltage appears across the load.**
- **During negative half cycle, diode gets reverse biased and becomes open circuit. The load is isolated from source. The current is ZERO.**

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Q:For Circuit in Fig 2.3, Plot Transfer Characteristics Vo/Vi

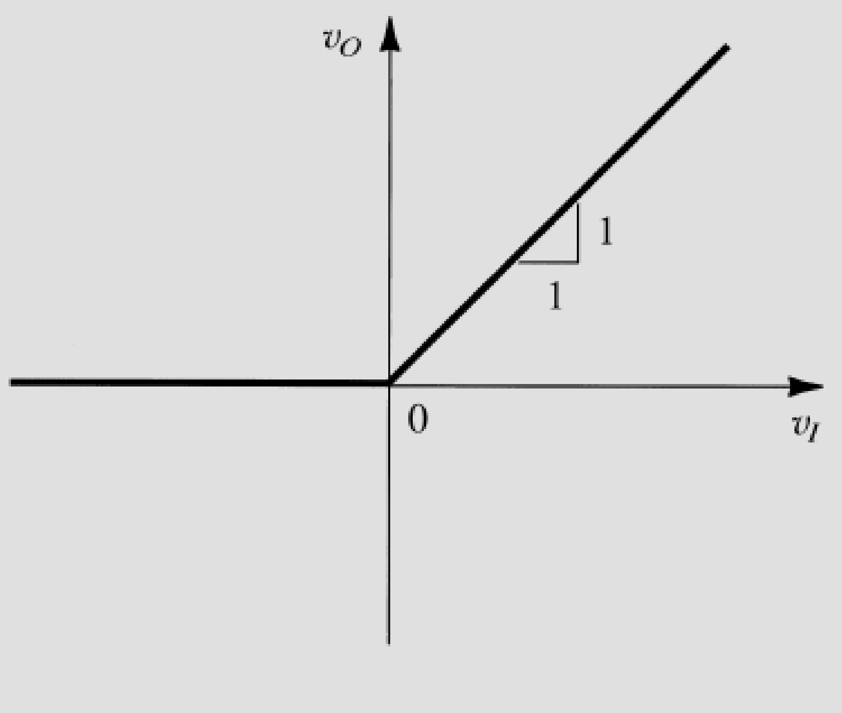

FIGURE E2.1

- For Vi> 0, positive half cycle, Vo= Vi and gain = 1. Slope = 1
- For Vi< 0, negative half cycle,
  Vo = 0 and
  Gain = Slope = 0.

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Q:For Circuit in Fig 2.3, Plot voltage across diode Vd.

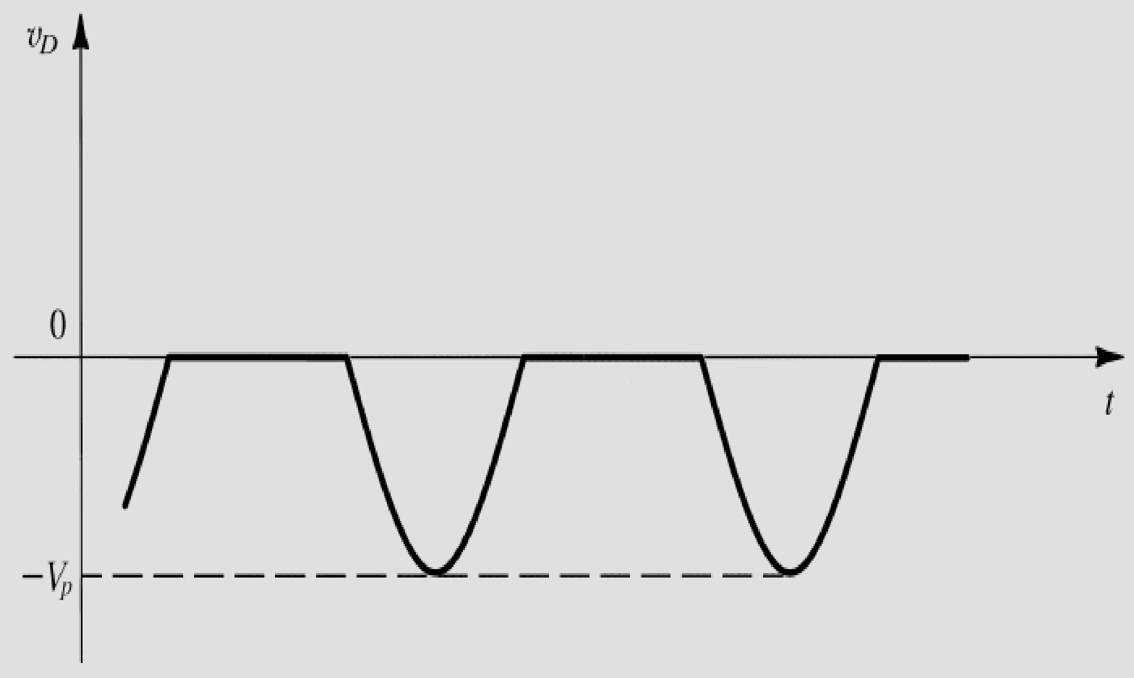

FIGURE E2.2

For Vi> 0, positive half cycle, short circuit, diode voltage

Vd = 0

For Vi< 0, negative half cycle, open circuit,

Vd = Vi-Vo = Vi- 0 = Vi.

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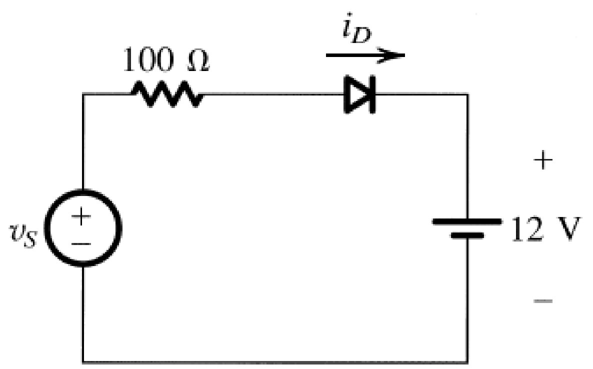
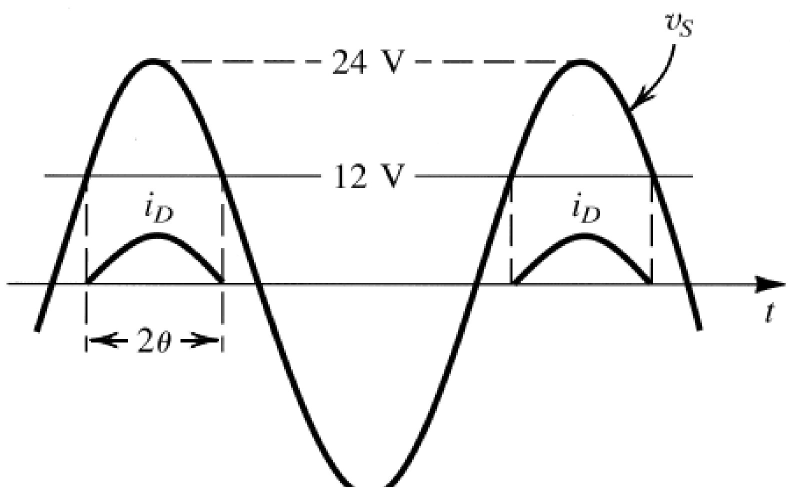
Q: Plot current Id in diode circuit

A: When (input voltage > 12V), diode shorts and current flows Id = (Vs- 12V)/ 100 otherwise diode is open and Id = 0.





The diode conducts when Vs exceeds 12 V, as shown in Fig. The conduction angle is 2ϴ, given by

$$24 \cos\theta = 12$$

Thus $\theta = 60°$ and the conduction angle is 120°, or one-third of a cycle.

The peak value of the diode current is given by

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

The maximum reverse voltage across the diode occurs when v_S is at its negative peak and is equal to $24 + 12 = 36$ V.

Q:Find V and I in each case

Hint: (Find out whether diode is on or off. Use ideal diode model)

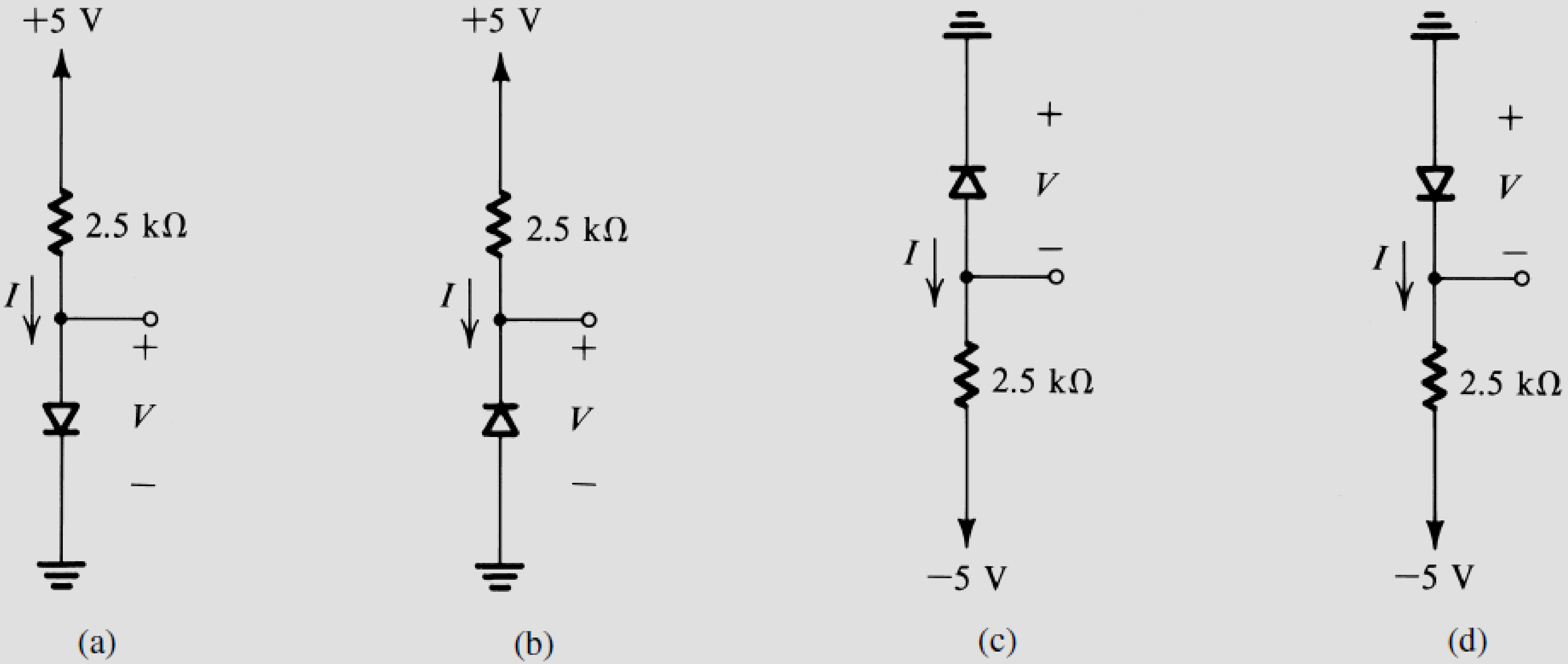


FIGURE E2.4

contd

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(a) 2 mA, 0 V

(b) 0 mA, 5 V

(c) 0 mA, 5 V

(d) 2 mA, 0 V

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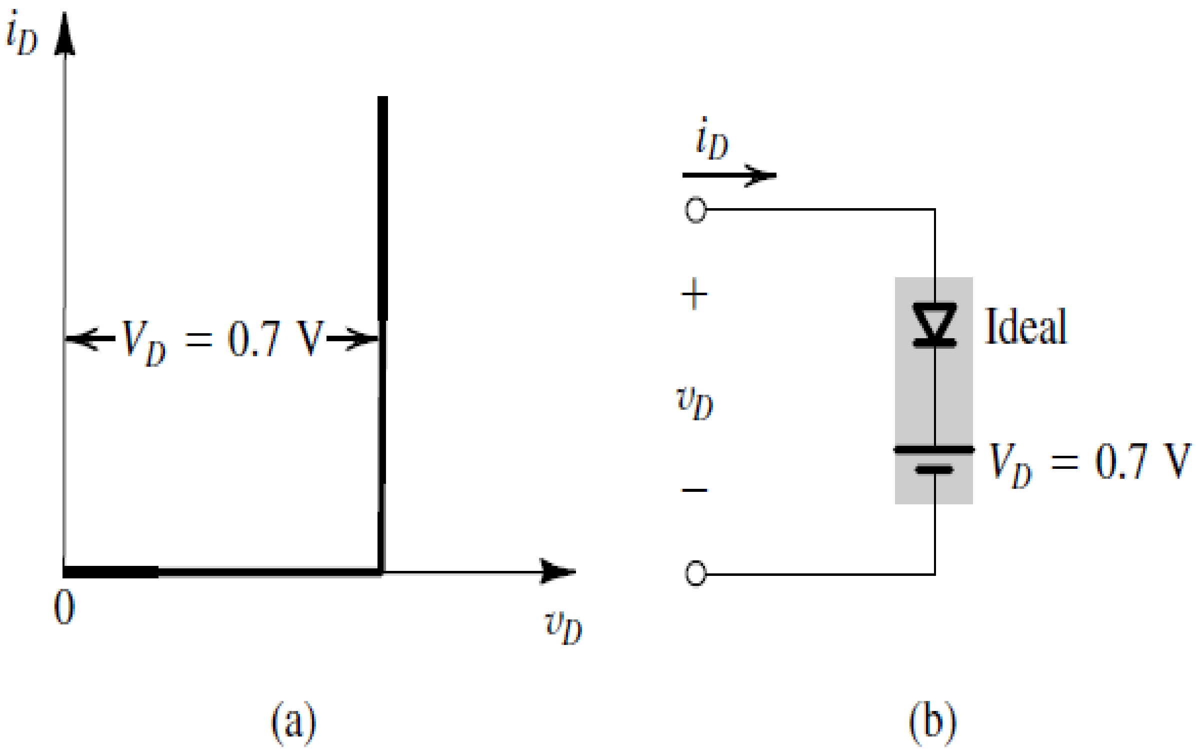
NON- IDEAL DIODE

Model – Constant Voltage Drop (behaves like a switch with offset voltage created by a battery)



For Vi> 0.7V (Cut-in voltage) diode behaves like short circuit

For Vi< 0.7V, diode behaves like open circuit.

FIGURE 2.16 The constant-voltage-drop model of the diode forward characteristics and its equivalent-circuit representation.

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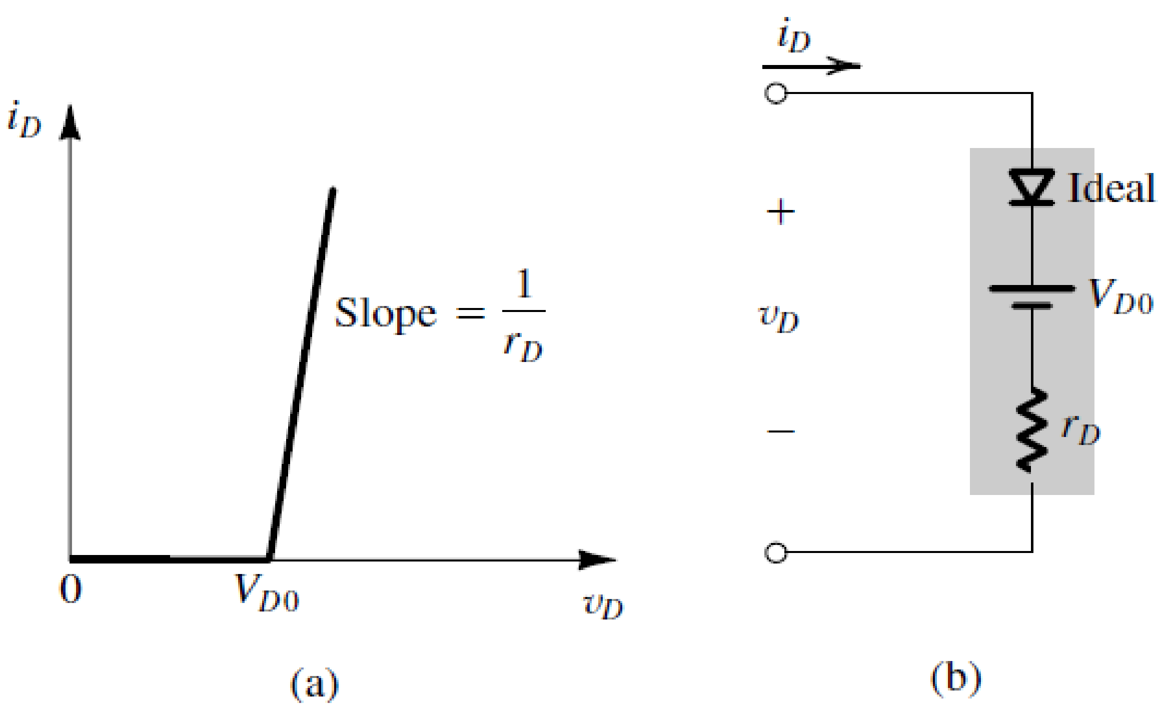
NON- IDEAL DIODE Model – II

Model – Piecewise Linear (behaves like a switch with battery and a small resistor)



For Vi> 0.7V (Cut-in voltage) diode behaves like a small resistor

For Vi< 0.7V, diode behaves like open circuit.

FIGURE 2.13 Piecewise-linear model of the diode forward characteristic and its equivalent circuit representation.

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Actual characteristics vs. piecewise linear model

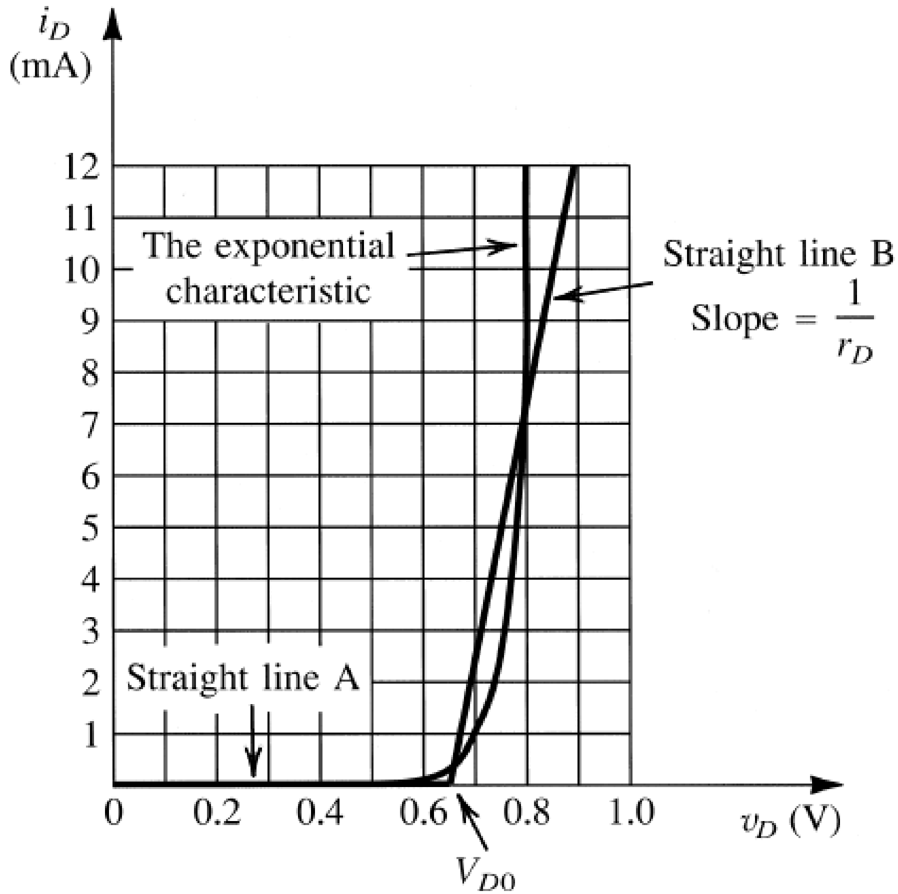

FIGURE 2.12 Approximating the diode forward characteristic with two straight lines: the piecewise-linear model.

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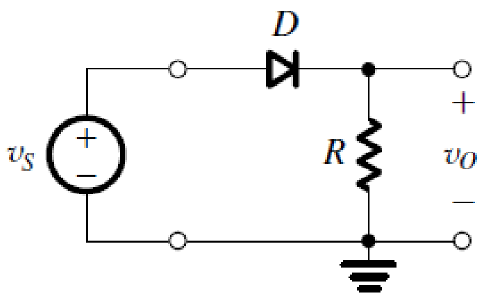
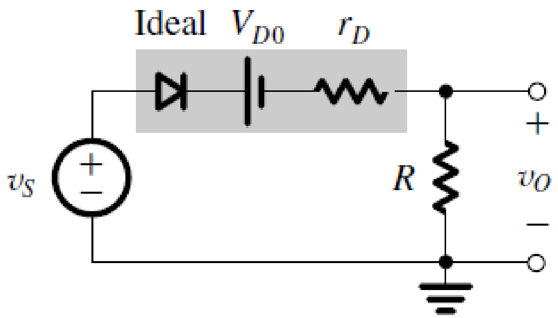
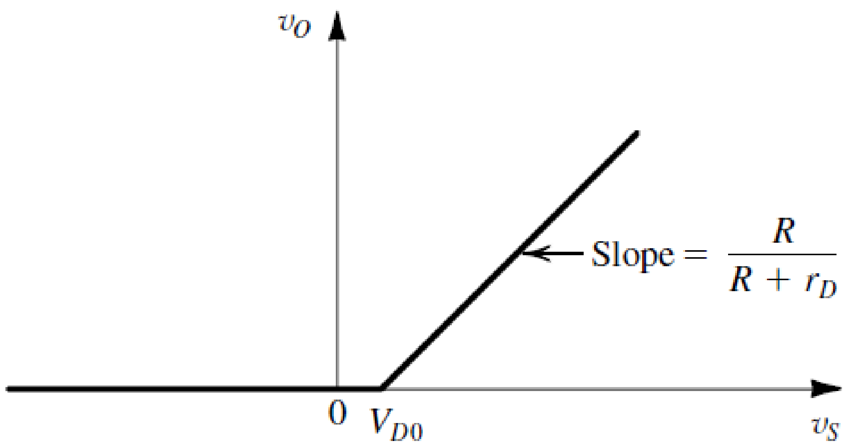
NON- IDEAL DIODE as a RECTIFIER (converts AC into DC)



(a)



(b)



(c)

Now the source voltage is shared by load resistor R and diode resistance rd.

The transfer characteristics slope is less than 1.

Cut-in begins at Vdo and not at 0V.

contd

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NON- IDEAL DIODE as a RECTIFIER (converts AC into DC)

contd

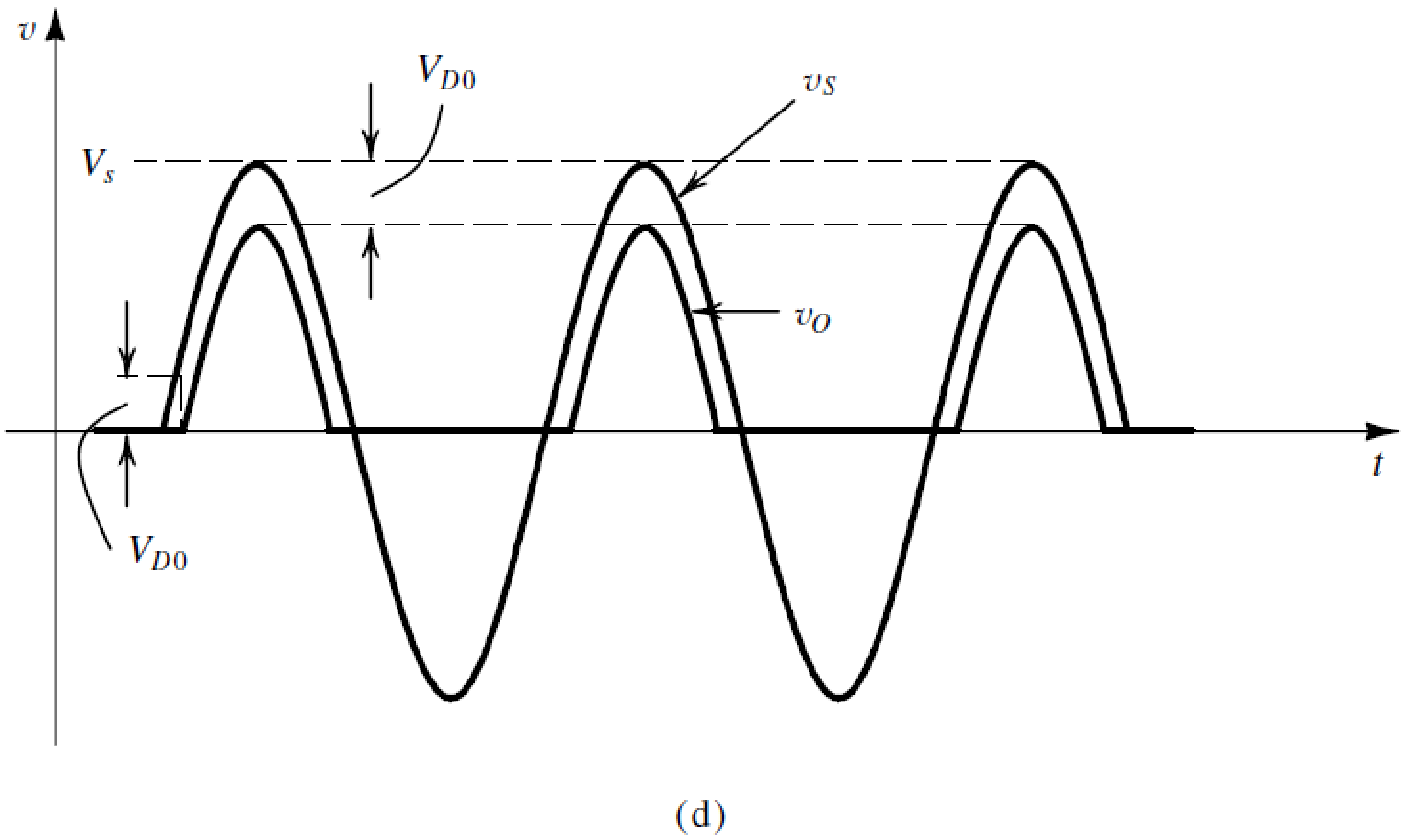

FIGURE 2.25 (a) Half-wave rectifier. (b) Equivalent circuit of the half-wave rectifier with the diode replaced with its battery-plus-resistance model. (c) Transfer characteristic of the rectifier circuit. (d) Input and output waveforms, assuming that $r_D \ll R$.

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Actual DIODE Terminal Characteristics (studied in detail)

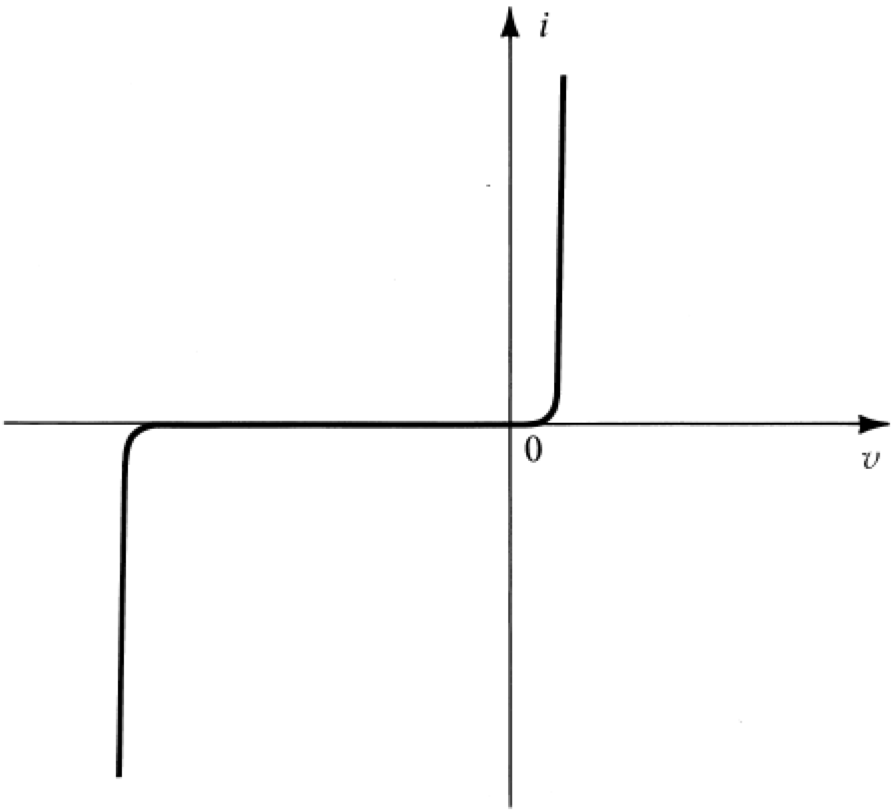

FIGURE 2.7 The i–v characteristic of a silicon junction diode.

For v> 0V, forward bias region, exponential curve

For v< 0V, reverse bias region, virtually open circuit or very high resistance.

For Vi< V_{zk}, breakdown region, constant voltage source.

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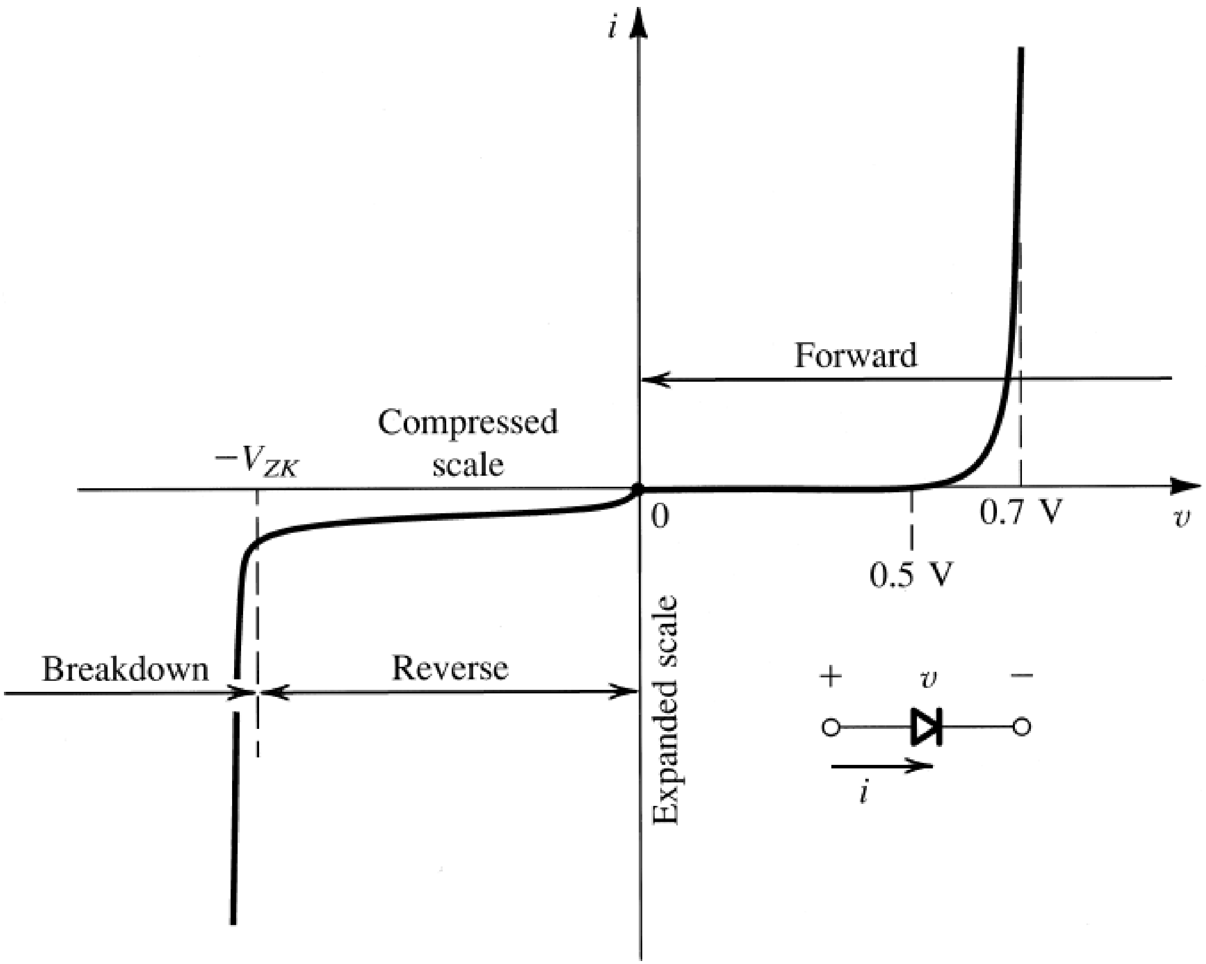
DIODE Terminal Characteristics

(X-axis expanded on positive side and compressed on negative side)



For 0<Vi < 0.5V, negligible current

For 0.5<Vi exponentially rising current

For 0 > Vi > -Vzk, reversed bias leakage current

For Vzk >Vi, constant terminal voltage.

FIGURE 2.8 The diode i–v relationship with some scales expanded and others compressed in order to reveal details.

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DIODE Terminal Characteristics (Forward Bias Region)

When diode is forward biased i.e. anode voltage is > cathode voltage then i-v relationship is approximated by:

$$i = I_s \left(\exp(v / n{*}V_T) - 1 \right)$$

- where I_s is called as Saturation Current which is constant for a given diode at a given temperature.
- V_T = constant (kT/q) called as Thermal Voltage
- N = constant 1 or 2 depending upon construction.

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DIODE Terminal Characteristics (Forward Bias Region)

1. Is is of the order of 10 ^ (-15) Amps or 0.001 pico A.
2. Is doubles every 5 deg C rise in temperature.
3. At room temperature 25 deg C, V_T = 25.8 mV but we take it as 25 mV for simplicity.
4. For I >> Is, we can approximate it further as

$$i = I_s \exp(v / n*V_T) \quad \text{or}$$

$$V = n\, V_T \ln (i / I_s)$$

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DIODE Terminal Characteristics (Forward Bias Region)

1. If v1 is diode voltage and current is i1 then

$$I1 = Is \exp (V1 / n * V_T)$$

2. If v2 is diode voltage and current is i2 then

$$I2 = Is \exp (V2 / n * V_T)$$

3. Dividing I2 by I1 we get,

$(I2 / I1) = \exp ((V2-V1) / (n * V_T))$ taking log,

$V2-V1 = n\, VT \ln (I2/I1)$ i.e. for a decade change in current, the diode voltage drop changes only 60mV or 120 mV depending upon n = 1 or 2.

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Temperature Dependence of DIODE Terminal characteristics (Forward Bias Region)

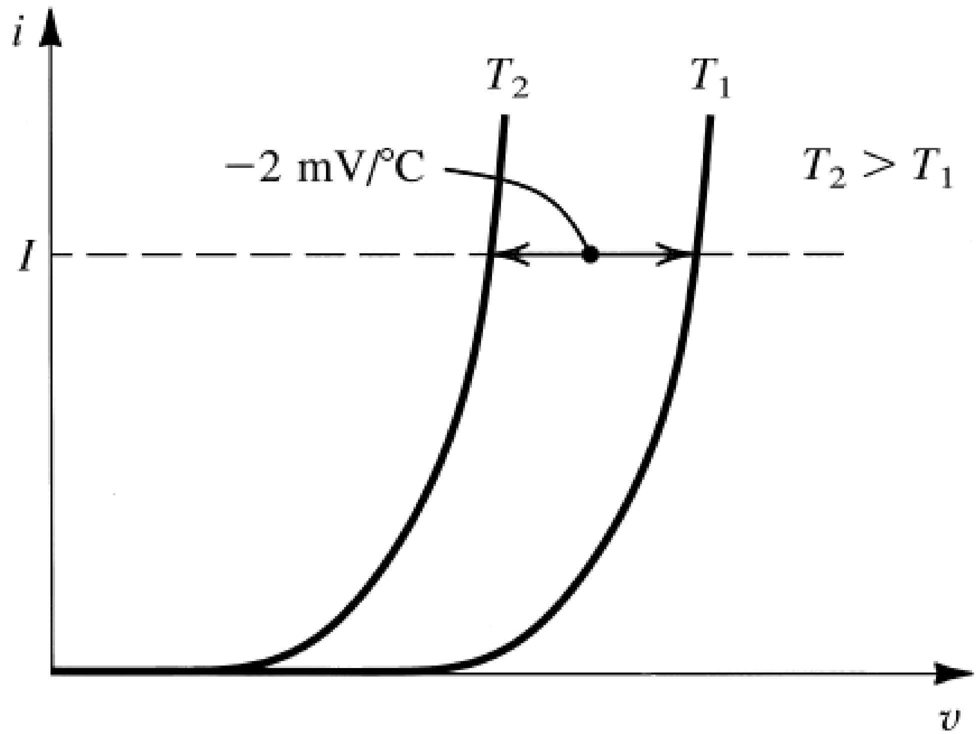

FIGURE 2.9 Illustrating the temperature dependence of the diode forward characteristic. At a constant current, the voltage drop decreases by approximately 2 mV for every 1°C increase in temperature.

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DIODE Terminal Characteristics (Reverse Bias Region)

When diode is reversed biased i.e. anode voltage is < cathode voltage i.e. if v is negative and larger than V_T or 25 mV then exponential term becomes negligible and 1 predominates. Then i-v relationship is approximated by:

$$i = -Is$$

The current in reverse direction is constant and is called Saturation Current. It is of the order of 0.001 pico amps to 1 nA. Also called as Leakage Current.

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3.3 For the circuits shown in Fig. P3.3 using ideal diodes, find the values of the labeled voltages and currents.

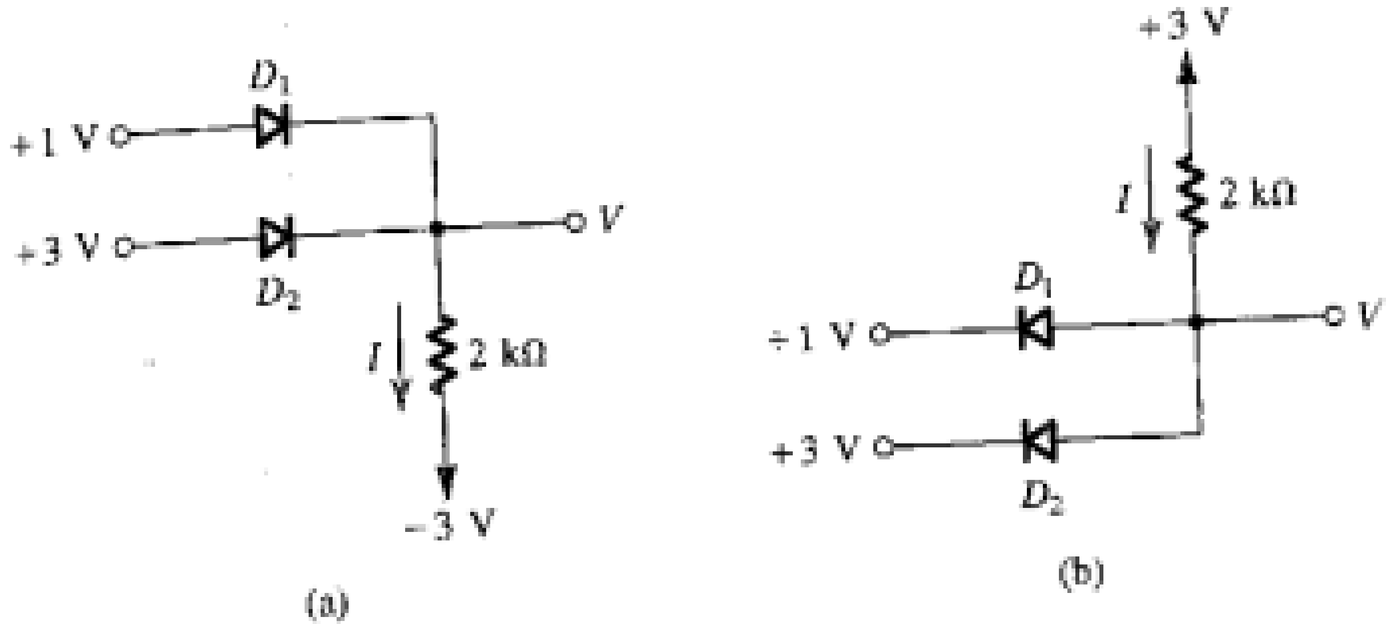

FIGURE P3.3

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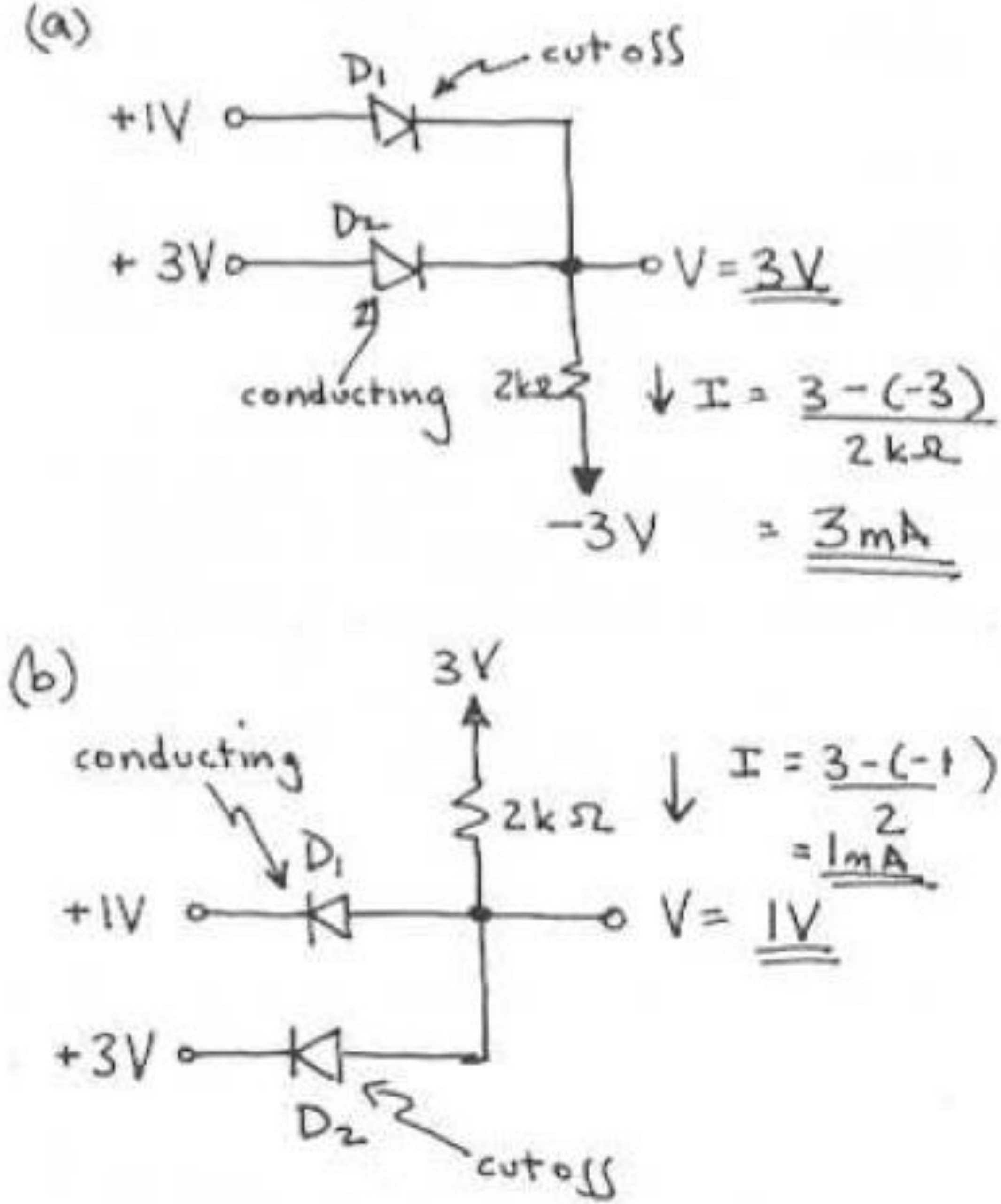

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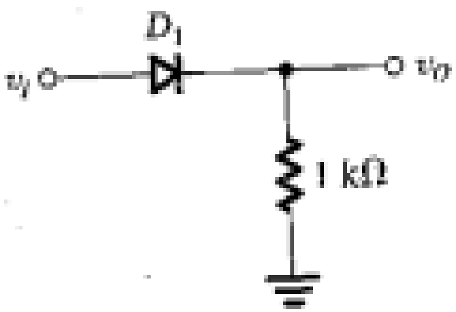
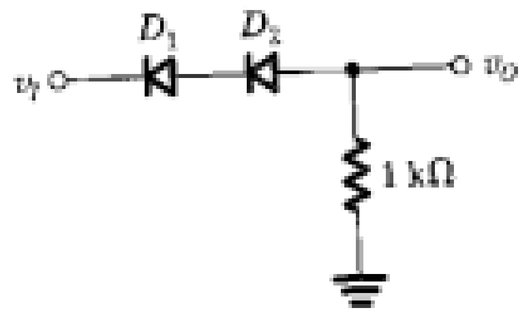
3.4 In each of the ideal-diode circuits shown in Fig. P3.4, v_I is a 1-kHz, 10-V peak sine wave. Sketch the waveform resulting at v_O. What are its positive and negative peak values?

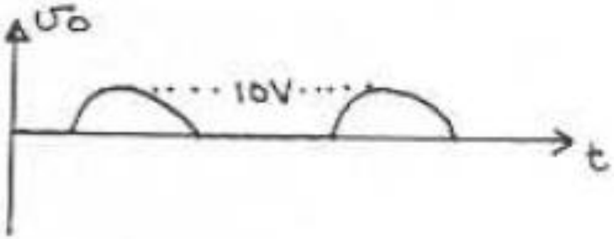


(a)



(b)

(a)



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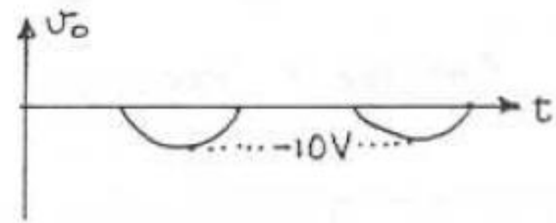

$V_{p+} = \underline{\underline{10V}}$ $\quad V_{p-} = \underline{\underline{0V}}$

$f = 1kHz.$

$V_{p+} = \underline{\underline{0V}}$ $\quad V_{p-} = \underline{\underline{-10V}}$

$f = 1kHz$

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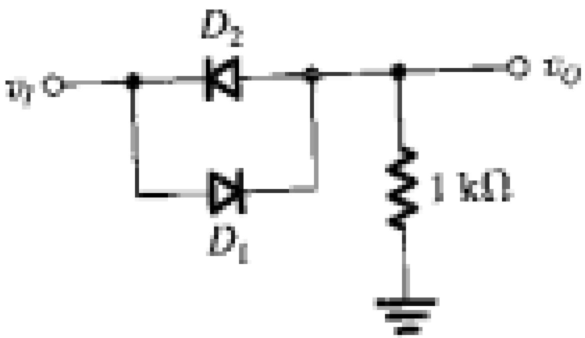
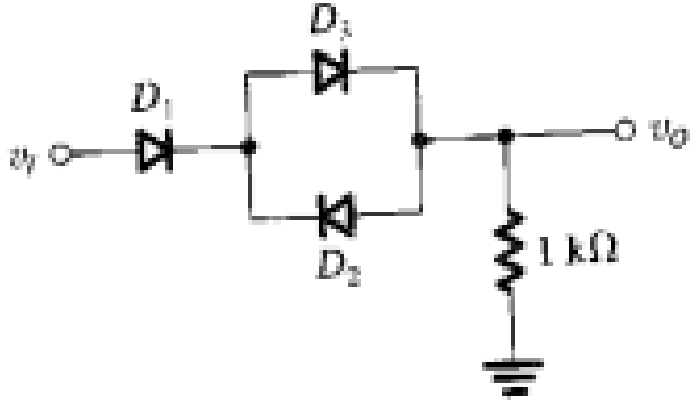
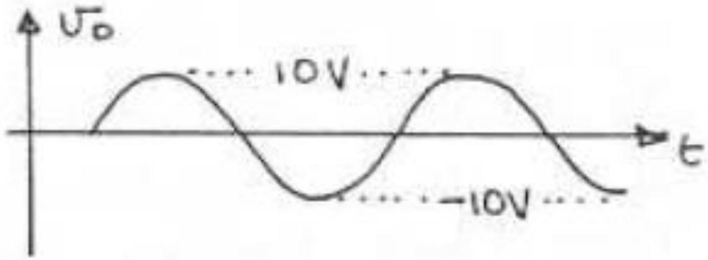


(e)



(f)

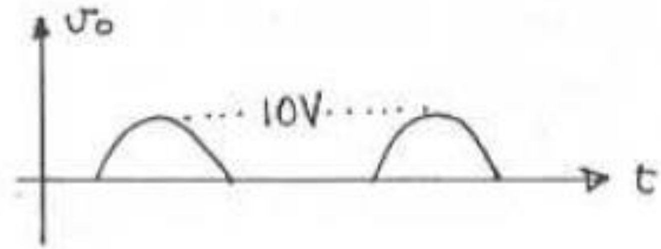
(e)



$V_{p+} = \underline{\underline{10V}}$ $V_{p-} = \underline{\underline{-10V}}$ $f = 1\,kHz$

D_1 conducts when $v_I > 0$ and D_2 conducts when $v_I < 0$. Thus the output follows the input.

(f)



$V_{p+} = \underline{\underline{10V}}$ $V_{p-} = \underline{\underline{0V}}$ $f = 1\,kHz$

- D_1 is cutoff when $v_I < 0$

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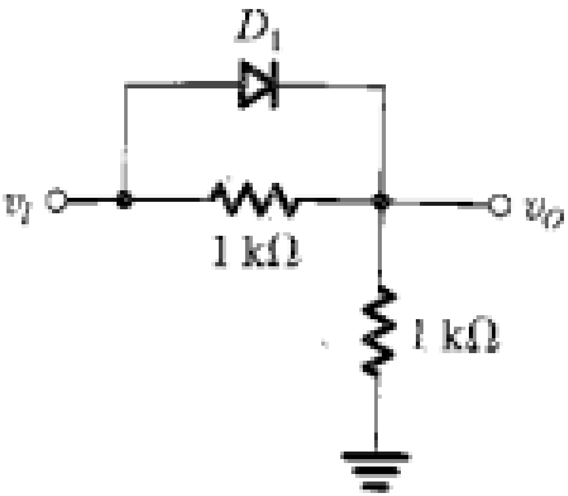
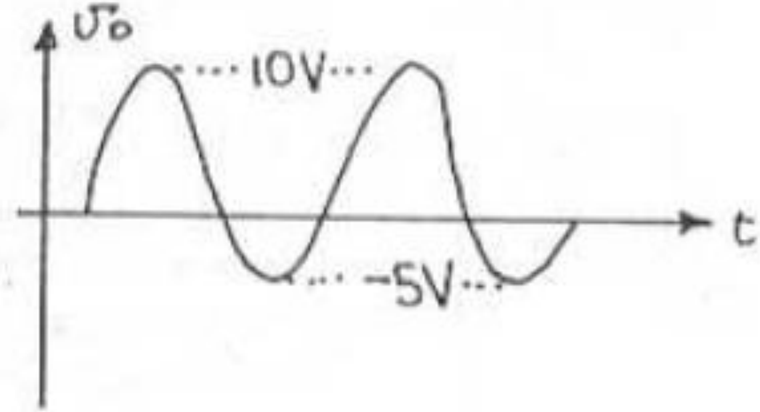


(j)

(j)



$V_{p+} = \underline{\underline{10V}}$ $V_{p-} = \underline{\underline{-5V}}$ $f = 1kHz$

- When $v_I > 0$, the output follows the input as D_1 is conducting.
- When $v_I < 0$, D_1 is cut off and the circuit becomes a voltage divider.

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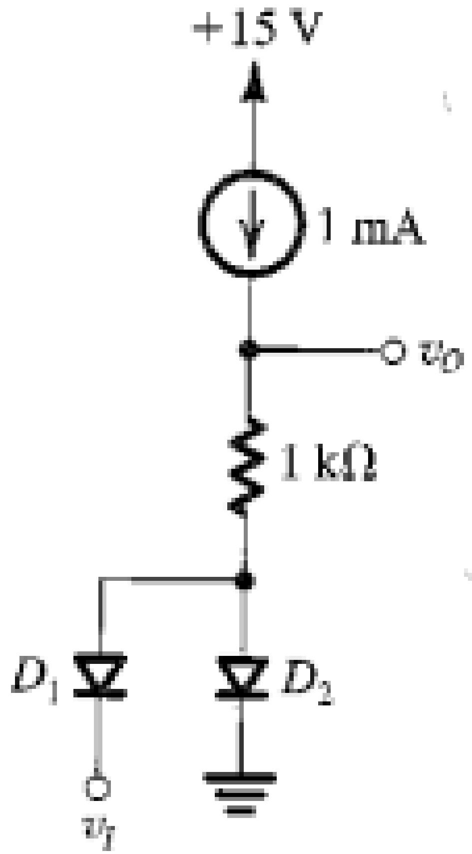
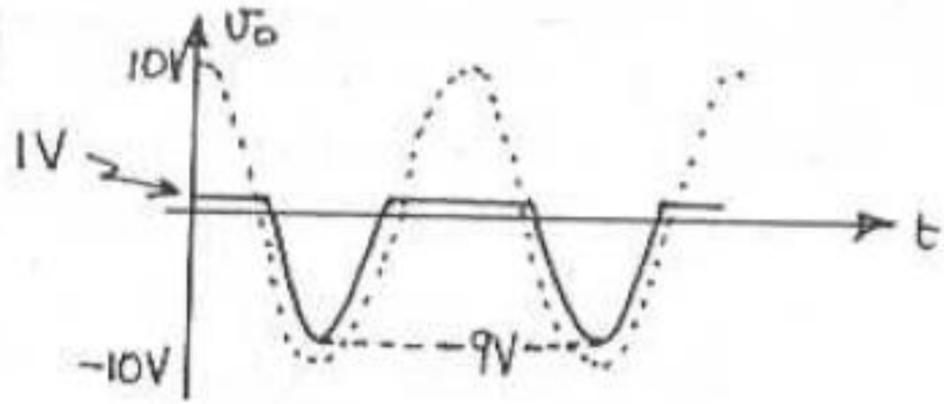


(k)

(k)



$V_{p+} = \underline{\underline{1V}}$ $V_{p-} = -\underline{\underline{9V}}$ $f = 1kHz$

- When $v_I > 0$, D_1 is cutoff and D_2 is conducting. The output becomes 1V.
- When $v_I < 0$, D_1 is conducting and D_2 is cutoff. The output becomes :-

$$v_O = v_I + 1V .$$

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DIODE Small Signal Model

- Since Diode exhibits a non-linear characteristics, we can calculate diode “resistance” at different points of curve by calculating slope of curve as

Dynamic resistance rd = delta v / delta i

which comes to

$$R_d = n\,V_T / I_D$$

- Note resistance is inversely proportional to diode current.

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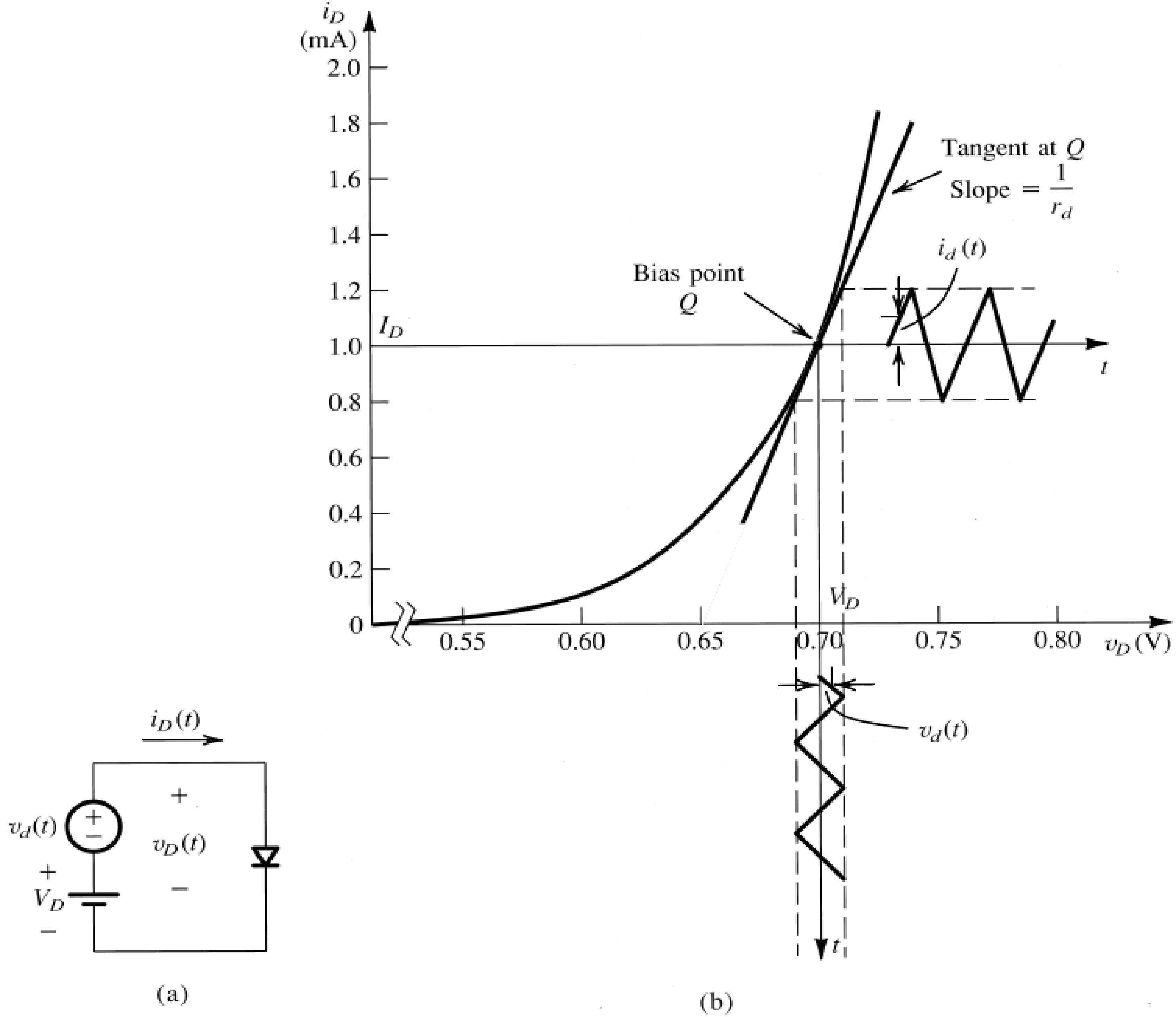

FIGURE 2.17 Development of the diode small-signal model. Note that the numerical values shown are for a diode with $n = 2$.

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Determining Diode Current graphically

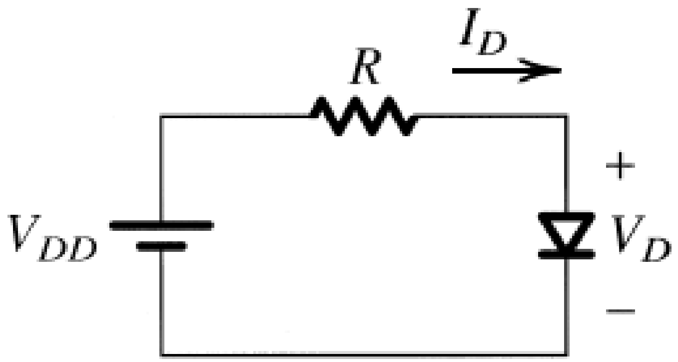

FIGURE 2.10 A simple circuit used to illustrate the analysis of circuits in which the diode is forward conducting.

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

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

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Determining Diode Current graphically

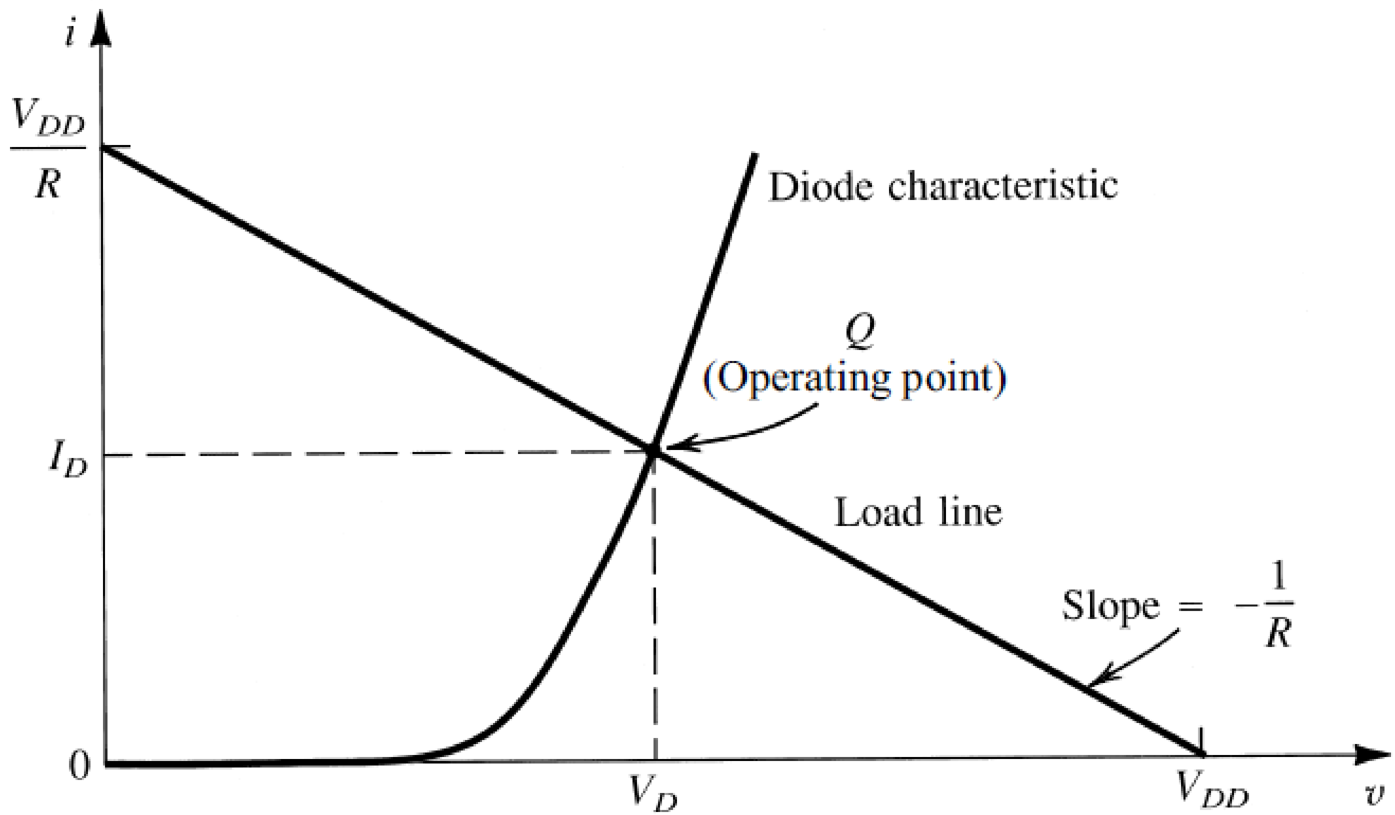

FIGURE 2.11 Graphical analysis of the circuit in Fig. 2.10 using the exponential diode model.

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Zener DIODE

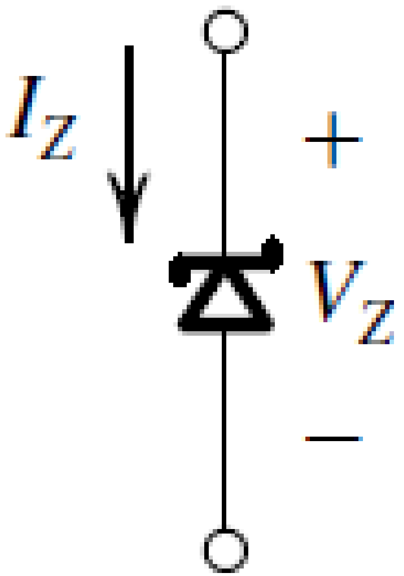

FIGURE 2.20 Circuit symbol for a Zener diode.

1. In breakdown region, diode exhibits a very steep curve of i-v characteristics similar to a voltage source.
2. In Zener diode, current flows into Cathode and leaves Anode.
3. Manufacturer specifies Zener voltage at a specific test current. Say 2.7V @ 10 mA. That will define a dynamic resistance Rz of 2.7V/ 0.010 A = 270 ohms.

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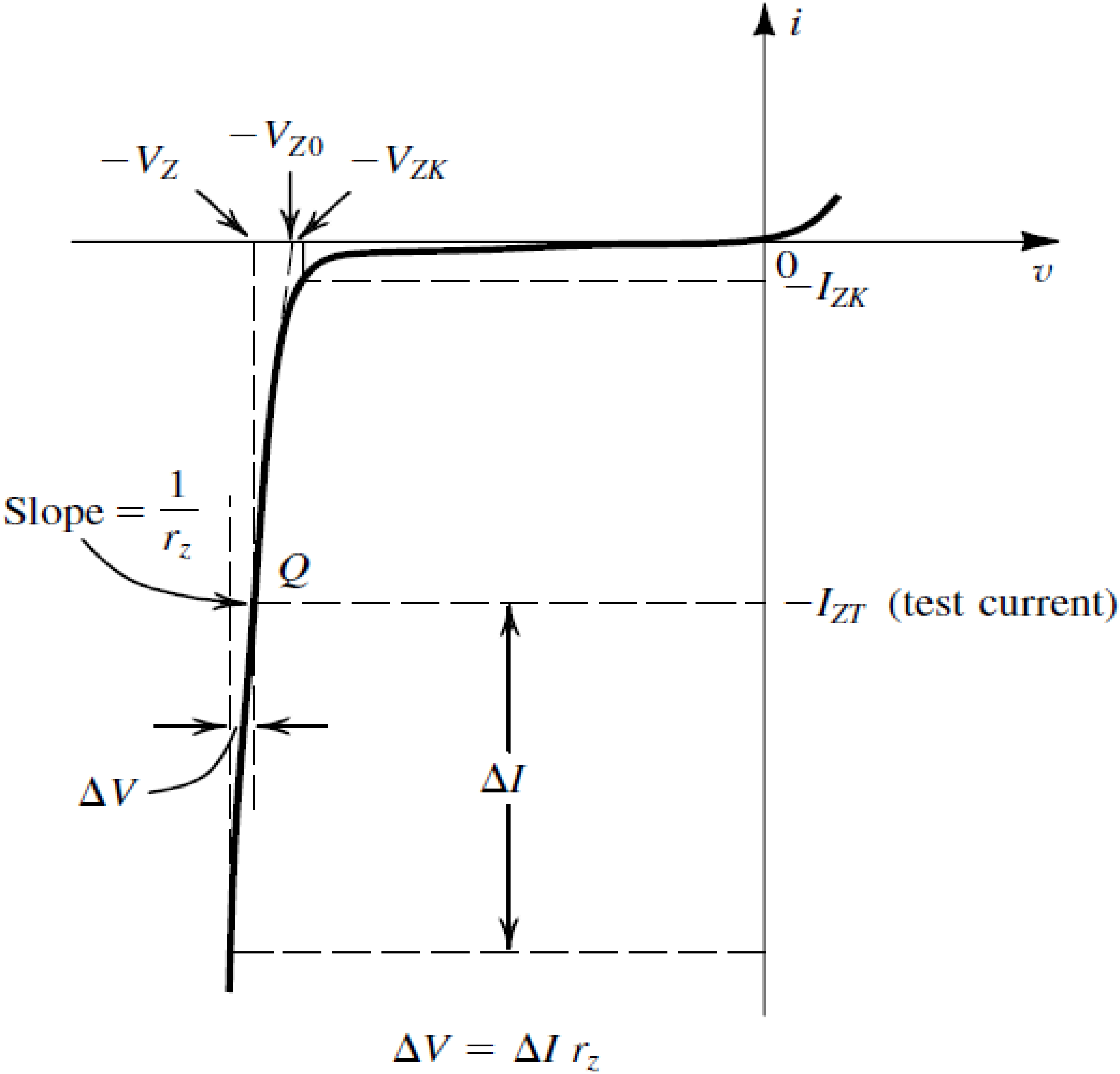

1. Zener diodes are fabricated for few volts to few hundred volts.
2. Max. power dissipation (Vz x Iz) is also specified.
3. Model includes a battery of voltage Vz and resistance Rz.

FIGURE 2.21 The diode i–v characteristic with the breakdown region shown in some detail.

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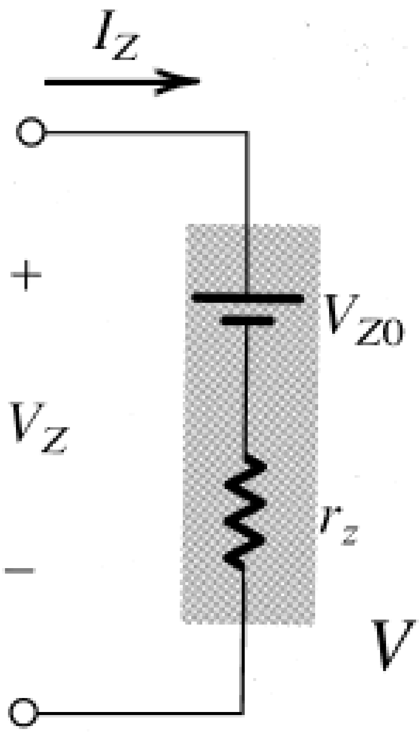
Piecewise Linear Model for Zener DIODE



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

FIGURE 2.22 Model for the zener diode.

Very similar to Diode model except that:

1. Voltage source direction is reversed and value could be anything as manufactured.
2. Resistance Rz value range very wide due to steep slope.

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Application of Diodes in a Regulated Power Supply

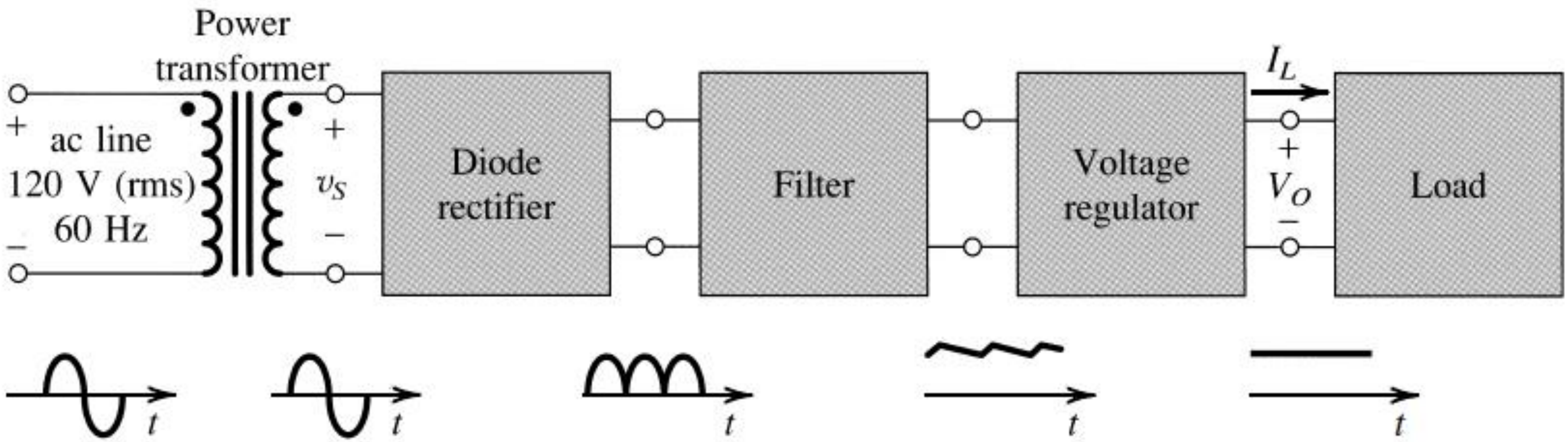

FIGURE 2.24 Block diagram of a dc power supply.

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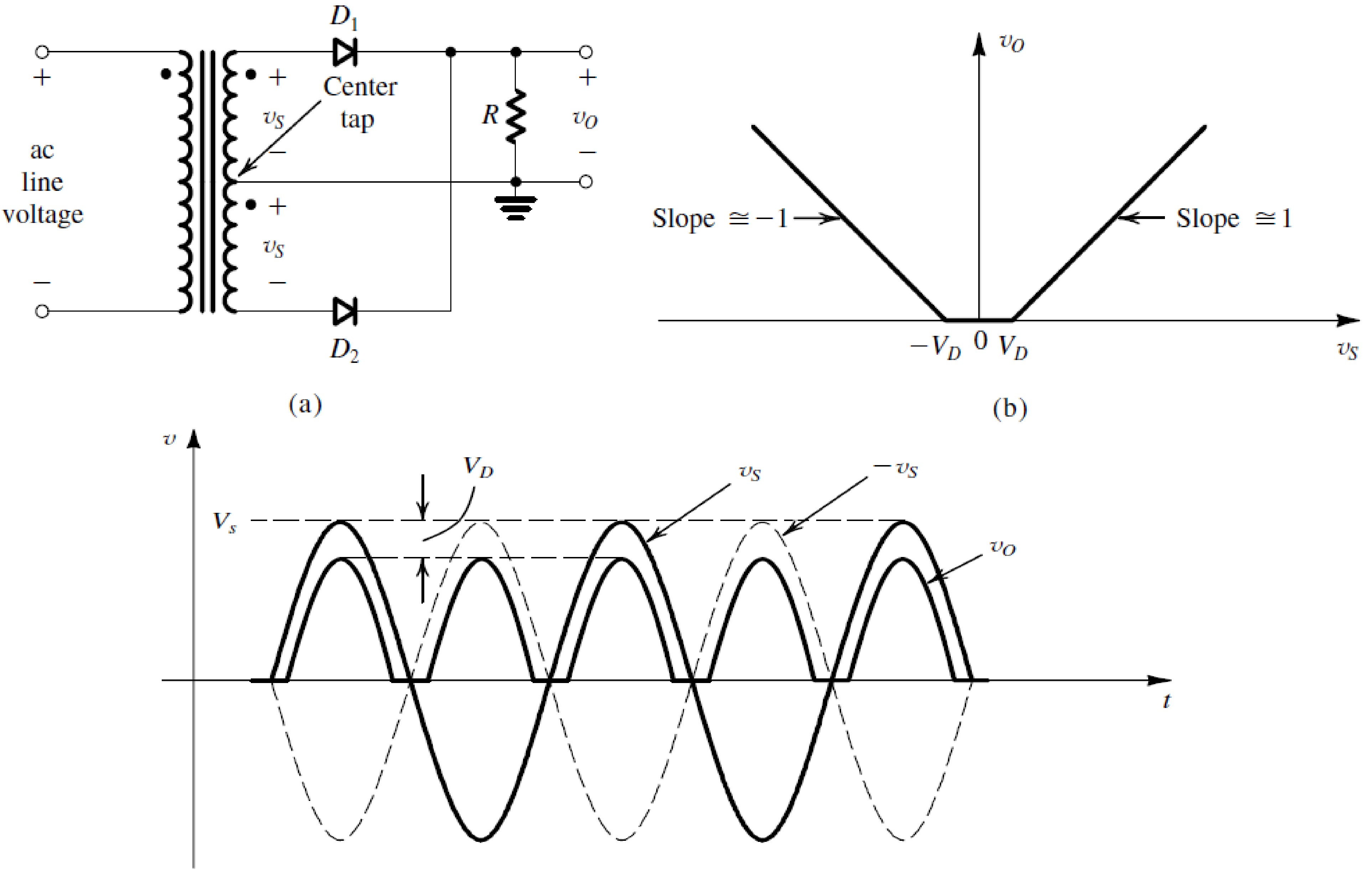

FIGURE 2.26 Full-wave rectifier utilizing a transformer with a center-tapped secondary winding: (a) circuit; (b) transfer characteristic assuming a constant-voltage-drop model for the diodes; (c) input and output waveforms.

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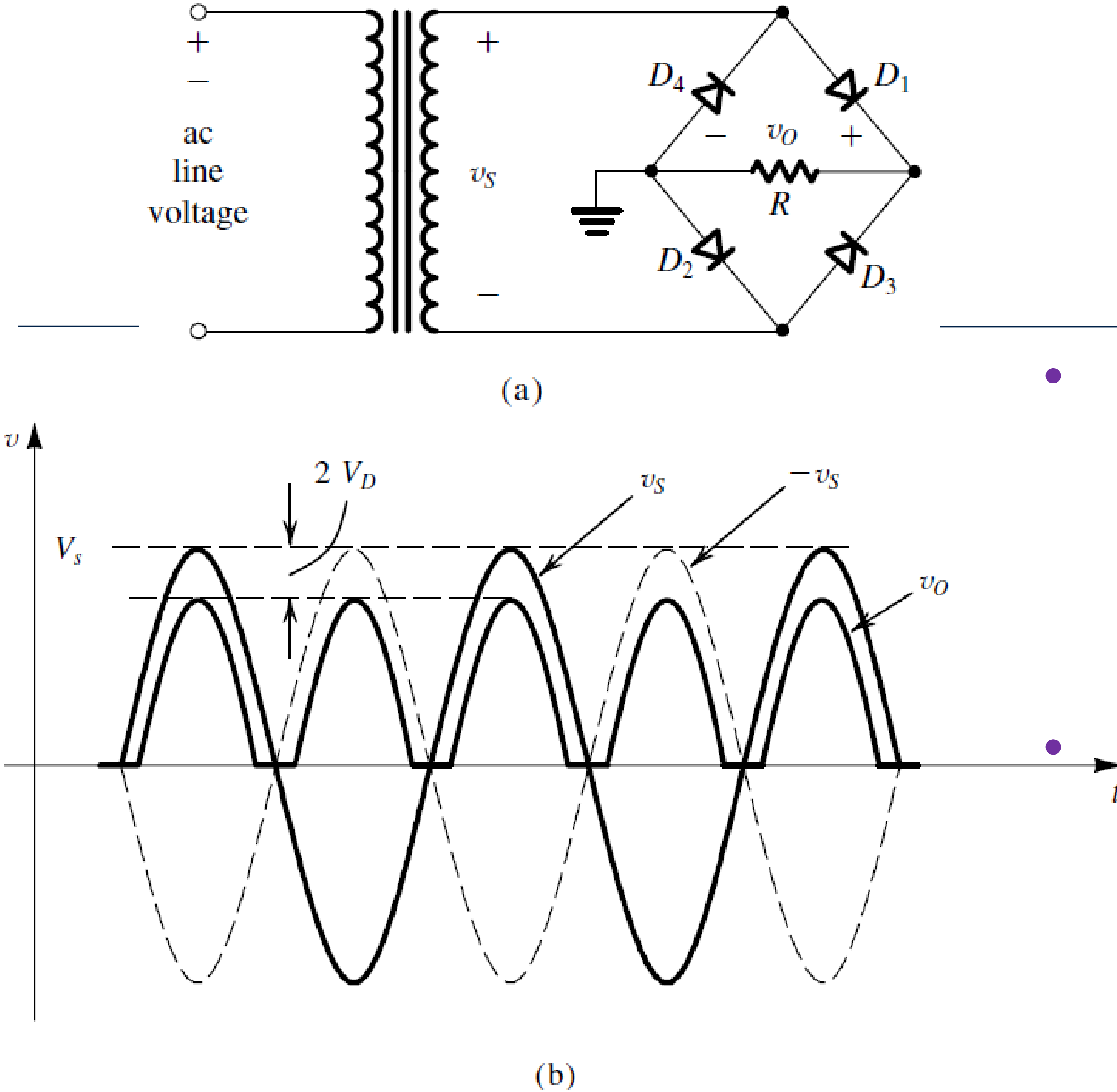

- Note 2 diode drop between input peak and output peak.
- Note both halves of sinusoid are converted into DC.

FIGURE 2.27 The bridge rectifier: (a) circuit; (b) input and output waveforms.

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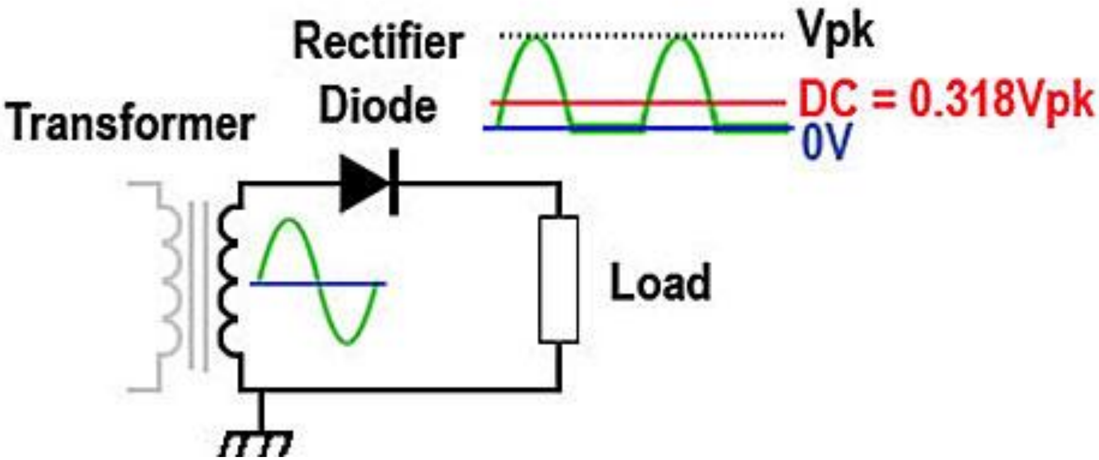
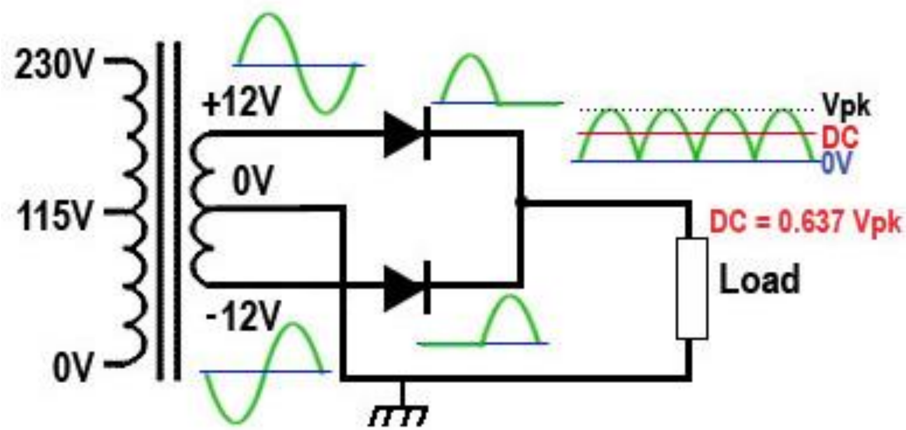
Half Wave Rectification



Full Wave Rectification



The Bridge Rectifier

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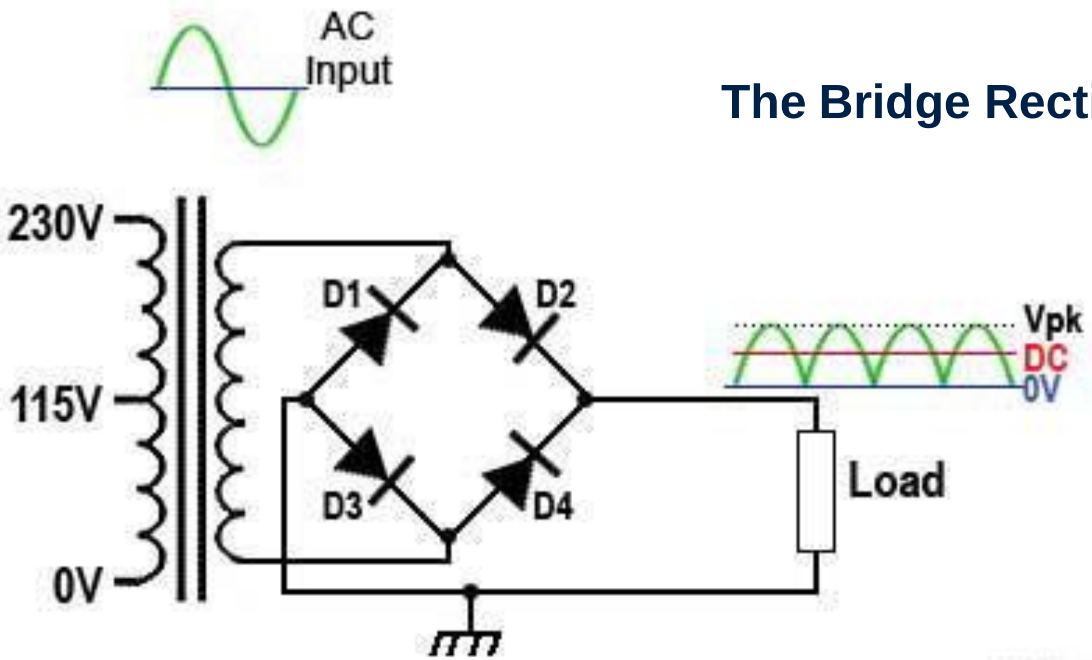

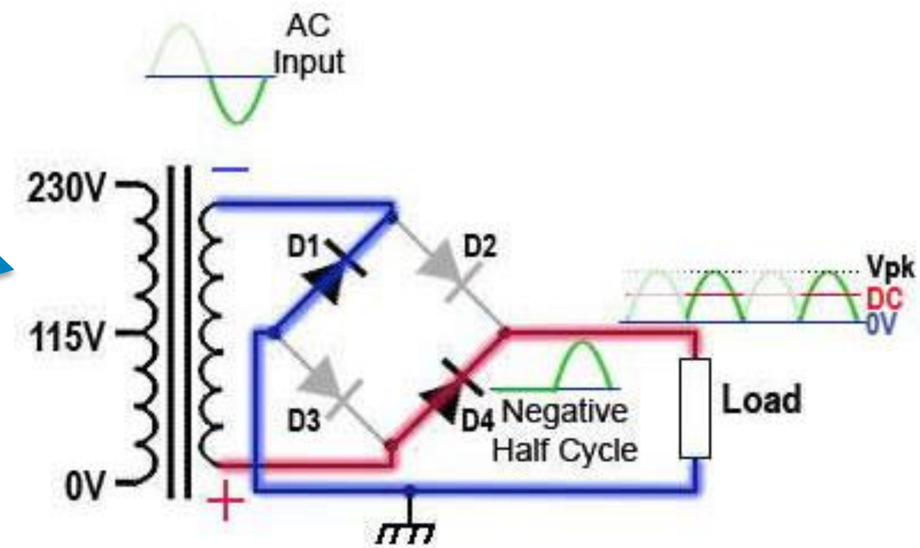

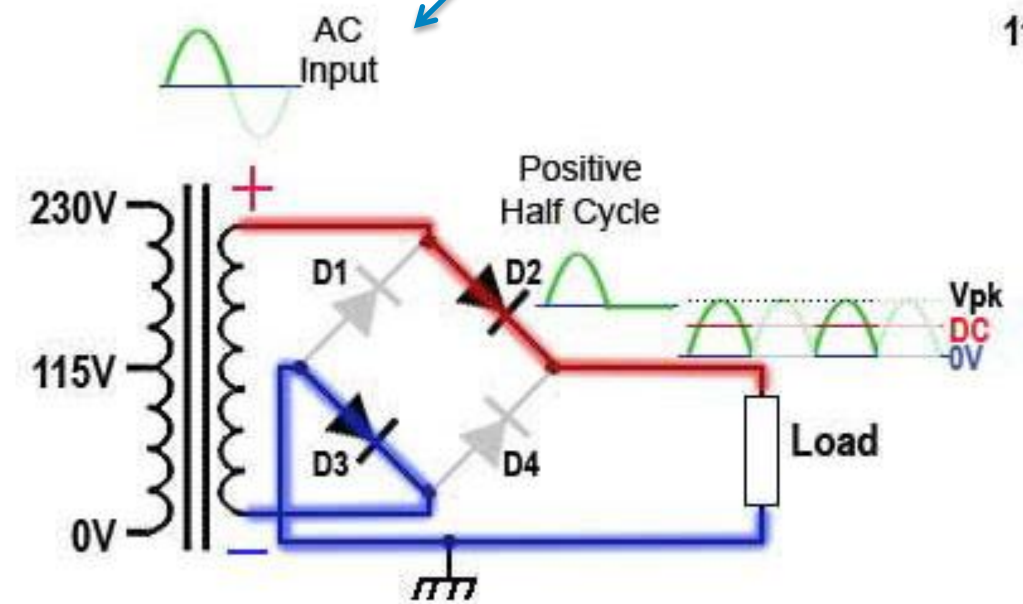

Application of Capacitor & Diode as a Peak Detector

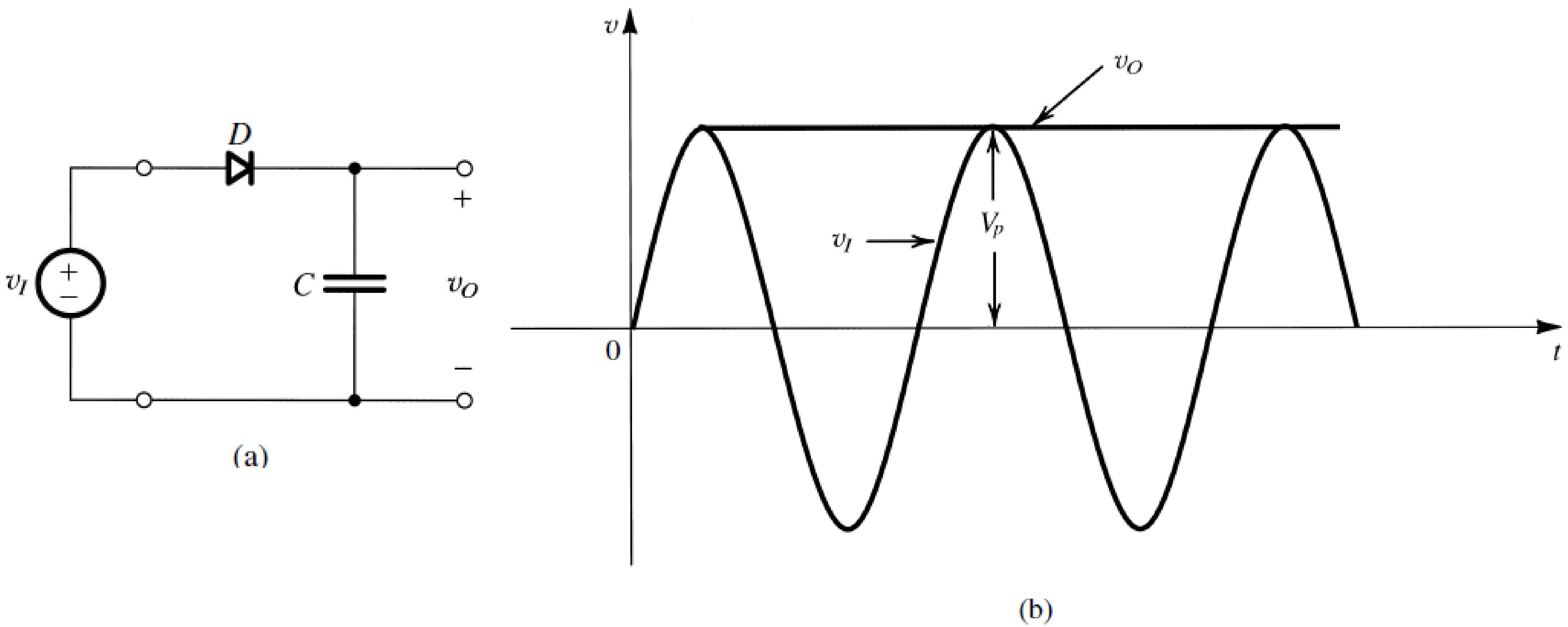

FIGURE 2.28 (a) A simple circuit used to illustrate the effect of a filter capacitor. (b) Input and output waveforms assuming an ideal diode. Note that the circuit provides a dc voltage equal to the peak of the input sine wave. The circuit is therefore known as a peak rectifier or a peak detector.

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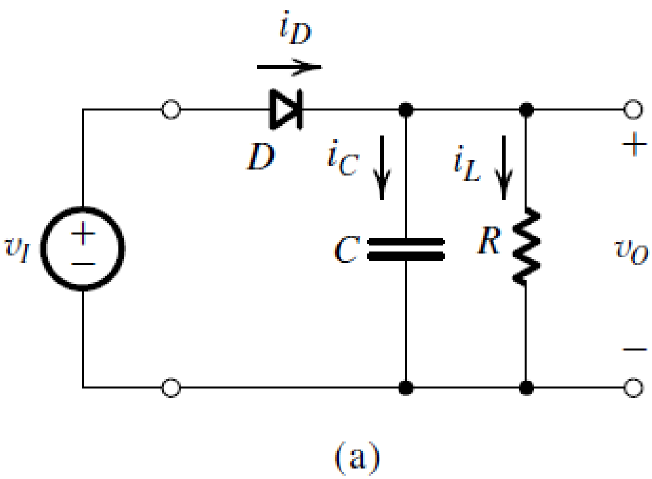
Leaky Peak Detector (Half Wave)



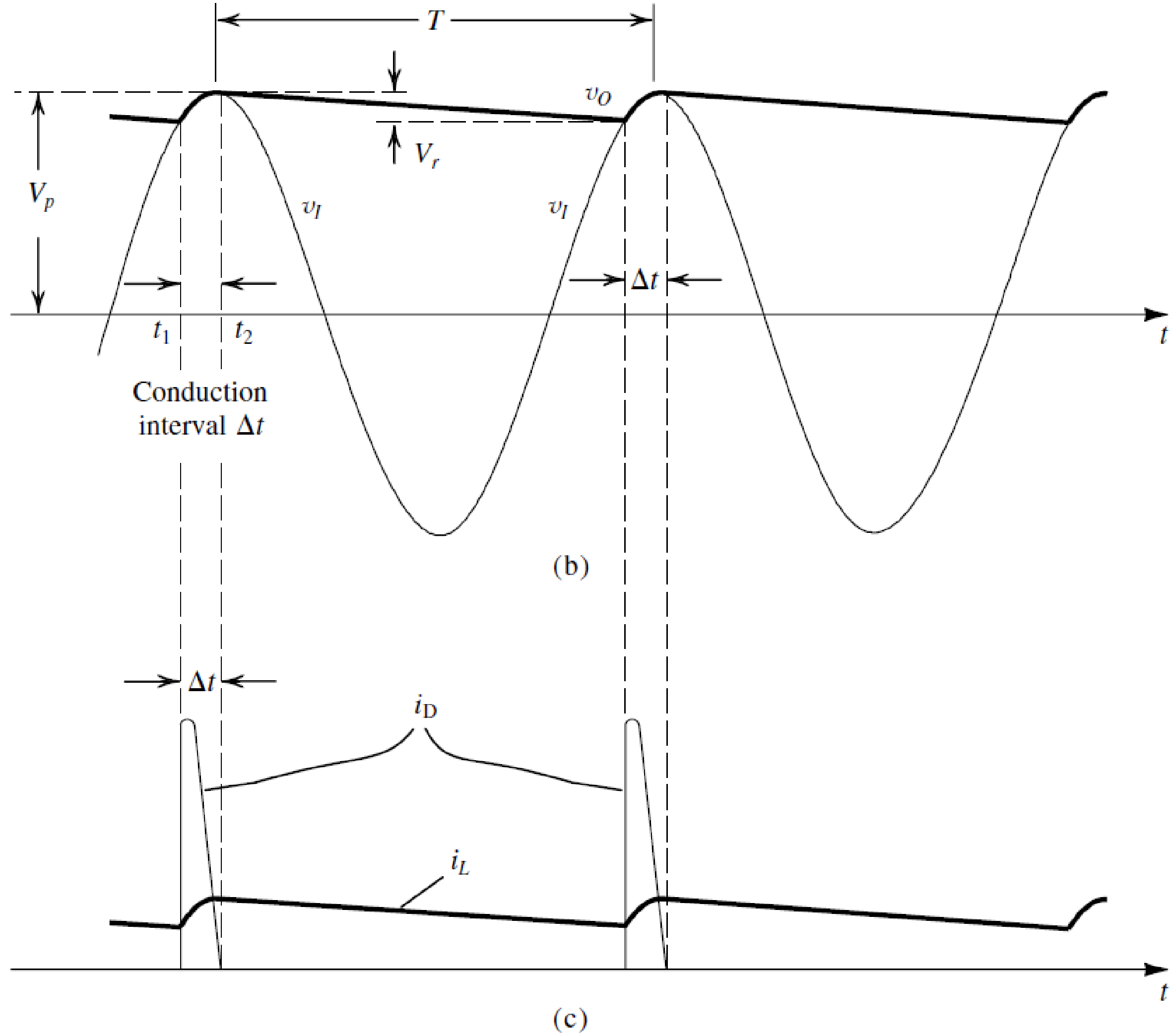


FIGURE 2.29 Voltage and current waveforms in the peak rectifier circuit with $CR \gg T$. The diode is assumed ideal.

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Leaky Peak Detector (Full Wave)

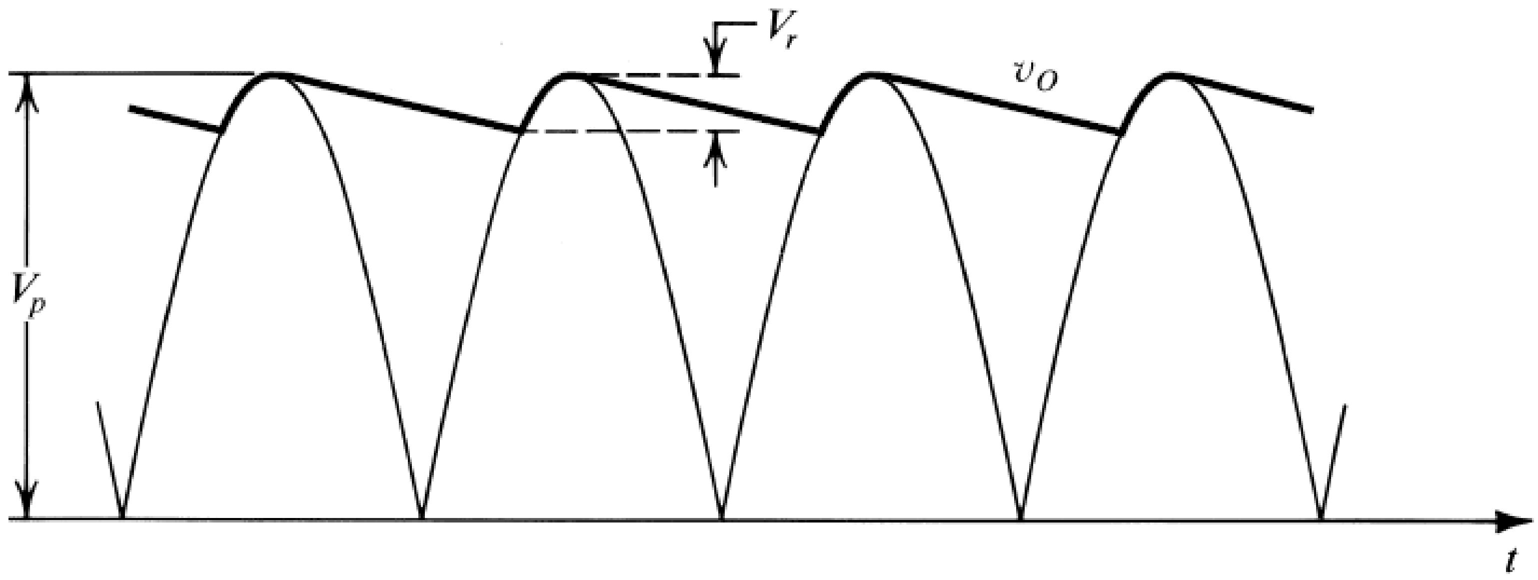

FIGURE 2.30 Waveforms in the full-wave peak rectifier.

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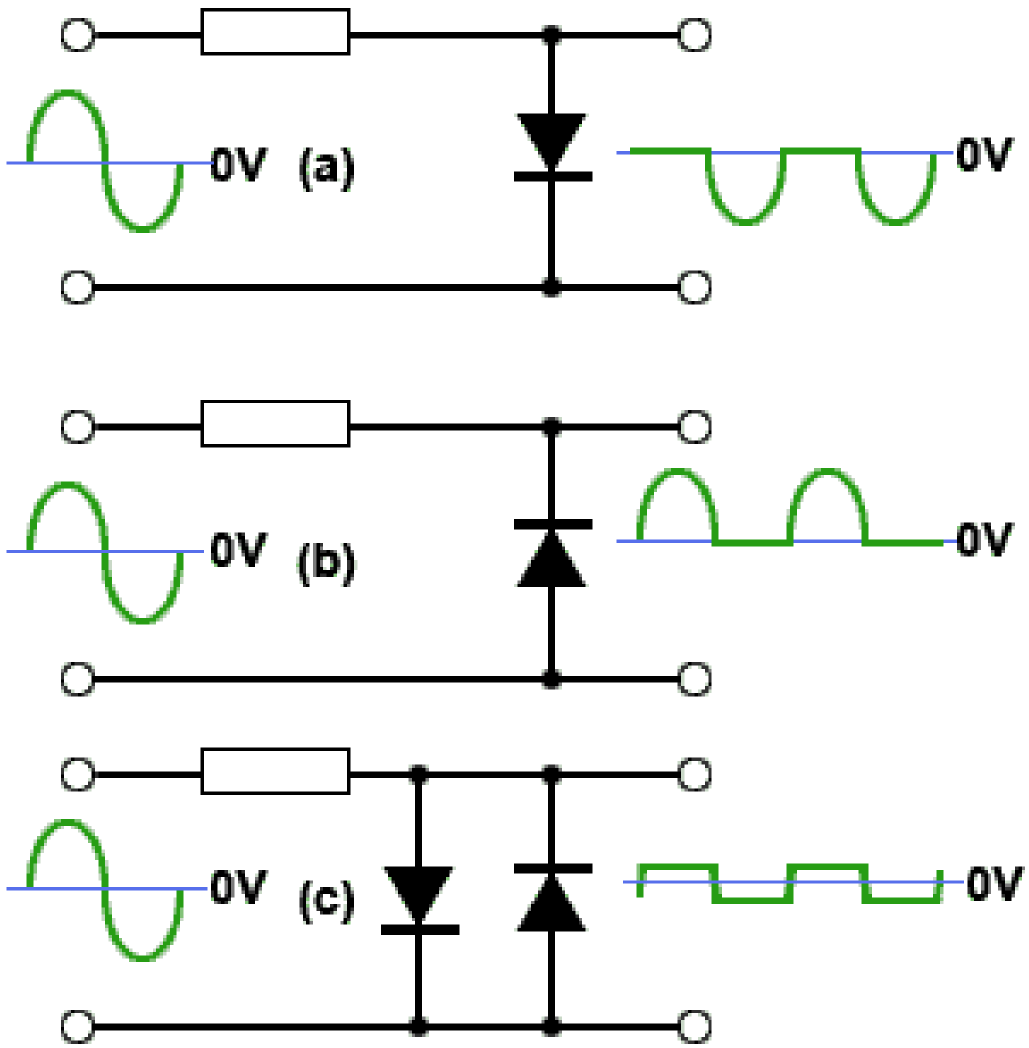
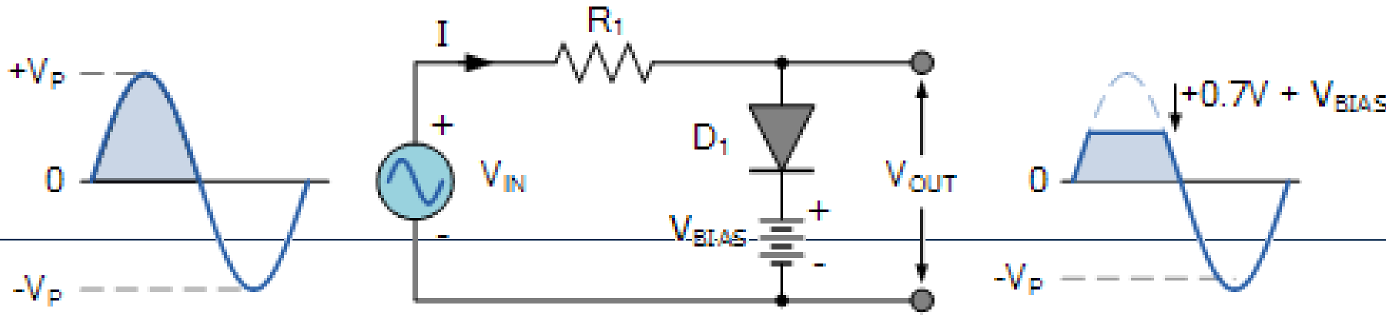
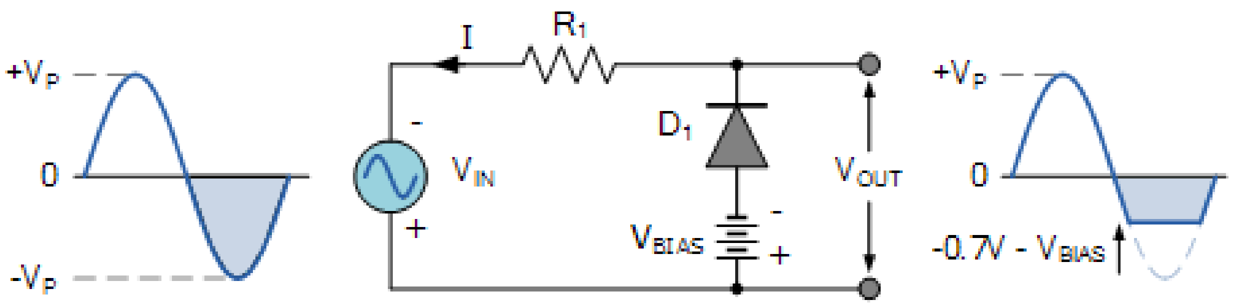
Clipping Action



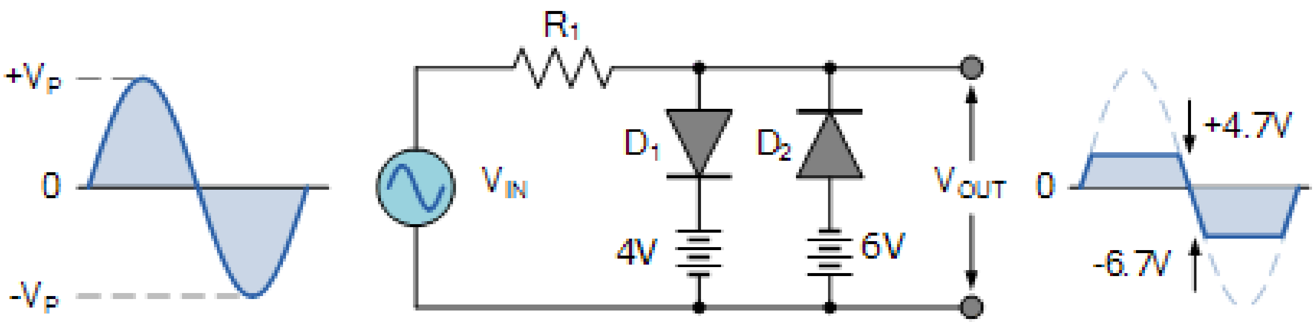
Positive Bias Diode Clipping



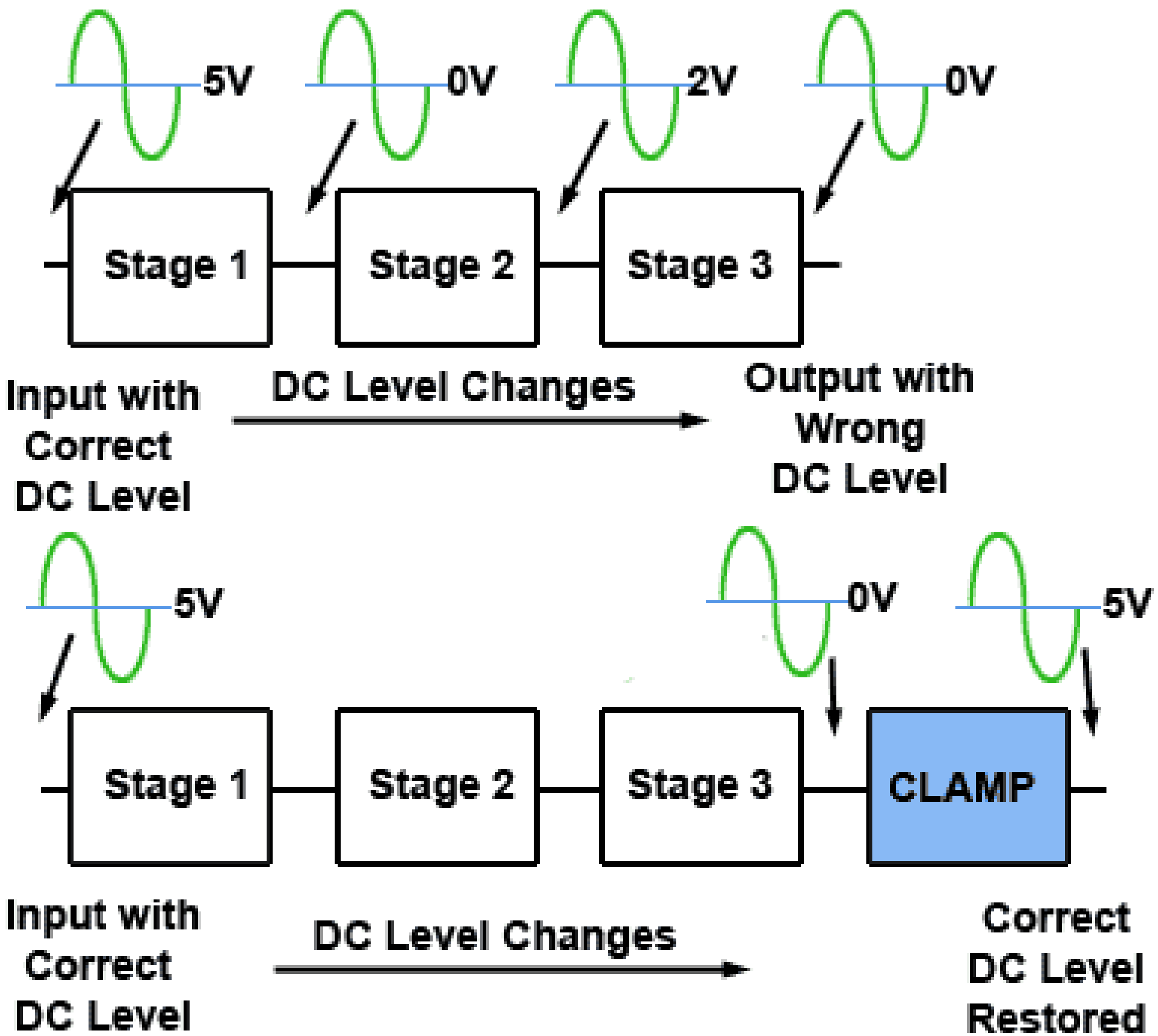
Negative Bias Diode Clipping



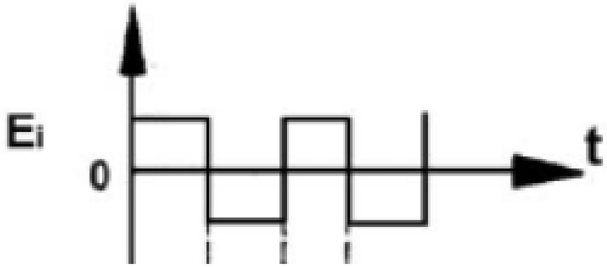
Diode Clipping of Different Bias levels

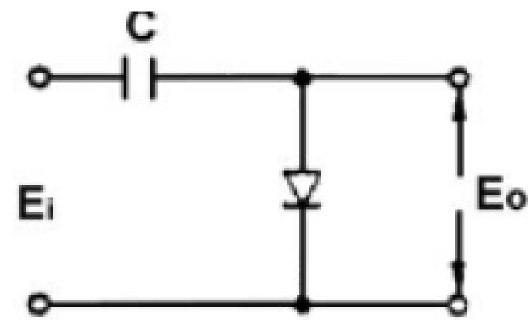


Clamping or DC Restoration

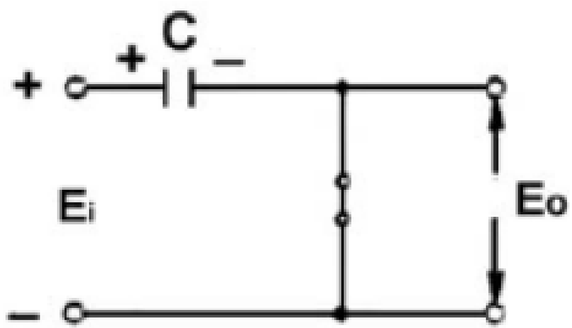


Typical clamping circuit

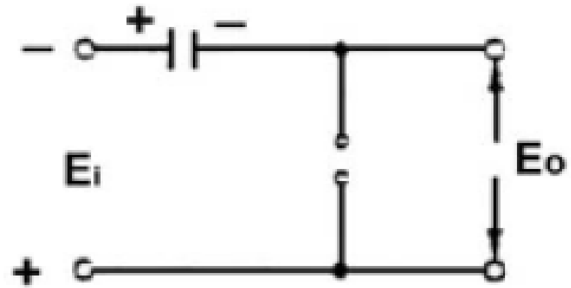




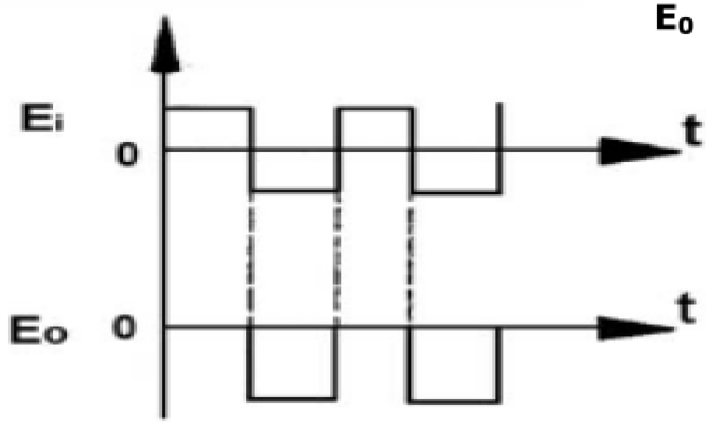
Diode conducts for positive cycle



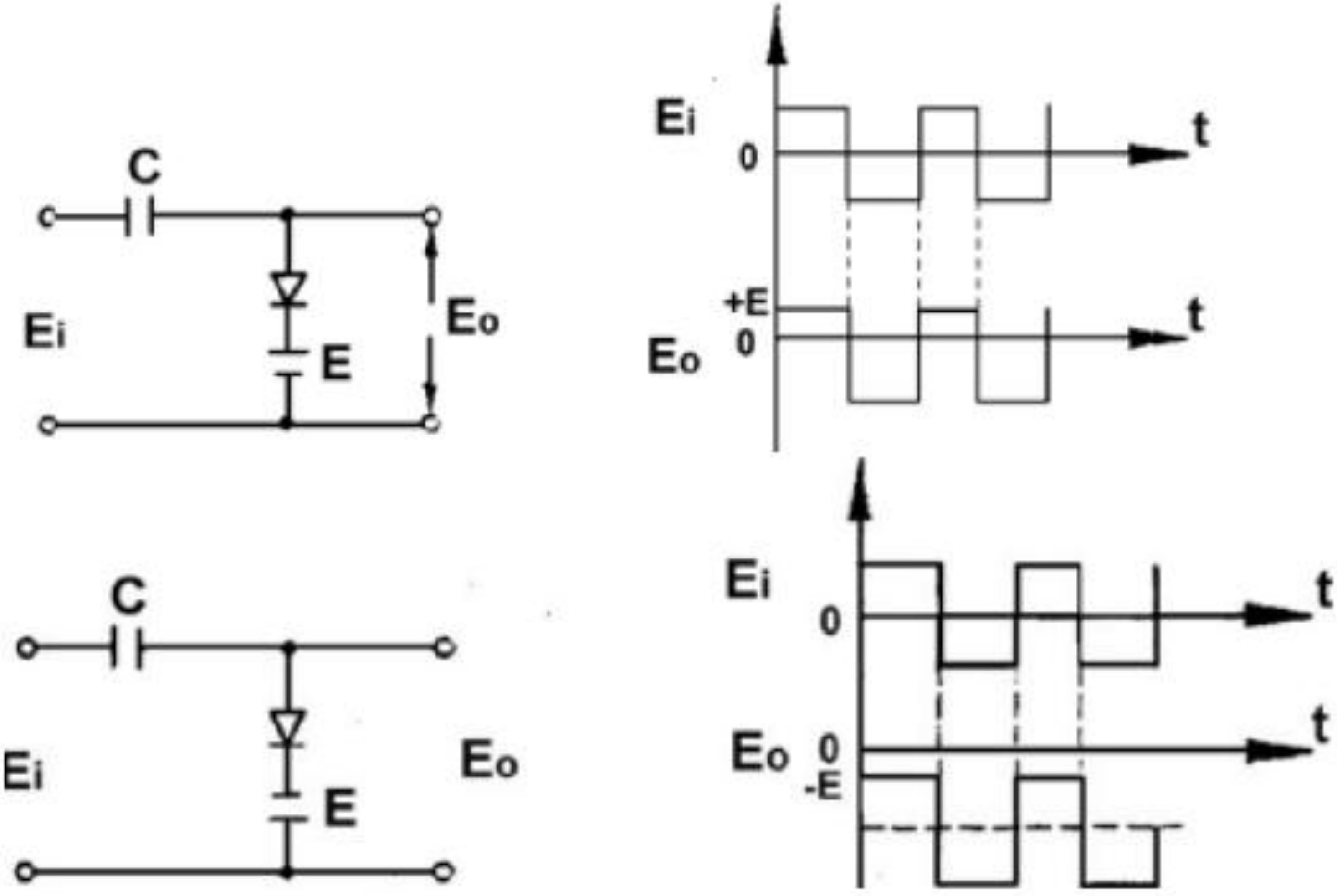
Diode is switched off during negative cycle



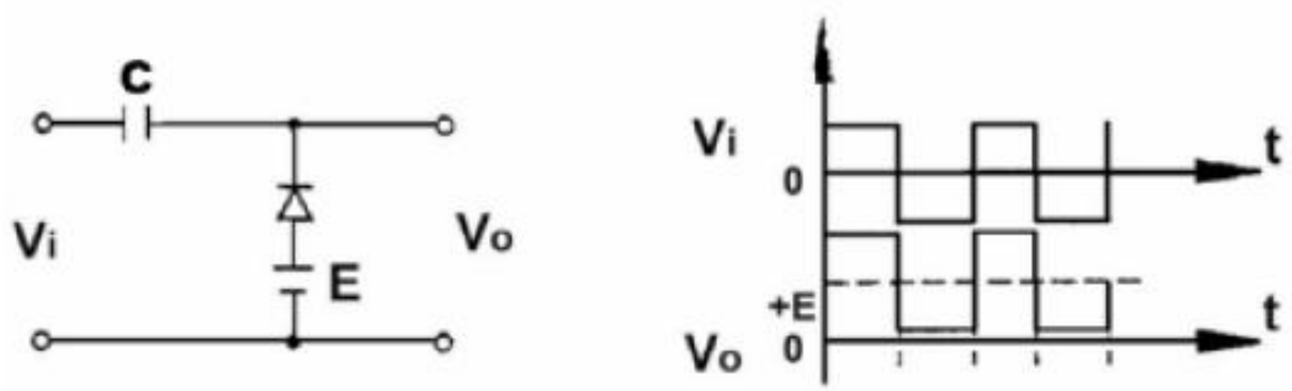
$E_0 = - (|E_i| + |E_c|)$

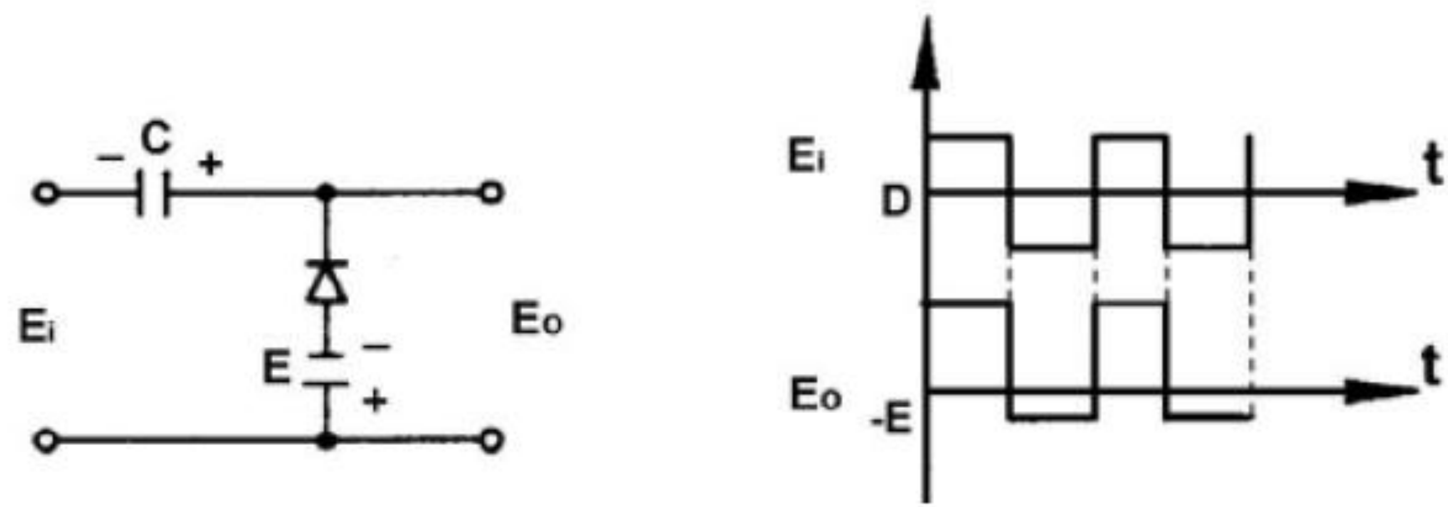


Clamping circuit in which threshold voltage is inserted



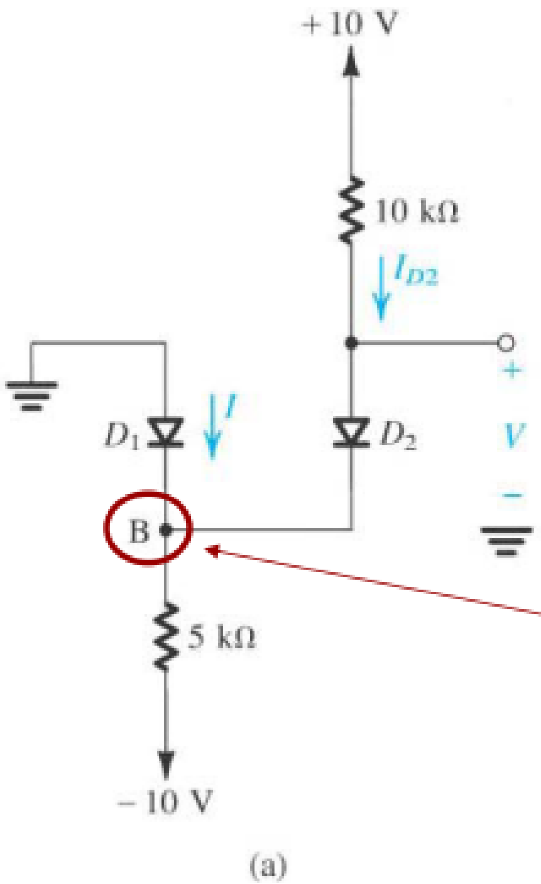
Clamping circuit in which threshold voltage is inserted





Clamping circuits (3)

Example Assuming the diode to be ideal, Find the values of I and V in the circuit of Fig. (a) and (b)



Sol:

Asssume that both diodes are conducting

$V_B = 0$ and $V = 0$

$$I_{D_2} = \frac{(10-0)\text{V}}{10\text{k}\Omega} = 1\text{mA}$$

Writting a node equation at B (K.C.L)

$$I + 1 = \frac{0-(-10)}{5} \Rightarrow I = 1\text{mA}$$

Results in $I = 1\text{mA}$,

Thus D_1 is conducting as originally assumed

and the find resuit is $I = 1\text{mA}$ and $V = 0\text{V}$

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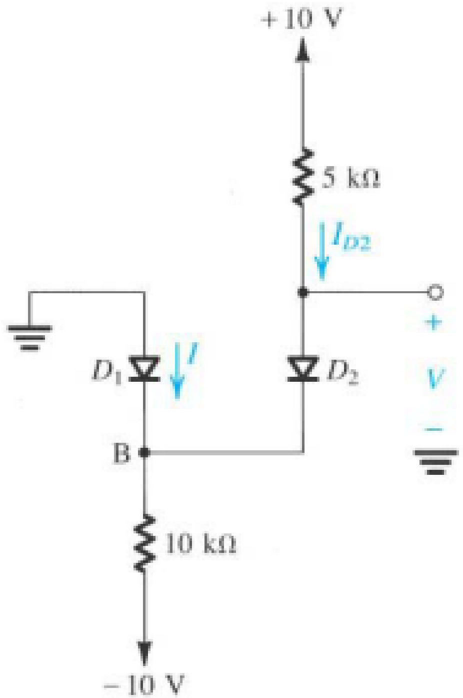

Sol:

We asssume that both diodes are conducting

then $V_B = 0$ and $V = 0$

$$I_{D_2} = \frac{(10-0)V}{5k\Omega} = 2mA$$

The node equation at B is

$$I + 2 = \frac{0-(-10)}{10} \Rightarrow I = -1mA$$

(This is not possible)

Our assumption is not correct, we start again assuming that D_1 is OFF and D_2 is ON.

The current I_{D_2} is given by

$$I_{D_2} = \frac{10-(-10)}{15} = 1.33mA$$

$$V_B = -10 + 10 \cdot 1.33 = 3.3V$$

Thus D_1 is reverse biased as assumed

$$\therefore I = 0A \text{ and } V = 3.3V$$

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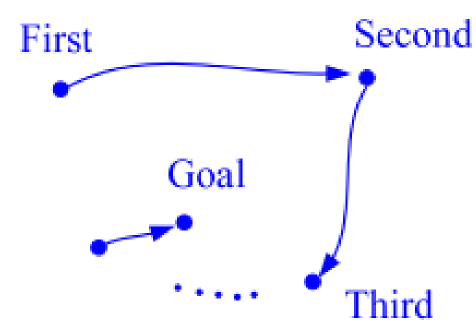
3.3.3 Iterative analysis using the exponential model

Example3.4 determine the current I_D and the diode voltage V_D for the circuit in Fig.3.10 with $V_{DD} = 5\text{V}$ and $R = 1\text{k}\Omega$, assume that the diode has a current of 1mA at voltage of 0.7V and that its voltage drop changes by 0.1V for every decade change in current.

Sol: We assume that $V_D = 0.7\text{V},\ I_D = 1\text{mA}$

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



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

$$V_2 = V_1 + 0.1 \cdot \log\frac{I_2}{I_1} \left(n = 2,\ 2.3 \cdot n \cdot V_T \cong 0.1\text{V}\right)$$

$$V_2 = 0.7 + 0.1 \cdot \log\frac{4.3\text{mA}}{1\text{mA}} = 0.763\text{V}$$

The first iteration are $I_D = 4.3\text{mA},\ V_D = 0.763\text{V}$

Please see slide no 23 and 34.

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We assume that $V_D = 0.763\text{V},\ I_D = 4.3\text{mA}$

$$I_D = \frac{V_{DD} - V_D}{R} = \frac{(5 - 0.763)\text{V}}{1\text{k}\Omega} = 4.237\text{mA}$$

$$V_2 = 0.763 + 0.1 \cdot \log\frac{4.237\text{mA}}{4.3\text{mA}} = 0.762\text{V}$$

The second iteration are $I_D = 4.237\text{mA},\ V_D = 0.762\text{V}$

We assume that $V_D = 0.762\text{V},\ I_D = 4.237\text{mA}$

$$I_D = \frac{V_{DD} - V_D}{R} = \frac{(5 - 0.762)\text{V}}{1K\Omega} = 4.238\text{mA}$$

$$V_2 = 0.762 + 0.1 \cdot \log\frac{4.238\text{mA}}{4.237\text{mA}} = 0.762\text{V}$$

Because I_D did not change by much stop here and the solution is

$I_D = 4.237\text{mA}$ and $V_D = 0.762\text{V}$

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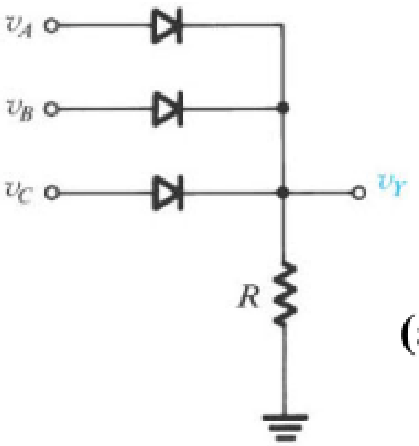
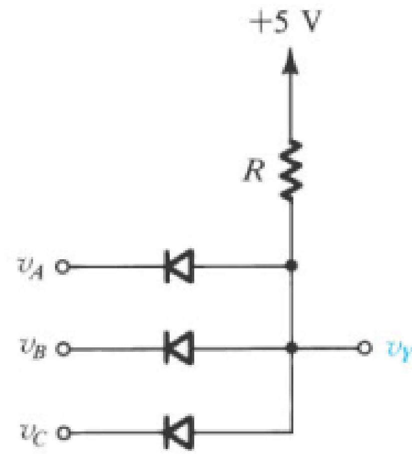
3.1.3 Another Application: Diode Logic Gates



(a) OR gate



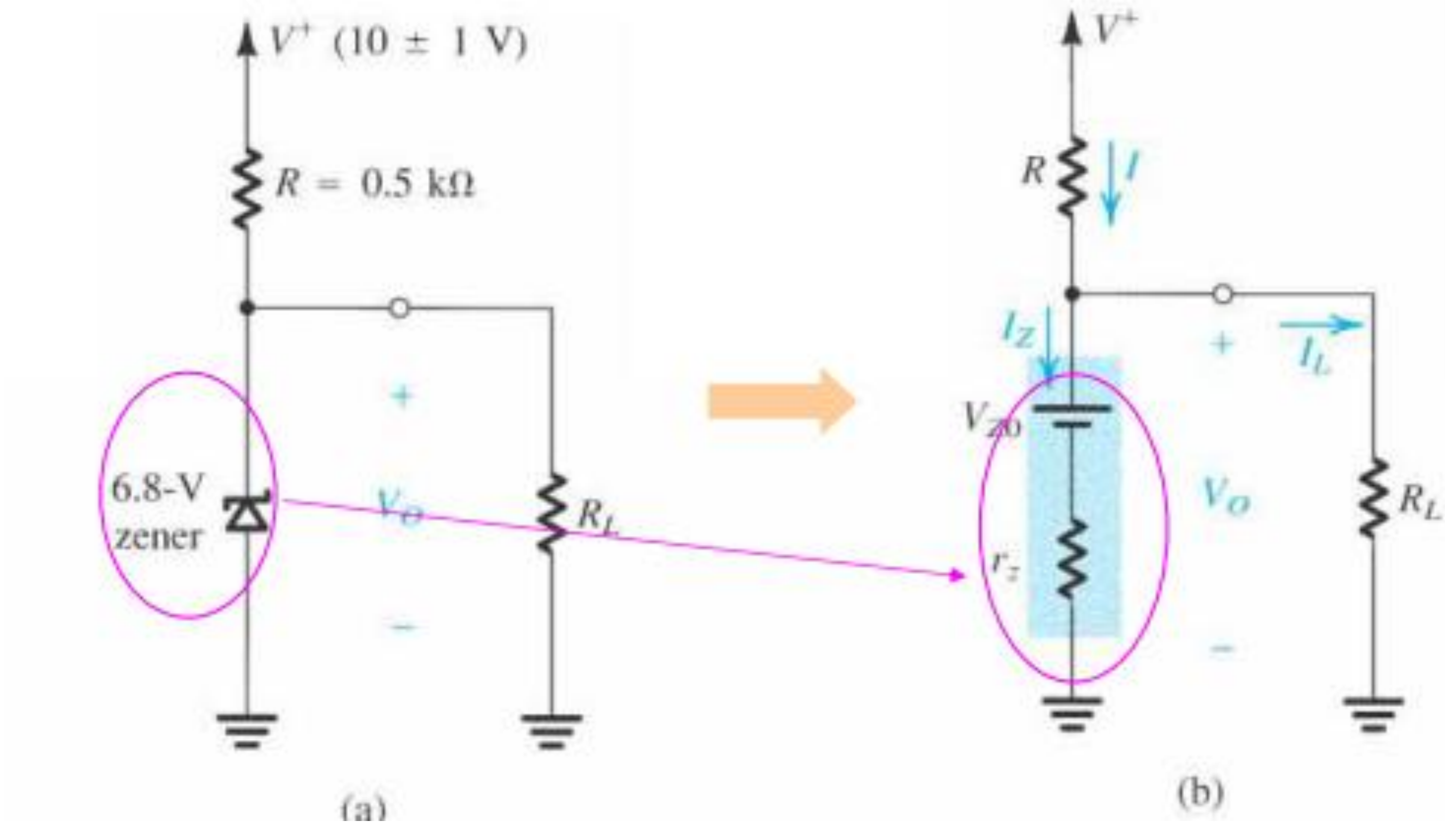
(b) AND gate

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

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

The 6.8V Zener diode in the circuit below

is specified to have $V_Z = 6.8\text{V}$ at $I_Z = 5\text{mA}, r_z = 20\Omega$ and $I_{ZK} = 0.2\text{mA}$, the V^+ is $10\text{V} \pm 1\text{V}$.



With these ratings

$$V_Z = V_{Z0} + r_z I_Z \quad \Rightarrow \quad V_{Z0} = V_Z - r_z I_Z$$

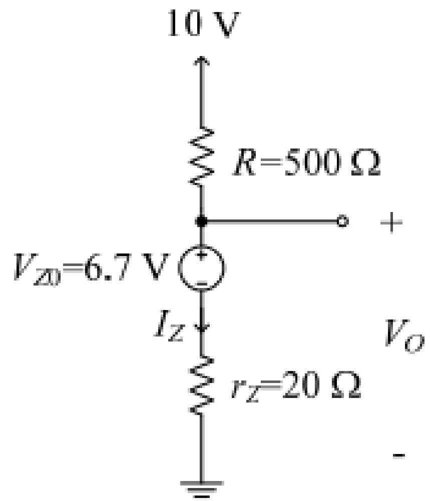
or

$$V_{Z0} = 6.8 - 20 \cdot 5 \times 10^{-3} = 6.7 \text{ V}$$

Note that the supply voltage can fluctuate by ± 1 V. Imagine this fluctuation is a random process rather than a time periodic variation.

Determine the following quantities:

(b) Find V_O with no load and V^+ at the nominal value. The equivalent circuit for the reverse bias operation of the Zener diode is



From this circuit we calculate

$$I_Z = \frac{10-6.7}{500+20} = 6.35 \text{ mA}$$

Therefore,

$$V_O = 10 - I_Z \cdot 500 = 10 - 6.35 \times 10^{-3} \cdot 500 = 6.83 \text{ V}$$

(c) Find the change in V_O resulting from a ± 1 V change in V^+. Using the circuit above the $V^+ = 11$ V:

$$V_O = 11 - \frac{11-6.7}{500+20} \cdot 500 = 6.865 \text{ V}$$

Similarly, with V^+=9 V:

$$V_O = 9 - \frac{9-6.7}{500+20} \cdot 500 = 6.788 \text{ V}$$

Consequently, $\Delta V_O = 6.865 - 6.788 = 0.077$ V or $\Delta V_O = \pm 38.5$ mV.

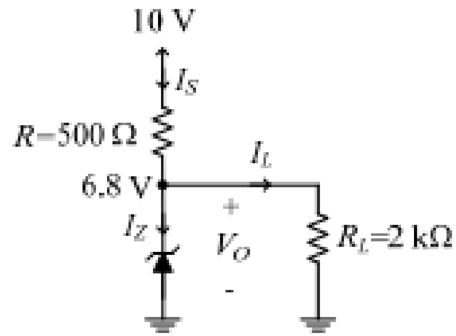
The ratio of the change in output voltage to the change in the source voltage ($\Delta V_O / \Delta V^+$) is called the line regulation

of the regulator circuit. It's often expressed in units of mV/V. For this example and no load attached,

$$\text{Line Regulation} \equiv \frac{\Delta V_O}{\Delta V^+} = \frac{77}{11-9}\frac{\text{mV}}{\text{V}} = 38.5\frac{\text{mV}}{\text{V}}$$

(d) Find the change in V_O resulting from connecting a load of $R_L = 2\ \text{k}\Omega$ with a nominal $V^+ = 10$ V.

Assuming that the diode is operating in the breakdown region:



then $$I_L = \frac{6.8}{2000} = 3.4\ \text{mA}.$$

Is this a reasonable value? Calculate I_S:
$$I_S = \frac{10 - 6.8}{500} = 6.4\ \text{mA}.$$
So, yes, this is a reasonable value because $I_L < I_S$, as it must.

From (1), $\Delta V_O = r_z \Delta I_Z$ and since $\Delta I_Z = -3.4$ mA then

$$\Delta V_O = 20\left(-3.4\times10^{-3}\right) = -68\ \text{mV}$$

The ratio of the change in output voltage to the change in the load current ($\Delta V_O/\Delta I_L$) is called the load regulation of the regulator circuit. It's often expressed in units of mV/mA. For this example,

$$\text{Load Regulation} \equiv \frac{\Delta V_O}{\Delta I_L} = \frac{-68\ \text{mV}}{3.4\ \text{mA}} = -20\ \frac{\text{mV}}{\text{mA}}$$

Home-work

From the text book find out the solutions to problems no, 3.10, 3.23, 3.26, 3.95, 3.96, 3.99, 3.105.