3. Diodes and Diode Circuits

3.1 Diode Characteristics

Small-Signal Diodes

Diode: a semiconductor device, which conduct the current in one direction only.

Two terminals: **anode** and **cathode**.

When the positive polarity is at the anode – the diode is **forward biased** and is conducting.

When the positive polarity is at the cathode – the diode is **reversed biased** and is not conducting.

If the reverse-biasing voltage is sufficiently large the diode is in **reverse-breakdown** region and large current flows though it.

Breakdown voltage.

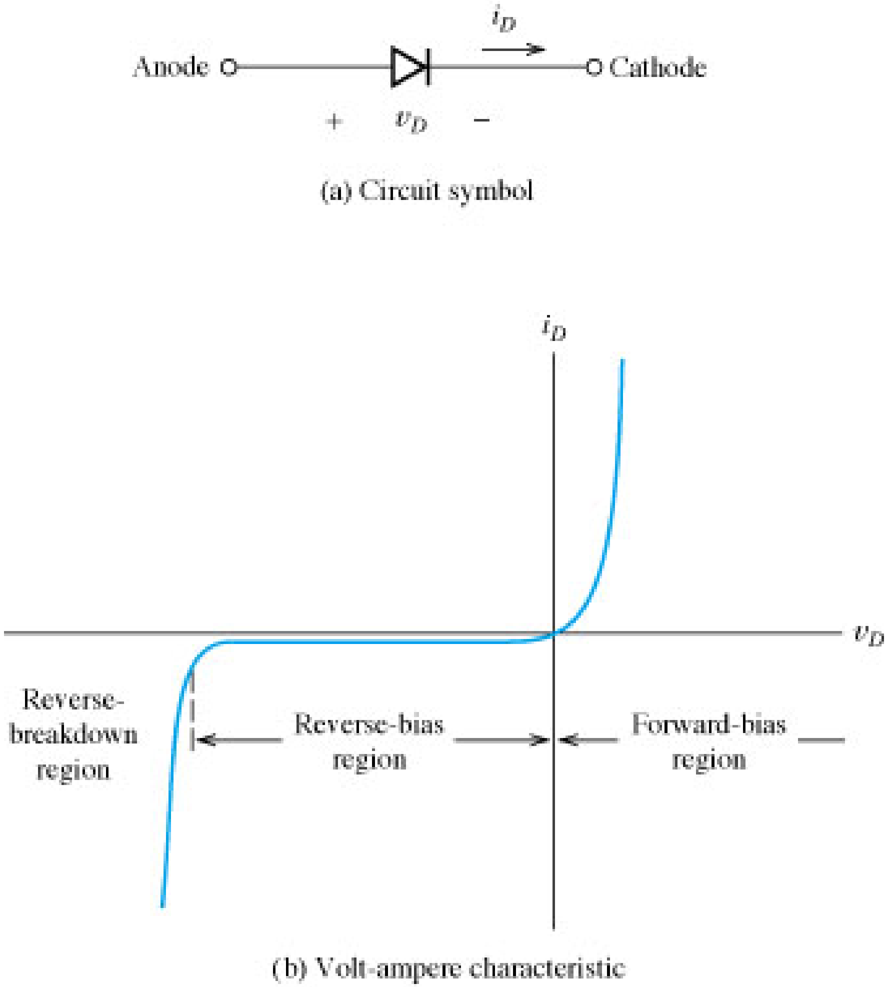


Figure 3.1 Semiconductor diode.

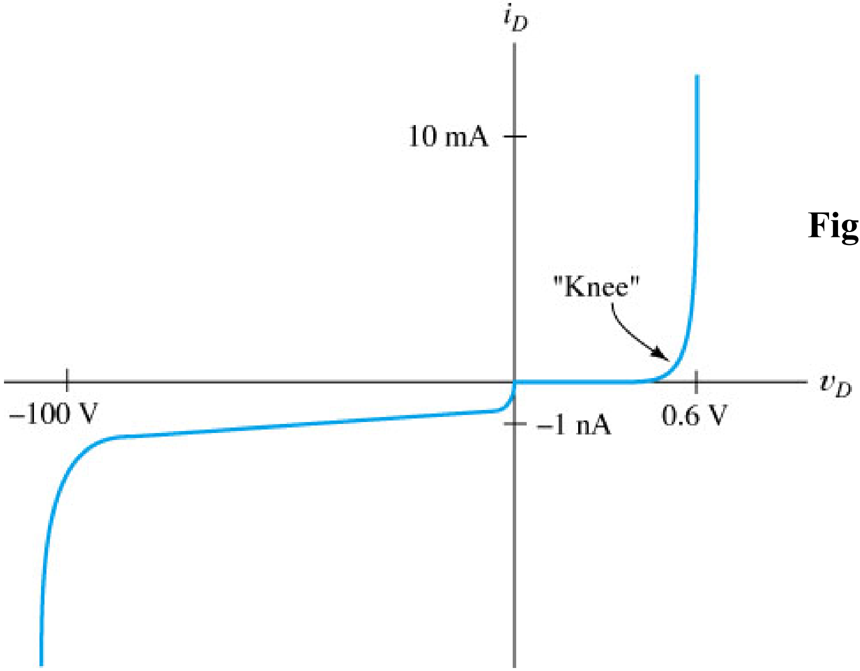


Figure 3.2 Volt-ampere characteristic for a typical small-signal silicon diode at a temperature of 300 K. Notice the changes of scale.

Voltage drop across the diode when forward biased: **0.6-0.7V**.

The current though the diode when reversed biased: ~ **1nA** (10^{-9}A)

Temperature dependence:

- As the temperature increases, the voltage of the knee decreases by 2mV/K.
- The reverse current doubles for each 10K increase in the temperature.

Zener Diodes

Zener diodes: doides intended to operate in breakdown region.

If breakdown voltage > 6V: **avalanche** breakdown.

If breakdown voltage < 6V: **tunneling** mechanism of breakdown.

Figure 3.3 Zener diode symbol.

3.3 The Ideal - Diode Model

Ideal diode:

- perfect conductor with zero voltage drop when the diode is forward biased;
- open circuit, when the diode is reversed biased.

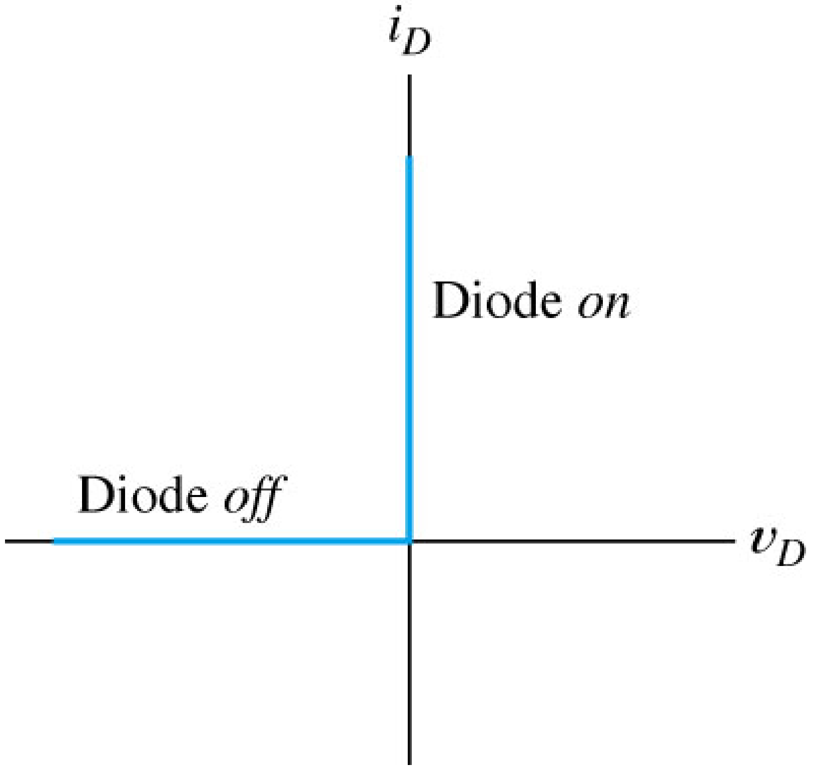
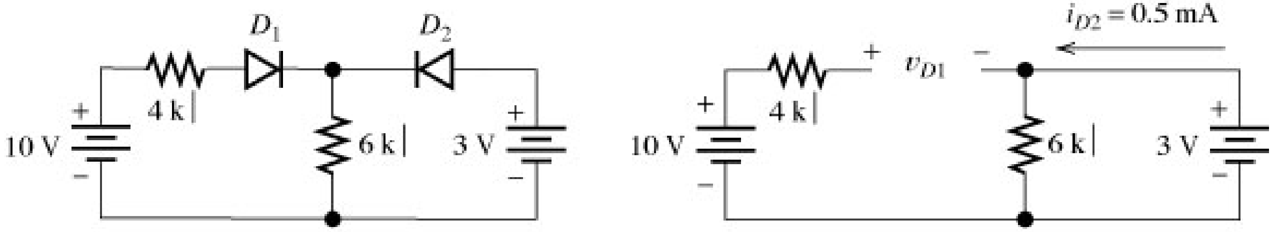


Figure 3.8 Ideal-diode volt-ampere characteristic.

Assumed States for Analysis of Ideal - Diode Circuits

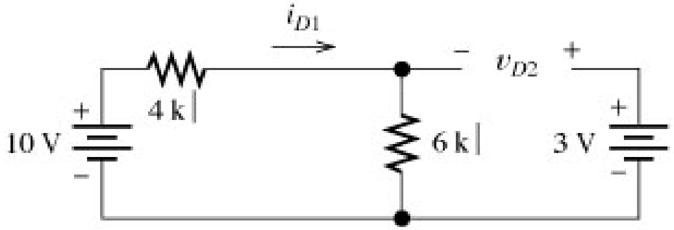
Example 3.3 Circuit Solution By Assumed Diode States

Analyze the circuit illustrated in Figure 3.9a using the ideal - diode model.



(a) Circuit diagram

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



(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 to be a negative value)

Figure 3.9 Analysis of a diode circuit using the ideal-diode model.

Solution

Step 1. We start by *assuming that D_1 is off and D_2 is on*.

Step 2. The equivalent circuit is shown in Figure 3.9b. i_{D2}=0.5mA and v_{D1}=7V.

Step 3. We have v_{D1}=+7V, which is not consistent with our assumption.

Another Assumption

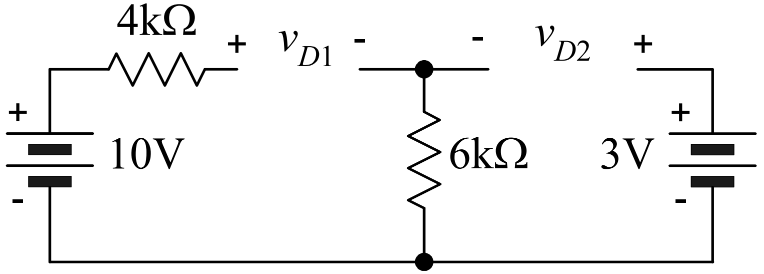
Step 1. We assume that *D_1 is on and D_2 is off.*

Step 2. The equivalent circuit is shown in Figure 3.5c. i_{D1}=1 mA and v_{D2}= -3 V.

Step 3. These conditions are consistent with the assumption.

Exercise 3.2

Show that the condition D_1 off and D_2 off is not valid for the circuit of the Figure 3.9a.



Equivalent circuit to Figure 3.9a when D_1 is off and D_2 is off.

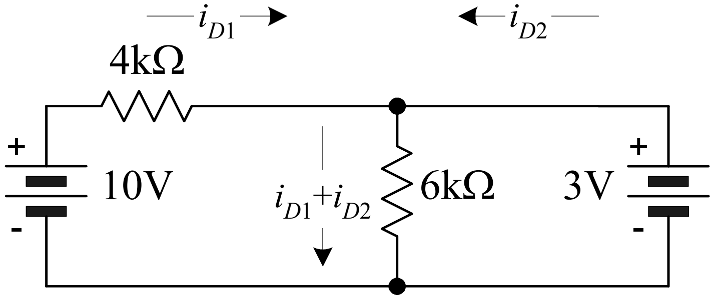
Solution

v_{D1} = 10V; v_{D2} = 3V.

The both diodes must be on since the voltages across them are positive.

Exercise 3.3

Show that the condition D_1 on and D_2 on is not valid for the circuit of the Figure 3.9a.



Equivalent circuit to Figure 3.9a when D_1 is on and D_2 is on.

Solution

$$i_{D1} + i_{D2} = \frac{3\text{V}}{6\text{k}\Omega} = 0.5\text{mA}$$

$$i_{D1} = \frac{10\text{V} - 3\text{V}}{4\text{k}\Omega} = 1.75\text{mA}$$

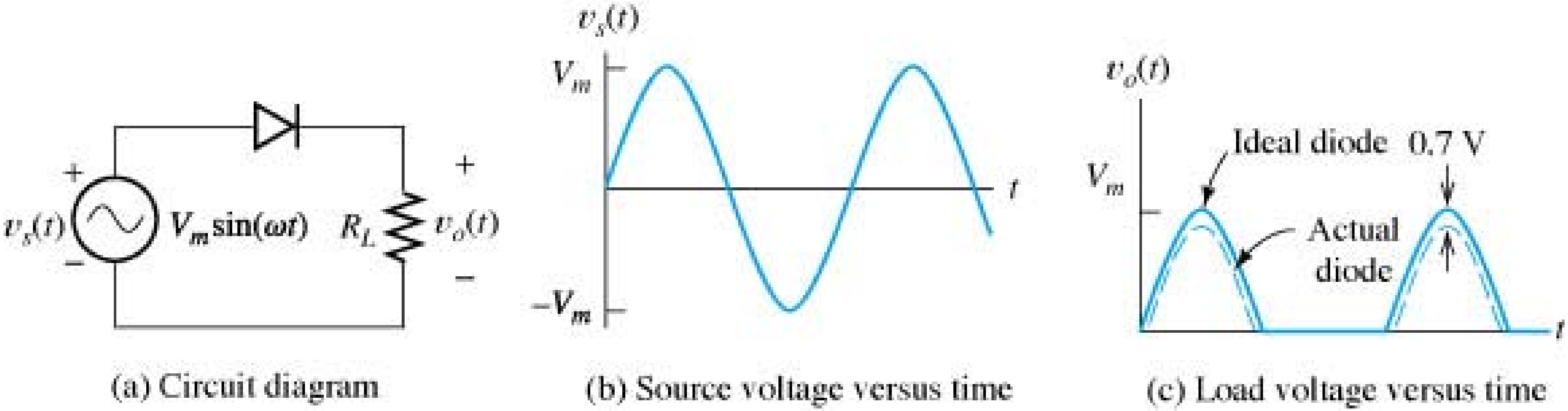
$$i_{D2} = \left(i_{D1} + i_{D2}\right) - i_{D1} = 0.5 - 1.75 = -1.25\text{mA}$$

The negative sign of i_{D2} means that it flows in the opposite direction to the assumed, i.e. from the cathode to the anode of D_2. This is impossible.

3.4 Rectifier Circuits

Rectifiers: circuits, which convert ac power into dc power.

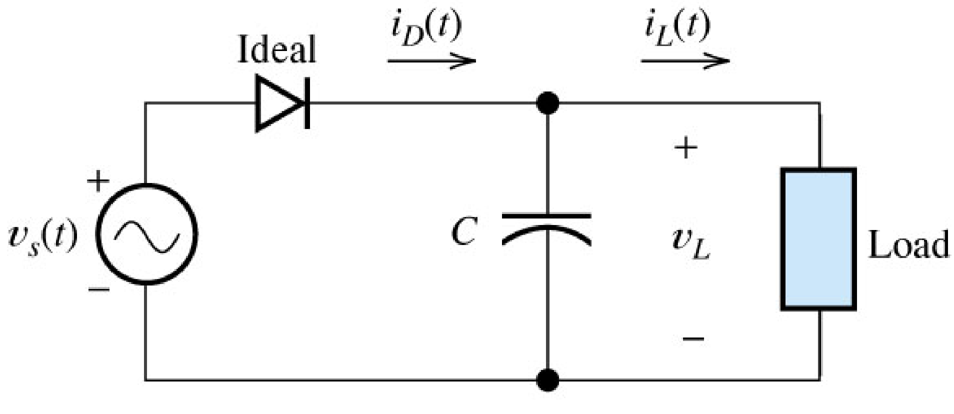
Half - Wave Rectifier Circuits



(a) Circuit diagram (b) Source voltage versus time (c) Load voltage versus time

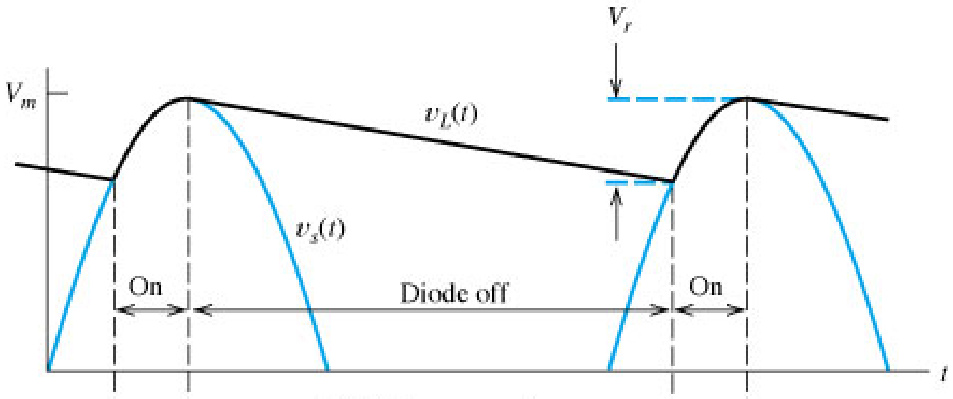
Figure 3.11 Half-wave rectifier with resistive load.

Half - Wave Rectifier with Smoothing Capacitor

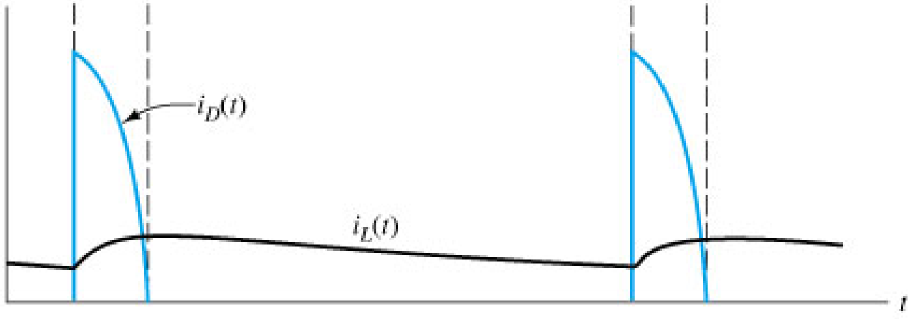


(a) Circuit diagram

Figure 3.12a Half-wave rectifier with smoothing capacitor.



(b) Voltage waveforms



(c) Current waveforms

Figure 3.12b & c Half-wave rectifier with smoothing capacitor.

Peak Inverse Voltage

Peak inverse voltage (PIV) across the diode: a parameter, which defines the choice of the diode.

For Figure 3.11 PIV = V_m;

For Figure 3.12 PIV $\approx 2V_m$.

Problem 3.24 Half-wave battery charger.

Consider the battery charging circuit in Figure P3.24 with $V_m = 20\text{V}$, $R = 10\Omega$ and $V_B = 14\text{V}$. Find the peak current assuming an ideal diode. Also, find the percentage of each cycle in which the diode is in on state. Sketch $v_s(t)$ and $i(t)$ to scale against time.

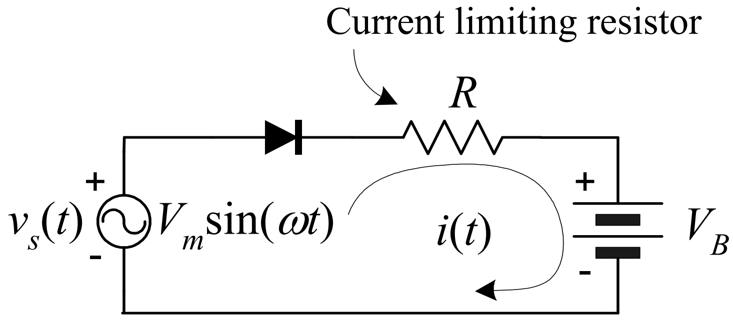


Figure P3.24 Half-wave battery charger.

Solution:

The diode is on when

$$V_m \sin(\omega t) > V_B \quad \text{or} \quad 20\sin(\omega t) > 14$$

The diode goes to on state at

$$20\sin(\omega t) = 14$$

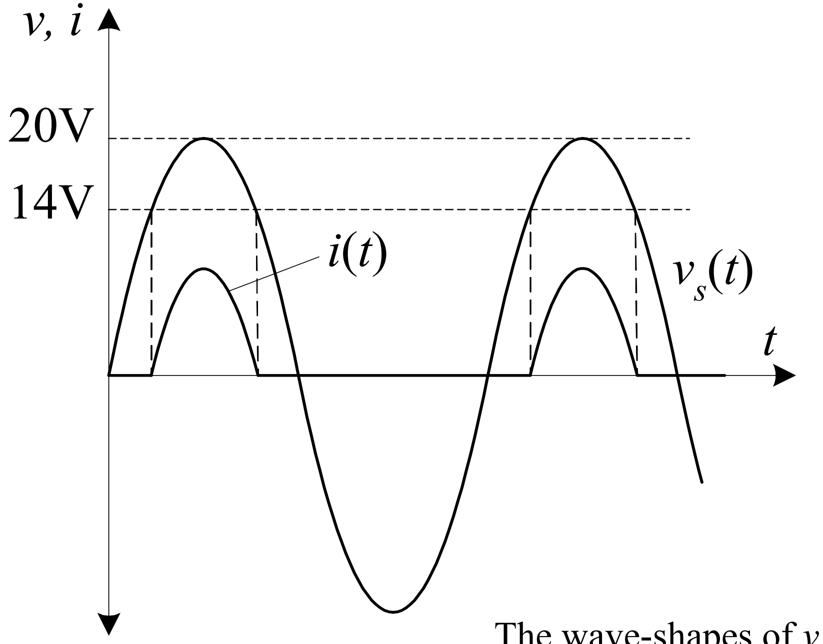
$$\omega t = \arcsin\frac{14}{20} = \arcsin 0.7 \approx 45^0;\ 135^0$$

The diode is on for $45° \le \omega t \le 135°$ or for 90° of the phase angle. The whole period is 360°, so the diode is on for

$$\frac{90^0}{360^0} = 0.25 = 25\% \text{ of the time.}$$

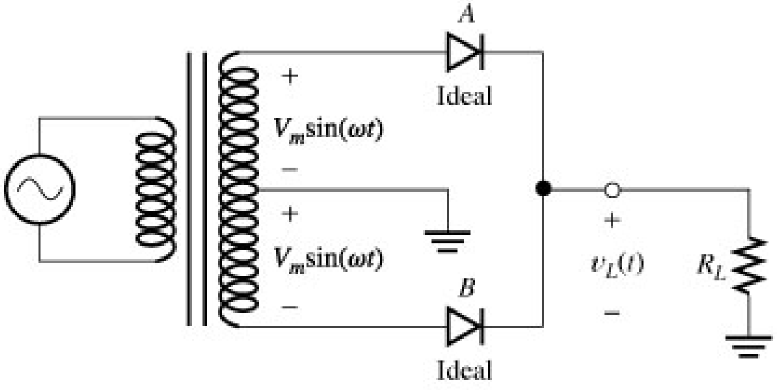
The peak current is when the ac voltage is at the peak and is

$$I_m = \frac{V_m - V_B}{R} = \frac{20-14}{10} = 0.6\text{A}$$

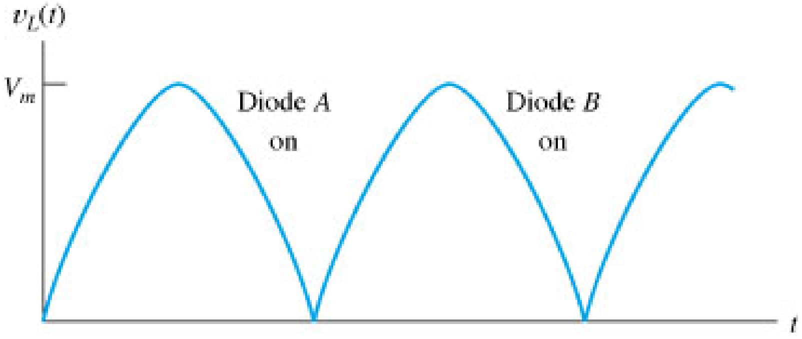


The wave-shapes of $v_s(t)$ and $i(t)$.

Full - Wave Rectifier Circuits

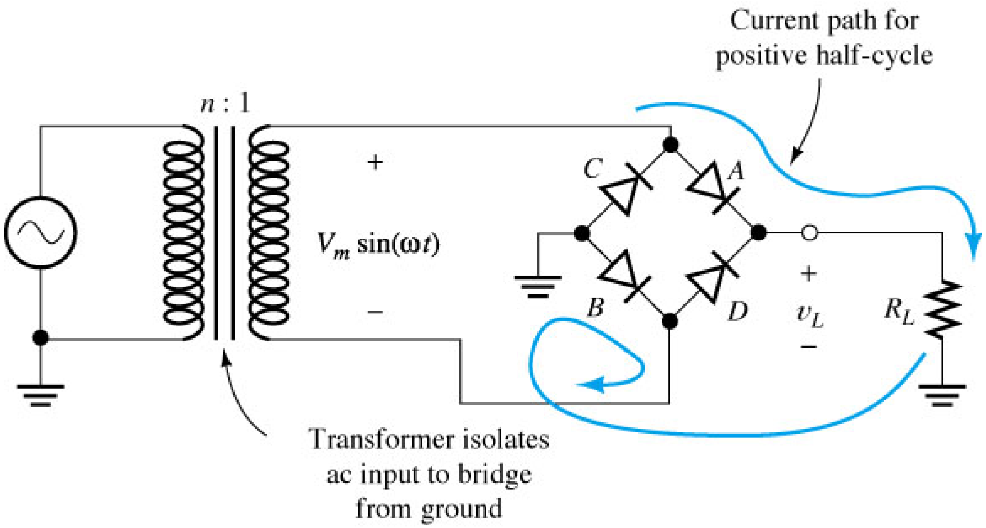


(a) Circuit diagram



(b) Output voltage

Figure 3.13 Full-wave rectifier.



Current path for positive half-cycle

Transformer isolates ac input to bridge from ground

Figure 3.14 Diode-bridge full-wave rectifier.

3.7 Voltage - Regulator Circuits

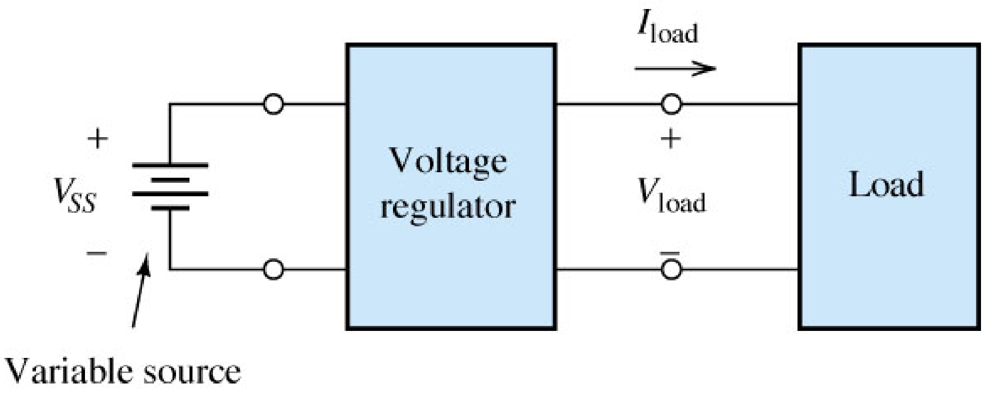


Figure 3.24 A voltage regulator supplies constant voltage to a load.

A Simple Zener-Diode Voltage Regulator

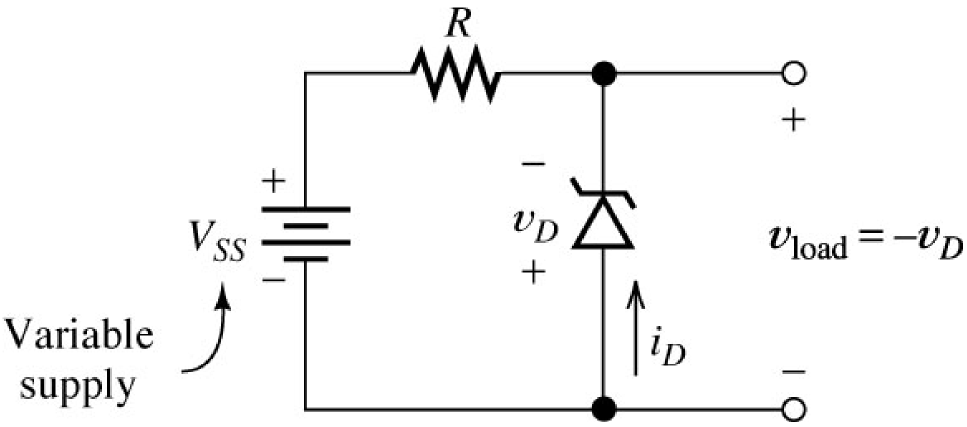
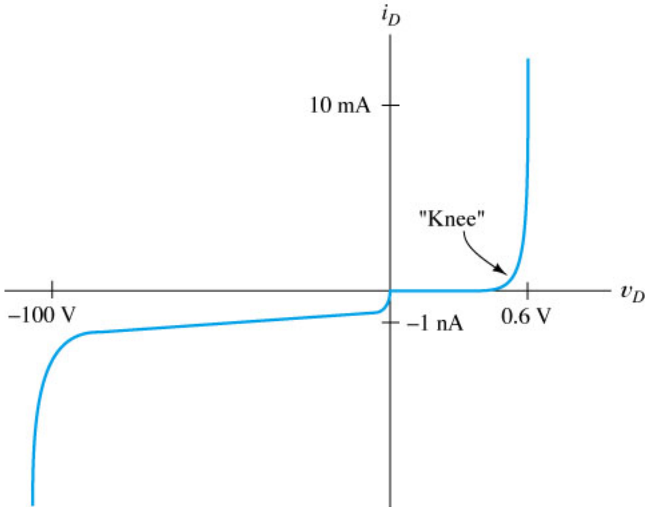


Figure 3.25 A simple regulator circuit that provides a nearly constant output voltage from a variable supply voltage.



In the voltage regulator the zener-diode operates in the breakdown region, which ensures approximately constant voltage across it.

3.6 Linear Small - Signal Equivalent Circuits

Dynamic Resistance

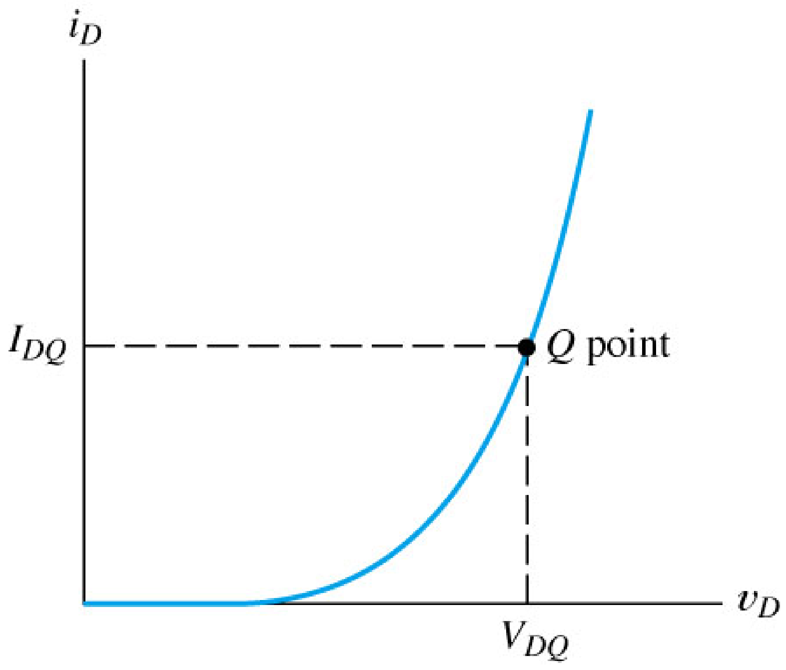


Figure 3.31 Diode characteristic, illustrating the *Q*-point.

$$\Delta i_D \cong \left(\frac{di_D}{dv_D}\right)_Q \Delta v_D \qquad (3.11)$$

$$r_D \cong \left[\left(\frac{di_D}{dv_D}\right)_Q\right]^{-1} \qquad (3.12)$$

$$\Delta i_D \cong \frac{\Delta v_D}{r_D} \qquad (3.13)$$

$$i_D = \frac{v_D}{r_D} \qquad (3.14)$$

The Shockley Equation

$$i_D = I_s \left[\exp\left(\frac{v_D}{nV_T} \right) - 1 \right] \qquad (3.15)$$

I_s – **saturation current**. For small signal diodes at 300K: $I_s \sim 10^{-14}$A.

n – **emission coefficient**; $n = 1 .. 2$ for small-signal diodes.

V_T – thermal voltage:

$$V_T = \frac{kT}{q} \qquad (3.16)$$

T – absolute temperature in K;

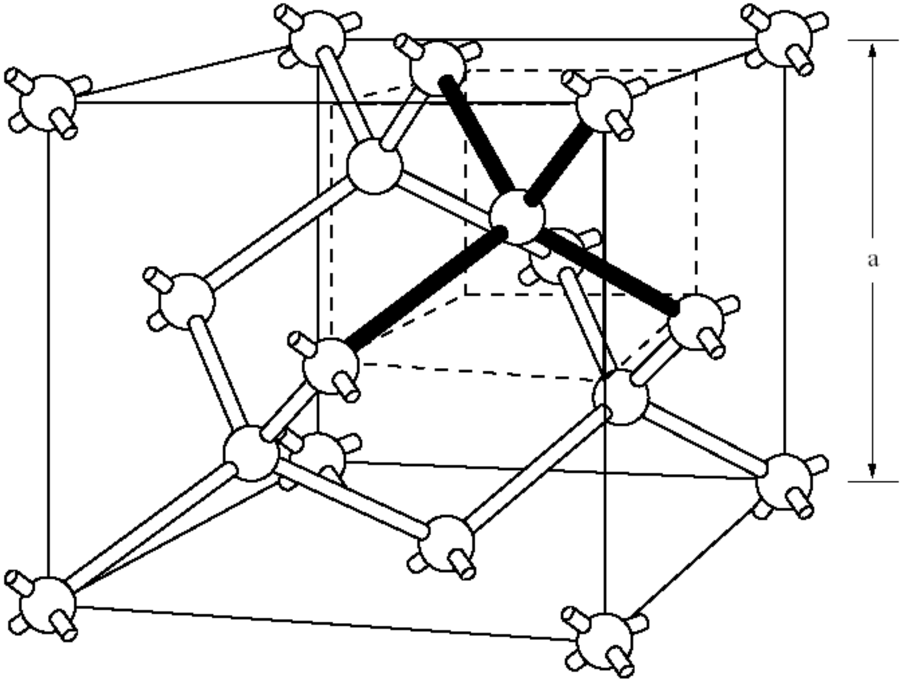
$k = 1.38\times10^{-23}$J/K – the Boltzmann's constant;

$q = 1.60\times10^{-19}$C – the charge of the electron;

At $T = 300$K **$V_T \approx 0.026$V = 26mV**

3.7 Basic Semiconductor Concepts

Intrinsic Silicon



Crystalline lattice of intrinsic silicon in the space.

Bohr model of the silicon atom:

- 14 electrons surround the nucleus;
- Electron orbits grouped in shells
- Outermost orbit contains 4 electrons – **valence shell**;
- Atoms are arranged in crystalline lattice;
- Each pair of neighbor atoms in the lattice form a **covalent bond**;
- The covalent bond consists from two electrons that orbit around the both atoms. Each atom contributes one electron in the pair.
- At 0K temperature all valence electrons are in bound in the covalence bonds and the conductivity is 0.

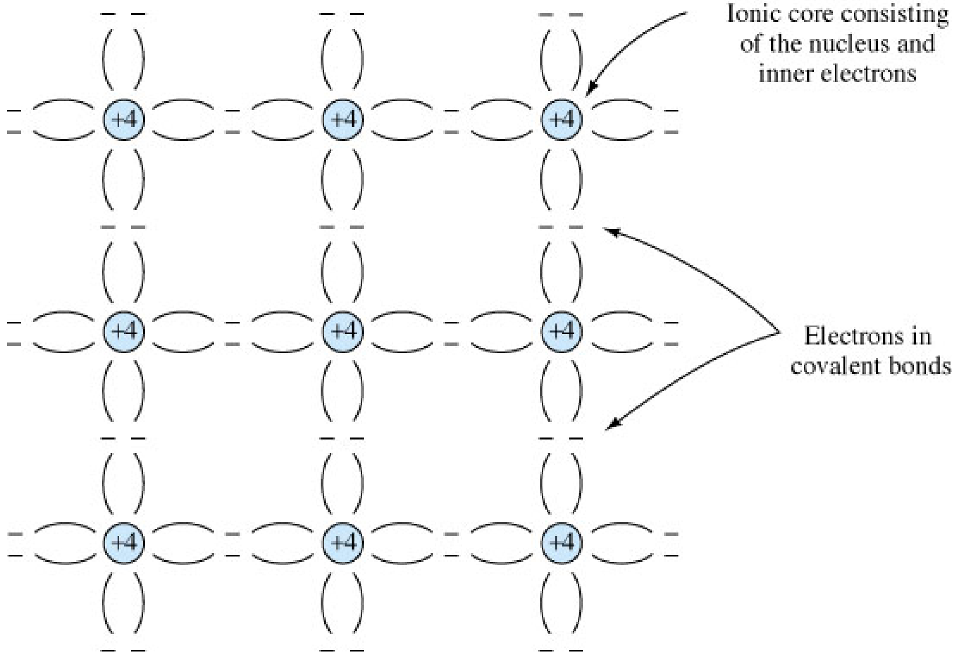


Figure 3.36 Intrinsic silicon crystal (simplified picture in the plane).

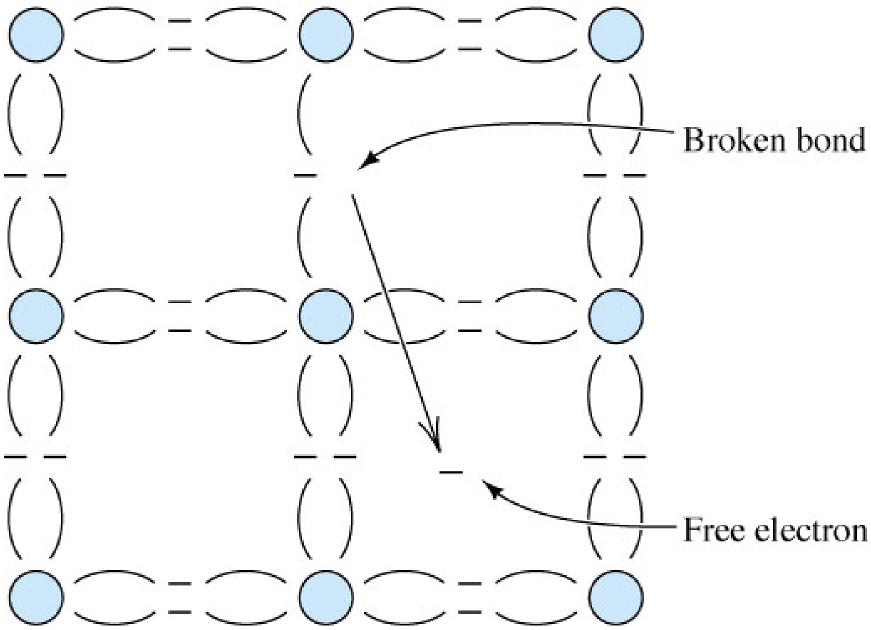


Figure 3.37 Thermal energy can break a bond, creating a vacancy and a free electron, both of which can move freely through the crystal.

Free electrons appear at room temperature due to breaking of the covalent bonds. Only one per 1.4×10^{13} bonds is broken.

The concentration of the free electrons is small, $n_i \approx 10^{14}$ free electrons per cm^3.

The conductivity is small: **semiconductor**.

Conduction by Holes

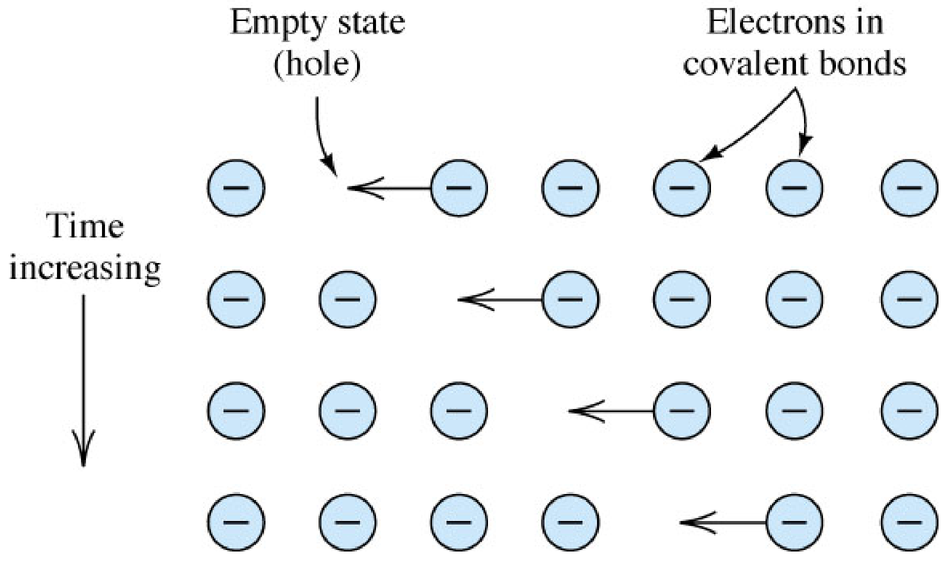


Figure 3.38 As electrons move to the left to fill a hole, the hole moves to the right.

After breaking the bond the atom is positive charged and the vacancy of the electron is called **hole**.

In the intrinsic silicon the concentration of the electrons n_i is equal to the concentration of the holes p_i:

$$n_i = p_i \qquad (3.24)$$

Generation and Recombination

Generation: breaking the covalent bonds and appearing free electrons and holes.

Recombination: free electron encounters a hole.

At higher temperature the rate of the generation is higher.

When the temperature is constant, the generation and recombination are in equilibrium.

n - Type Semiconductor Material

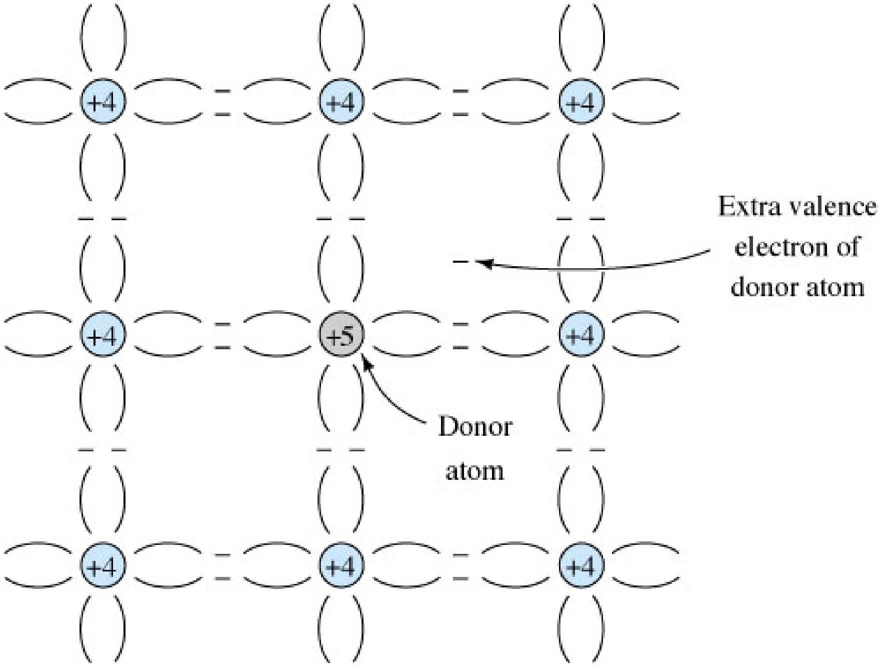


Figure 3.39 *n*-type silicon is created by adding valence five impurity atoms.

Extrinsic semiconductor: silicon with small concentration of impurities, which change its conductivity.

Donor atom: atom of 5th valence. Example: phosphorus.

The extra valence electron of the phosphorus always is free electron.

$$n = p + N_D \tag{3.25}$$

***n*-type semiconductor:** semiconductor with 5th valence impurities and conductivity, based on the free electrons mostly.

Majority carriers in *n*-type silicon: *electrons*.

Minority carriers in *n*-type silicon: *holes*.

p - Type Semiconductor Material

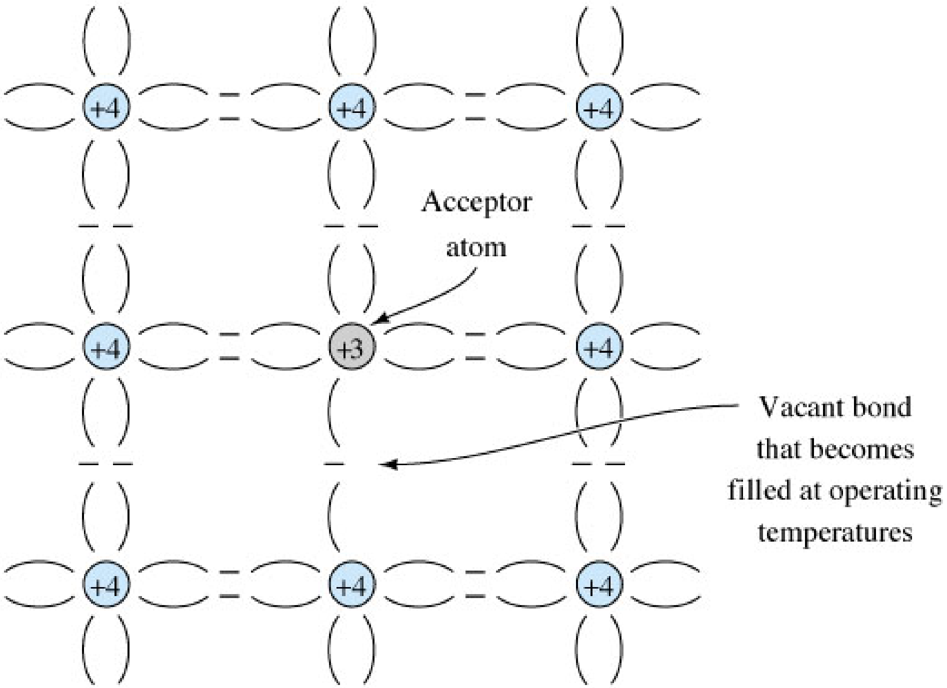


Figure 3.40 *p*-type silicon is created by adding valence three impurity atoms.

Acceptor: atom of 3rd valence. Example: boron.

The acceptor atoms always accept an extra electron, creating negative ionized cores and shortage of free electrons.

$$N_A + n = p \qquad (3.28)$$

***p*-type semiconductor:** semiconductor with 3rd valence impurities and conductivity, based on the holes mostly.

Majority carriers in *p*-type silicon: *holes*.

Minority carriers in *p*-type silicon: *electrons*.

The Mass - Action Law

$$pn = p_i n_i \qquad (3.26)$$

Since $p_i = n_i$

$$pn = n_i^2 \qquad (3.27)$$

Cycling the type of the material

In fabricating the integrated circuits the impurities are added in stages, changing every time the type of the conductivity

$$p + N_D = n + N_A \tag{3.29}$$

Drift

- The carriers move in random fashion in the crystal due to thermal agitation.
- If electric field is applied to the random motion is added a constant component.
- The averaged motion of the charge carriers due to the electric field: **drift.**
- Drift velocity is proportional to the electric field vector.

$$\mathbf{V}_n = -\mu_n \mathbf{E} \tag{3.30}$$

$$\mathbf{V}_p = \mu_p \mathbf{E} \tag{3.31}$$

μ_n is the mobility of the free electrons;
μ_p is the mobility of the holes.

$$\mu_p < \mu_n$$

Diffusion

If there is a difference in the concentration of the charges in the crystal, appears a flow of charges toward the region with small concentration, determining **diffusion current**.

3.8 Physics of the Junction Diode

The Unbiased *pn* Junction

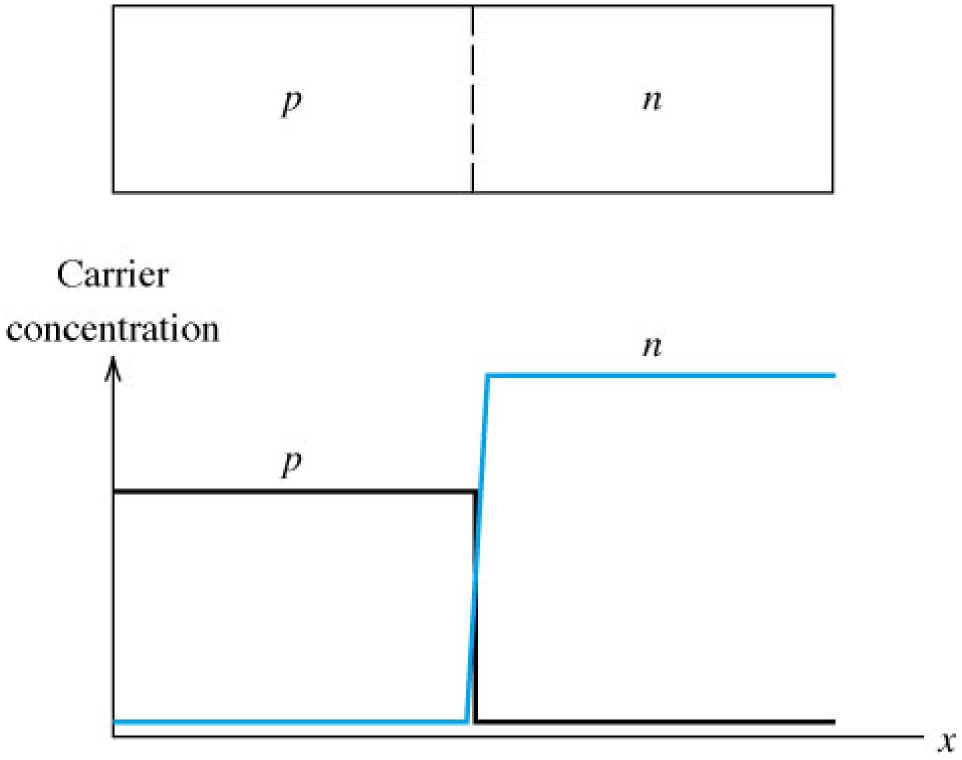
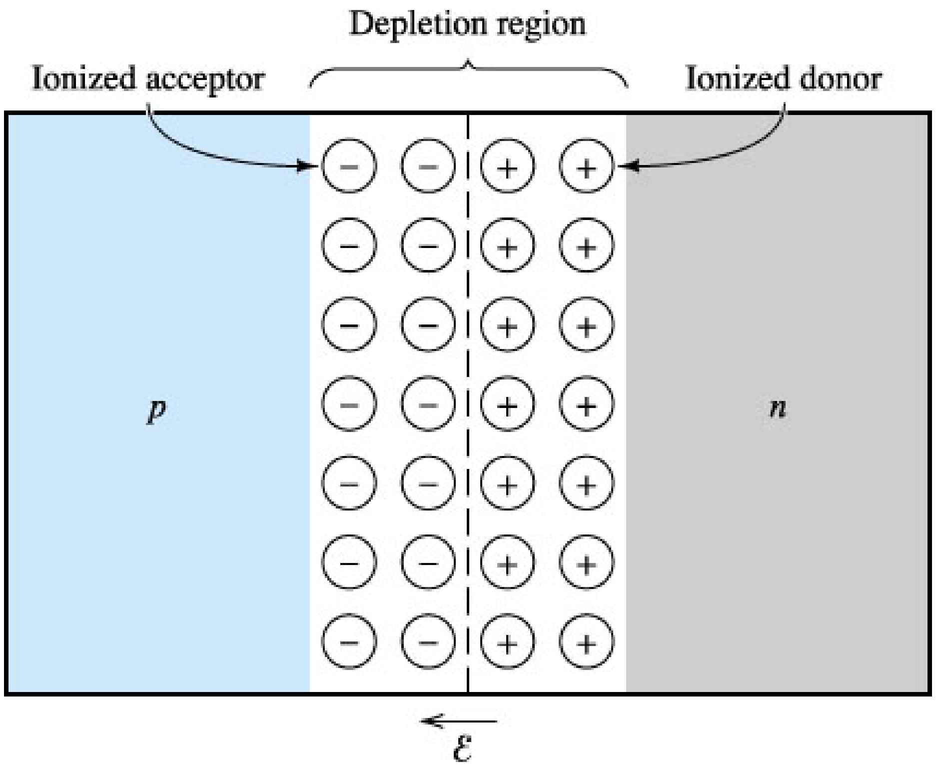
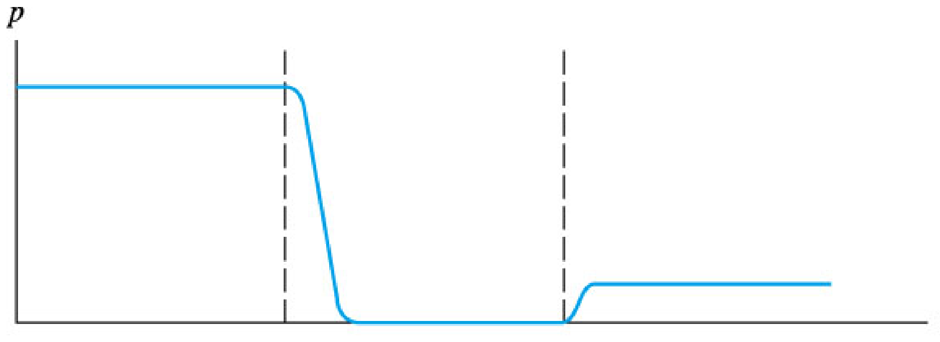


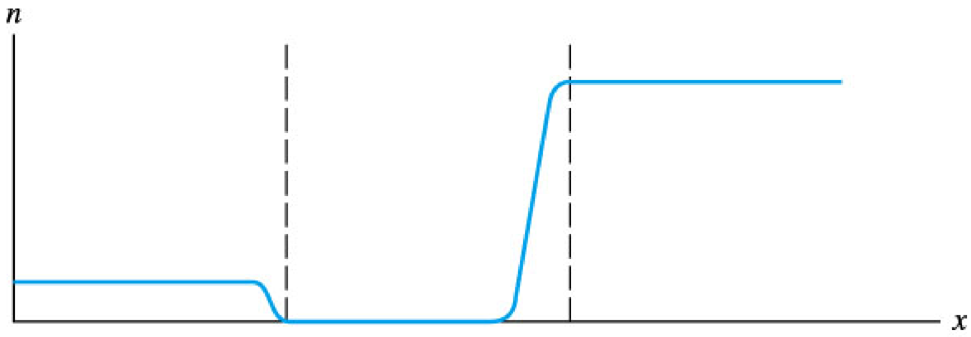
Figure 3.42 If a *pn* junction could be formed by joining a *p*-type crystal to an *n*-type crystal, a sharp gradient of hole concentration and electron concentration would exist at the junction immediately after joining the crystals.



(a) *pn* junction



(b) Hole concentration



(c) Free-electron concentration

Figure 3.43 Diffusion of majority carriers into the opposite sides causes a **depletion region** to appear at the junction.

The field of depletion region prevents the flow of majority carriers.
A **built-in barrier potential** exists for them due to depletion region.

The *pn* Junction with Reverse Bias

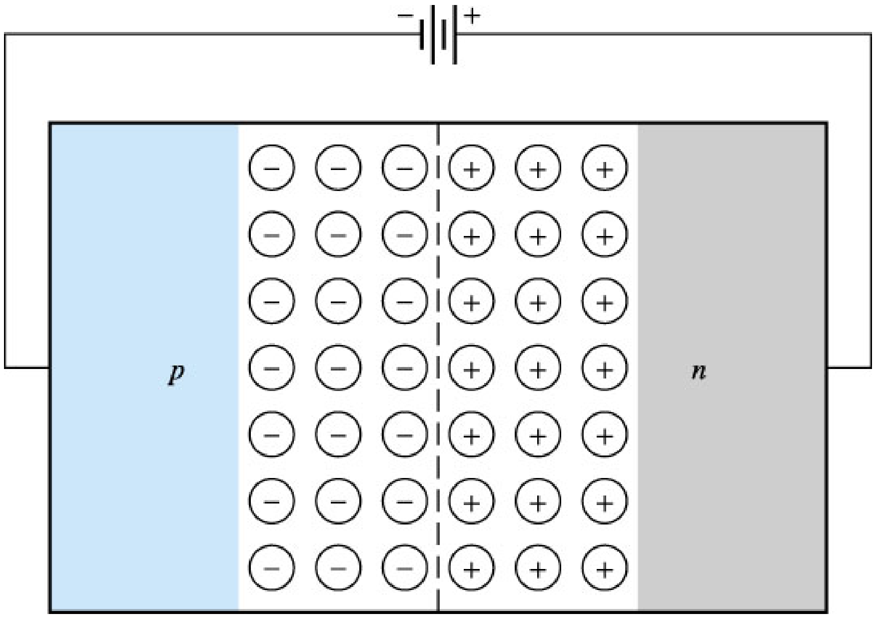


Figure 3.44 Under reverse bias, the depletion region becomes wider.

Reverse bias: when the external voltage has the same polarity as the field of the depletion region.

Reversed biasing extends the depletion region and fully stops the current through the diode.

The *pn* Junction with Forward Bias

Forward bias: when the external voltage has opposite polarity to the field of the depletion region.

Forward biasing narrows the depletion region and reduces the barrier potential. When the barrier potential is reduced to 0, a significant current flows through the diode.

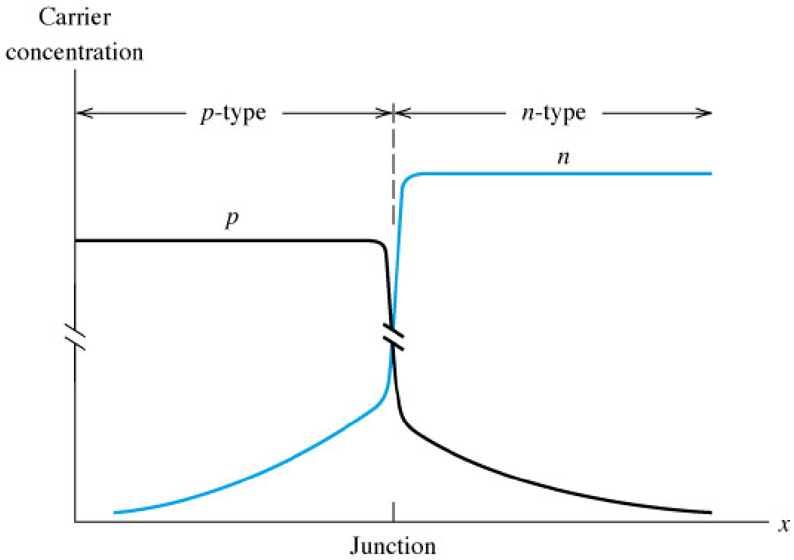


Figure 3.45 Carrier concentration versus distance for a forward biased *pn* junction.

3.9 Switching and High - Frequency Behavior

Review of Capacitance

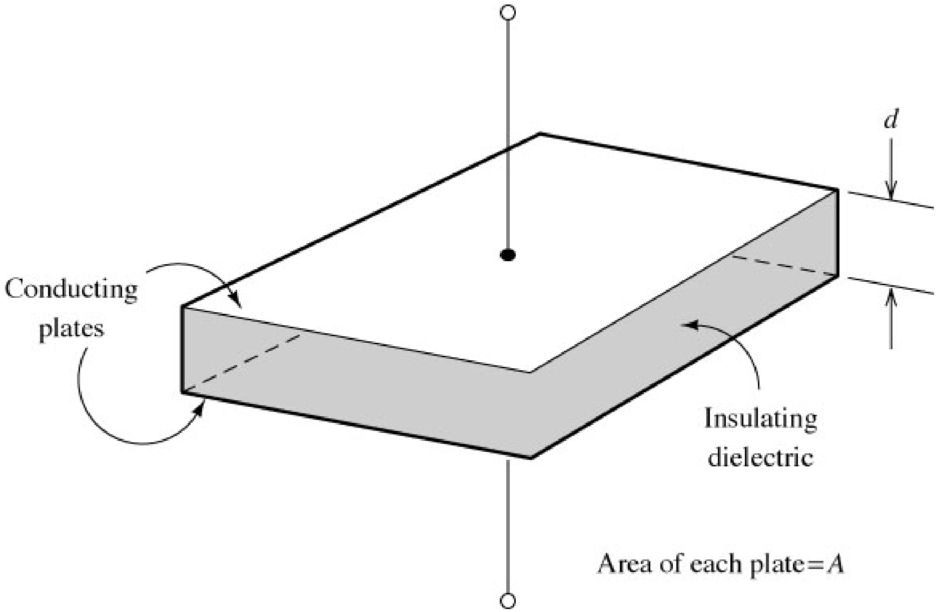


Figure 3.46 Parallel-plate capacitor.

$$Q = CV \qquad (3.33)$$

$$C = \frac{\varepsilon A}{d} \qquad (3.34)$$

Depletion Capacitance

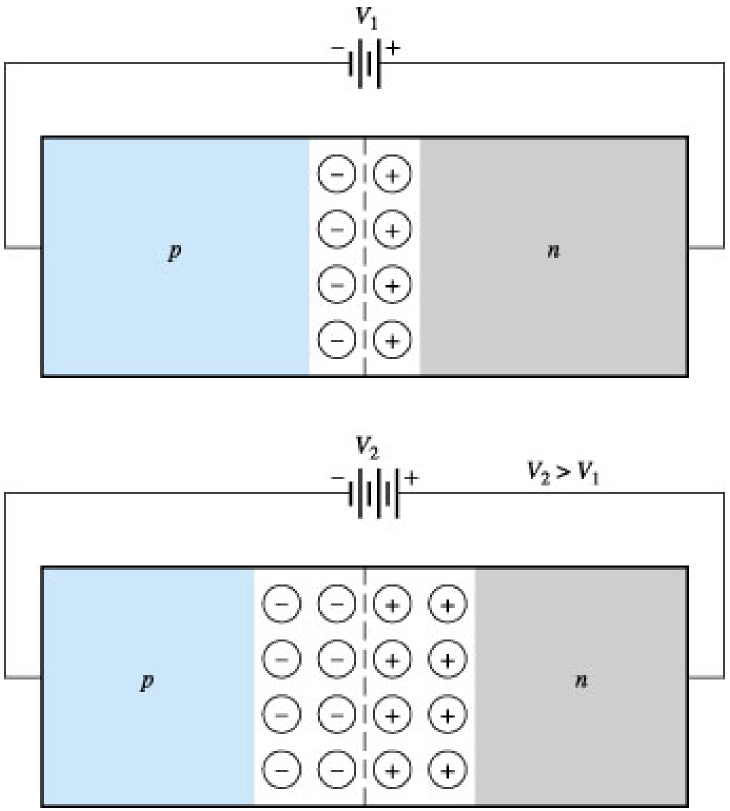


Figure 3.46 As the reverse bias voltage becomes greater, the charge stored in the depletion region increases.

$$C = \left| \frac{dQ}{dv_D} \right| \tag{3.36}$$

$$C = \frac{C_{j0}}{\left[1 - \left(V_{DQ}/\phi_0\right)\right]^m} \tag{3.37}$$

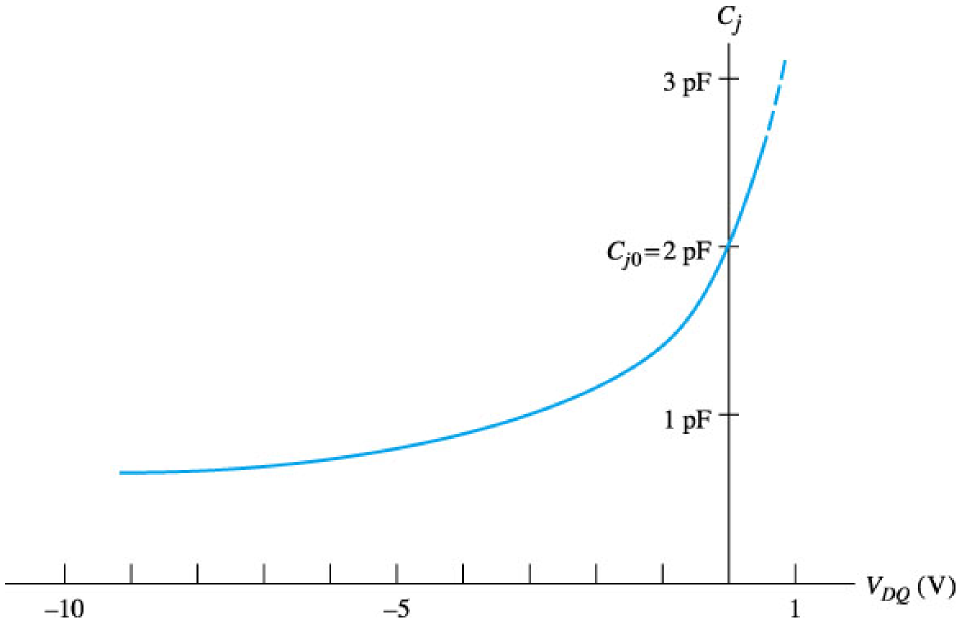
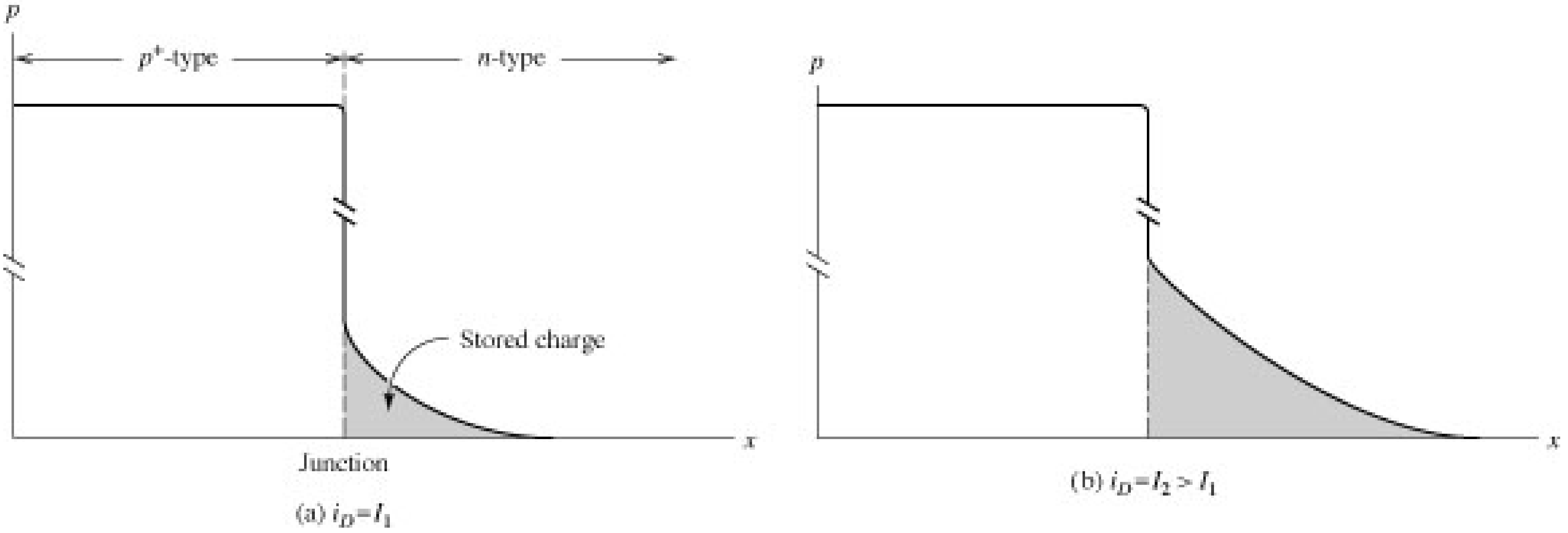


Figure 3.48 Depletion capacitance versus bias voltage for the 1N4148 diode.

Diffusion Capacitance



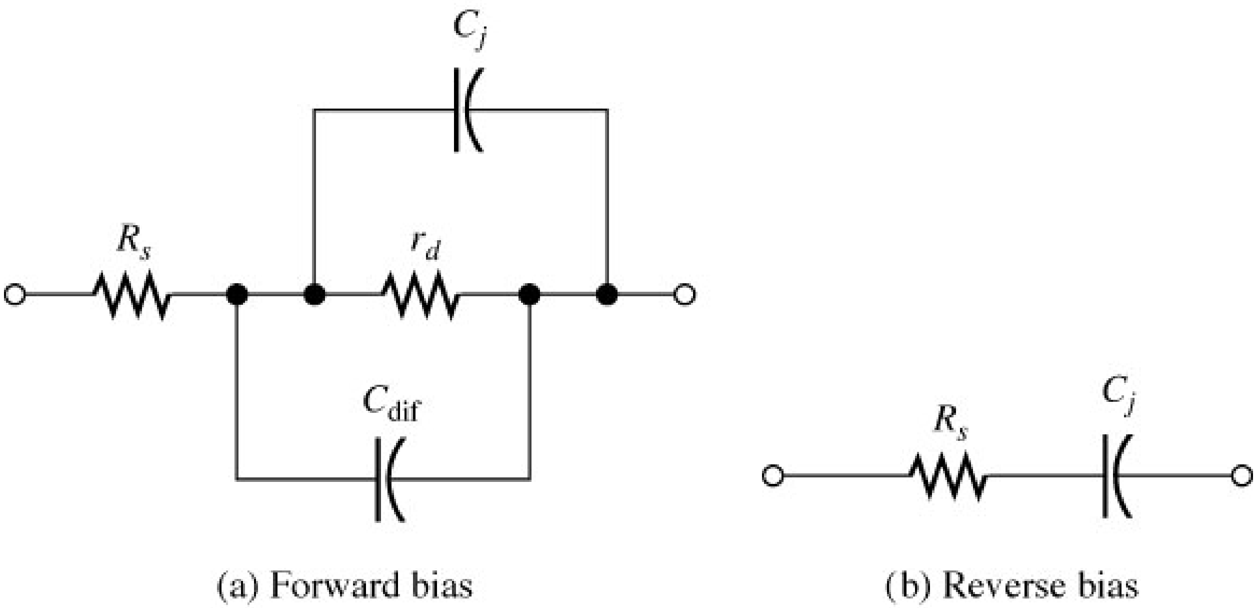
(a) $i_D = I_1$

(b) $i_D = I_2 > I_1$

Figure 3.49 Hole concentration versus distance for two values of forward current.

$$C_{dif} = \frac{\tau_T I_{DQ}}{V_T} \qquad (3.38)$$

Complete Small - Signal Diode Model



(a) Forward bias

(b) Reverse bias

Figure 3.50 Small-signal linear circuits for the *pn*-junction diode.

Large - Signal Switching Behavior

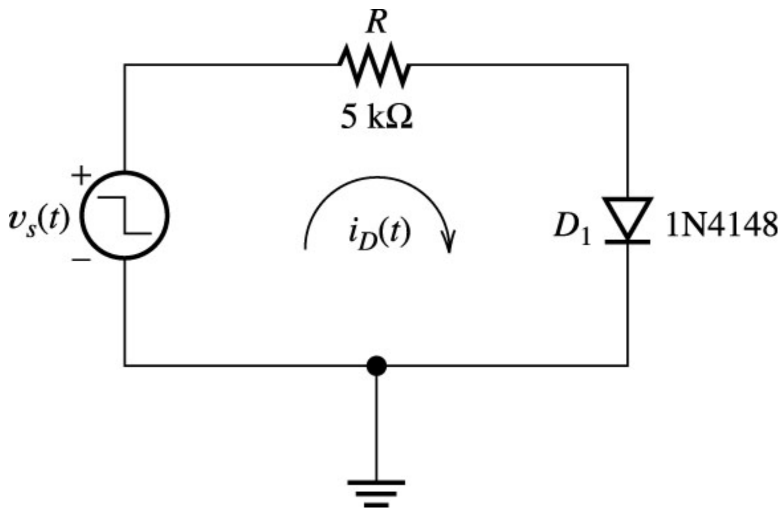


Figure 3.51 Circuit illustrating switching behavior of a *pn*-junction diode.

t_s – **storage interval;**

t_t – **transition time;**

t_{rr} – **reverse recovery time:** total time in which the diode is open after switching

$$t_{rr} = t_s + t_t \qquad (3.40)$$

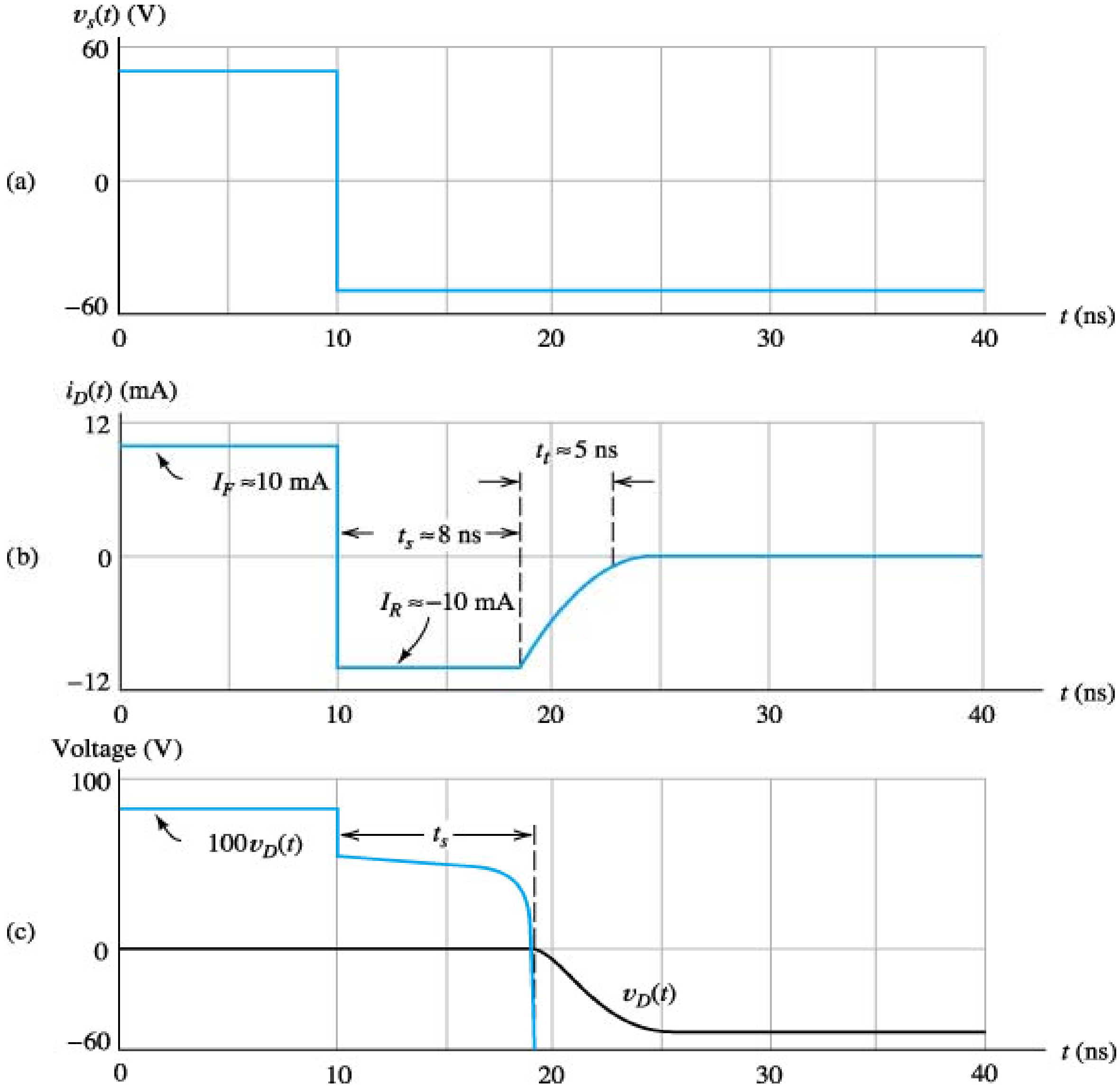


Figure 3.52 Waveforms for the circuit of Figure 3.51.

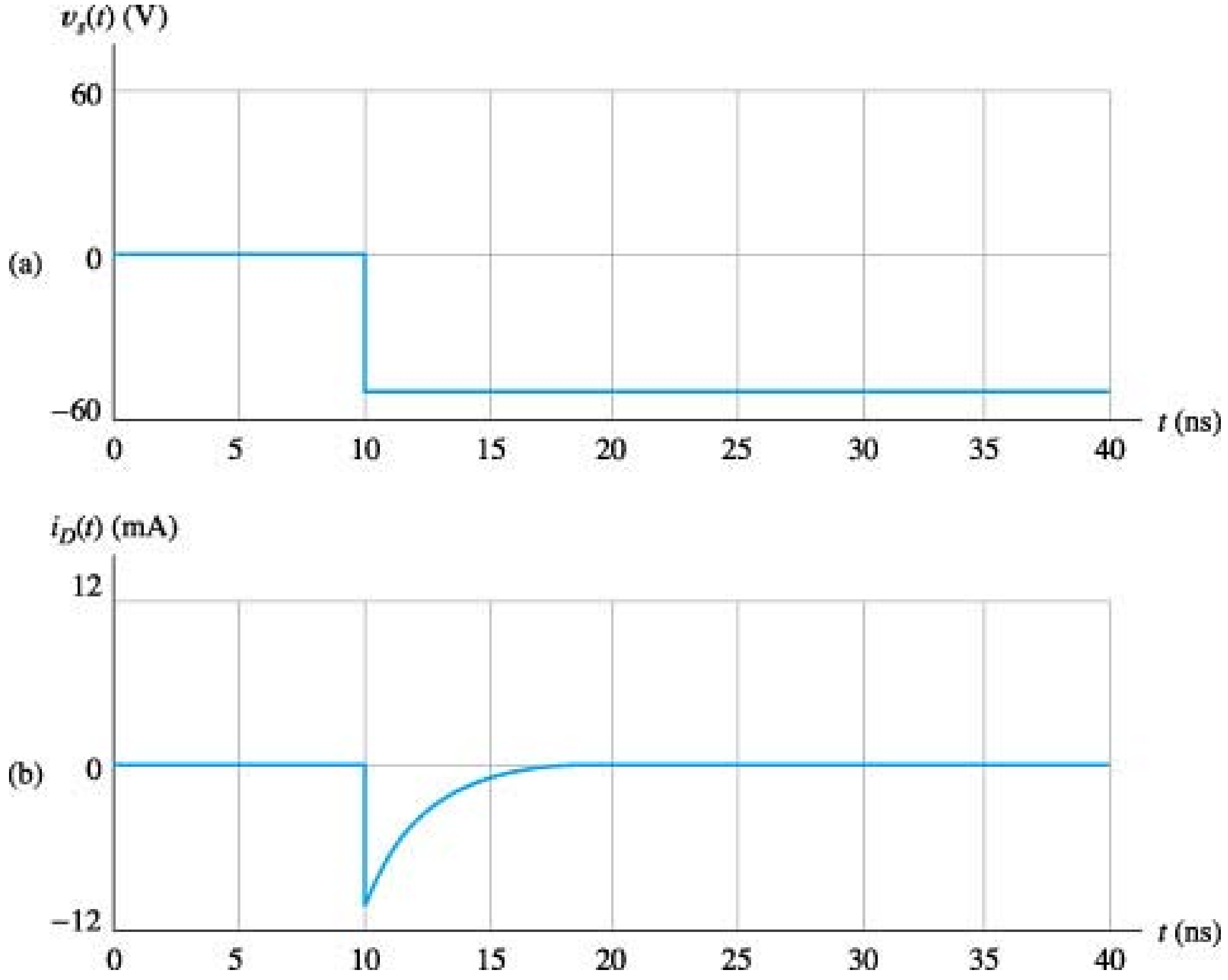


Figure 3.53 Another set of waveforms for the circuit of Figure 3.51. Notice the absence of a storage interval.