EE281 (Introduction to Electrical Engineering II) and EE285 (Electronics I) - Lecture 1

Diodes
(Two terminal semiconductor devices)

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Intrinsic Semiconductor

- Definition

  A crystal of pure and regular lattice structure is called intrinsic semiconductor.

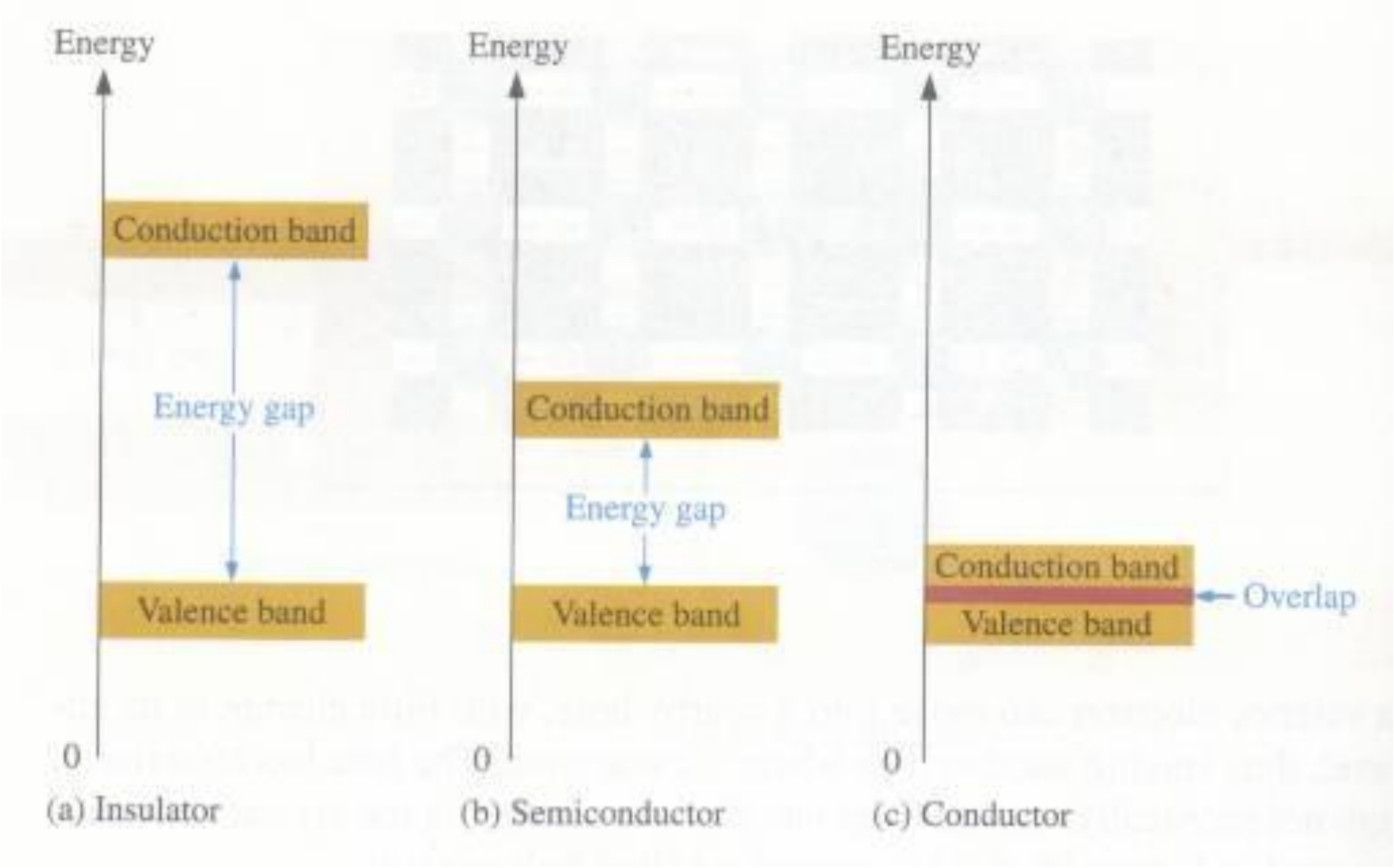
- Materials
  - Silicon---today's IC technology is based entirely on silicon
  - Germanium---early used
  - Gallium arsenide---used for microwave circuits

10.1 Basic Diode Concepts

10.1.1 Intrinsic Semiconductors

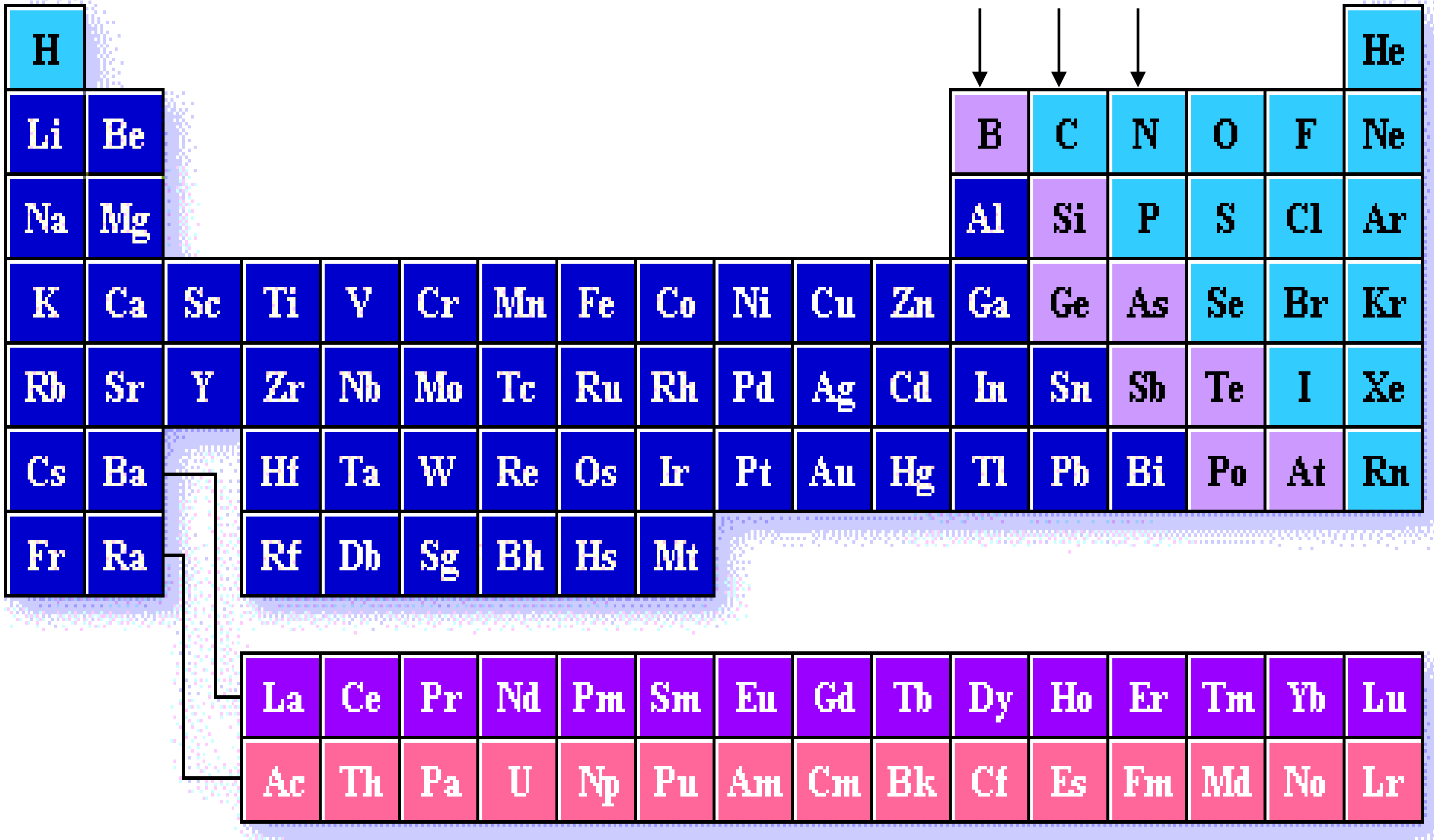
* Energy Diagrams – *Insulator, Semiconductor, and Conductor*

the energy diagram for the three types of solids

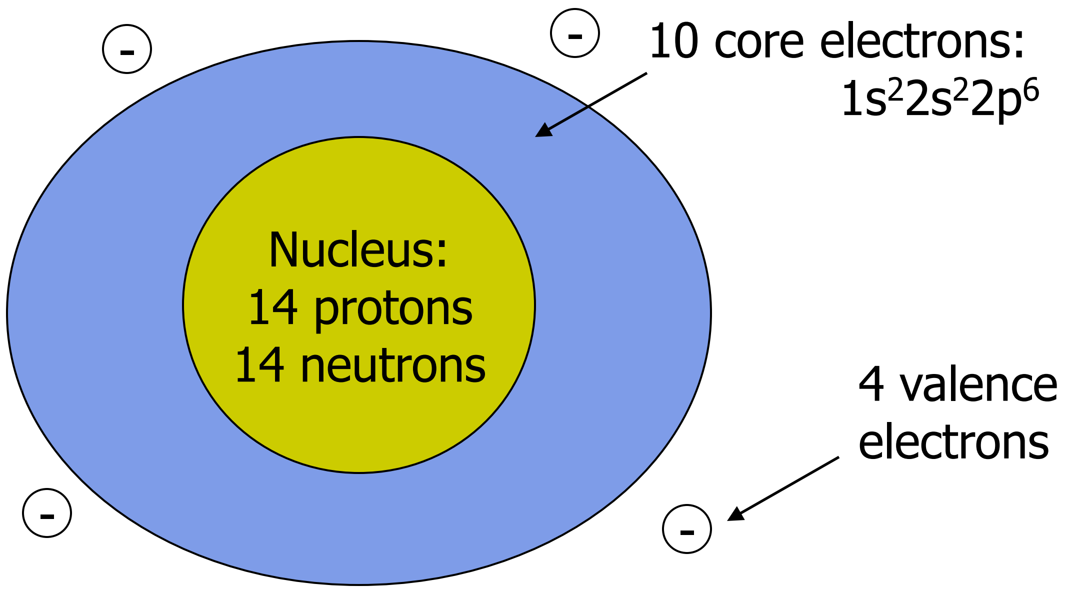


Periodic Table of Elements

Relevant Columns: III IV V



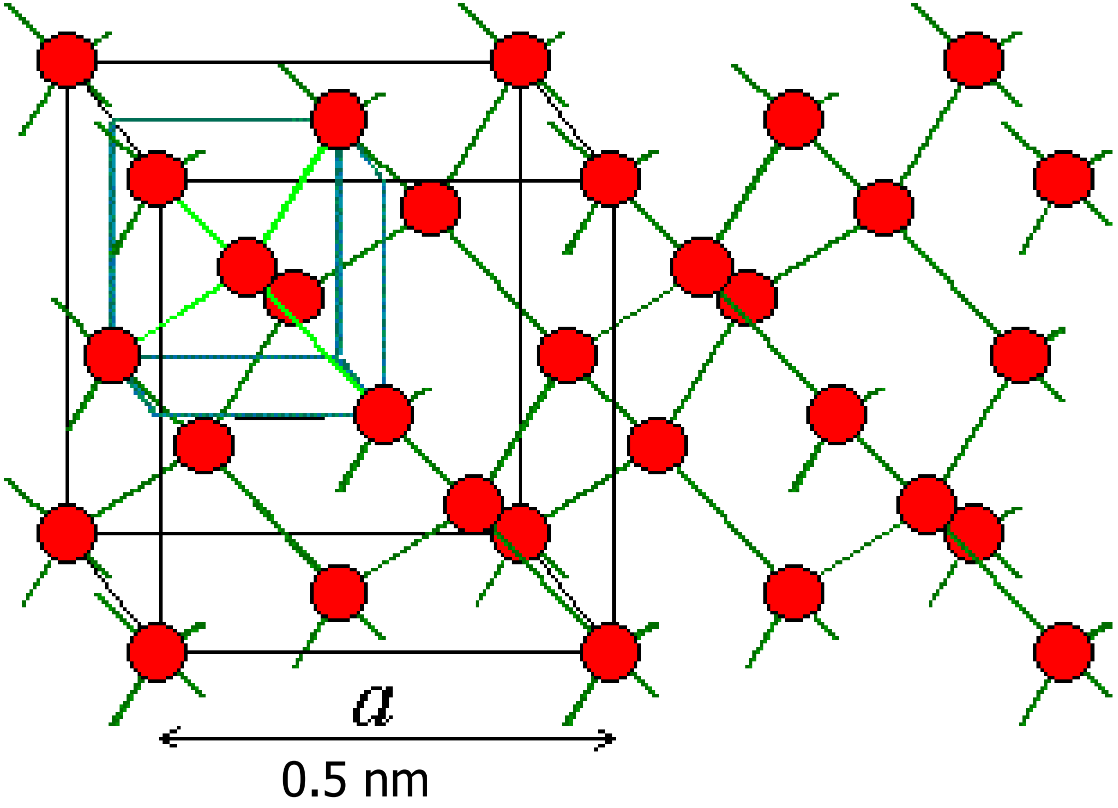
The Silicon Atom



The 4 valence electrons are responsible for forming covalent bonds

Silicon Crystal

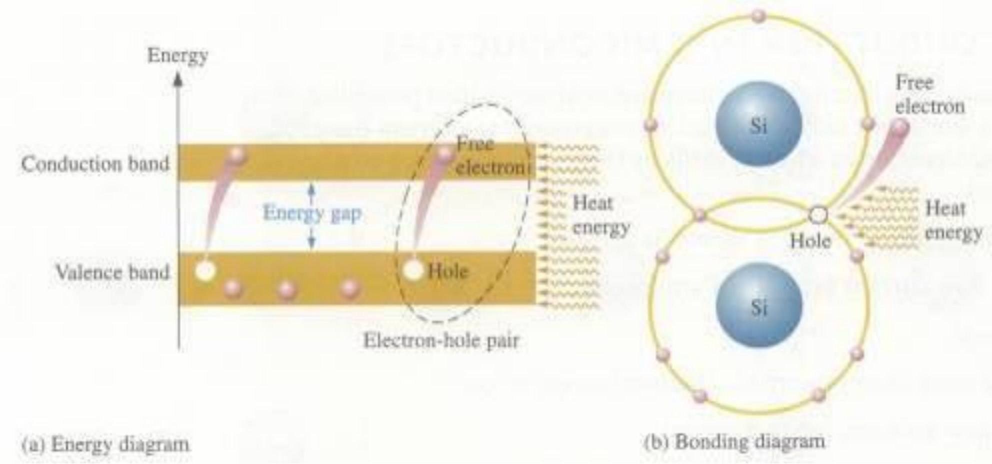
Each Si atom has <u>four</u> nearest neighbors — one for each valence electron

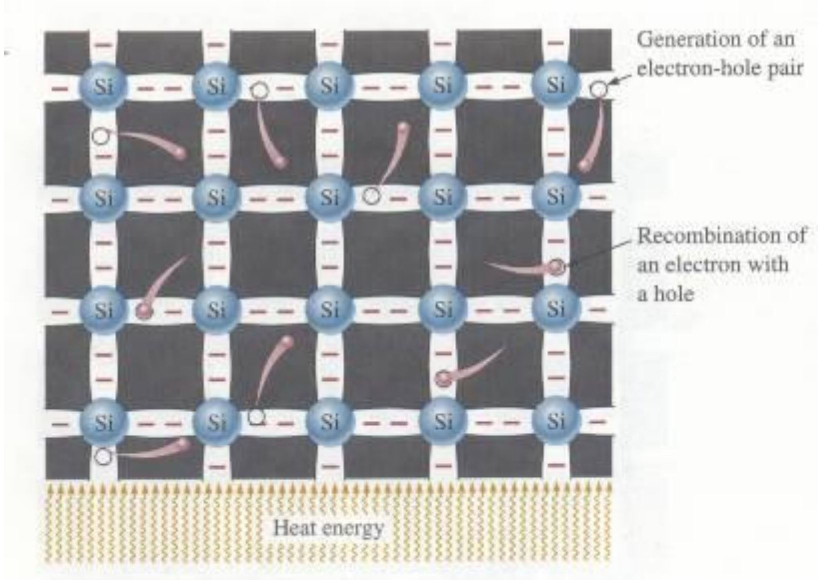


10.1.1 Intrinsic Semiconductors

* Intrinsic (pure) *Si* Semiconductor:

Thermal Excitation, Electron-Hole Pair, Recombination, and Equilibrium





When equilibrium between excitation and recombination is reached :

electron density = hole density

$$n_i = p_i = 1.5 \times 10^{10}\ cm^{-3}$$

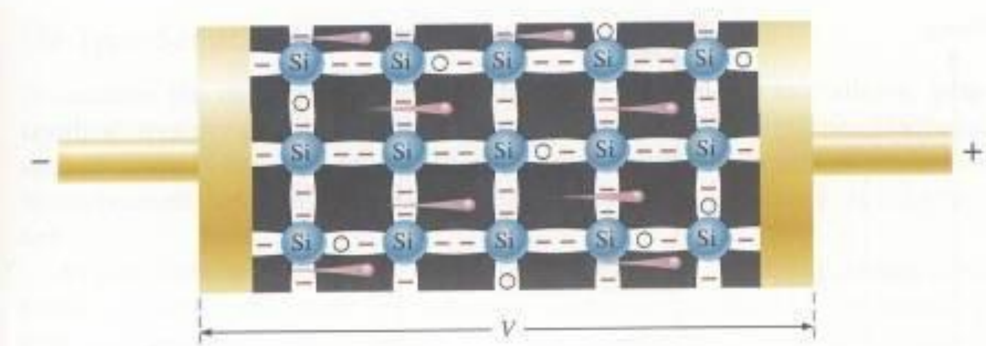
for intrinsic Si crystal at 300 K

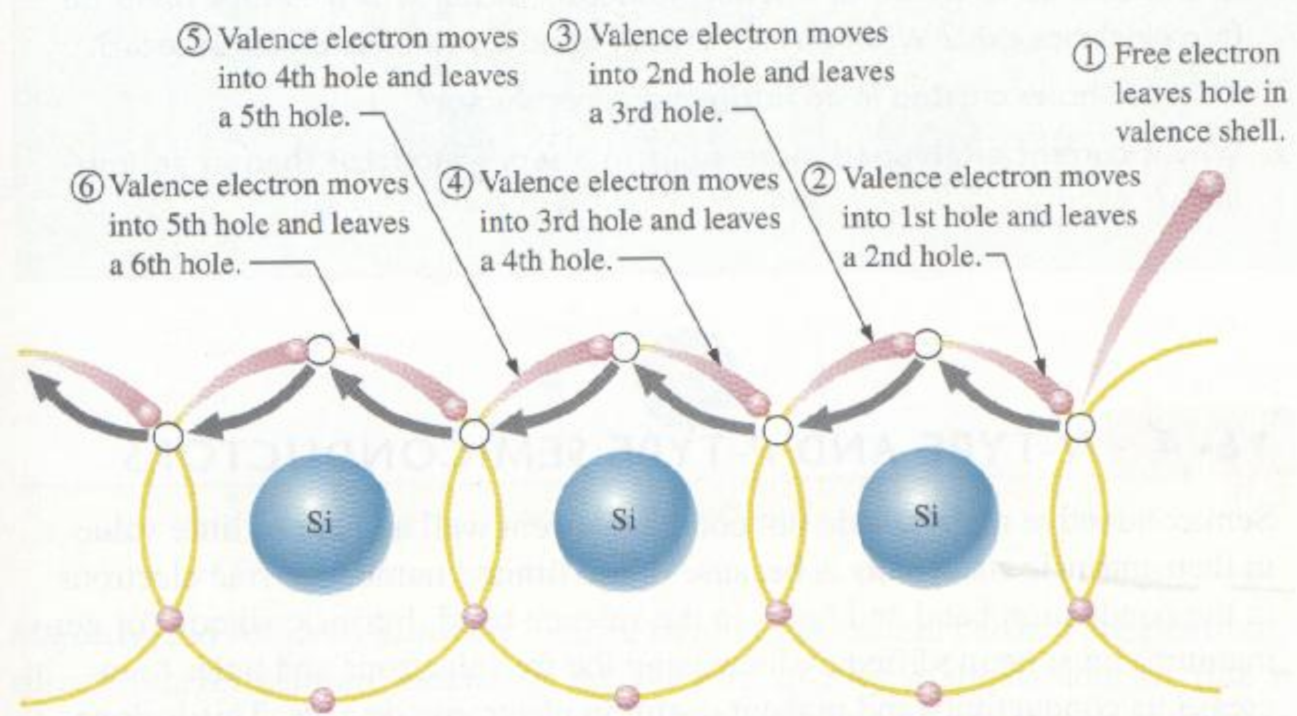
(Note : Si crystal atom density is $\sim 5 \times 10^{22}\ cm^{-3}$ *)*

10. Diodes – Basic Diode Concepts

10.1.1 Intrinsic Semiconductors

*Apply a voltage across
a piece of *Si:*
electron current
and hole current



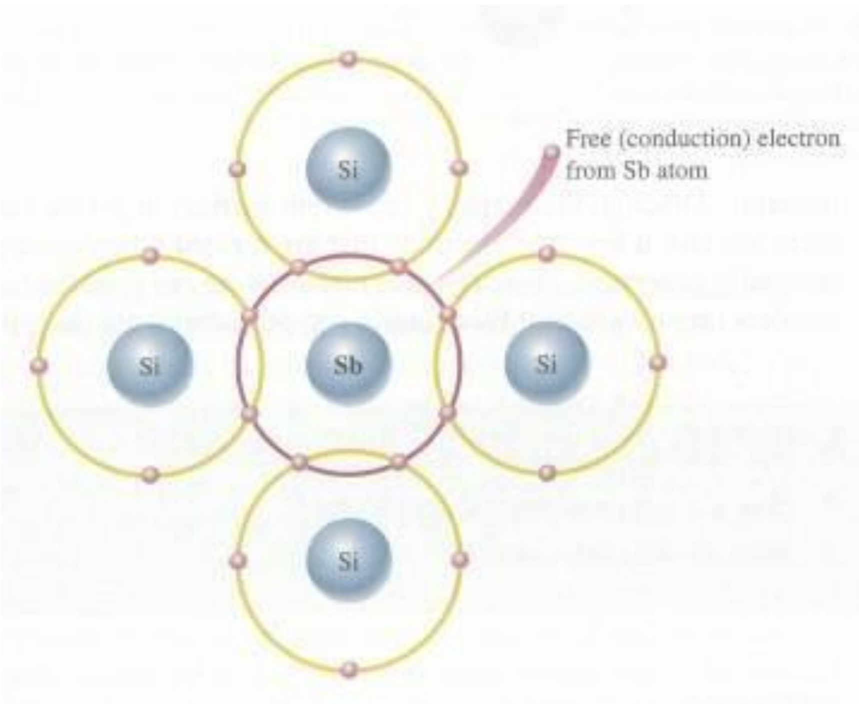


When a valence electron moves left to right to fill a hole while leaving another hole behind, a hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.

10. Diodes – Basic Diode Concepts

10.1.2 N- and P- Type Semiconductors

* *Doping*: adding of impurities (i.e., dopants) to the intrinsic semi-conductor material.
* *N-type*: adding Group V dopant (or donor) such as As, P, Sb,…



$n \cdot p = constant \ \ for \ a \ semiconductor$

$For \ \ Si \ \ at \ 300K$

$n \cdot p = n_i^2 = p_i^2 = \left(1.5 \times 10^{10}\right)^2$

$In \ \ n\text{-}type \ material$

$n \cong N_d \ \ the \ donor \ conceration$

$n = N_d >> n_i \, , \ \ p << p_i$

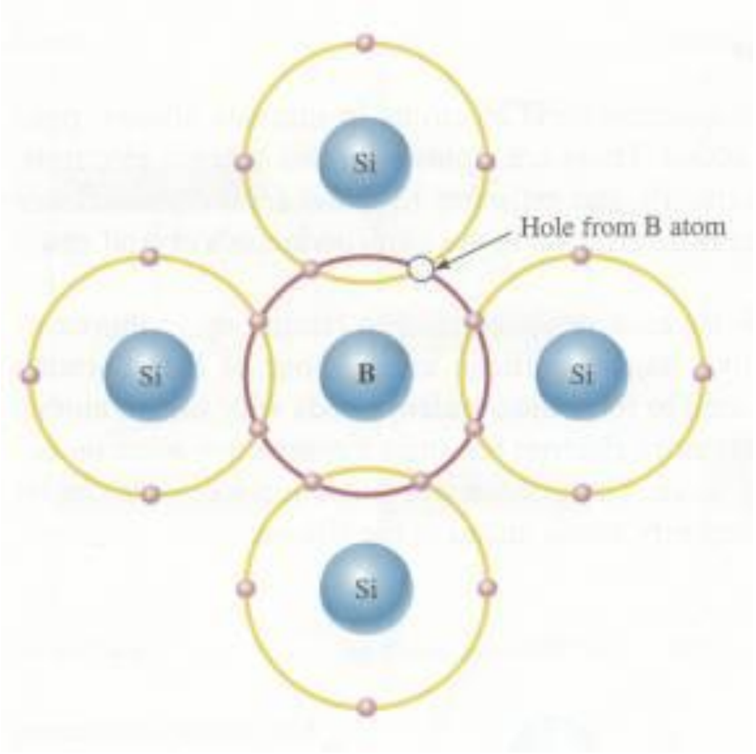
$We \ call$

$\boxed{\begin{array}{l} electron \ the \ major \ charge \ carrier \\ hole \ the \ minor \ cahage \ carrier \end{array}}$

10.1.2 N- and P- Type Semiconductors

* *Doping*: adding of impurities (i.e., dopants) to the intrinsic semi-conductor material.

* *P-type*: adding Group III dopant (or acceptor) such as Al, B, Ga,…



$$n \cdot p = constant \ \ for\ a\ semiconductor$$

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$$n \cdot p = n_i^2 = p_i^2 = \left(1.5 \times 10^{10}\right)^2$$

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$$p \cong N_a \ \ the\ acceptor\ conceration$$

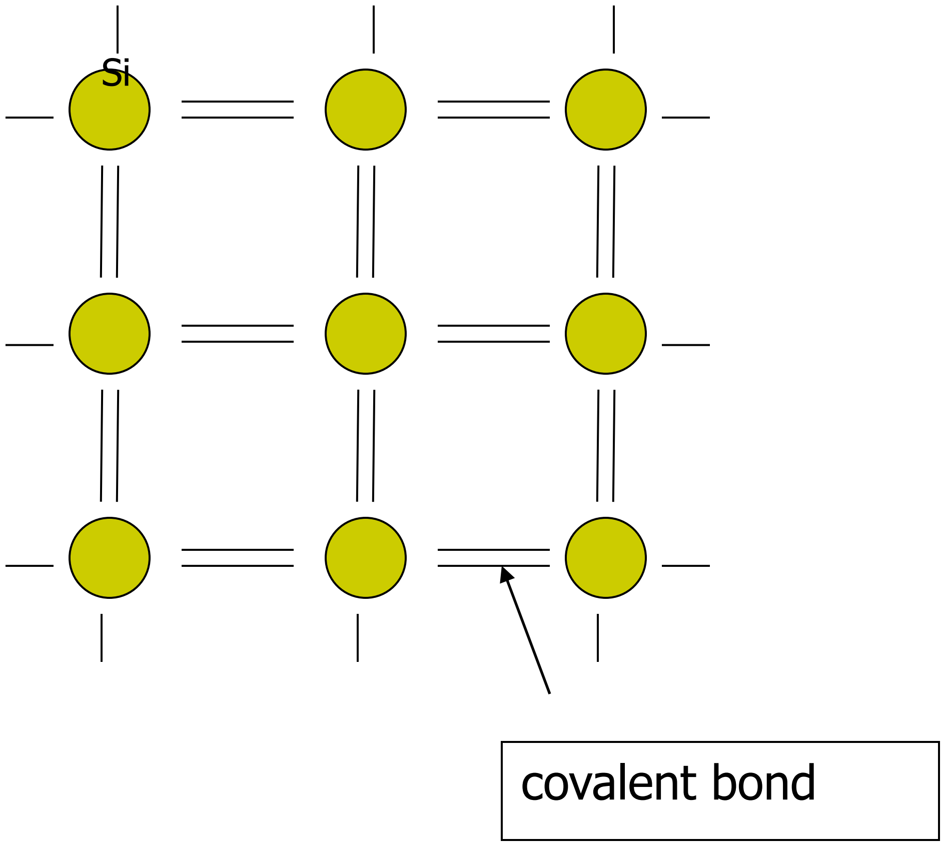
$$p = N_a >> p_i\ , \ n << n_i$$

$$We\ call$$

$$\boxed{\begin{array}{l} hole\ the\ major\ charge\ carrier \\ electron\ the\ minor\ cahage\ carrier \end{array}}$$

Two-dimensional Picture of Si

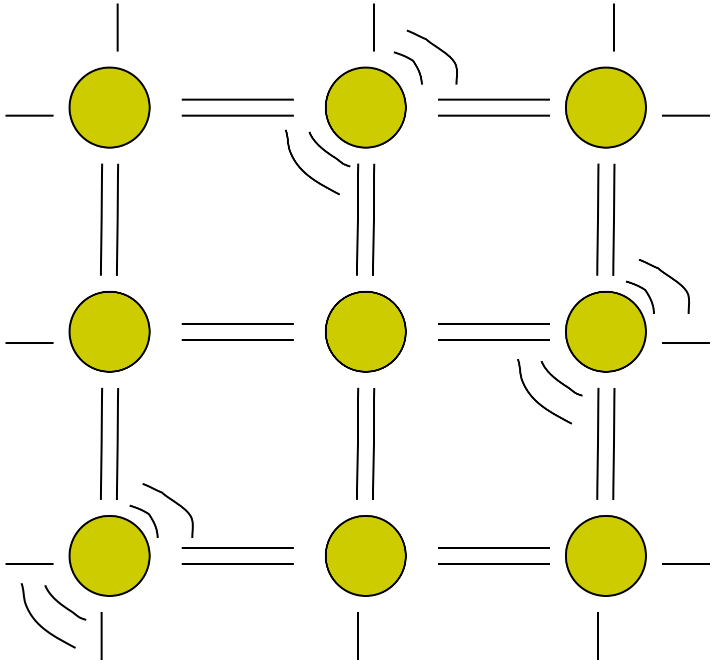
note: **each line (—) represents a valence electron**



At T=0 Kelvin, all of the valence electrons are participating in covalent bonds

There are no "free" electrons, therefore no current can flow in the silicon → INSULATOR

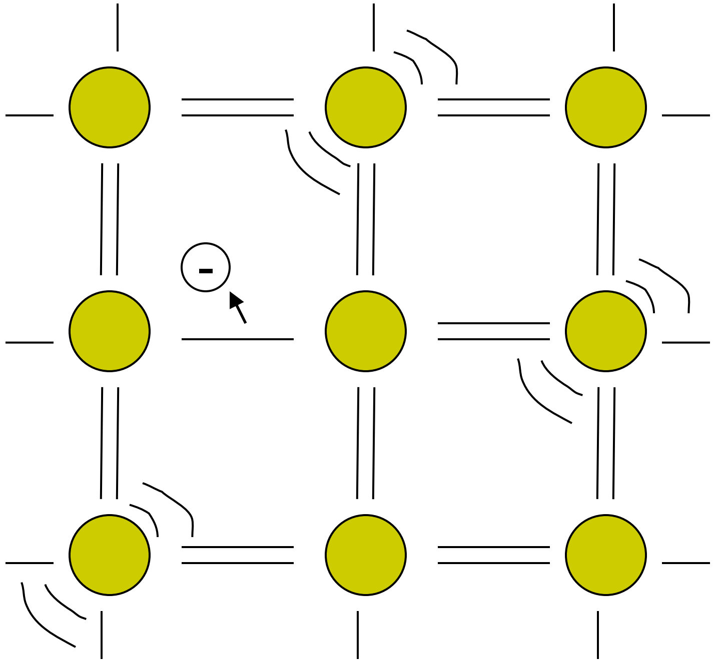
Silicon at Room Temperature



For T>0 K, the silicon atoms vibrate in the lattice. This is what we humans sense as "heat."

Occasionally, the vibrations cause a covalent bond to break and a valence electron is free to move about the silicon.

Silicon at Room Temperature

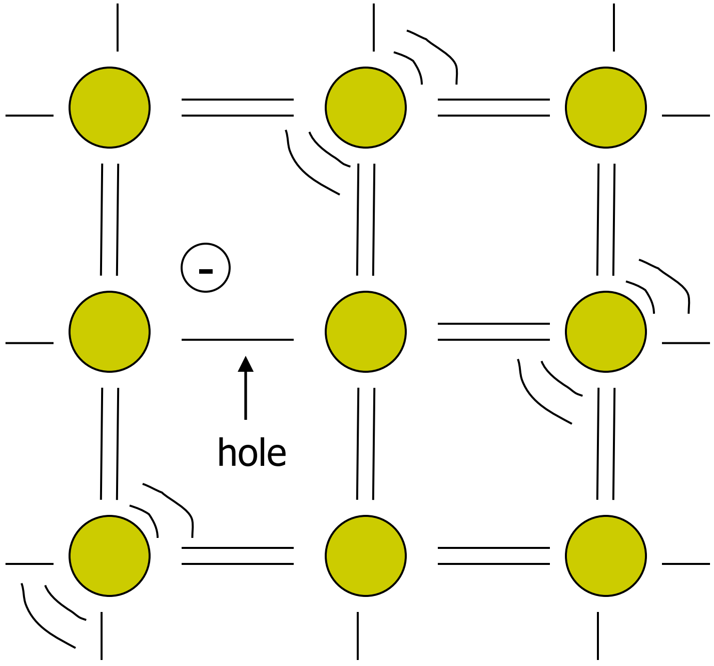


For T>0 K, the silicon atoms vibrate in the lattice. This is what we humans sense as "heat."

Occasionally, the vibrations cause a covalent bond to break and a valence electron is free to move about the silicon.

- = free electron

Silicon at Room Temperature



The broken covalent bond site is now *missing* an electron.

This is called a “hole”

The hole is a missing negative charge and has a charge of **+1**.

= a hole

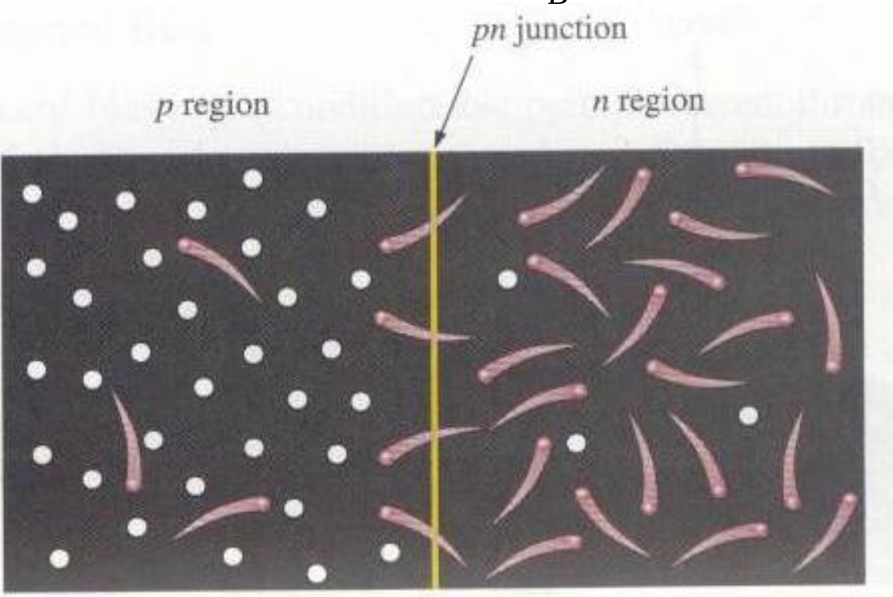
$\oplus$

10.1.3 The PN-Junction

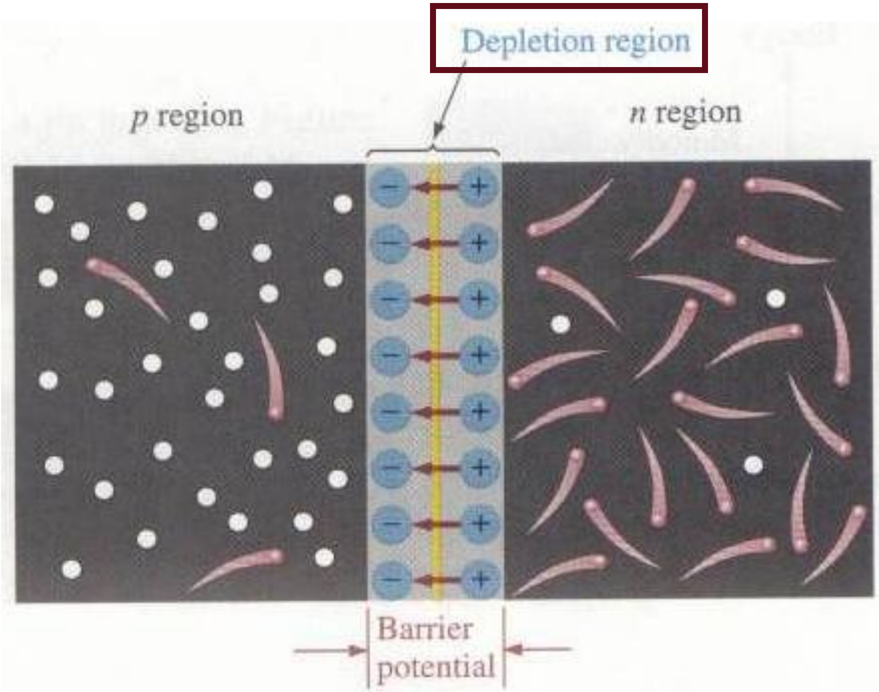
* The interface in-between p-type and n-type material is called a *pn-junction*.

$$The\ barrier\ potential\ V_B \cong 0.6-0.7V\ for\ Si\ and\ 0.3V\ for\ Ge$$

$$at\ 300K:\ as\ T\uparrow, V_B\downarrow.$$



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



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

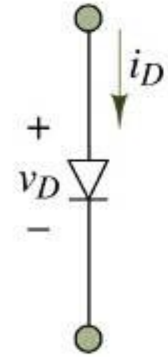
10. Diodes – Basic Diode Concepts

10.1.4 Biasing the PN-Junction

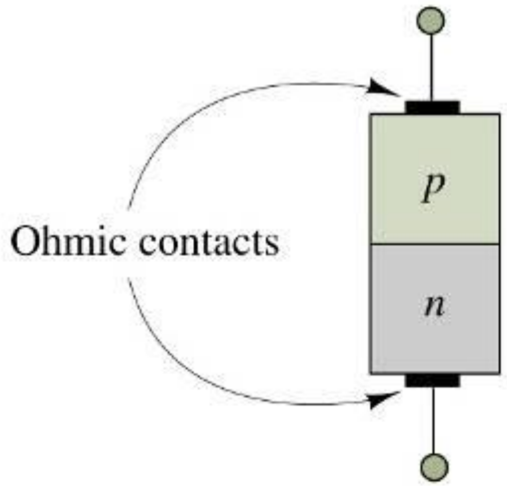
* There is no movement of charge through a pn-junction at equilibrium.

* The pn-junction form a *diode* which allows current in only one direction and prevent the current in the other direction as determined by the *bias*.

The arrow in the circuit symbol for the diode indicates the direction of current flow when the diode is forward-biased.



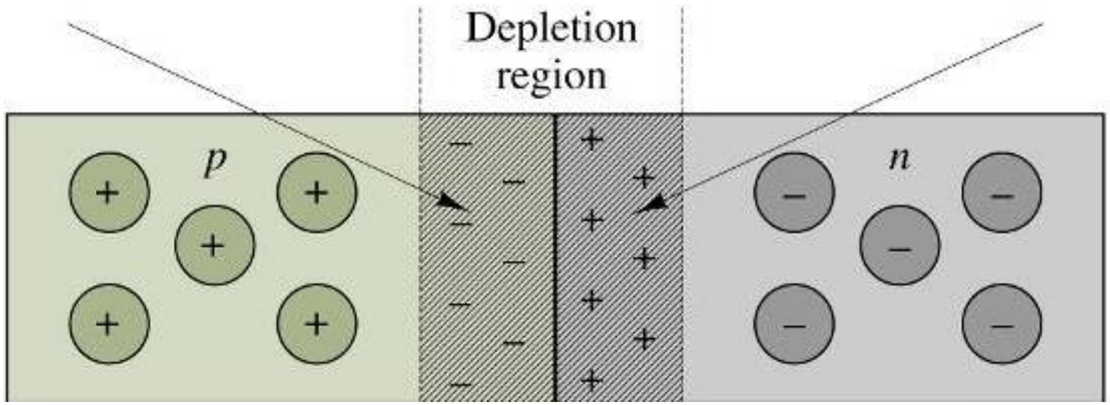
Circuit symbol

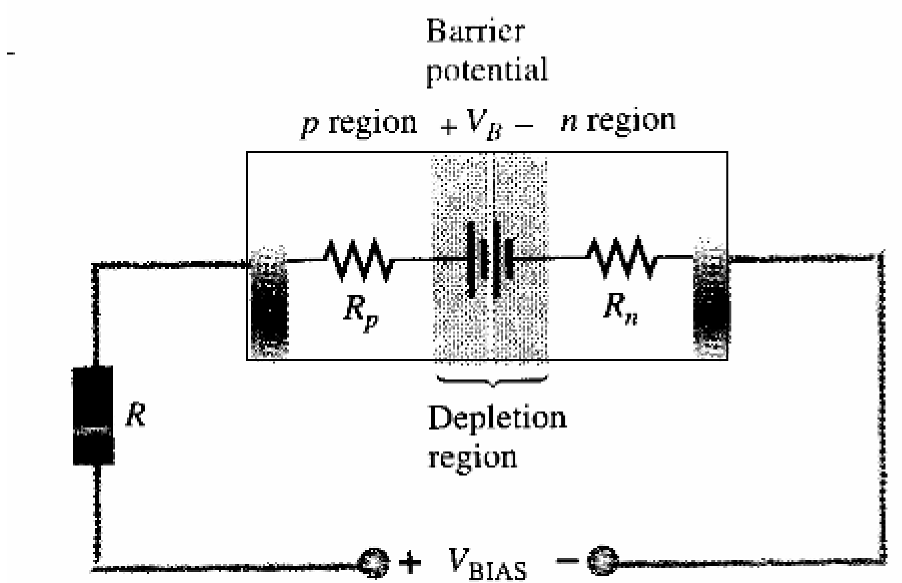


pn junction

10.1.4 Biasing the PN-Junction

****Forward Bias***: *dc voltage positive terminal connected to the p region and negative to the n region*. It is the condition that permits current through the pn-junction of a diode.





10.1.4 Biasing the PN-Junction

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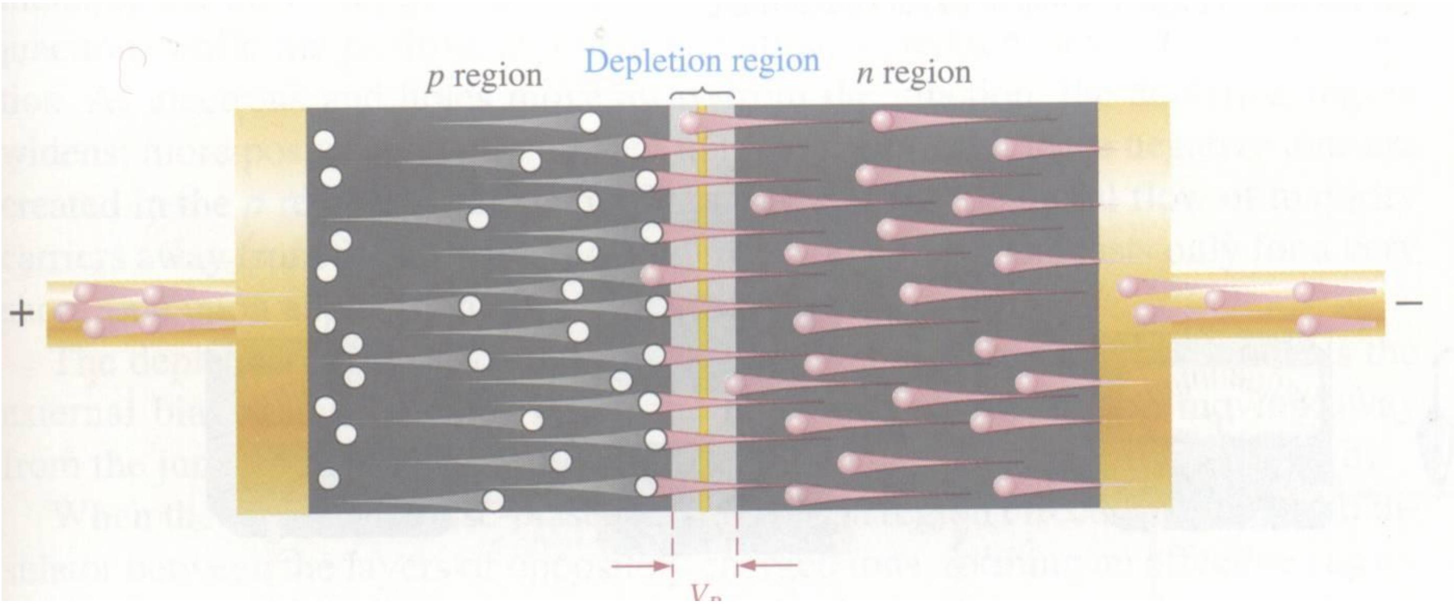
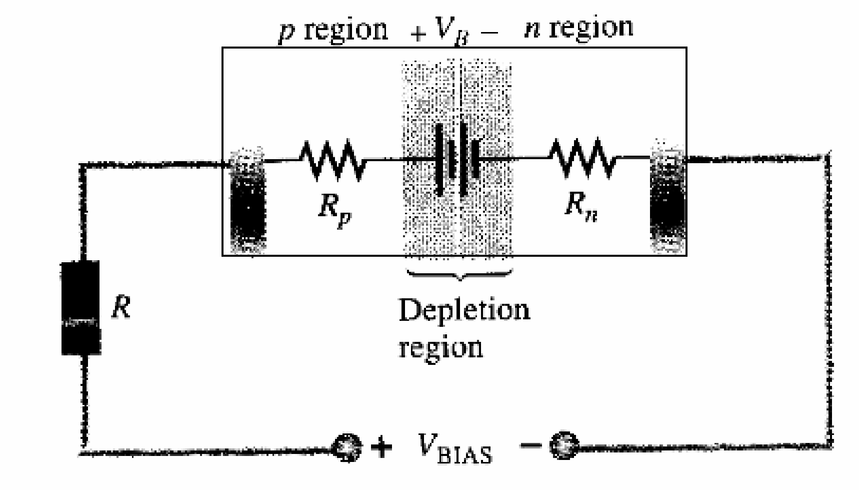
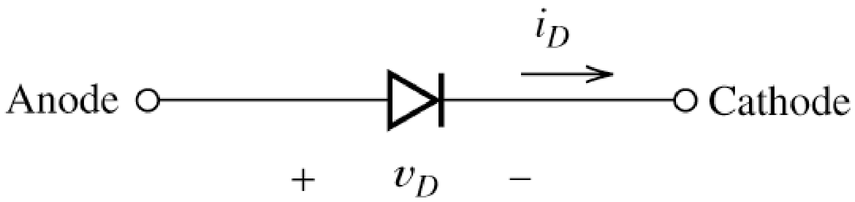


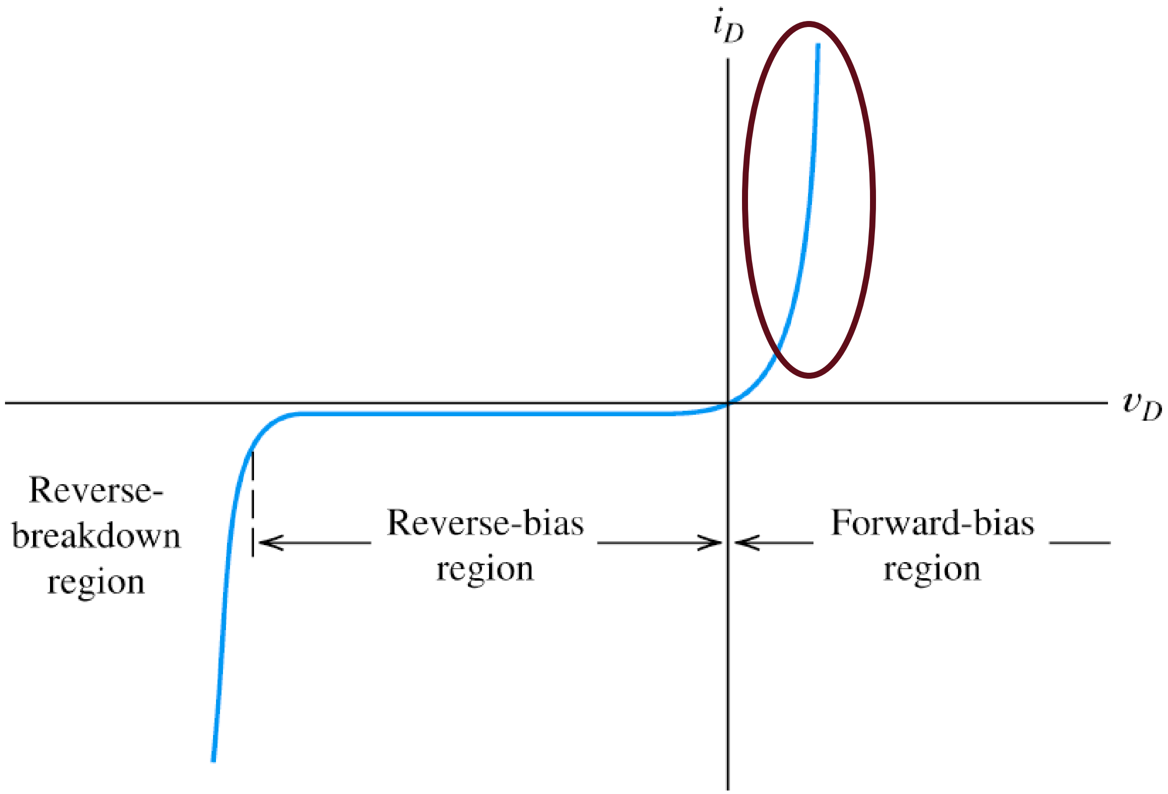


10. Diodes – Basic Diode Concepts

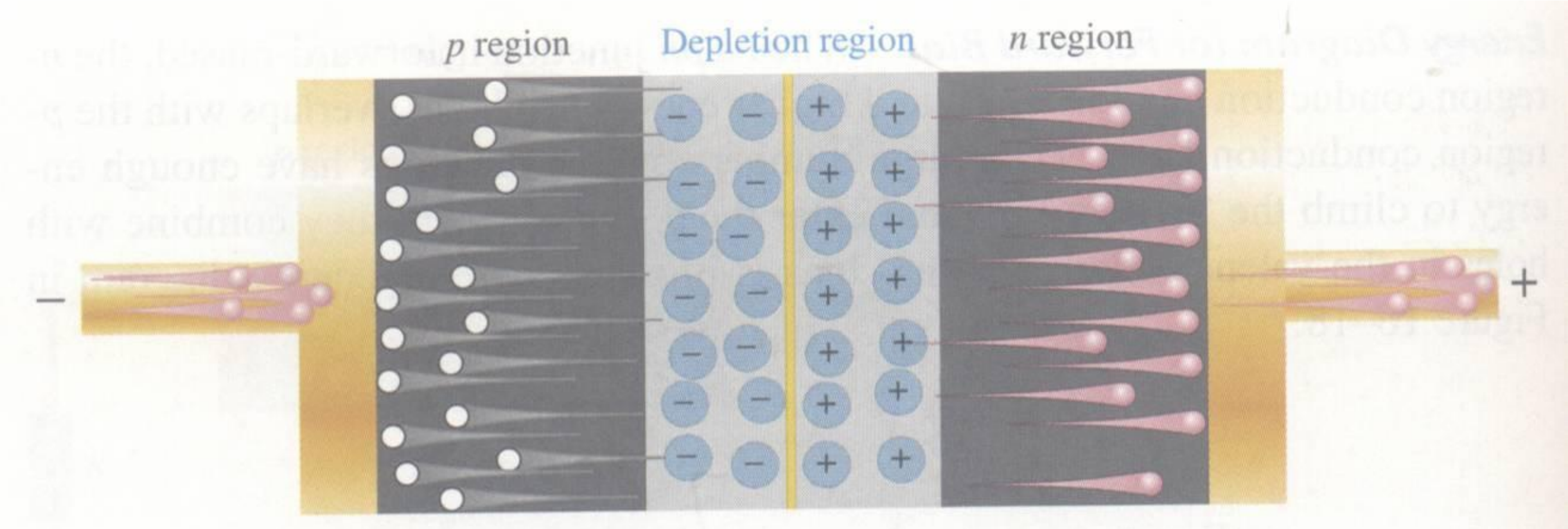
10.1.4 Biasing the PN-Junction

Forward Bias:





Reverse Bias: *dc voltage negative terminal connected to the p region and positive to the n region*. *Depletion region widens* until its potential difference equals the bias voltage, *majority-carrier current ceases*.

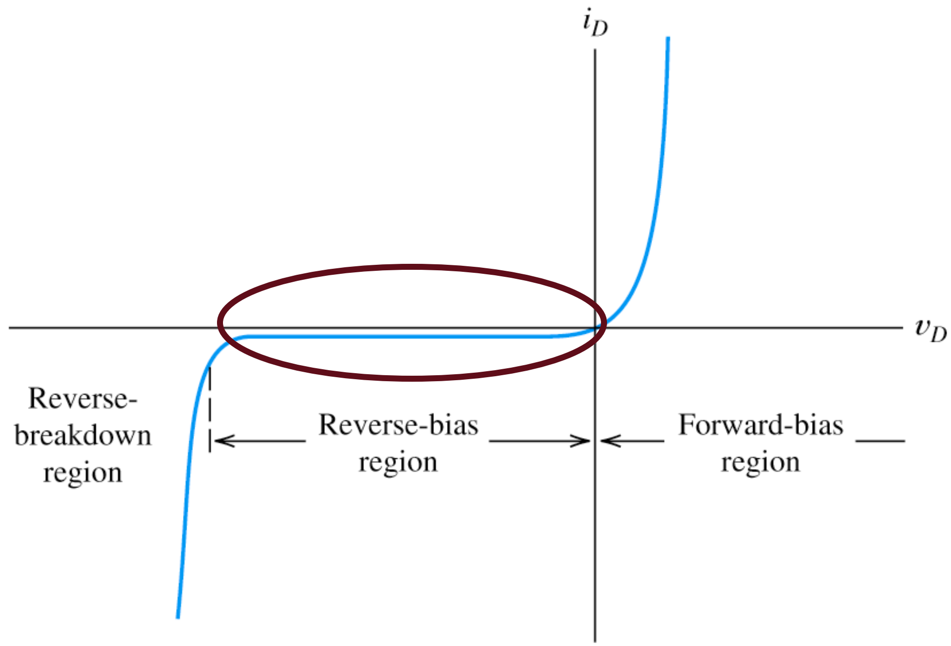


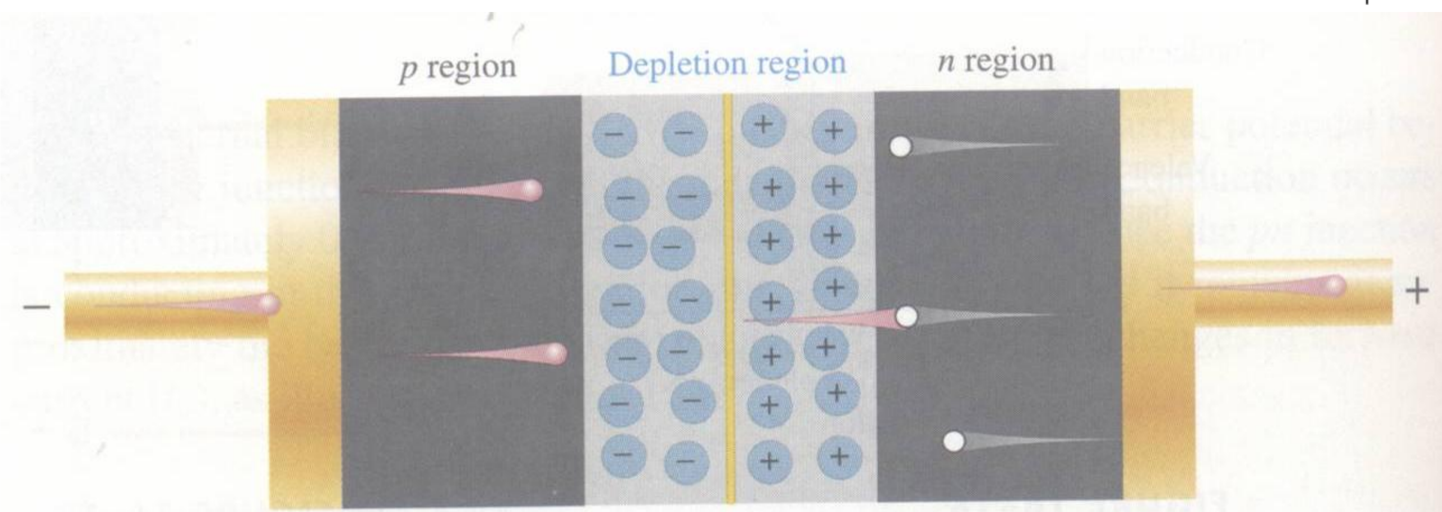
(a) There is transient current as depletion region widens.

Reverse Bias:

majority-carrier current ceases.

* However, there is still a very small current produced by minority carriers.

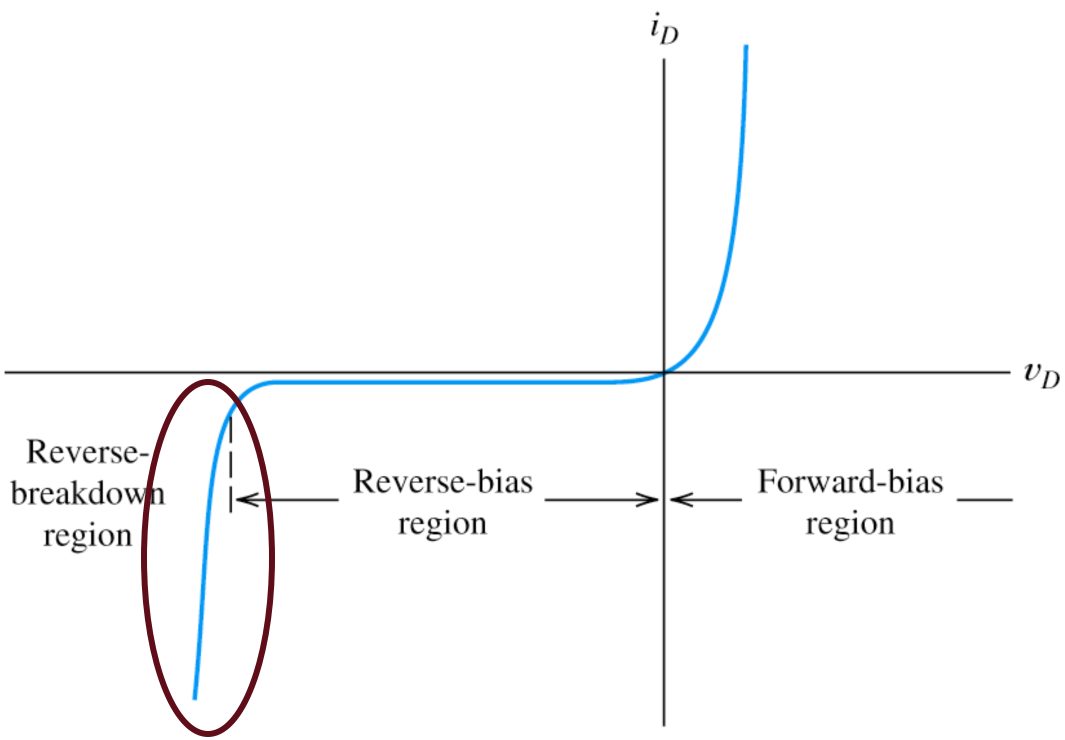




(b) Majority current ceases when barrier potential equals bias voltage. There is an extremely small reverse current due to minority carriers.

10.1.4 Biasing the PN-Junction

* **Reverse Breakdown:** As reverse voltage reach certain value, avalanche occurs and generates large current.



(b) Volt–ampere characteristic

10. Diodes – Basic Diode Concepts

10.1.5 The Diode Characteristic I-V Curve

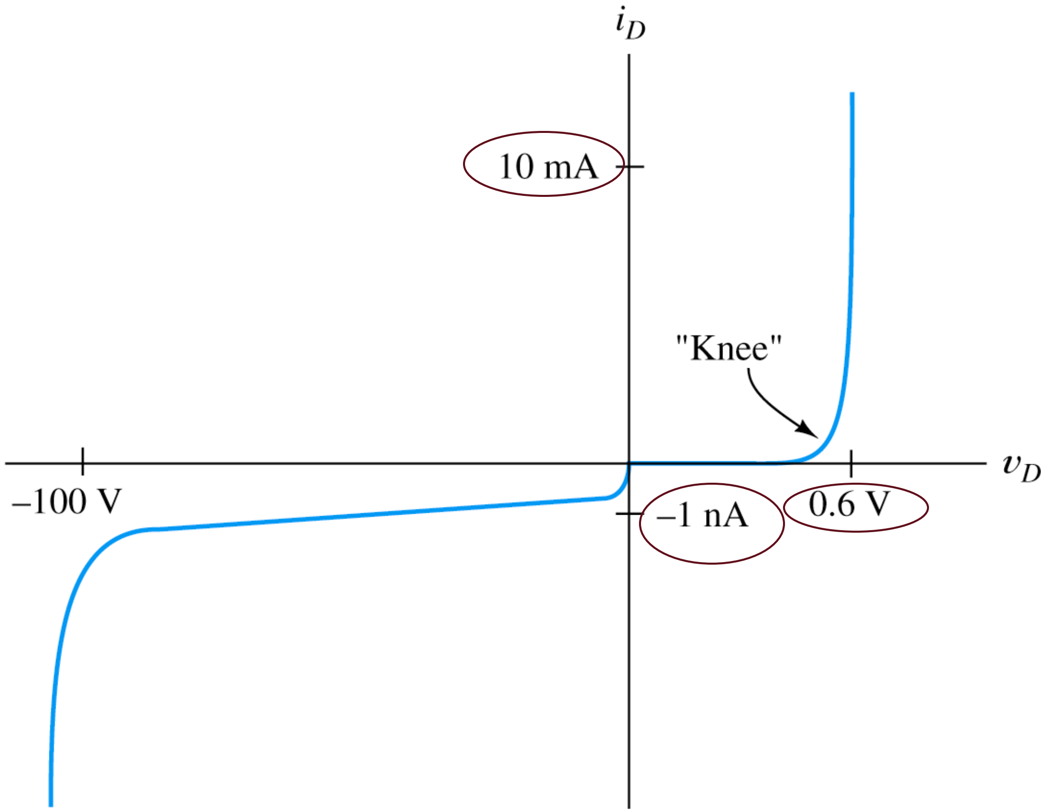
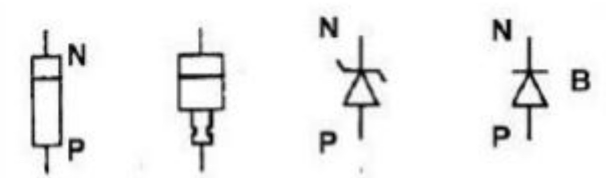


Figure 10.2 Volt–ampere characteristic for a typical small-signal silicon diode at a temperature of 300 K. Notice the change of scale for negative current and voltage.

Two-terminal Devices with p-n Junction – Zener diode

Two-terminal Devices with p-n Junction 1.3.a Zener Diode (ZD) (also referred as regulated diode) is a two terminal device that is widely used in voltage regulators. As shown in the characteristic curve of diode (Fig 1.5 (b)), when the reverse bias, applied to the semiconductor, has reached to Vz , the current will be dramatically increased while the voltage keeps constant. The value of Vz can be controlled by changing the doping concentration. If the doping concentration is increased, the increased amount of impurity will decrease the value of Vz. The regulated values of the zener diode are thus distributed in the range from 3V to several hundreds of volts, whereas the power range is distributed

100W.



(a) appearance (b) symbol

Light Emitting Diode (LED)

Fig. 1.8 1.3.b Light Emitting Diode (LED) LED is one kind of p-n junction device made of galliumarsenic phosphide or gallium phosphide. When the electrons and holes of LED Are combined under the forward bias, the energy carried by free electrons will be transformed into light energy that is within the spectrum of visible light. If the silicon or germanium is used as material, the energy will be transformed into heat energy, but no visible light will be generated. Typically, the operating voltage of LED is around 1.7 V ~ 3.3 V, the power consumption is around 10 ~ 50 mW and the operating life is more than 100 thousand hours. The LEDs can generate visible lights with colors red, yellow, green..etc. depending on the selected materials. The LED will be illuminated if minimum 1.5V forward voltage is applied. If more than 1.5 V is continuously applied to LED, it will burn down. Moreover, as the breakdown voltage of LED is very low, the applied reverse voltage of LED should not exceed 3 V. Appearance (a and b) and symbol (c) of LED is given below.

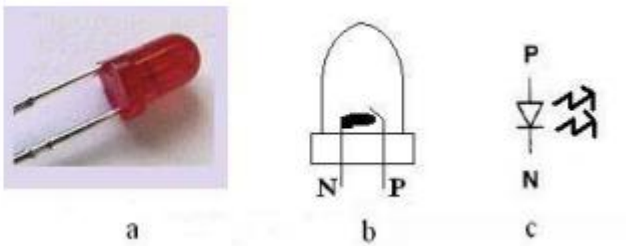
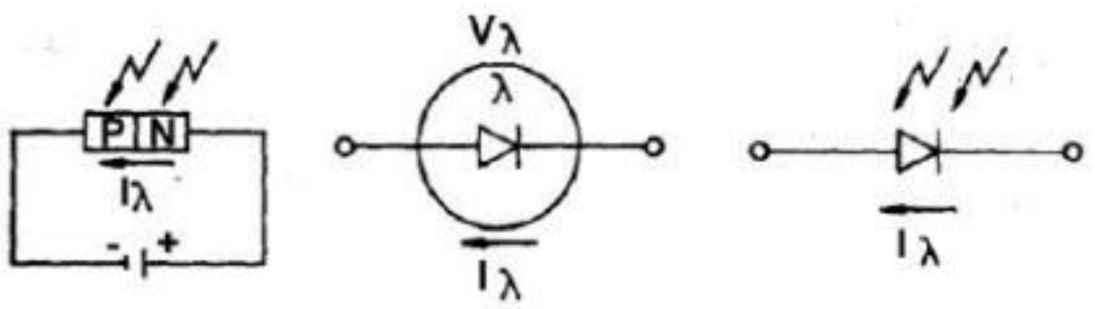


Photo-diode

Photo-diode is one kind of junction type semiconductor device with operating region limited at the reverse bias region, that is, a photo is never applied forward bias. The reverse current of photo-diode is directly proportional to the strength of the light.

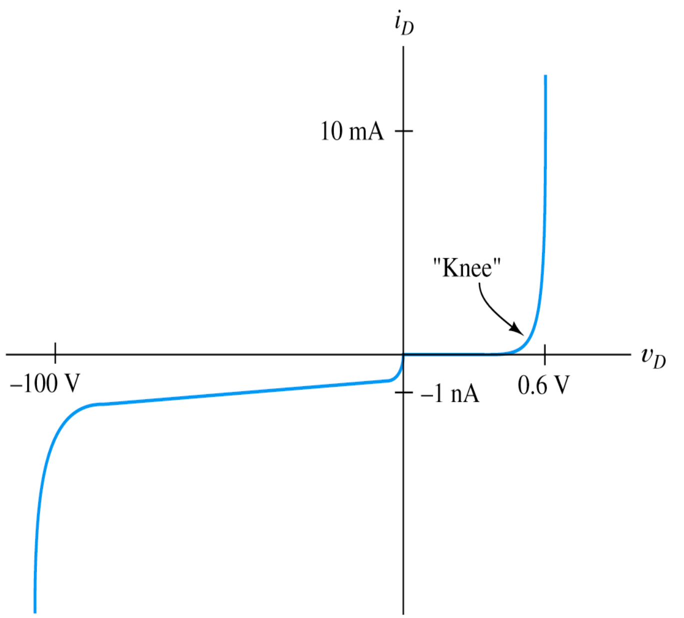


10. Diodes – Basic Diode Concepts

10.1.6 Shockley Equation

* The Shockley equation is a theoretical result under certain simplification:

$$\boxed{i_D = I_s\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right]}$$



$$where\ I_s \cong 10^{-14}\ A\ at\ 300K\ is\ the\ (reverse)\ saturation$$

$$current,\ n \cong 1\ to\ 2\ is\ the\ emission\ coefficient,$$

$$V_T = \frac{kT}{q} \cong 0.026V\ at\ 300K\ is\ the\ thermal\ voltage$$

$$k\ is\ the\ Boltzman's\ constant,\ q = 1.60 \times 10^{-19}\ C$$

$$when\ \boxed{v_D \geq\approx 0.1V,\ i_D \cong I_s \exp\left(\frac{v_D}{nV_T}\right)}$$

$$This\ equation\ is\ not\ applicable\ when\ v_D < 0$$

10.2 Load-Line Analysis of Diode Circuit

$$We\ can\ use\ v = iR, i = C\frac{dv}{dt}, v = L\frac{di}{dt}, \ldots$$

$$but\ when\ there\ is\ a\ diode: i_D = I_s\left[exp\left(\frac{v_D}{nV_T}\right) - 1\right]$$

It is difficult to write KCL or KVL equations.

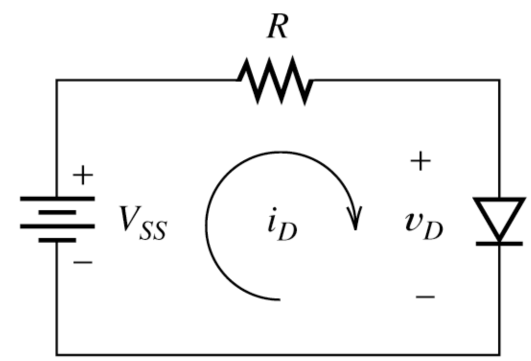


Figure 10.5 Circuit for load-line analysis.

For the circuit shown,

KVL gives:

$$\boxed{V_{SS} = Ri_D + v_D}$$

If the I-V curve of the diode is given,

we can perform the

$\boxed{\text{" Load - Line Analysis"}}$

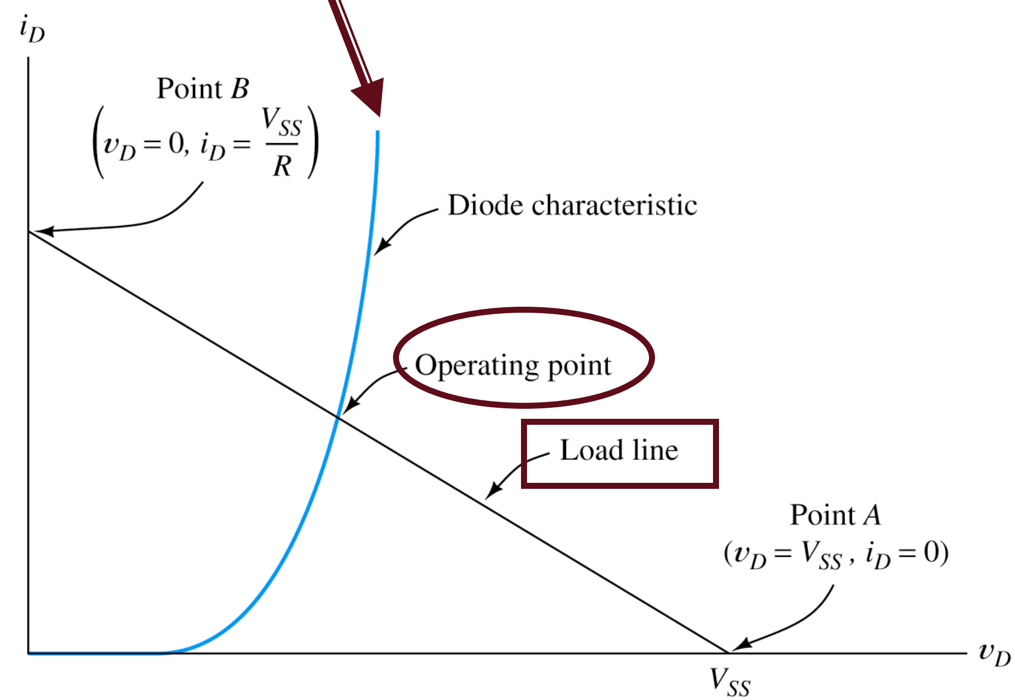


Figure 10.6 Load-line analysis of the circuit of Figure 10.5.

Example 10.1- Load-Line Analysis

For the circuit shown,

Given: $V_{SS} = 2V, R = 1k\Omega,$

the I-V curve of the diode

Find: the diode current and voltage at the operating point (Q-point)

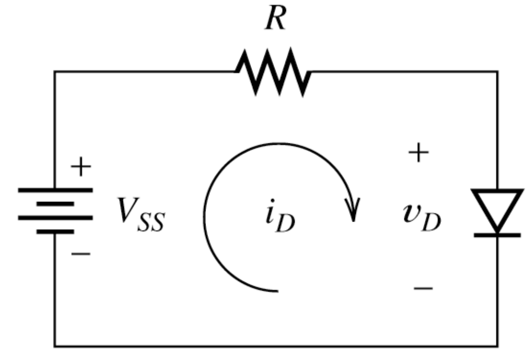


Figure 10.5 Circuit for load-line analysis.

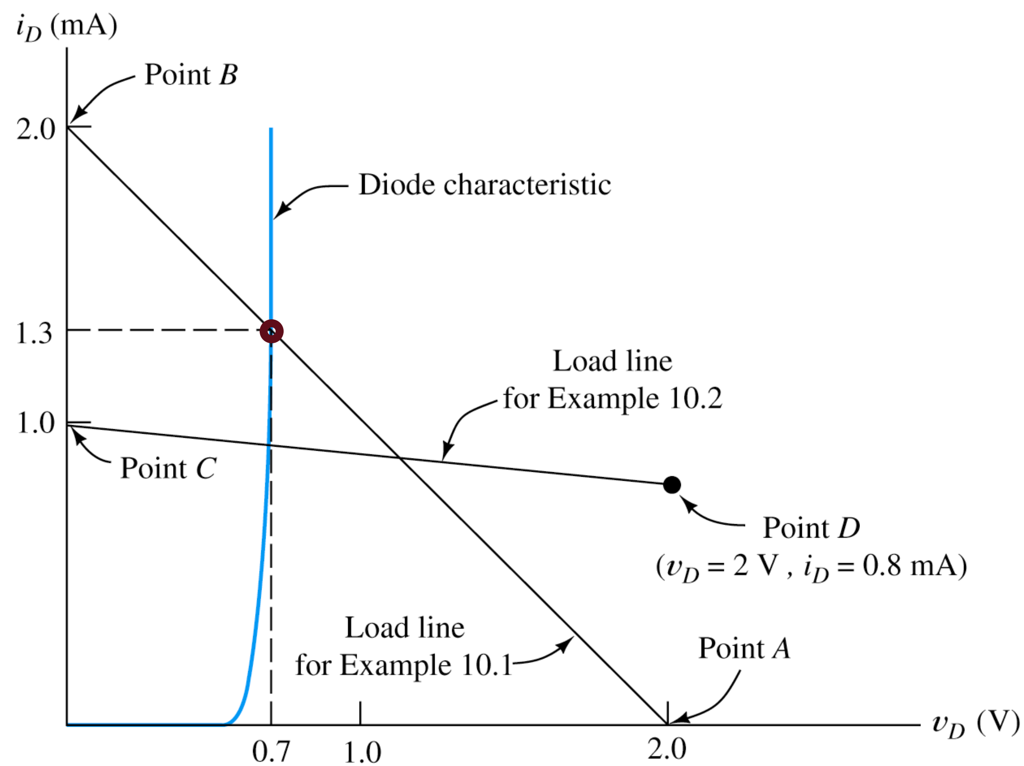
$$V_{SS} = R i_D + v_D, \text{ i.e.,}$$

$$2 = 1000 i_D + v_D$$

$\Rightarrow$ perform load-line analysis

$\Rightarrow$ at the operating point

$$\boxed{V_{DQ} \cong 0.70V, \; i_{DQ} \cong 1.3\,mA}$$



Example 10.2 - Load-Line Analysis

$$\begin{aligned}&\text{For the circuit shown,}\\ &\text{Given}: V_{SS} = 10\,V, R = 10\,k\Omega,\\ &\qquad \text{the I-V curve of the diode}\\ &\text{Find}: \text{the diode current and voltage}\\ &\qquad \text{at the operating point}\end{aligned}$$

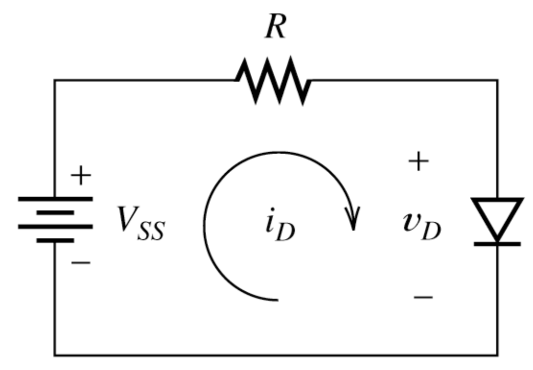


Figure 10.5 Circuit for load-line analysis.

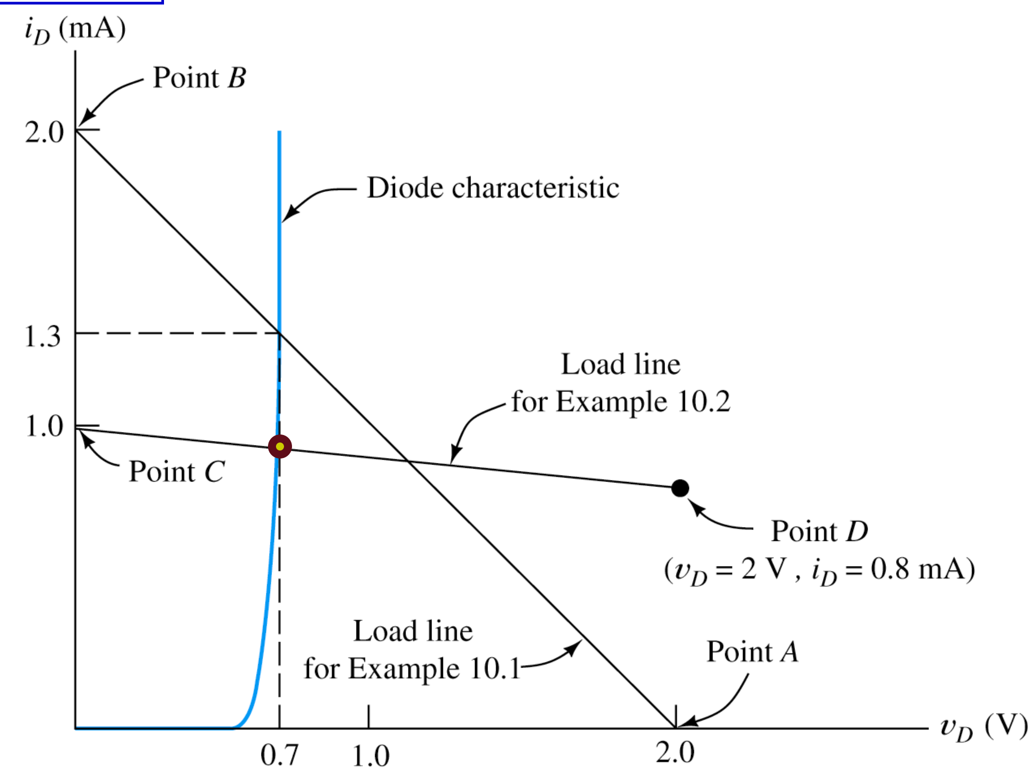
$$V_{SS} = R\,i_D + v_D,\ i.e.,$$

$$10 = 10k\,i_D + v_D$$

$$\Rightarrow \text{perform load-line analysis}$$

$$\Rightarrow \text{at the operating point}$$

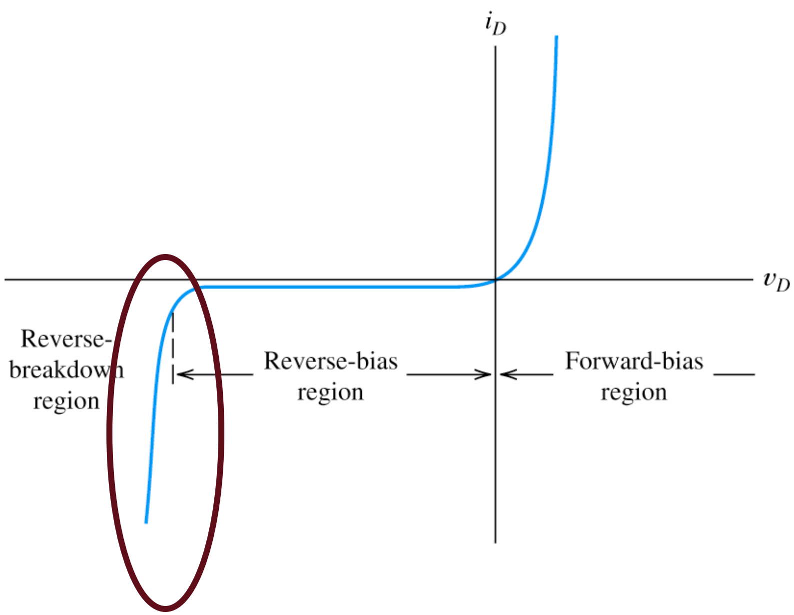
$$\boxed{V_{DQ} \cong 0.68\,V,\ i_{DQ} \cong 0.93\,mA}$$



10.3 Zener-Diode Voltage-Regulator Circuits

10.3.1 The Zener Diode

* *Zener diode* is designed for operation in the reverse-breakdown region.
* The *breakdown voltage* is controlled by the doping level *(-1.8 V to -200 V)*.
* The major application of Zener diode is to provide an output reference that is stable despite changes in input voltage – power supplies, voltmeter,…



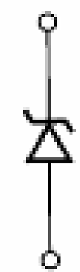


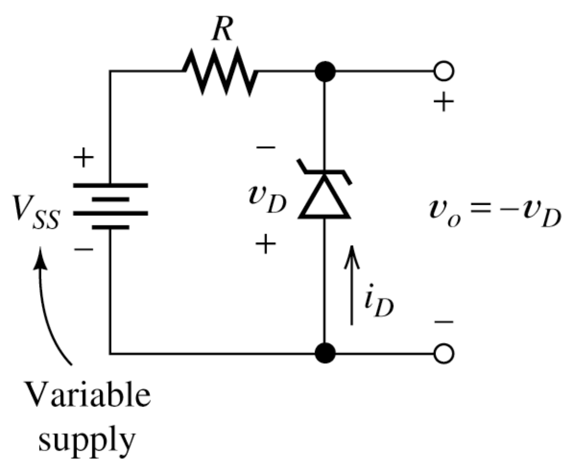
Figure 7.3 Zener diode symbol.

10.3.2 Zener-Diode Voltage-Regulator Circuits

* Sometimes, a circuit that produces constant output voltage while operating from a variable supply voltage is needed. Such circuits are called *voltage regulator*.

* The Zener diode has a breakdown voltage equal to the desired output voltage.

* The resistor limits the diode current to a safe value so that Zener diode does not overheat.



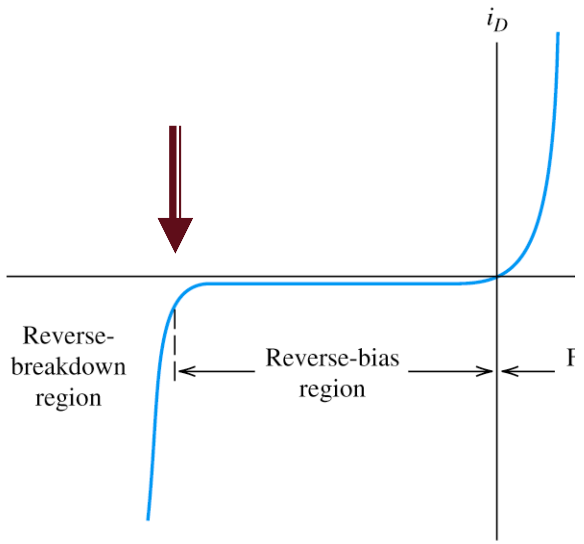
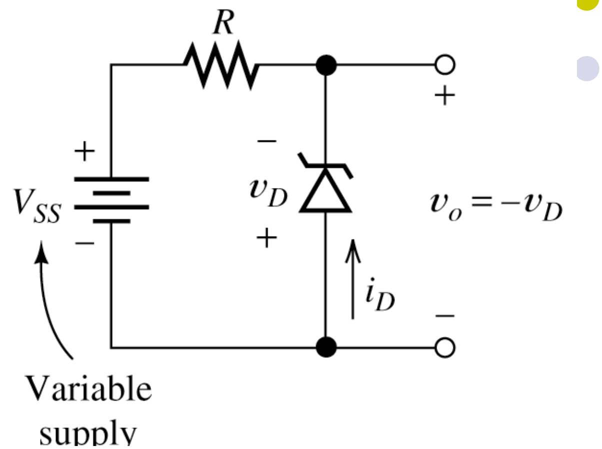


Figure 10.9 A simple regulator circuit that provides a nearly constant output voltage v_o from a variable supply voltage.

Example 10.3 – Zener-Diode Voltage-Regulator Circuits



$$Given: the\ Zener\ diode\ I\text{-}V\ curve,\ R = 1k\Omega$$
$$Find: the\ output\ voltage\ for\ V_{SS} = 15V\ and$$
$$V_{SS} = 20V$$

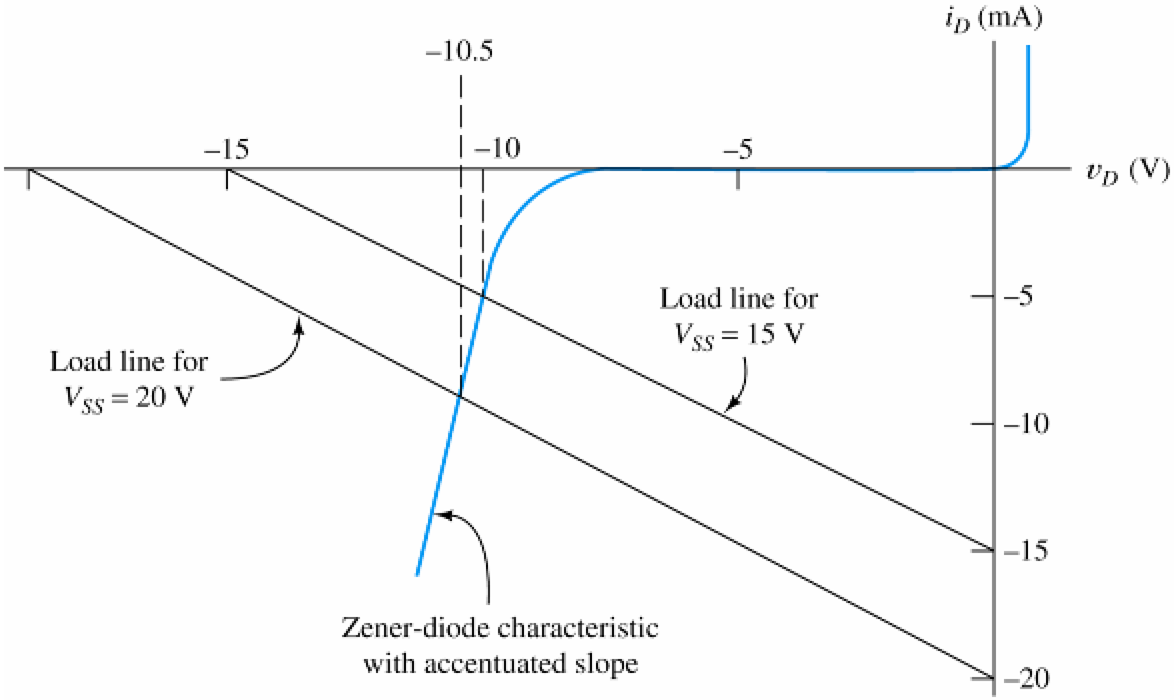
KVL gives the load line:

$$V_{SS} + R\,i_D + v_D = 0$$

From the Q-point we have:

$$v_o = 10.0V\ \ for\ V_{SS} = 15V$$
$$v_o = 10.5V\ \ for\ V_{SS} = 20V$$

$$\boxed{\begin{array}{l} 5V\ change\ in\ input \\ \Rightarrow 0.5V\ change\ in\ v_o \end{array}}$$



Actual Zener diode performs much better!

10.3.3 Load-Line Analysis of Complex Circuits

* Use the Thevenin Equivalent

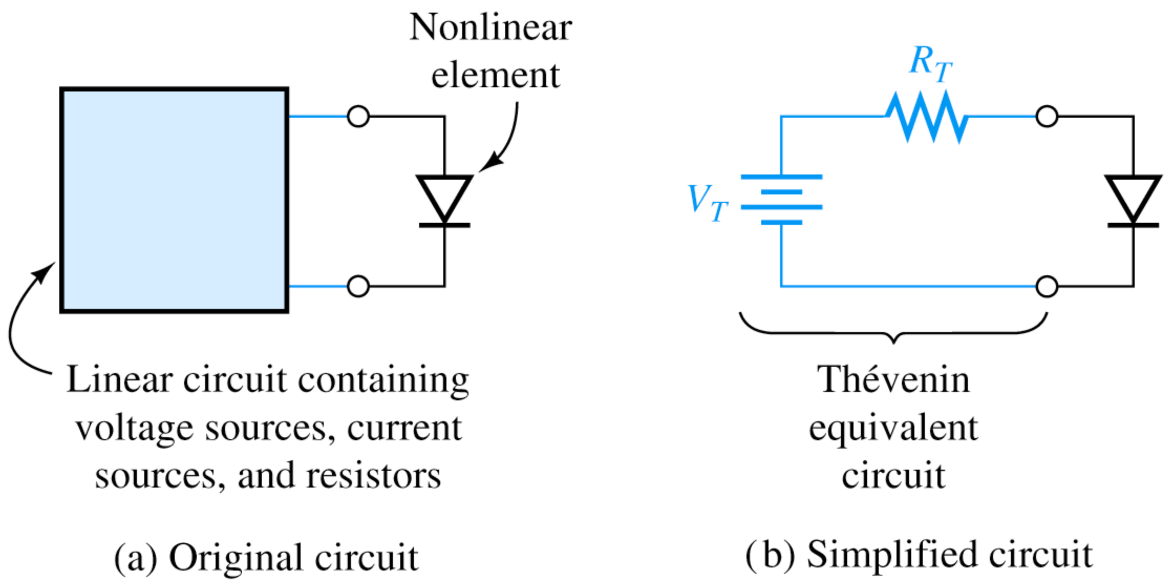


Figure 10.11 Analysis of a circuit containing a single nonlinear element can be accomplished by load-line analysis of a simplified circuit.

Example 10.4 – Zener-Diode Voltage-Regulator with a Load

$$Given: Zener\ diode\ I\text{-}V\ curve,\ V_{SS} = 24V, R = 1.2k\Omega, R_L = 6k\Omega$$
$$Find: the\ load\ voltage\ v_L\ and\ source\ currents\ I_S$$

$$Applying\ Thevenin\ Equivalent \Rightarrow V_T = V_{SS}\frac{R_L}{R+R_L} = 20V,\ R_T = \frac{R\,R_L}{R+R_L} = 1k\,\Omega$$

$$\Rightarrow V_T + R_T\, i_D + v_D = 0$$

$$\Rightarrow v_L = -v_D = 10.0V$$

$$I_S = (V_{SS} - v_L)/R = 11.67\,mA$$

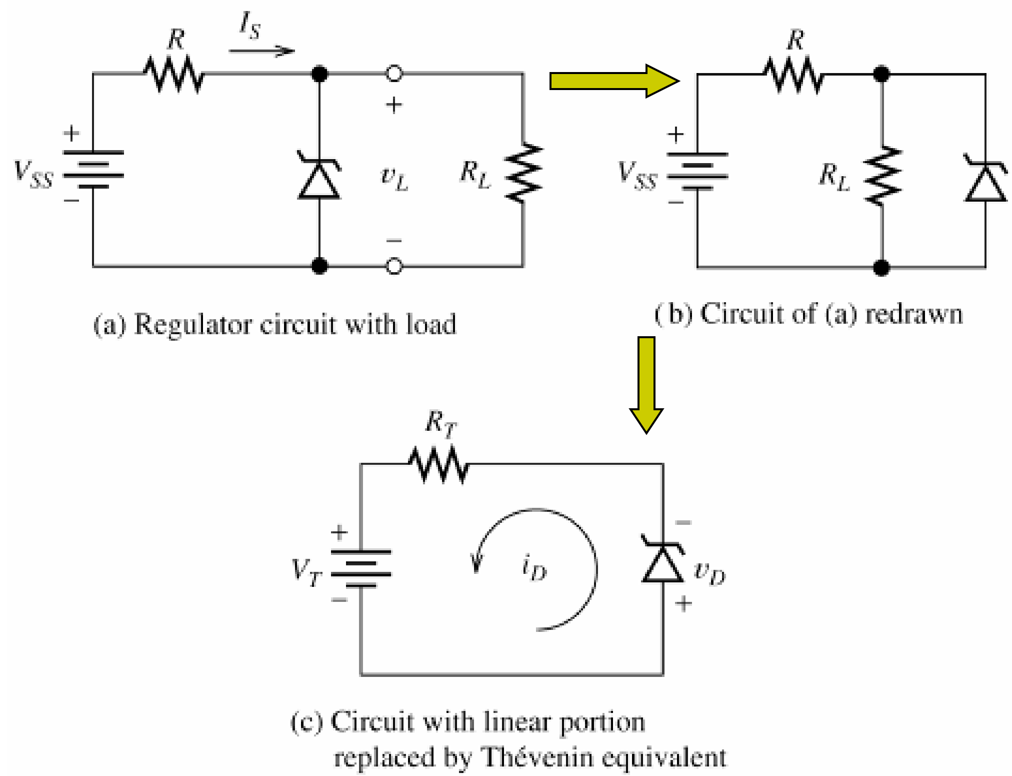


Figure 10.12 See Example 10.4.

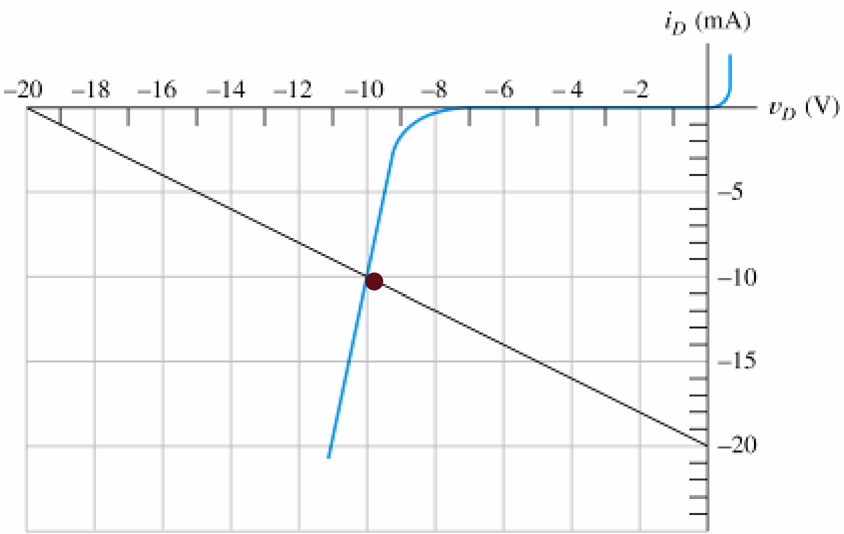


Figure 10.13 Zener-diode characteristic for Example 10.4 and Exercise 10.4.

10. Diodes – Zener-Diode Voltage-Regulator Circuits

Quiz – Exercise 10.5

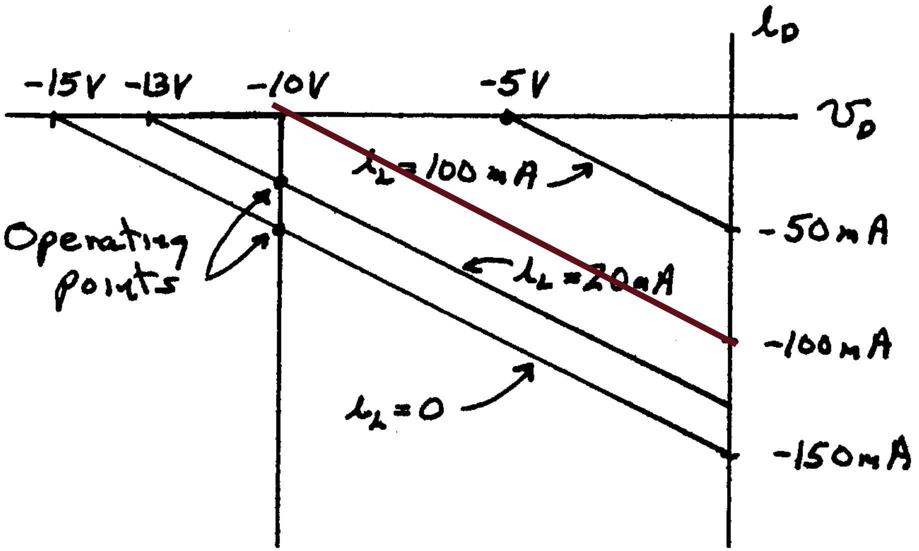
Given : the circuit and the Zener doide I - V curve as shown.

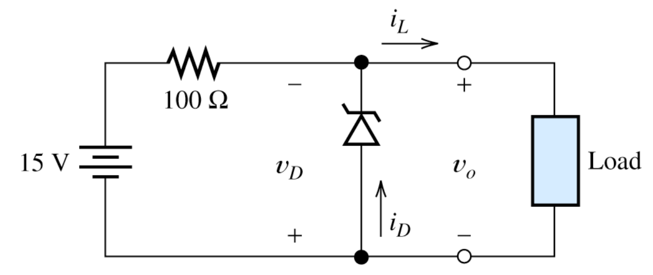
Find : the output voltage v_o for $i_L = 0, i_L = 20mA$, and $i_L = 100mA$

Writing a KVL equation for the loop consisting of the source, the resistor, and the load, we obtain:

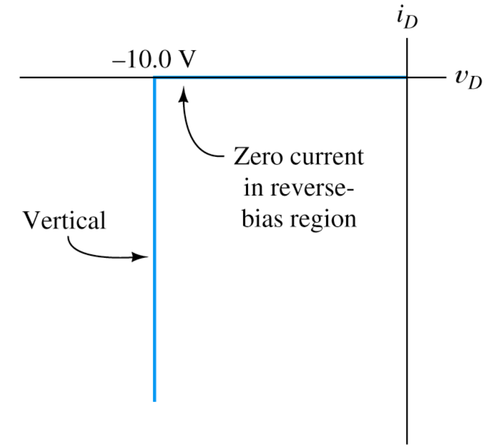
$$15 = 100(i_L - i_D) - v_D$$

The corresponding load lines for the three specified values of i_L are shown:





(a) Circuit diagram



(b) Zener-diode characteristic

At the intersections of the load lines with the diode characteristic, we find (a) $v_o = -v_D = 10$ V; (b) $v_o = -v_D = 10$ V; (c) $v_o = -v_D = 5$ V. Notice that the regulator is effective only for values of load current up to 50 mA.

10. Diodes – Ideal-Diode Model

10.4 Ideal-Diode Model

* Graphical load-line analysis is too cumbersome for complex circuits,
* We may apply "*Ideal-Diode Model*" to simplify the analysis:

(1) in forward direction: *short-circuit assumption*, zero voltage drop;
(2) in reverse direction: *open-circuit assumption*.

* The ideal-diode model can be used when the forward voltage drop and reverse currents are negligible.

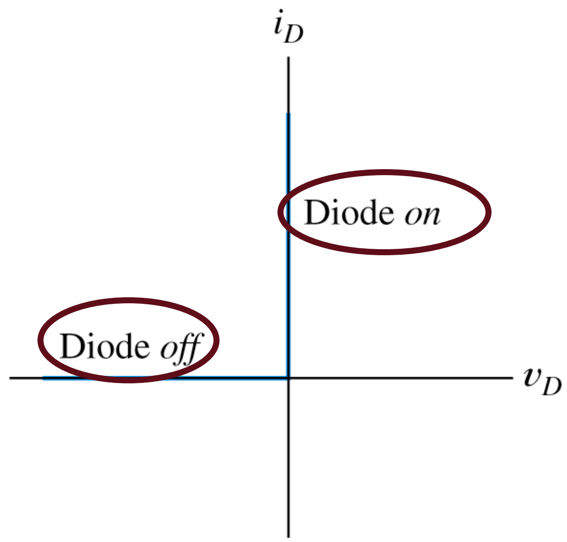


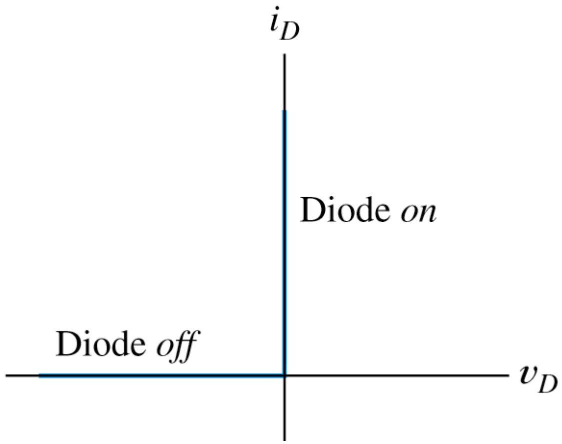
Figure 10.15 Ideal-diode volt–ampere characteristic.

10.4 Ideal-Diode Model

* In analysis of a circuit containing diodes, we may not know in advance *which diodes are on and which are off*.

* What we do is first to make a guess on the state of the diodes in the circuit:

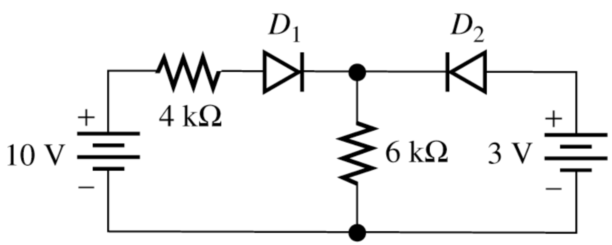
$$
\boxed{
\begin{array}{l}
(1)\,For\text{" }assumed\ on\ diodes\text{"}: check\ if\ i_D\ is\ positive;\\
(2)\,For\text{" }assumed\ off\ \ diodes\text{"}: check\ if\ v_D\ is\ negative\\
\Rightarrow ALL\ YES \Rightarrow BINGO!\\
\Rightarrow not\ \ ALL\ YES \Rightarrow make\ another\ guess....\\
\qquad\qquad\qquad\qquad iterates\ until\text{" }ALL\ YES\text{"}
\end{array}
}
$$



10. Diodes – Ideal-Diode Model

Example 10.5 – Analysis by Assumed Diode States

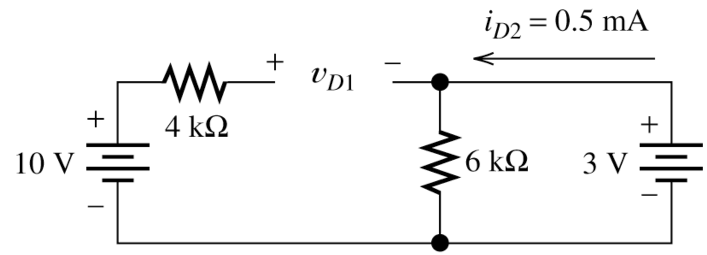
$$\boxed{Analysis\ the\ circuit\ by\ assuming\ D_1\ is\ off\ and\ D_2\ on}$$



(a) Circuit diagram

(1) assume

D_1 off, D_2 on $\Rightarrow$



(b) Equivalent circuit assuming D_1 off and D_2 on (since $v_{D1} = +7$ V, this assumption is not correct)

$\Downarrow$

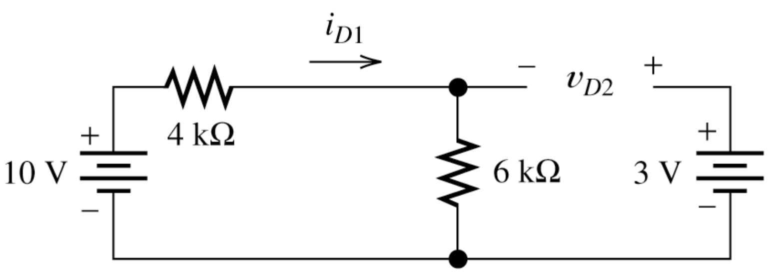
$$i_{D2} = 0.5mA \quad OK!$$

$$v_{D1} = 7V \quad not\ OK!$$

$\Downarrow$

(2) assume

D_1 on, D_2 off

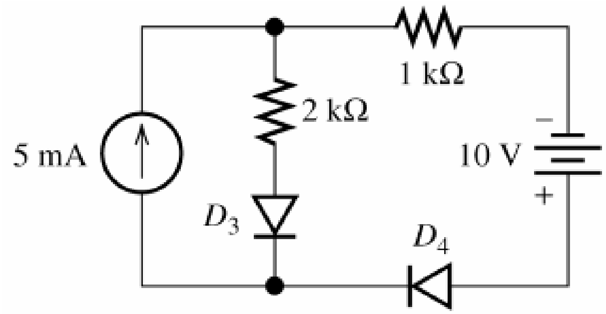


(c) Equivalent circuit assuming D_1 on and D_2 off (this is the correct assumption since i_{D1} turns out to be a positive value and v_{D2} turns out negative)

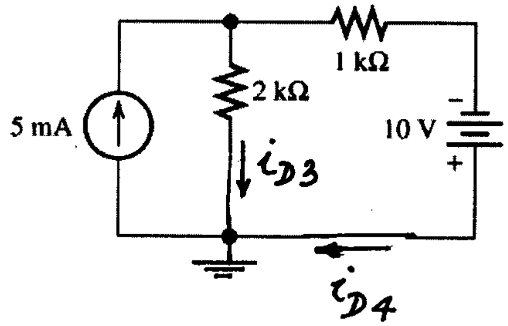
$$\boxed{\begin{aligned} \Rightarrow\ i_{D1} &= 1\,mA \quad OK! \\ v_{D2} &= -3V \quad OK! \end{aligned}}$$

Quiz – Exercise 10.8c

* Find the diode states by using ideal-diode model. Starting by assuming both diodes are on.



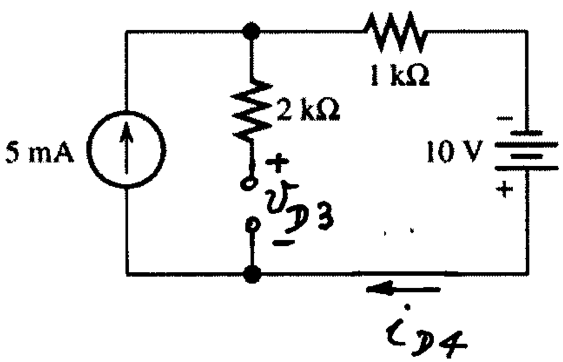
$$(1)\, assume \quad D_3 \;\; on \quad D_4 \;\; on \quad \Rightarrow$$



$$\Downarrow$$

$$i_{D3} = \text{-}1.7\, mA, \;\; not\ OK$$
$$i_{D4} = 6.7\, mA, \;\; OK$$

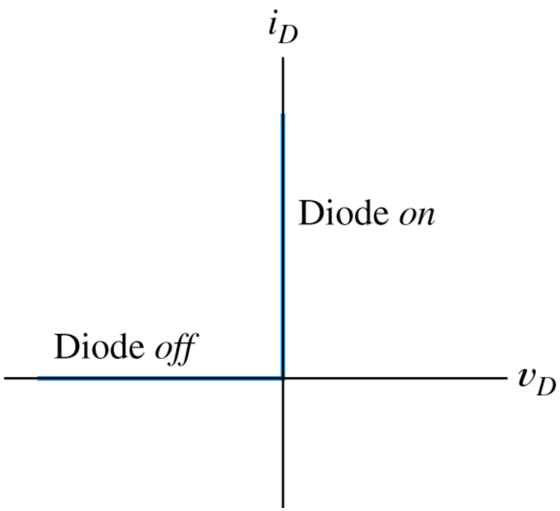
$$(2)\, assume \;\; D_3 \; off \;\; and \;\; D_4 \; on$$
$$\Downarrow$$



$$\boxed{\begin{aligned} \Rightarrow\ i_{D4} &= 5\, mA, \quad OK \\ v_{D3} &= \text{-}5V, \quad OK \end{aligned}}$$

10.5 Piecewise-Linear Diode Models

10.5.1 Modified Ideal-Diode Model



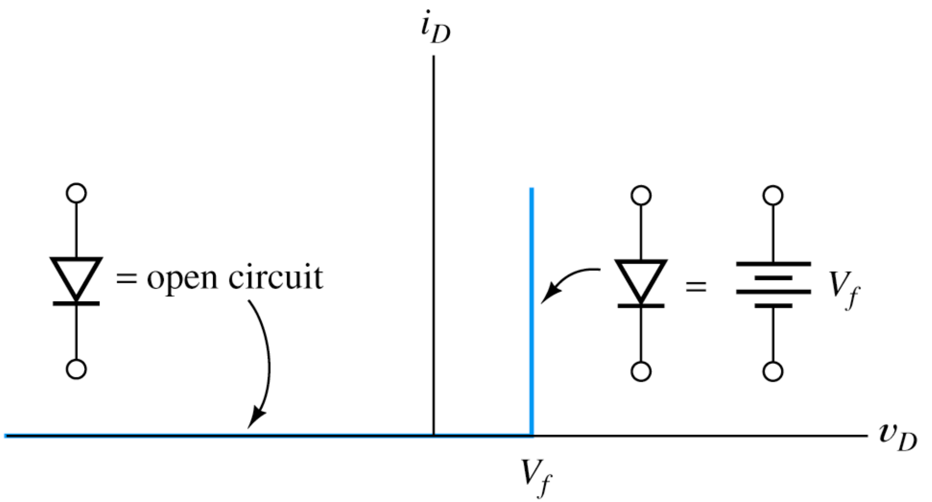
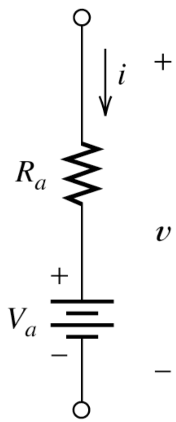


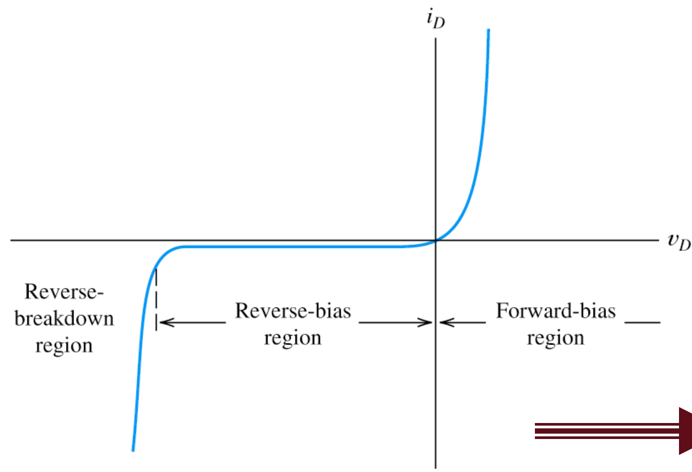
Figure 10.23 Simple piecewise-linear equivalent for the diode.

* This modified ideal-diode model is usually accurate enough in most of the circuit analysis.

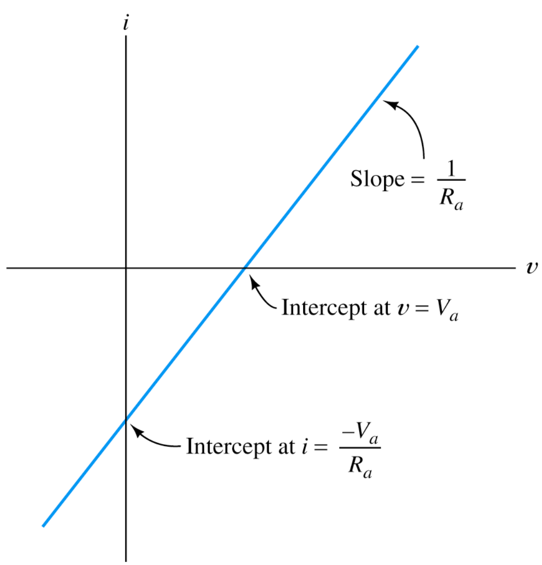
10. Diodes – Piecewise-Linear Diode Models

10.5.2 Piecewise-Linear Diode Models





$$v = R_a\, i + V_a$$



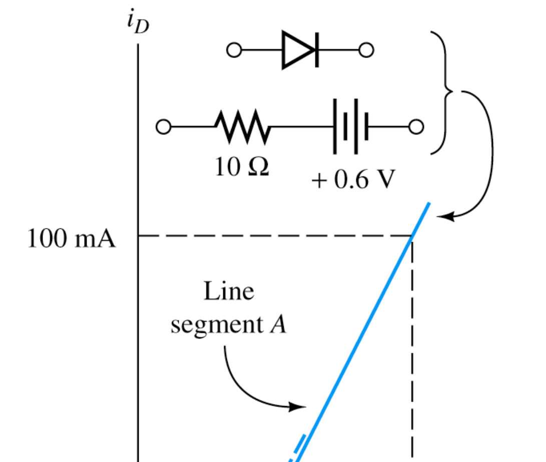
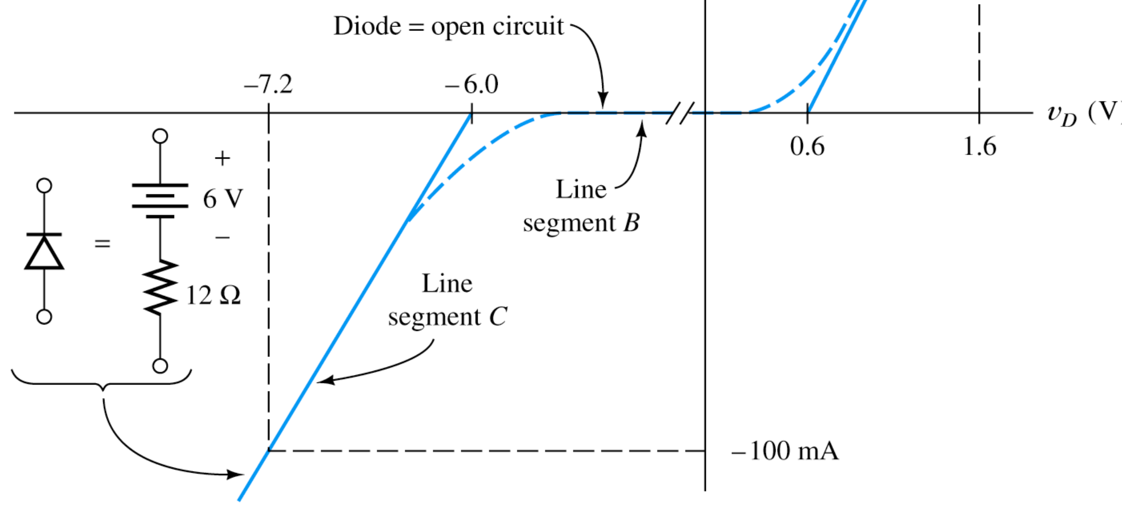



Figure 10.19 Piecewise-linear models for the diode of Example 10.6.

10.6 Rectifier Circuits

* *Rectifiers* convert ac power to dc power.

* Rectifiers form the basis for electronic power suppliers and battery charging circuits.

10.6.1 Half-Wave Rectifier

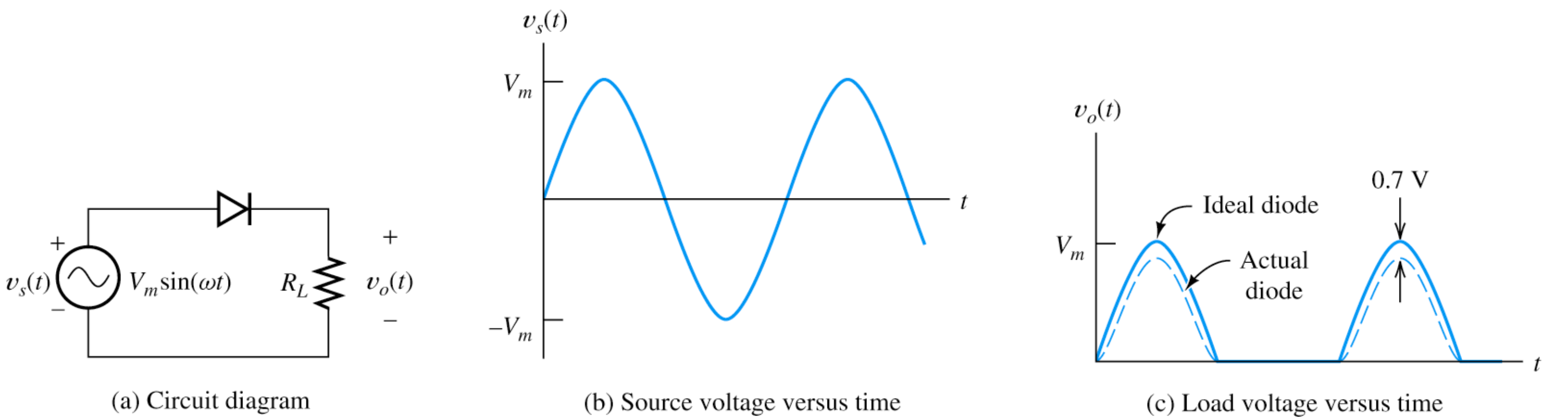
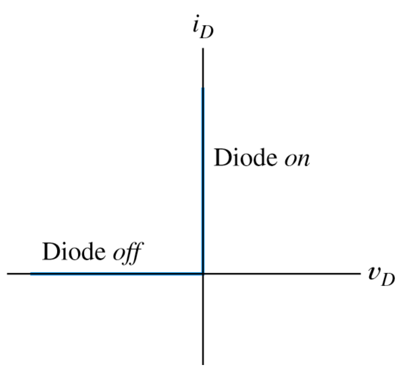
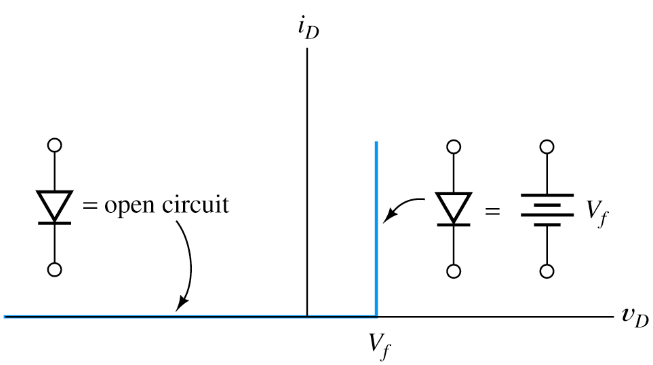


Figure 10.24 Half-wave rectifier with resistive load.





* Battery-Charging Circuit

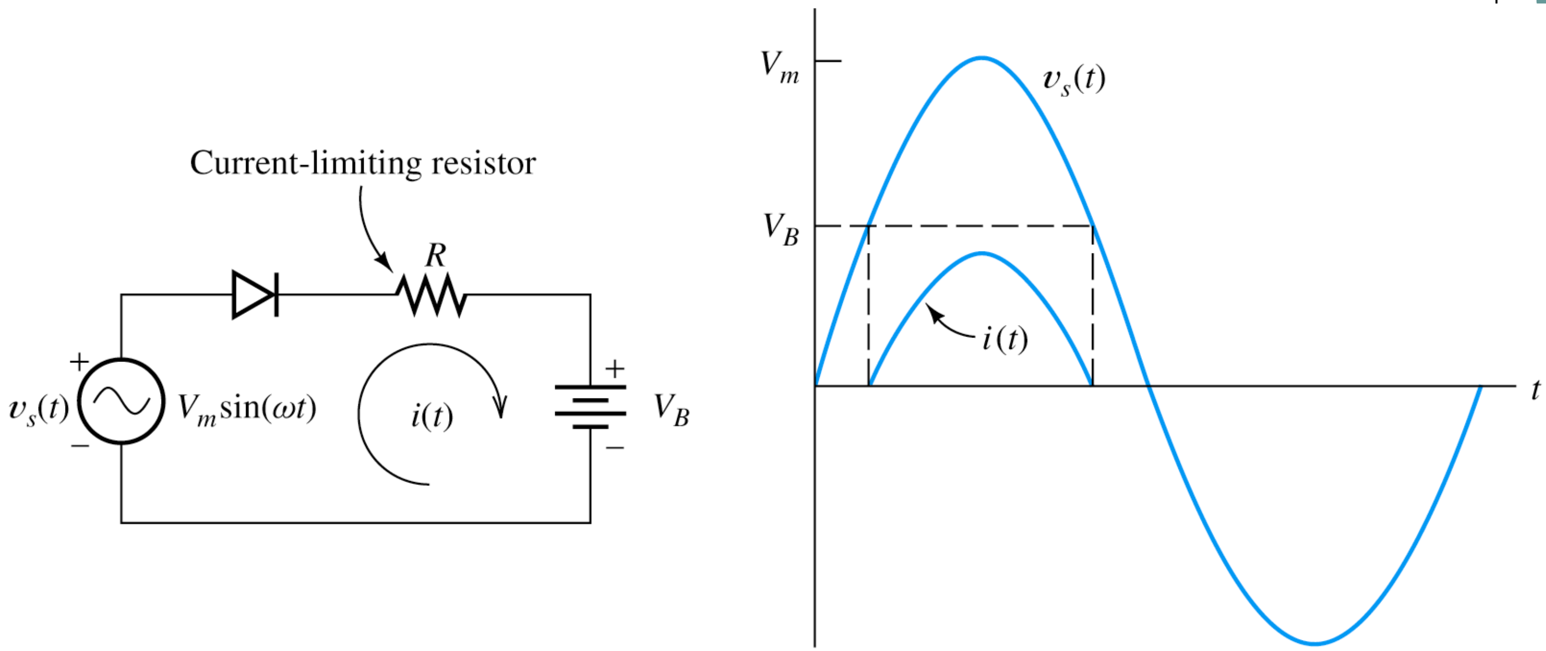
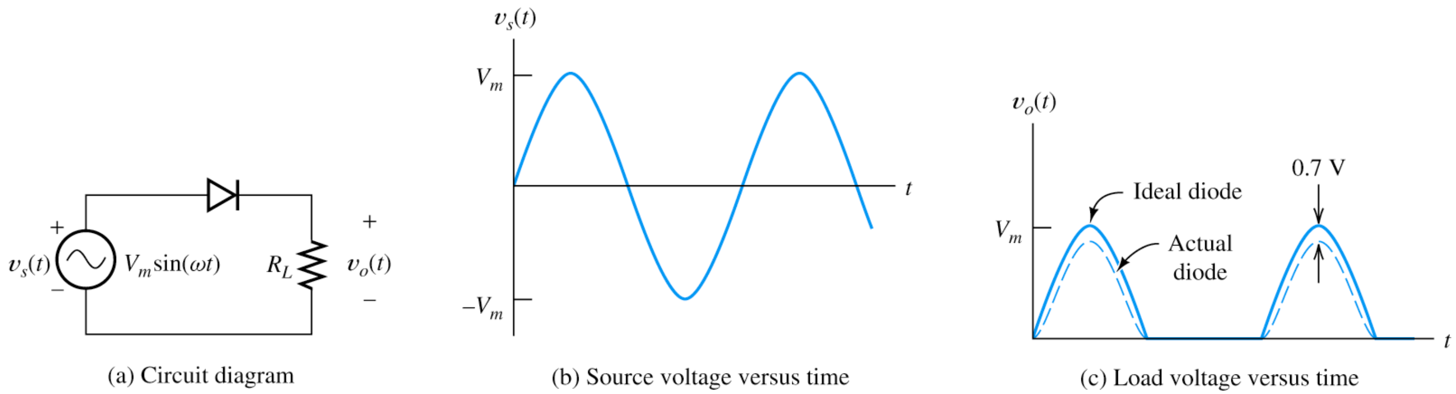


Figure 10.25 Half-wave rectifier used to charge a battery.

* The current flows only in the direction that charges the battery.

10. Diodes – Rectifier Circuits

* Half-Wave Rectifier with Smoothing Capacitor



* To place a large capacitance across the output terminals:

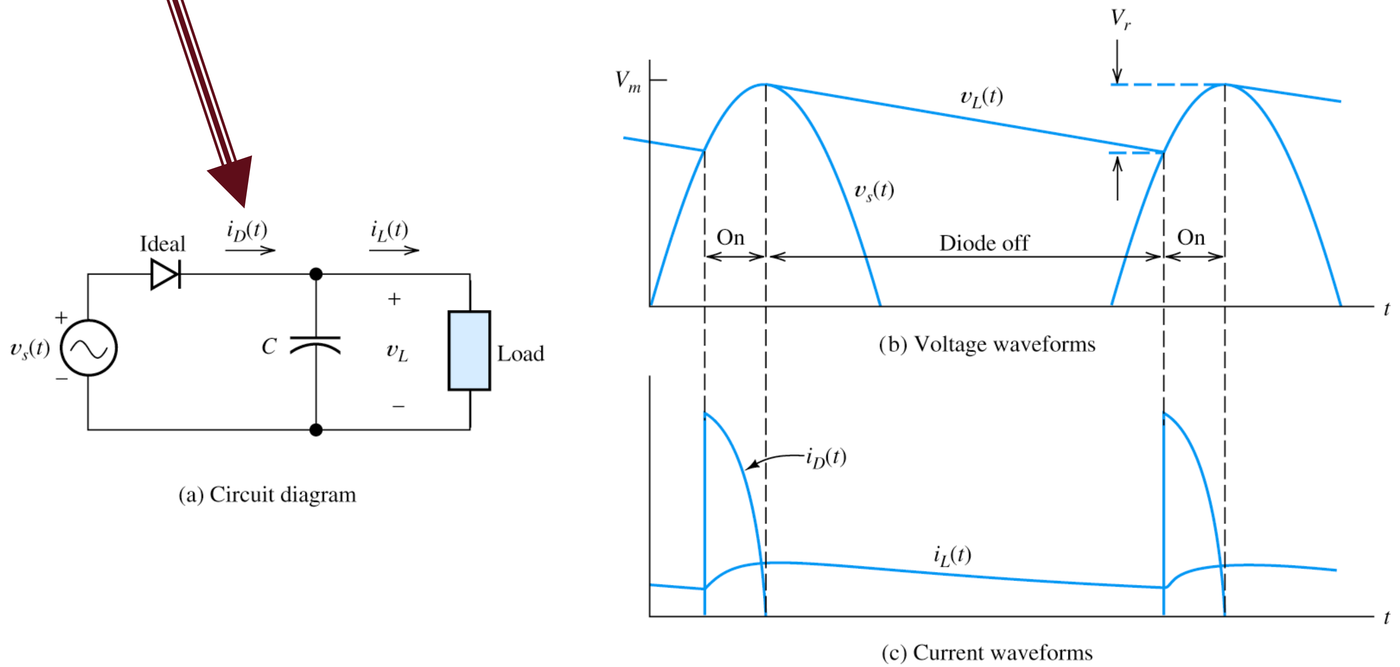


Figure 10.26 Half-wave rectifier with smoothing capacitor.

10.6.2 Full-Wave Rectifier Circuits

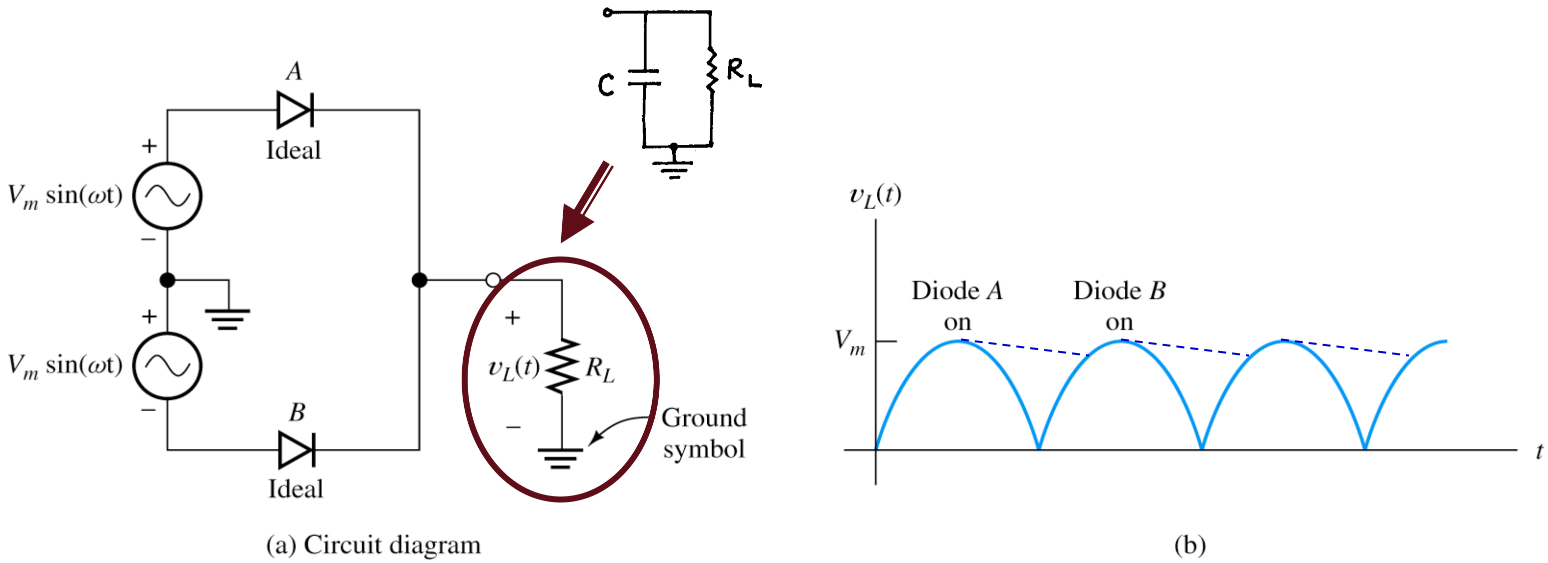


Figure 10.27 Full-wave rectifier.

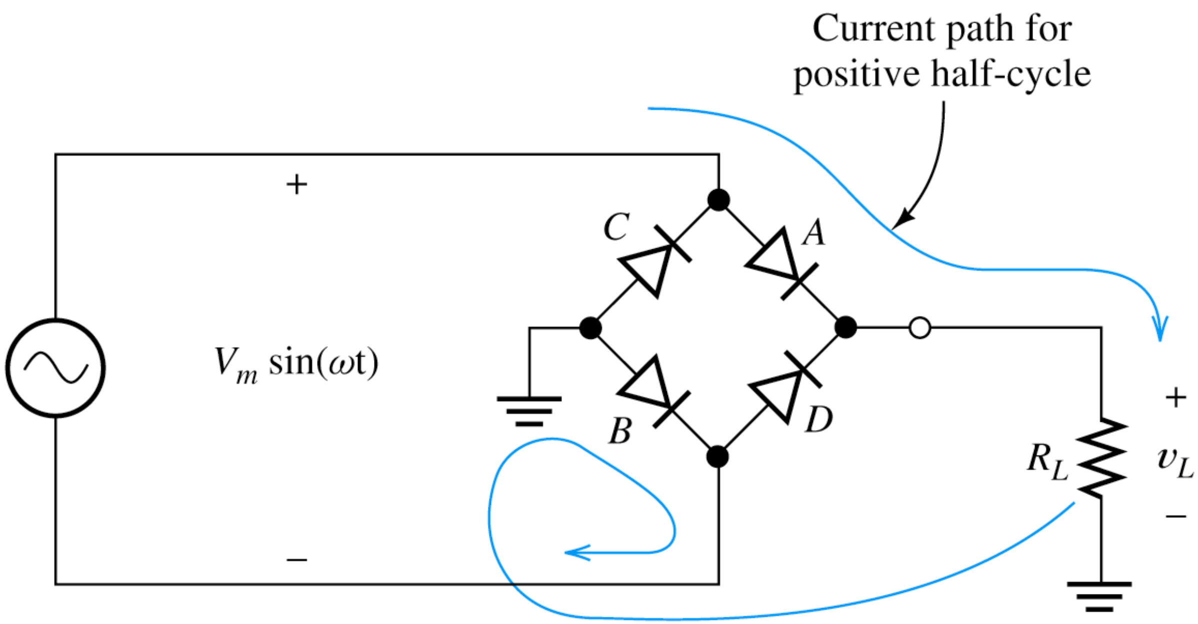
* *Center-Tapped Full-Wave Rectifier* – two half-wave rectifier with out-of-phase source voltages and a common ground.

* When upper source supplies "+" voltage to diode A,
the lower source supplies "-" voltage to diode B;
and vice versa.

* We can also smooth the output by using a large capacitance.

10.6.2 Full-Wave Rectifier Circuits

* The *Diode-Bridge Full-Wave Rectifier*:



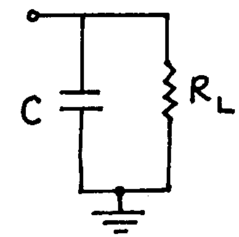
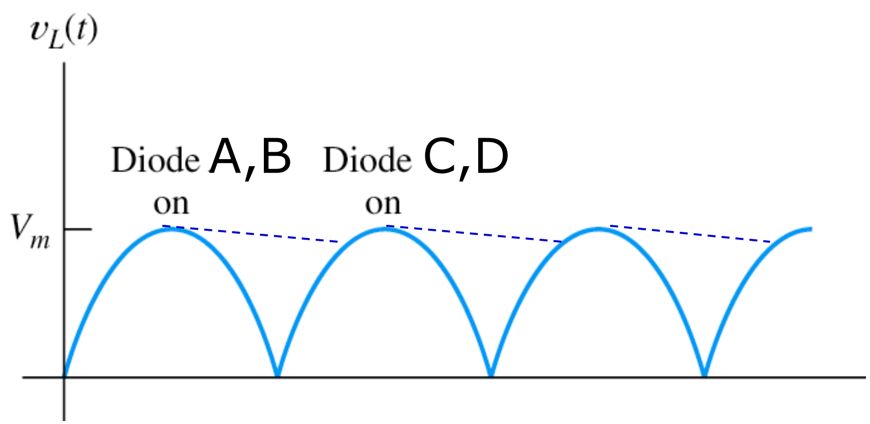


Figure 10.28 Diode-bridge full-wave rectifier.



Clipping (Limiting) circuits

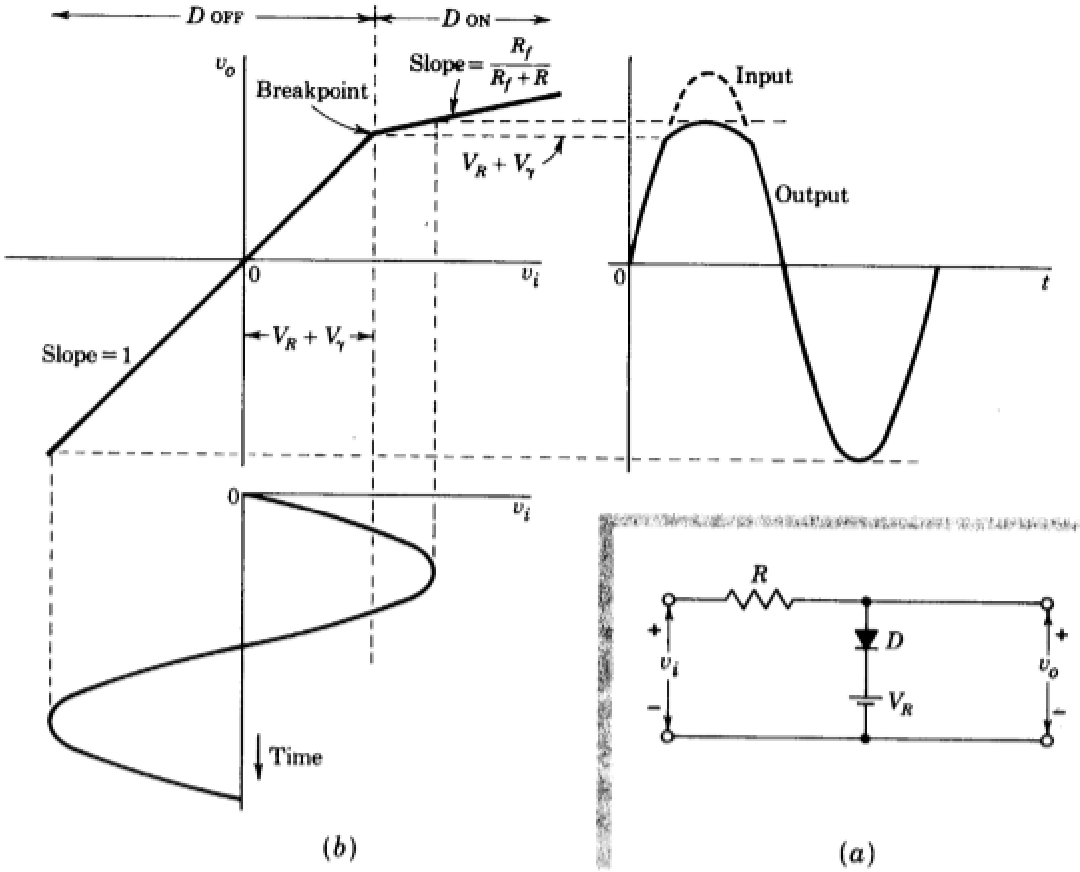


Fig. 4-7 (a) A diode clipping circuit which transmits that part of the waveform more negative than $V_R + V_\gamma$. (b) The piecewise linear transmission characteristic of the circuit. A sinusoidal input and the clipped output are shown.

Clipping (Limiting) circuits

Consider the circuit of Fig. 4-7a. Using the piecewise linear model, the transfer characteristic of Fig. 4-7b is obtained, as may easily be verified. For example, if D is OFF, the diode voltage $v < V_\gamma$ and $v_i < V_\gamma + V_R$. However, if D is OFF, there is no current in R and $v_o = v_i$. This argument justifies the linear portion (with slope unity) of the transmission characteristic extending from arbitrary negative values to $v_i = V_R + V_\gamma$. For v_i larger than $V_R + V_\gamma$, the diode conducts, and it behaves as a battery V_γ in series with a resistance R_f, so that increments Δv_i in the input are attenuated and appear at the output as increments $\Delta v_o = \Delta v_i R_f/(R_f + R)$. This verifies the linear portion of slope $R_f/(R_f + R)$ for $v_i > V_R + V_\gamma$ in the transfer curve. Note that the transmission characteristic is piecewise linear and continuous and has a break point at $V_R + V_\gamma$.

Figure 4-7b shows a sinusoidal input signal of amplitude large enough so that the signal makes excursions past the break point. The corresponding output exhibits a suppression of the positive peak of the signal. If $R_f \ll R$, this suppression will be very pronounced, and the positive excursion of the output will be sharply limited at the voltage $V_R + V_\gamma$. The output will appear as though the positive peak had been "clipped off" or "sliced off."

Clipping (Limiting) circuits

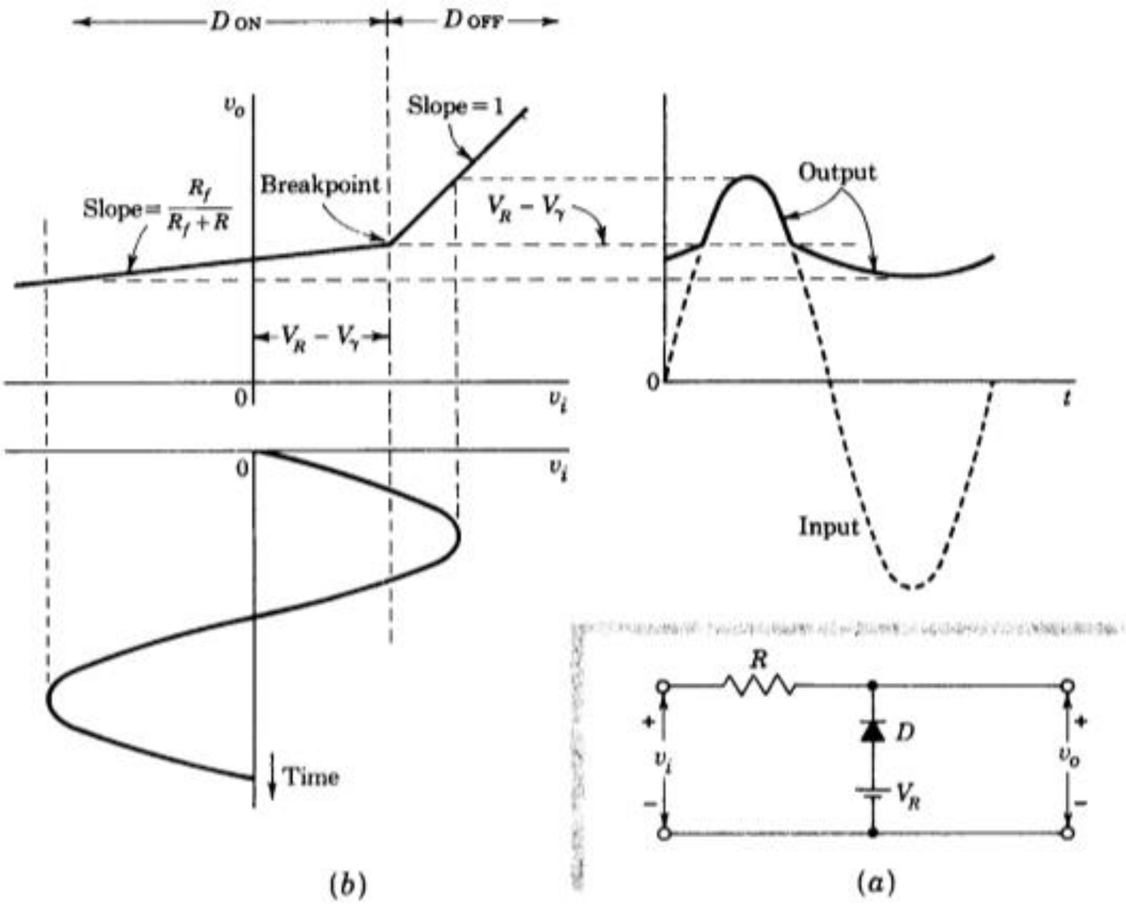


Fig. 4-8 (a) A diode clipping circuit which transmits that part of the waveform more positive than $V_R - V_\gamma$. (b) The piecewise linear transmission characteristic of the circuit. A sinusoidal input and the clipped output are shown.

Clipping (Limiting) circuits

In Fig. 4-8*a* the clipping circuit has been modified in that the diode in Fig. 4-7*a* has been reversed. The corresponding piecewise linear representation of the transfer characteristic is shown in Fig. 4-8*b*. In this circuit, the portion of the waveform more positive than $V_R - V_\gamma$ is transmitted without attenuation, but the less positive portion is greatly suppressed.

In Figs. 4-7*b* and 4-8*b* we have assumed R_r arbitrarily large in comparison with R. If this condition does not apply, the transmission characteristics must be modified. The portions of these curves which are indicated as having unity slope must instead be considered to have a slope $R_r/(R_r + R)$.

In a transmission region of a diode clipping circuit we require that $R_r \gg R$, for example, that $R_r = kR$, where k is a large number. In the attenuation region, we require that $R \gg R_f$, for example, that $R = kR_f$. From these two equations we deduce that $R = \sqrt{R_f R_r}$ and that $k = \sqrt{R_r/R_f}$. On this basis we conclude that it is reasonable to select R as the geometrical mean of R_r and R_f. And we note that the ratio R_r/R_f may well serve as a figure of merit for diodes used in the present application.

Additional clipping circuits

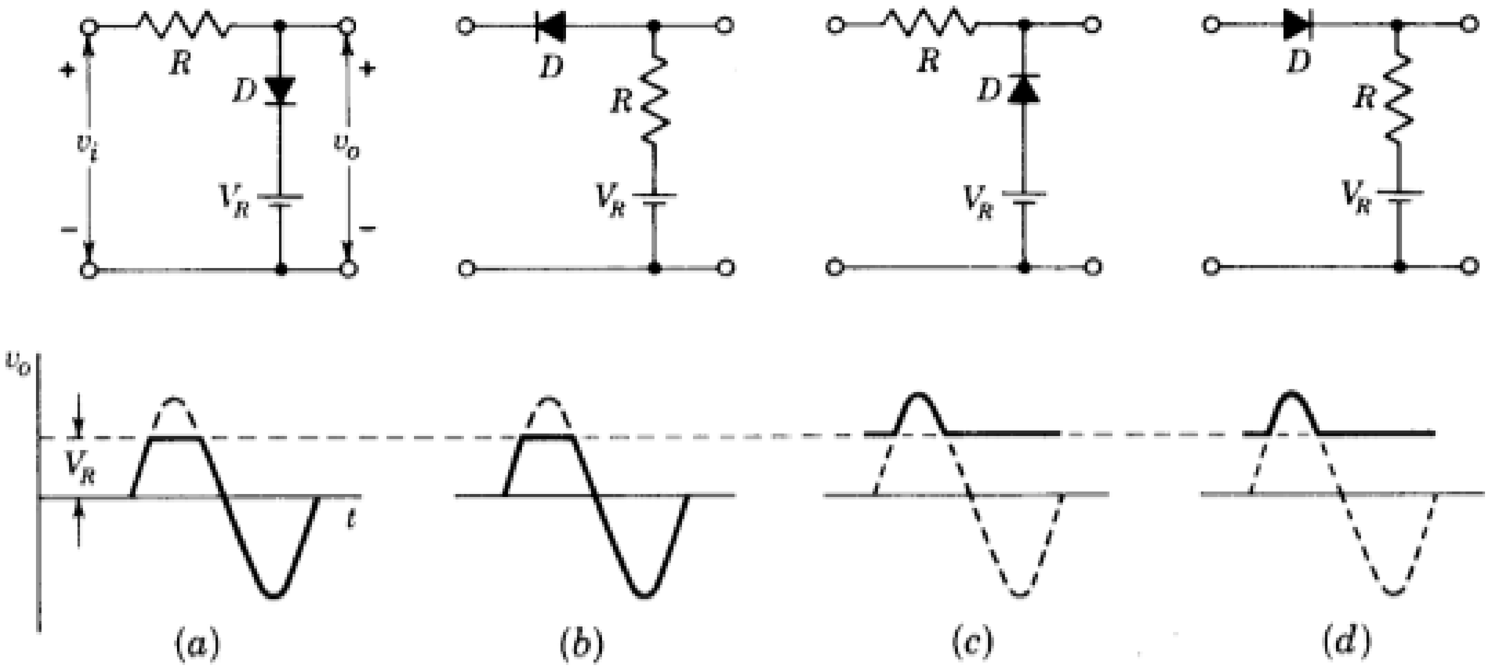


Fig. 4-9 Four diode clipping circuits. In (a) and (c) the diode appears as a shunt element. In (b) and (d) the diode appears as a series element. Under each circuit appears the output waveform (solid) for a sinusoidal input. The clipped portion of the input is shown dashed.

Clipping circuits

Input v_i	Output v_o	Diode states
$v_i \le V_{R1}$	$v_o = V_{R1}$	D1 ON, D2 OFF
$V_{R1} < v_i < V_{R2}$	$v_o = v_i$	D1 OFF, D2 OFF
$v_i \ge V_{R2}$	$v_o = V_{R2}$	D1 OFF, D2 ON

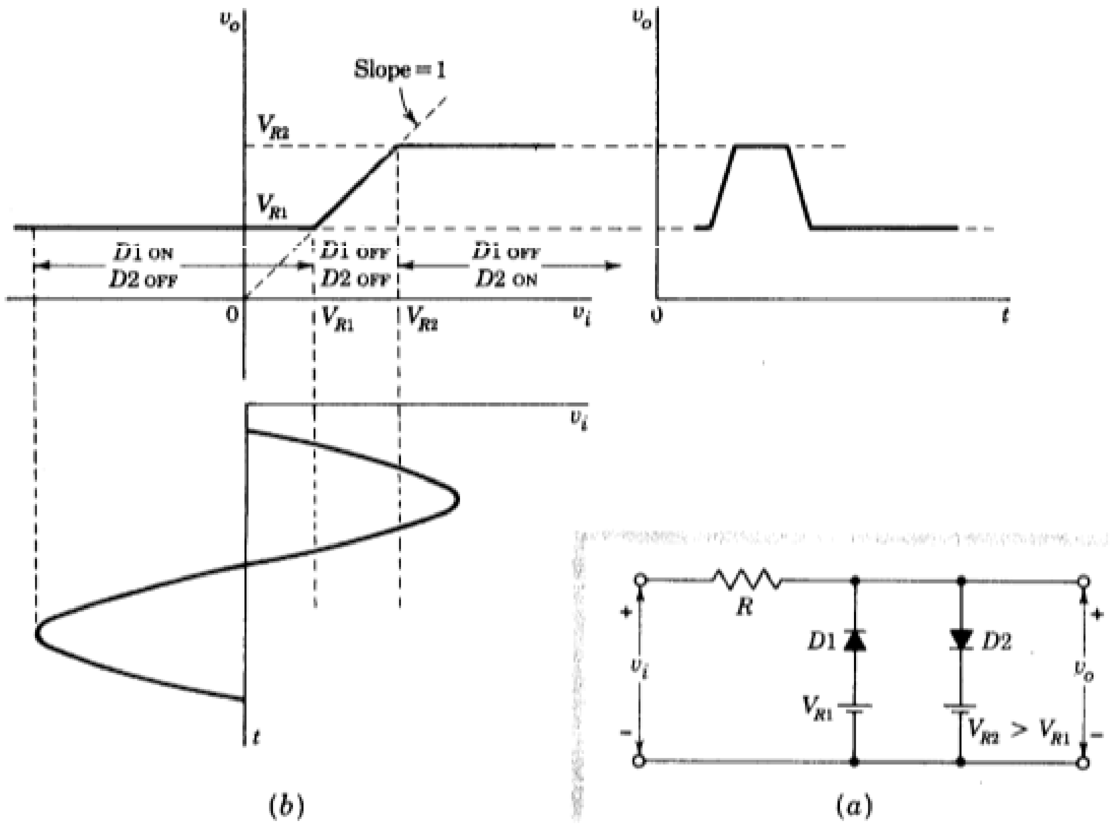


Fig. 4-10 (a) A double-diode clipper which limits at two independent levels. (b) The piecewise linear transfer curve for the circuit in (a). The doubly clipped output for a sinusoidal input is shown.

10.7 Wave-Shaping Circuits

10.7.1 Clipper Circuits

* A portion of an input signal waveform is "*clipped*" off.

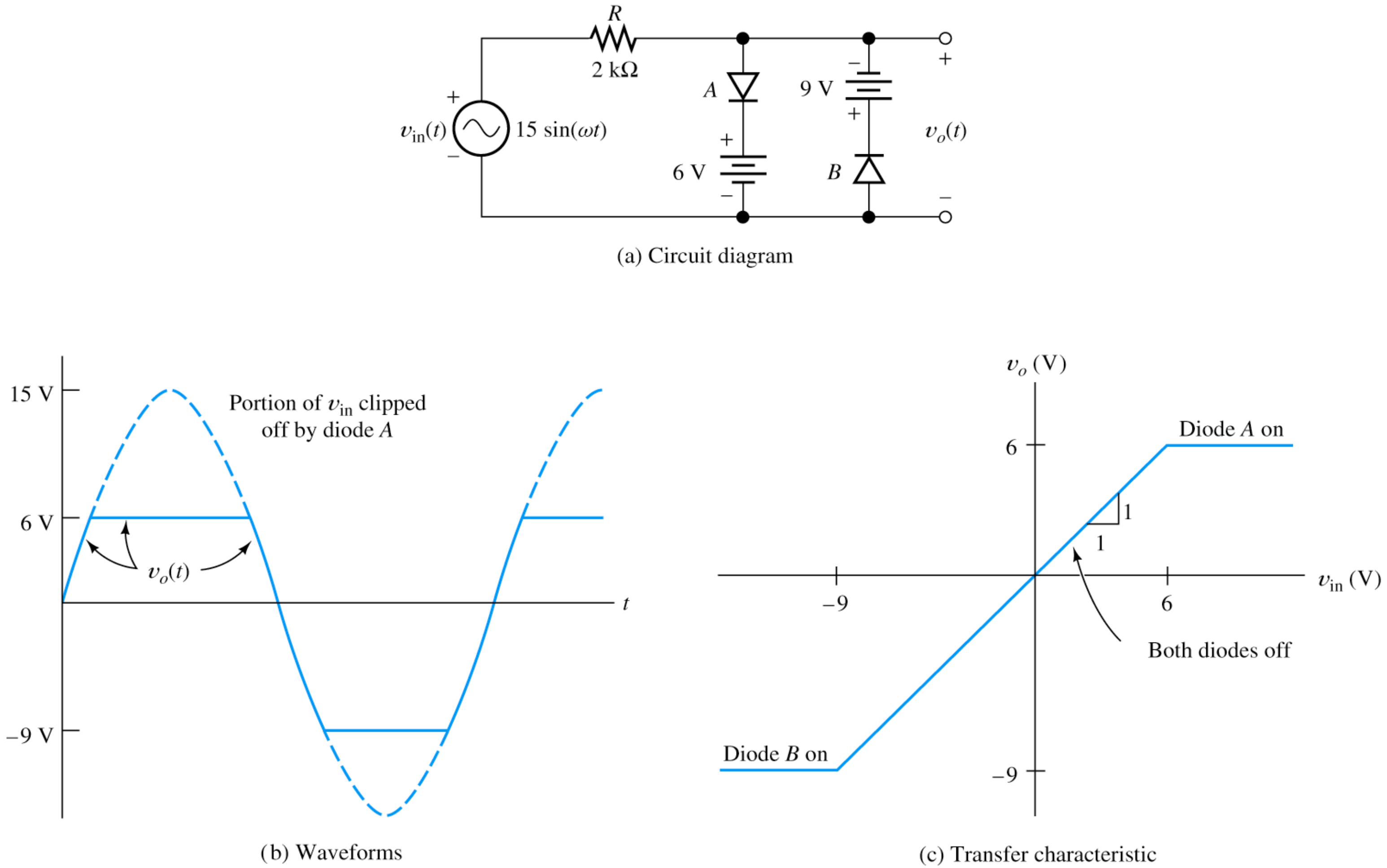
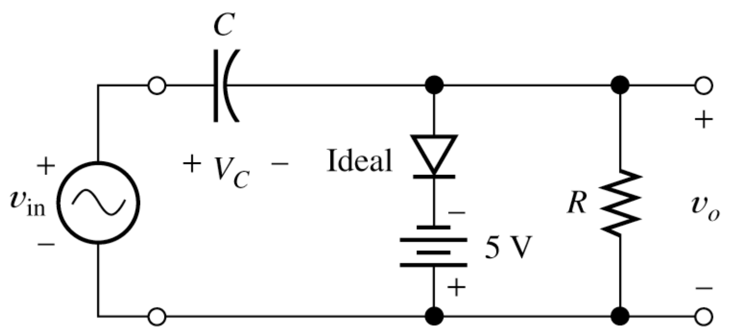


Figure 10.29 Clipper circuit.

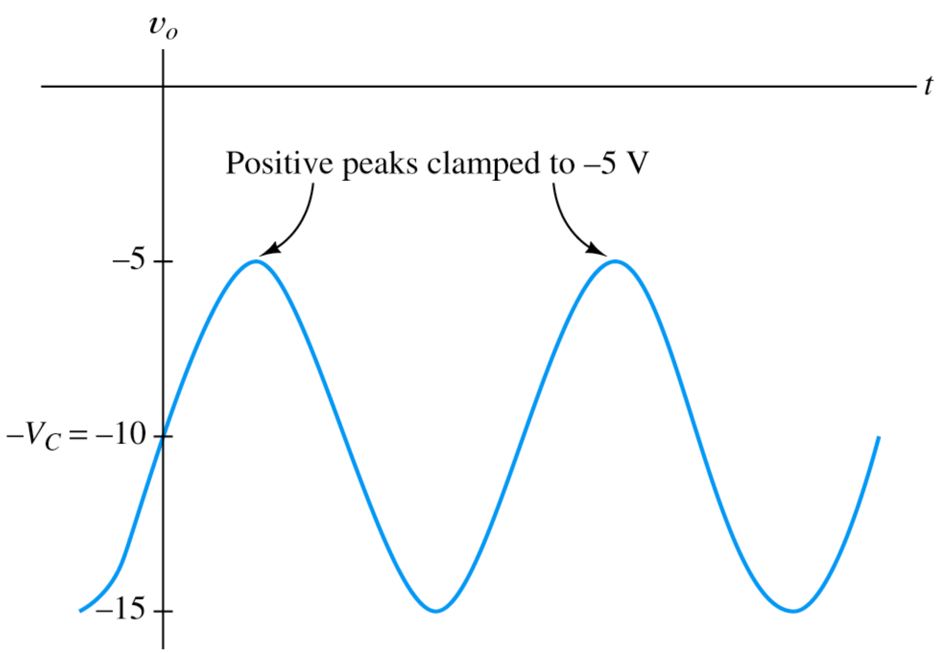
10.7 Wave-Shaping Circuits

10.7.2 Clamper Circuits

* Clamp circuits are used to add a dc component to an ac input waveform so that the positive (or negative) peaks are "*clamped*" to a specified voltage value.



(a) Circuit diagram



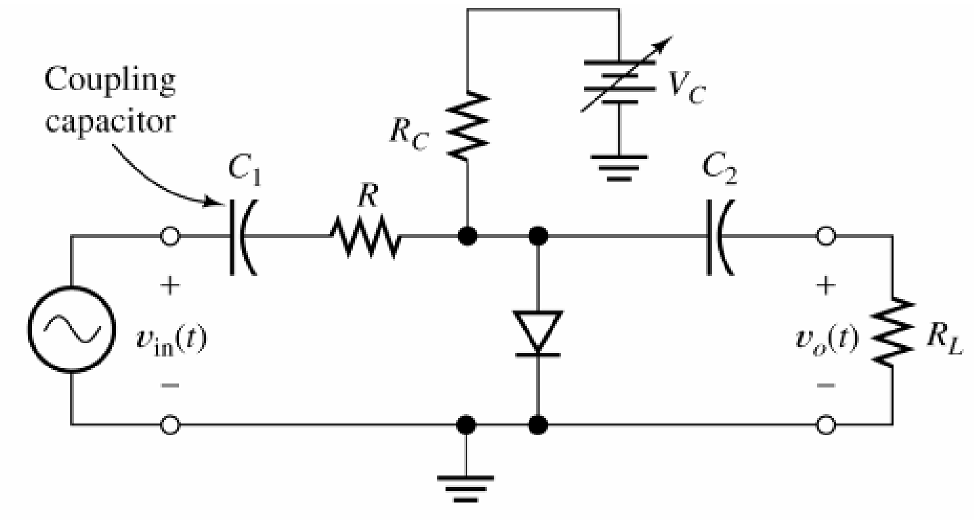
(b) Output waveform for $v_{in} = 5 \sin(\omega t)$

Figure 10.33 Example clamp circuit.

10. Diodes – Linear Small-Signal Equivalent Circuits

10.8 Linear Small-Signal Equivalent Circuits

* In most of the electronic circuits, dc supply voltages are used to *bias* a nonlinear device at an *operating point* and a *small signal* is injected into the circuits.



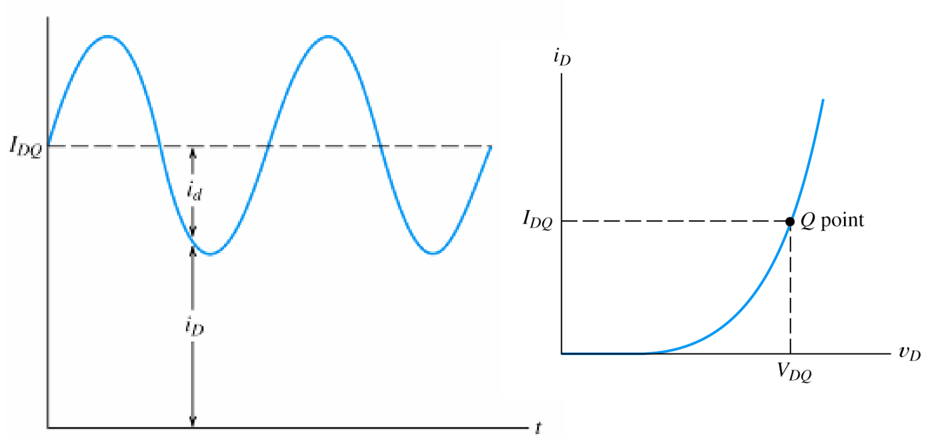


Figure 10.39 Illustration of diode currents.

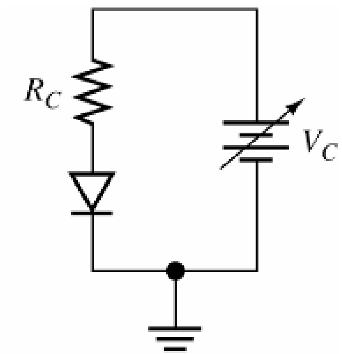
* We often split the analysis of such circuit into two parts:

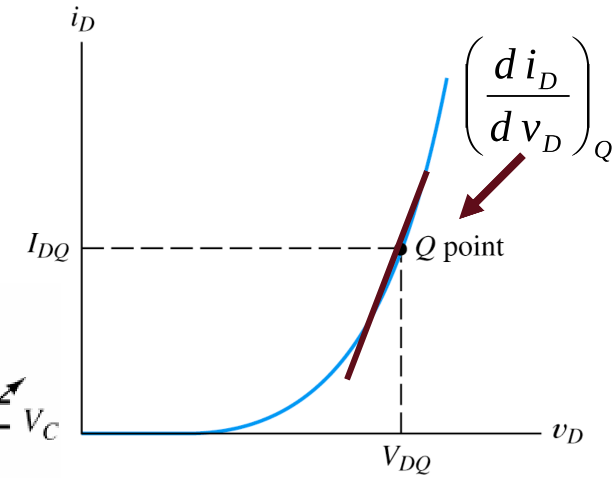
(1) Analyze the dc circuit to find operating point,

(2) Analyze the small signal (by using the "*linear small-signal equivalent circuit*".)

10.8 Linear Small-Signal Equivalent Circuits

* *A diode in linear small-signal equivalent circuit is simplified to a resistor.*
* We first determine the *operating point* (or the "*quiescent point*" or *Q point*) by dc bias.
* When small ac signal injects, it swings the Q point slightly up and down.
* If the signal is small enough, the characteristic is straight.





$$\Delta i_D \cong \left(\frac{d\,i_D}{d\,v_D}\right)_Q \Delta v_D$$

Δi_D *is the small change in diode current*

Δv_D *is the small change in diode voltage*

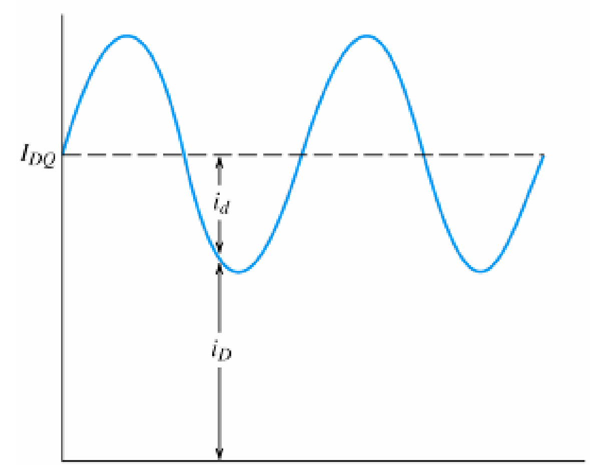


Figure 10.39 Illustration of diode currents.

10.8 Linear Small-Signal Equivalent Circuits

Define the dynamic resistance of the diode as :

$$r_d \cong \left[\left(\frac{d\,i_D}{d\,v_D} \right)_Q \right]^{-1} \quad \text{We will have :}$$

$$\Delta i_D \cong \left(\frac{d\,i_D}{d\,v_D} \right)_Q \Delta v_D \quad \Rightarrow \quad \Delta i_D \cong \frac{\Delta v_D}{r_d}$$

Replace Δi_D and Δv_D by i_d and v_d denoting small changes, we have for ac signals :

$$\boxed{i_d = \frac{v_d}{r_d}}$$

Furthermore, by applying the Shockley equation, we have : $\boxed{r_d = \dfrac{nV_T}{I_{DQ}}}$

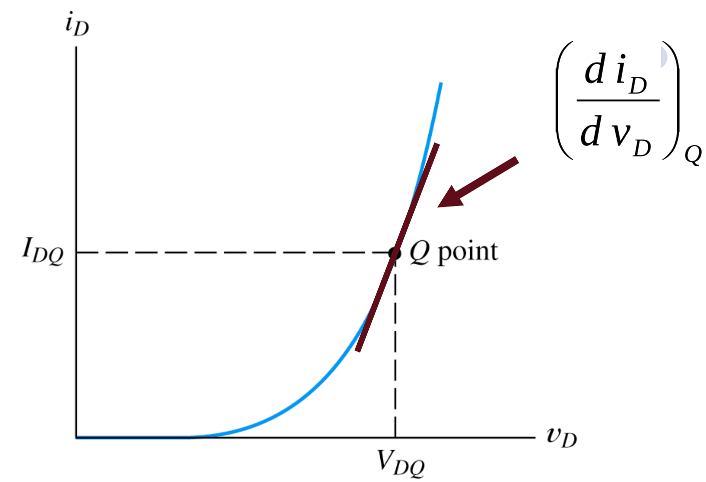


Figure 10.37 Diode characteristic, illustrating the Q point

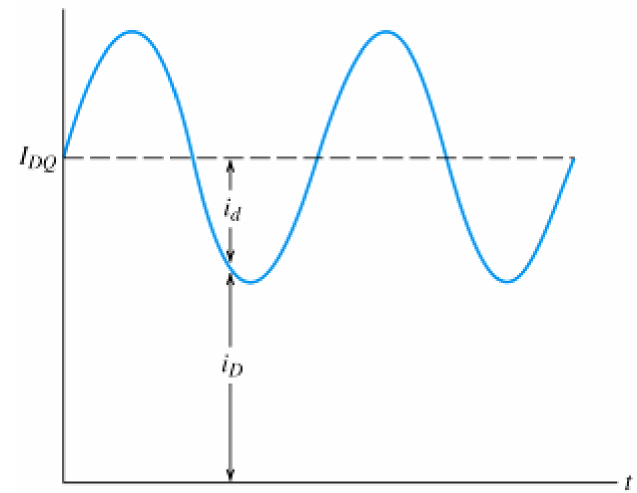


Figure 10.39 Illustration of diode currents.

10.8 Linear Small-Signal Equivalent Circuits

$$i_d = \frac{v_d}{r_d}, \quad r_d = \frac{nV_T}{I_{DQ}}$$

* By using these two equations, we can *treat diode simply as a linear resistor* in small ac signal analysis.
* Note: An ac voltage of fixed amplitude produces different ac current change at different Q point.

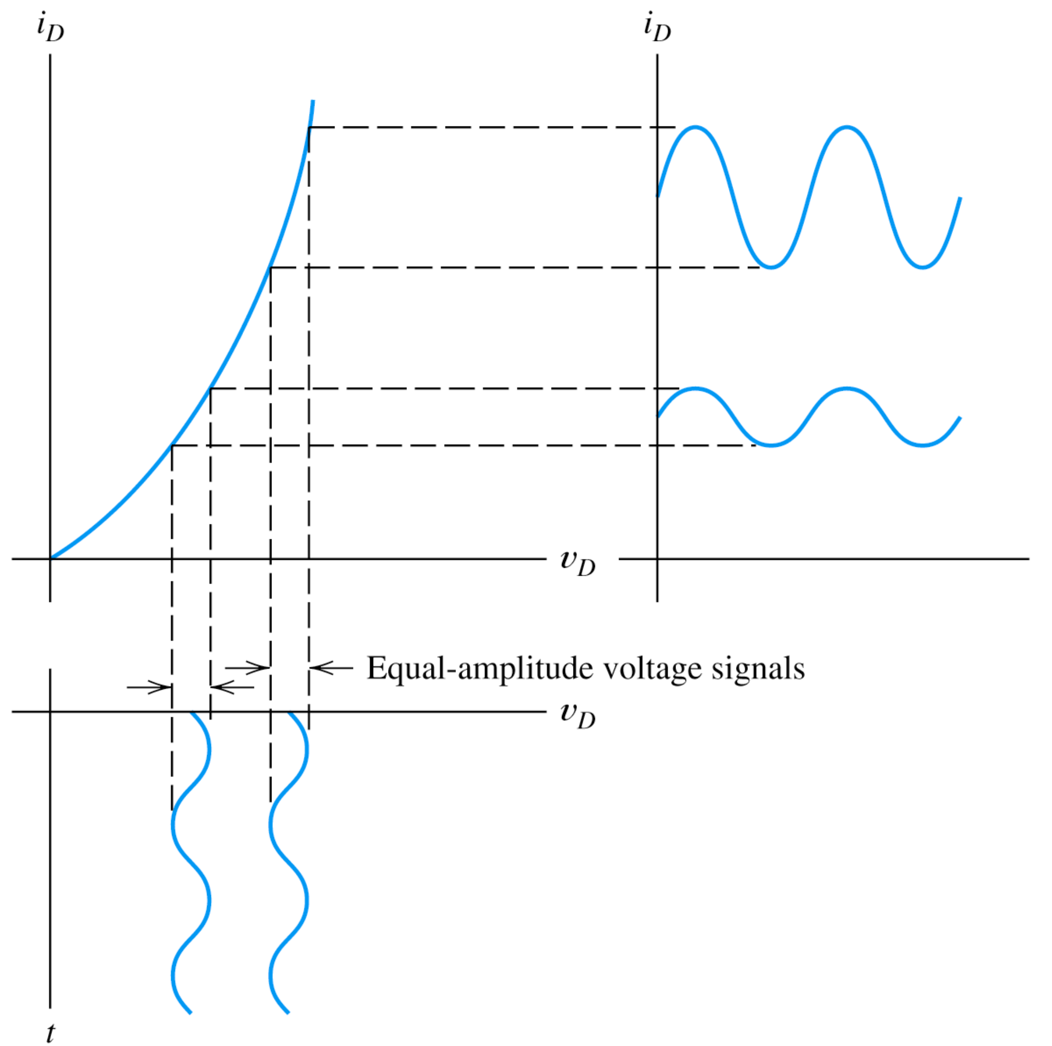
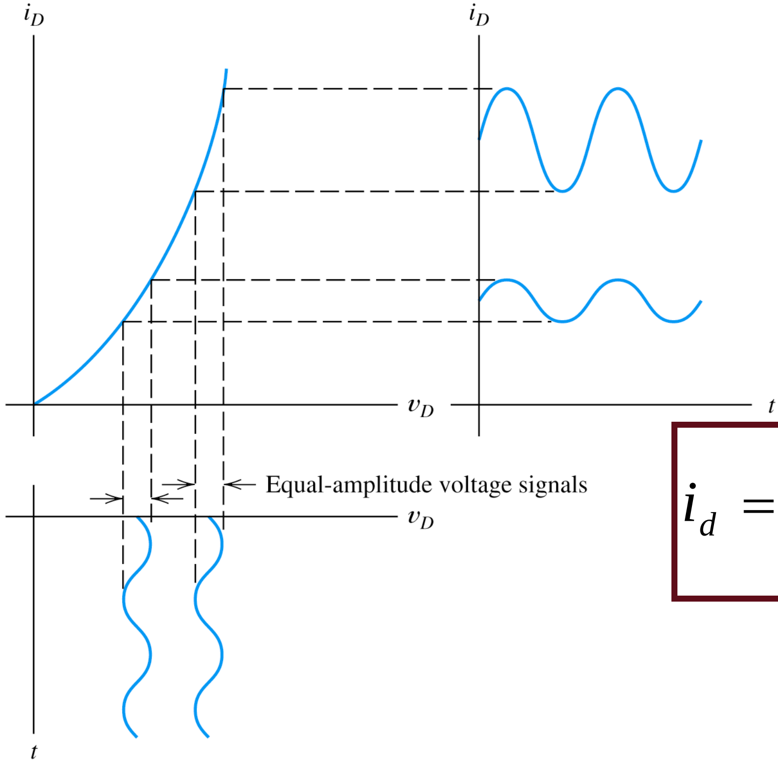


Figure 10.38 As the Q point moves higher, a fixed-amplitude ac voltage produces an ac current of larger amplitude.

10. Diodes – Linear Small-Signal Equivalent Circuits

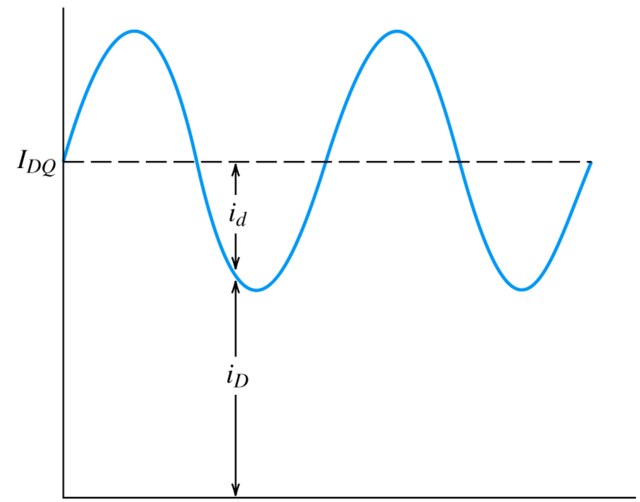
10.8 Linear Small-Signal Equivalent Circuits

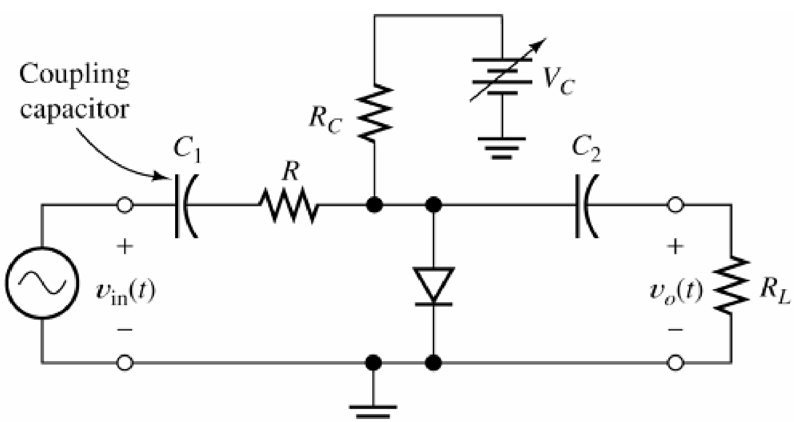


$$_D = I_{DQ} + i_d$$

$$_D = V_{DQ} + v_d$$

$$\boxed{i_d = \frac{v_d}{r_d}, \quad r_d = \frac{nV_T}{I_{DQ}}}$$



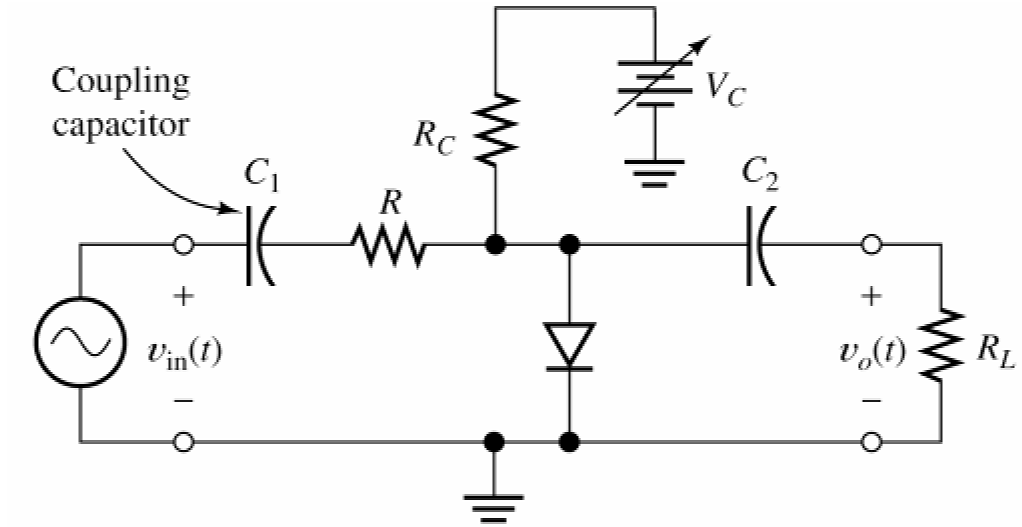


(1) V_{DQ} and I_{DQ} represent the dc signals at the Q point.

(2) v_d and i_d represent the small sc signals.

(3) v_D and i_D represent the total instantaneous diode voltage and current.

Voltage-Controlled Attenuator



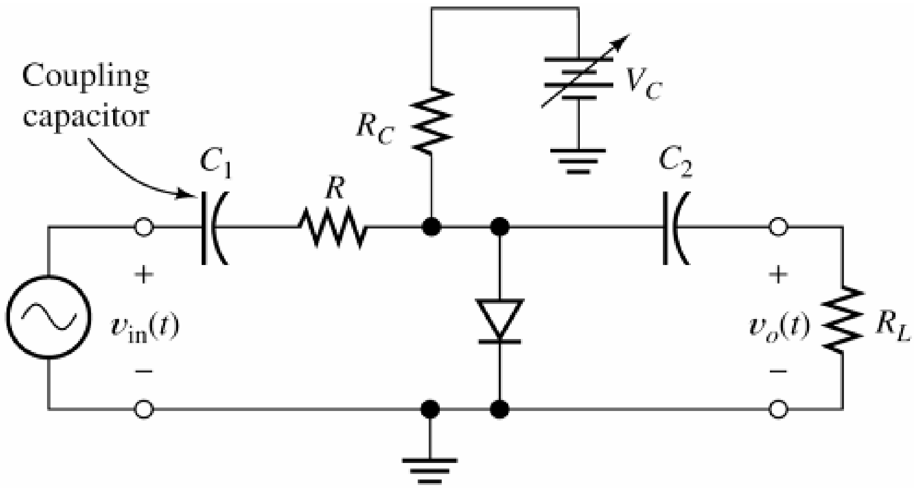
* The function of this circuit is to produce an output signal that is a variable fraction of the ac input signal.

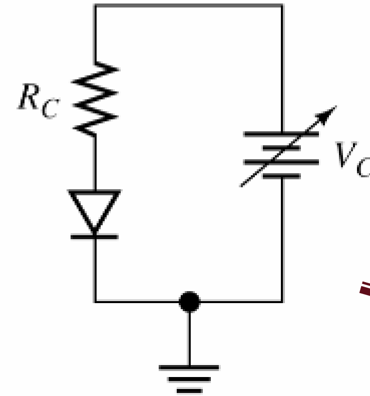
* Two large *coupling capacitors*: behave like short circuit for ac signal and open circuit for dc, thus the Q point of the diode is unaffected by the ac input and the load.

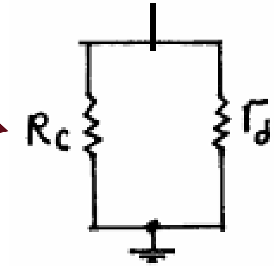
$$Z_C = \frac{1}{j\omega C}$$

10. Diodes – Linear Small-Signal Equivalent Circuits

Voltage-Controlled Attenuator

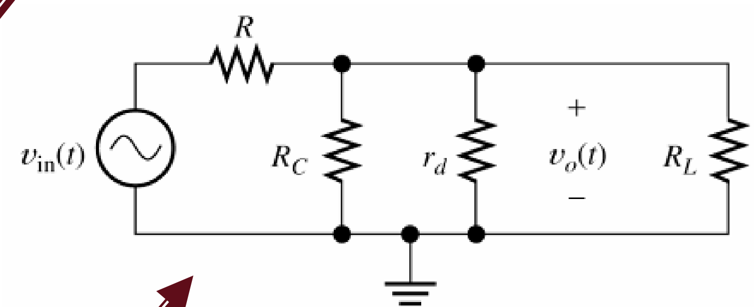






$First\ apply\ dc\ analysis\ to\ find\ the\ diode\ Q\ point,$

$determine\ I_{DQ}\ , then\ the\ r_d\ of\ the\ diode: r_d = \frac{nV_T}{I_{DQ}}$



$Next, we\ perform\ small\ ac\ signal\ analysis:$

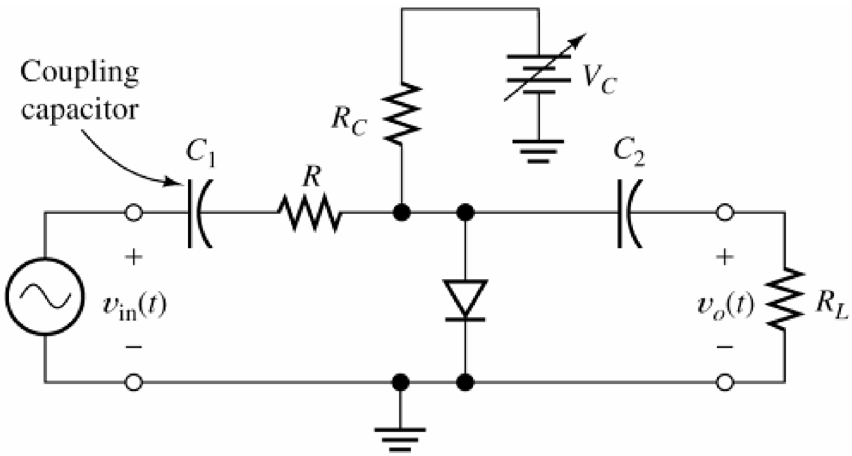
$(note: the\ dc\ voltage\ source\ has\ an\ ac\ component\ of\ current\ but\ no\ ac\ voltage,$

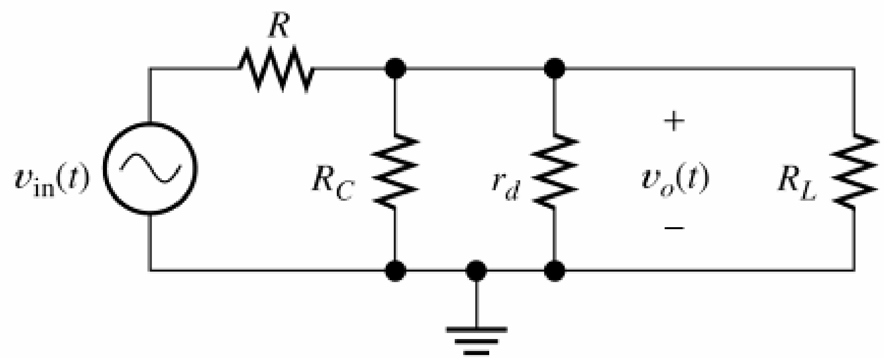
$the\ dc\ voltage\ source\ is\ equivalent\ to\ a\ short\ circuit\ for\ ac\ signal.)$

$$R_p = \frac{1}{1/R_C + 1/R_L + 1/r_d},\ based\ on\ voltage\ divider: \boxed{A_v = \frac{v_o}{v_{in}} = \frac{R_p}{R + R_p} < 1}$$

10. Diodes – Linear Small-Signal Equivalent Circuits

Exercise 10.20 - Voltage-Controlled Attenuator

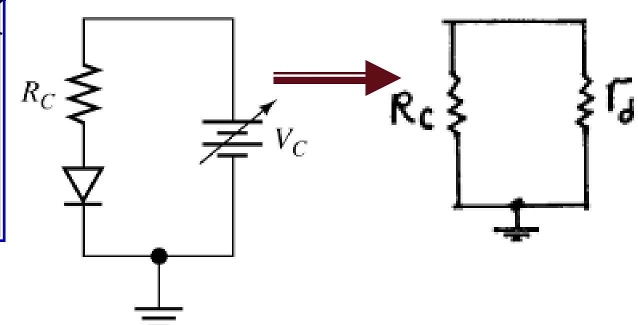




$Given: R = 100\Omega, R_C = R_L = 2k\Omega,$ diode $n = 1$ at $300K$

$Find$: the Q - point values assuming $V_f = 0.6V$

and A_v for $V_C = 1.6$ and $10.6V$



First apply dc analysis to find the diode Q point,

$$I_{DQ} = \frac{V_C - 0.6}{R_C}, \quad r_d = \frac{nV_T}{I_{DQ}} \quad with V_T = 0.026V$$

Next, we perform small ac signal analysis :

$$R_p = \frac{1}{1/R_C + 1/R_L + 1/r_d}, \quad A_v = \frac{v_o}{v_{in}} = \frac{R_p}{R + R_p}$$

Evaluating we have

V_C (V)	1.6	10.6
I_{DQ} (mA)	0.5	5.0
r_d (Ω)	52	5.2
R_p (Ω)	49.43	5.173
A_v	0.3308	0.04919

Thank you