- A silicon diode conducts a negligible current until the forward voltage is at least 0.5 V. Then the current increases rapidly, with the voltage drop increasing by 60 mV to 120 mV (depending on the value of n) for every decade of current change.
- In the reverse direction, a silicon diode conducts a current on the order of 10^{-9} A. This current is much greater than I_S and increases with the magnitude of reverse voltage.
- Beyond a certain value of reverse voltage (that depends on the diode) breakdown occurs, and current increases rapidly with a small corresponding increase in voltage.
- Diodes designed to operate in the breakdown region are called zener diodes. They are employed in the design of voltage regulators whose function is to provide a constant dc voltage that varies little with variations in power supply voltage and/or load current.
- A hierarchy of diode models exists, with the selection of an appropriate model dictated by the application.
- In many applications, a conducting diode is modeled as having a constant voltage drop, usually approximately 0.7 V.
- A diode biased to operate at a dc current I_D has a small-signal resistance $r_d = nV_T/I_D$.
- The silicon junction diode is basically a pn junction. Such a junction is formed in a single silicon crystal.
- In p-type silicon there is an overabundance of holes (positively charged carriers), while in n-type silicon electrons are abundant.
- A carrier-depletion region develops at the interface in a pn junction, with the n side positively charged and the p side negatively charged. The voltage difference resulting is called the barrier voltage.
- A diffusion current I_D flows in the forward direction (carried by holes from the p side and electrons from the n side), and a current I_S flows in the reverse direction (carried by thermally generated minority carriers). In an open-circuited junction, $I_D = I_S$ and the barrier voltage is denoted V_0. V_0 is also called the junction built-in voltage.
- Applying a reverse-bias voltage $|V|$ to a pn junction causes the depletion region to widen, and the barrier voltage increases to $(V_0 + |V|)$. The diffusion current decreases and a net reverse current of $(I_S - I_D)$ flows.
- Applying a forward-bias voltage $|V|$ to a pn junction causes the depletion region to become narrower, and the barrier voltage decreases to $(V_0 - |V|)$. The diffusion current increases, and a net forward current of $(I_D - I_S)$ flows.
- For a summary of the diode models in the forward region, refer to Table 3.1.
- For a summary of the relationships that govern the physical operation of the pn junction, refer to Table 3.2.

PROBLEMS

SECTION 3.1: THE IDEAL DIODE

3.1 An AA flashlight cell, whose Thévenin equivalent is a voltage source of 1.5 V and a resistance of 1 Ω, is connected to the terminals of an ideal diode. Describe two possible situations that result. What are the diode current and terminal voltage when (a) the connection is between the diode cathode and the positive terminal of the battery and (b) the anode and the positive terminal are connected?

3.2 For the circuits shown in Fig. P3.2 using ideal diodes, find the values of the voltages and currents indicated.

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

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?

3.5 The circuit shown in Fig. P3.5 is a model for a battery charger. Here v_I is a 10-V peak sine wave, D_1 and D_2 are ideal diodes, I is a 100-mA current source, and B is a 4.5-V battery. Sketch and label the waveform of the battery current i_B. What is its peak value? What is its average value? If the peak value

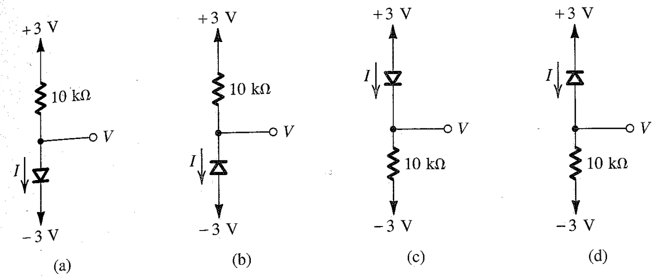

FIGURE P3.2

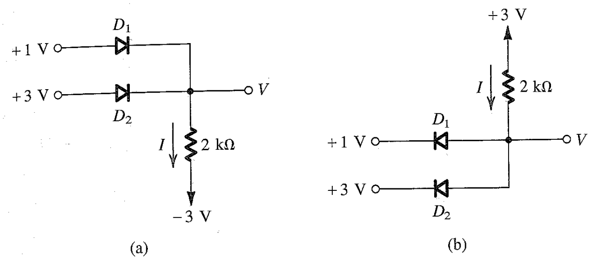

FIGURE P3.3

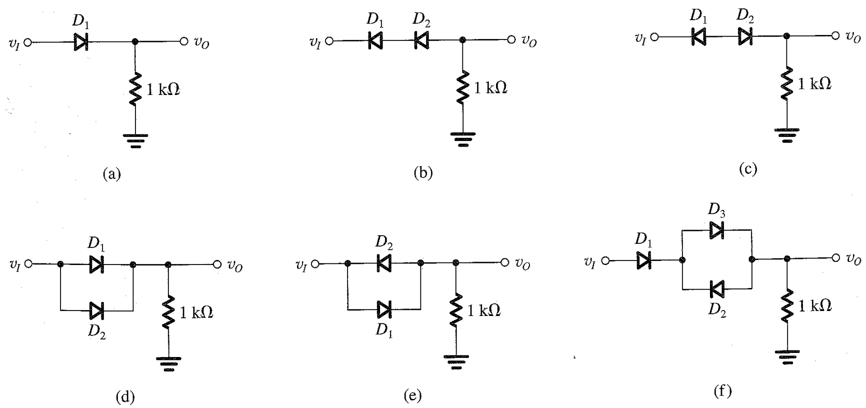

FIGURE P3.4 *(Continued)*

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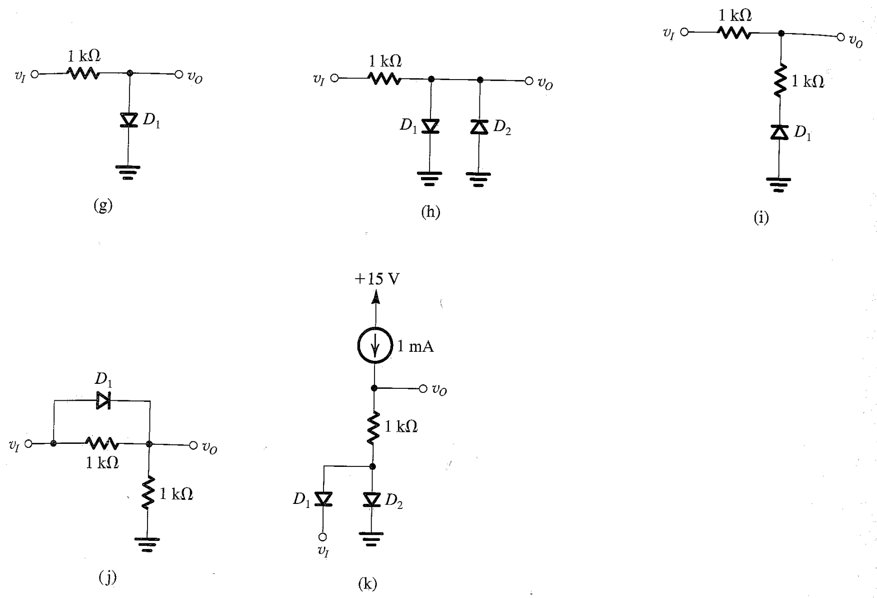

FIGURE P3.4 *(Continued)*

of v_I is reduced by 10%, what do the peak and average values of i_B become?

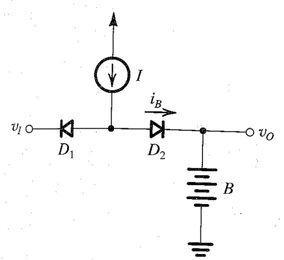

FIGURE P3.5

3.6 The circuits shown in Fig. P3.6 can function as logic gates for input voltages are either high or low. Using "1" to denote the high value and "0" to denote the low value, prepare a table with four columns including all possible input combinations and the resulting values of X and Y. What logic function is X of A and B? What logic function is Y of A and B? For what values of A and B do X and Y have the same value? For what values of A and B do X and Y have opposite values?

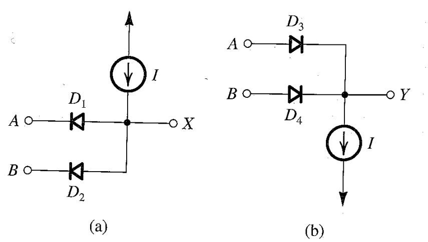

FIGURE P3.6

D3.7 For the logic gate of Fig. 3.5(a), assume ideal diodes and input voltage levels of 0 V and +5 V. Find a suitable value for R so that the current required from each of the input signal sources does not exceed 0.1 mA.

D3.8 Repeat Problem 3.7 for the logic gate of Fig. 3.5(b).

3.9 Assuming that the diodes in the circuits of Fig. P3.9 are ideal, find the values of the labeled voltages and currents.

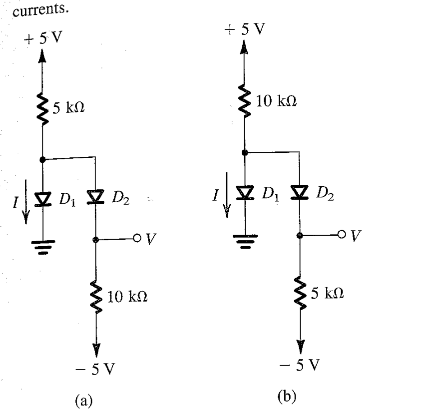

FIGURE P3.9

3.10 Assuming that the diodes in the circuits of Fig. P3.10 are ideal, utilize Thévenin's theorem to simplify the circuits and thus find the values of the labeled currents and voltages.

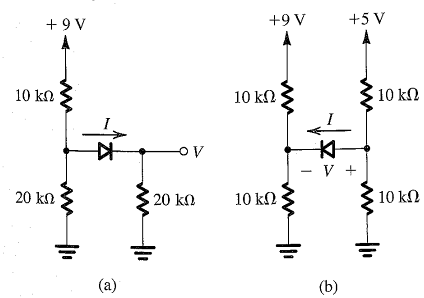

FIGURE P3.10

D3.11 For the rectifier circuit of Fig. 3.3(a), let the input sine wave have 120-V rms value and assume the diode to be ideal. Select a suitable value for R so that the peak diode current does not exceed 50 mA. What is the greatest reverse voltage that will appear across the diode?

3.12 Consider the rectifier circuit of Fig. 3.3 in the event that the input source v_I has a source resistance R_s. For the case $R_s = R$ and assuming the diode to be ideal, sketch and clearly label the transfer characteristic v_O versus v_I.

3.13 A square wave of 6-V peak-to-peak amplitude and zero average is applied to a circuit resembling that in Fig. 3.3(a) and employing a 100-Ω resistor. What is the peak output voltage that results? What is the average output voltage that results? What is the peak diode current? What is the average diode current? What is the maximum reverse voltage across the diode?

3.14 Repeat Problem 3.13 for the situation in which the average voltage of the square wave is 2 V while its peak-to-peak value remains at 6 V.

***D3.15** Design a battery-charging circuit, resembling that in Fig. 3.4 and using an ideal diode, in which current flows to the 12-V battery 20% of the time and has an average value of 100 mA. What peak-to-peak sine-wave voltage is required? What resistance is required? What peak diode current flows? What peak reverse voltage does the diode endure? If resistors can be specified to only one significant digit and the peak-to-peak voltage only to the nearest volt, what design would you choose to guarantee the required charging current? What fraction of the cycle does diode current flow? What is the average diode current? What is the peak diode current? What peak reverse voltage does the diode endure?

3.16 The circuit of Fig. P3.16 can be used in a signalling system using one wire plus a common ground return. At any moment, the input has one of three values: +3 V, 0 V, –3 V. What is the status of the lamps for each input value? (Note that the lamps can be located apart from each other and that there may be several of each type of connection, all on one wire!).

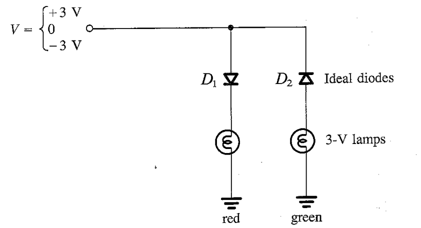

FIGURE P3.16

SECTION 3.2: TERMINAL CHARACTERISTICS OF JUNCTION DIODES

3.17 Calculate the value of the thermal voltage, V_T, at −40°C, 0°C, +40°C, and +150°C. At what temperature is V_T exactly 25 mV?

3.18 At what forward voltage does a diode for which $n = 2$ conduct a current equal to $1000I_S$? In terms of I_S, what current flows in the same diode when its forward voltage is 0.7 V?

3.19 A diode for which the forward voltage drop is 0.7 V at 1.0 mA and for which $n = 1$ is operated at 0.5 V. What is the value of the current?

3.20 A particular diode, for which $n = 1$, is found to conduct 5 mA with a junction voltage of 0.7 V. What is its saturation current I_S? What current will flow in this diode if the junction voltage is raised to 0.71 V? To 0.8 V? If the junction voltage is lowered to 0.69 V? To 0.6 V? What change in junction voltage will increase the diode current by a factor of 10?

3.21 The following measurements are taken on particular junction diodes to which V is the terminal voltage and I is the diode current. For each diode, estimate values of I_S and the terminal voltage at 1% of the measured current for $n = 1$ and for $n = 2$. Use $V_T = 25$ mV in your computations.

(a) $V = 0.700$ V at $I = 1.00$ A
(b) $V = 0.650$ V at $I = 1.00$ mA
(c) $V = 0.650$ V at $I = 10\ \mu$A
(d) $V = 0.700$ V at $I = 10$ mA

3.22 Listed below are the results of measurements taken on several different junction diodes. For each diode, the data provided are the diode current I, the corresponding diode voltage V, and the diode voltage at a current $I/10$. In each case, estimate I_S, n, and the diode voltage at $10I$.

(a) 10.0 mA, 700 mV, 600 mV
(b) 1.0 mA, 700 mV, 600 mV
(c) 10 A, 800 mV, 700 mV
(d) 1 mA, 700 mV, 580 mV
(e) 10 μA, 700 mV, 640 mV

3.23 The circuit in Fig. P3.23 utilizes three identical diodes having $n = 1$ and $I_S = 10^{-14}$ A. Find the value of the current I required to obtain an output voltage $V_O = 2$ V. If a current of 1 mA is drawn away from the output terminal by a load, what is the change in output voltage?

3.24 A junction diode is operated in a circuit in which it is supplied with a constant current I. What is the effect on the forward voltage of the diode if an identical diode is connected in parallel? Assume $n = 1$.

3.25 In the circuit shown in Fig. P3.25, both diodes have $n = 1$, but D_1 has 10 times the junction area of D_2. What value of V results? To obtain a value for V of 50 mV, what current I_2 is needed?

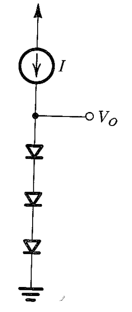

FIGURE P3.23

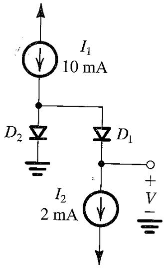

FIGURE P3.25

3.26 For the circuit shown in Fig. P3.26, both diodes are identical, conducting 10 mA at 0.7 V and 100 mA at 0.8 V. Find the value of R for which $V = 80$ mV.

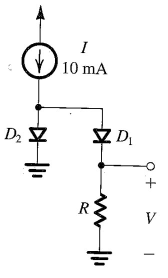

FIGURE P3.26

3.27 Several diodes having a range of sizes, but all with $n = 1$, are measured at various temperatures and junction currents as noted below. For each, estimate the diode voltage at 1 mA and 25°C.

(a) 620 mV at 10 μA and 0°C
(b) 790 mV at 1 A and 50°C
(c) 590 mV at 100 μA and 100°C
(d) 850 mV at 10 mA and −50°C
(e) 700 mV at 100 mA and 75°C

***3.28** In the circuit shown in Fig. P3.28, D_1 is a large-area high-current diode whose reverse leakage is high and independent of applied voltage while D_2 is a much smaller, low-current diode for which $n = 1$. At an ambient temperature of 20°C, resistor R_1 is adjusted to make $V_{R1} = V_2 = 520$ mV. Subsequent measurement indicates that R_1 is 520 kΩ. What do you expect the voltages V_{R1} and V_2 to become at 0°C and at 40°C?

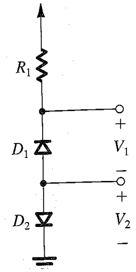

FIGURE P3.28

3.29 When a 15-A current is applied to a particular diode, it is found that the junction voltage immediately becomes 700 mV. However, as the power being dissipated in the diode raises its temperature, it is found that the voltage decreases and eventually reaches 580 mV. What is the apparent rise in junction temperature? What is the power dissipated in the diode in its final state? What is the temperature rise per watt of power dissipation? (This is called the thermal resistance.)

***3.30** A designer of an instrument that must operate over a wide supply-voltage range, noting that a diode's junction-voltage drop is relatively independent of junction current, considers the use of a large diode to establish a small relatively constant voltage. A power diode, for which the nominal current at 0.8 V is 10 A, is available. Furthermore, the designer has reason to believe that $n = 2$. For the available current source, which varies from 0.5 mA to 1.5 mA, what junction voltage might be expected? What additional voltage change might be expected for a temperature variation of ±25°C?

***3.31** As an alternative to the idea suggested in Problem 3.30, the designer considers a second approach to producing a relatively constant small voltage from a variable current supply: It relies on the ability to make quite accurate copies of any small current that is available (using a process called current mirroring). The designer proposes to use this idea to supply two diodes of different junction areas with the same current and to measure their junction-voltage difference. Two types of diodes are available; for a forward voltage of 700 mV, one conducts 0.1 mA while the other conducts 1 A. Now, for identical currents in the range of 0.5 mA to 1.5 mA supplied to each, what range of difference voltages result? What is the effect of a temperature change of ±25°C on this arrangement? Assume $n = 1$.

SECTION 3.3: MODELING THE DIODE FORWARD CHARACTERISTIC

***3.32** Consider the graphical analysis of the diode circuit of Fig. 3.10 with $V_{DD} = 1$ V, $R = 1$ kΩ, and a diode having $I_S = 10^{-15}$ A and $n = 1$. Calculate a small number of points on the diode characteristic in the vicinity of where you expect the load line to intersect it, and use a graphical process to refine your estimate of diode current. What value of diode current and voltage do you find? Analytically, find the voltage corresponding to your estimate of current. By how much does it differ from the graphically estimated value?

3.33 Use the iterative-analysis procedure to determine the diode current and voltage in the circuit of Fig. 3.10 for $V_{DD} = 1$ V, $R = 1$ kΩ, and a diode having $I_S = 10^{-15}$ A and $n = 1$.

3.34 A "1-mA diode" (i.e., one that has $v_D = 0.7$ V at $i_D = 1$ mA) is connected in series with a 200-Ω resistor to a 1.0-V supply.

(a) Provide a rough estimate of the diode current you would expect.
(b) If the diode is characterized by $n = 2$, estimate the diode current more closely using iterative analysis.

3.35 A collection of circuits, which are variants of that shown in Fig. 3.10, are listed below. For each diode used, the measured junction current I_0 at junction voltage V_0 is provided, along with the change of junction voltage ΔV measured when the current is increased 10-fold. For each circuit, find the diode current I_D and diode voltage V_D that result, using the diode exponential equation and iteration. (*Hint:* To reduce your workload, notice the very special relation between the circuit and diode parameters in many—but not all—cases. Finally, note that using such relationships, or approximations to them, can often make your first pass at a circuit design much easier and faster!)

Circuit	V_{DD} (V)	R (kΩ)	I_0 (mA)	V_0 (mV)	ΔV (mV)
a	10.0	9.3	1.0	700	100
b	3.0	2.3	1.0	700	100
c	2.0	2.0	10	700	100
d	2.0	2.0	1.0	700	100
e	1.0	0.30	10	700	100
f	1.0	0.30	10	700	60
g	1.0	0.30	10	700	120
h	0.5	30	10	700	100

D3.36 Assuming the availability of diodes for which v_D = 0.7 V at i_D = 1 mA and n = 1, design a circuit that utilizes four diodes connected in series, in series with a resistor R connected to a 10-V power supply. The voltage across the string of diodes is to be 3.0 V.

3.37 Find the parameters of a piecewise-linear model of a diode for which v_D = 0.7 V at i_D = 1 mA and n = 2. The model is to fit exactly at 1 mA and 10 mA. Calculate the error in millivolts in predicting v_D using the piecewise-linear model at i_D = 0.5, 5, and 14 mA.

3.38 Using a copy of the diode curve presented in Fig. 3.12, approximate the diode characteristic using a straight line that exactly matches the diode characteristic at both 10 mA and 1 mA. What is the slope? What is r_D? What is V_{D0}?

3.39 On a copy of the diode characteristics presented in Fig. 3.12, draw a load line corresponding to an external circuit consisting of a 0.9-V voltage source and a 100-Ω resistor. What are the values of diode drop and loop current you estimate using:

(a) the actual diode characteristics?
(b) the two-segment model shown?

3.40 For the diodes characterized below, find r_D and V_{D0}, the elements of the battery-plus-resistor model for which the straight line intersects the diode exponential characteristic at 0.1× and 10× the specified diode current.

(a) V_D = 0.7 V at I_D = 1 mA and n = 1
(b) V_D = 0.7 V at I_D = 1 A and n = 1
(c) V_D = 0.7 V at I_D = 10 μA and n = 1

3.41 The diode whose characteristic curve is shown in Fig. 3.15 is to be operated at 10 mA. What would likely be a suitable voltage choice for an appropriate constant-voltage-drop model?

3.42 A diode operates in a series circuit with R and V. A designer, considering using a constant-voltage model, is uncertain whether to use 0.7 V or 0.6 V for V_D. For what value of V is the difference in the calculated values of current only 1%? For V = 2 V and R = 1 kΩ, what two currents would result from the use of the two values of V_D? What is their percentage difference?

D3.43 A designer has a relatively large number of diodes for which a current of 20 mA flows at 0.7 V and the 0.1-V/decade approximation is relatively good. Using a 10-mA current source, the designer wishes to create a reference voltage of 1.25 V. Suggest a combination of series and parallel diodes that will do the job as well as possible. How many diodes are needed? What voltage is actually achieved?

3.44 Consider the half-wave rectifier circuit of Fig. 3.3(a) with R = 1 kΩ and the diode having the characteristics and the piecewise-linear model shown in Fig. 3.12 (V_{D0} = 0.65 V, r_D = 20 Ω). Analyze the rectifier circuit using the piecewise-linear model for the diode, and thus find the output voltage v_O as a function of v_I. Sketch the transfer characteristic v_O versus v_I for $0 \le v_I \le 10$ V. For v_I being a sinusoid with 10 V peak amplitude, sketch and clearly label the waveform of v_O.

3.45 Solve the problems in Example 3.2 using the constant-voltage-drop (V_D = 0.7 V) diode model.

3.46 For the circuits shown in Fig. P3.2, using the constant-voltage-drop (V_D = 0.7 V) diode model, find the voltages and currents indicated.

3.47 For the circuits shown in Fig. P3.3, using the constant-voltage-drop (V_D = 0.7 V) diode model, find the voltages and currents indicated.

3.48 For the circuits in Fig. P3.9, using the constant-voltage-drop (V_D = 0.7 V) diode model, find the values of the labeled currents and voltages.

3.49 For the circuits in Fig. P3.10, utilize Thévenin's theorem to simplify the circuits and find the values of the labeled currents and voltages. Assume that conducting diodes can be represented by the constant-voltage-drop model (V_D = 0.7 V).

D3.50 Repeat Problem 3.11, representing the diode by its constant-voltage-drop (V_D = 0.7 V) model. How different is the resulting design?

3.51 Repeat the problem in Example 3.1 assuming that the diode has 10 times the area of the device whose characteristics and piecewise-linear model are displayed in Fig. 3.12. Represent the diode by its piecewise-linear model (v_D = 0.65 + 2i_D).

3.52 The small-signal model is said to be valid for voltage variations of about 10 mV. To what percentage current change does this correspond (consider both positive and negative signals) for:

(a) n = 1?
(b) n = 2?

For each case, what is the maximum allowable voltage signal (positive or negative) if the current change is to be limited to 10%?

3.53 In a particular circuit application, ten "20-mA diodes" (a 20-mA diode is a diode that provides a 0.7-V drop when the current through it is 20 mA) connected in parallel operate at a total current of 0.1 A. For the diodes closely matched, with n = 1, what current flows in each? What is the corresponding small-signal resistance of each diode and of the combination? Compare this with the incremental resistance of a single diode conducting 0.1 A. If each of the 20-mA diodes has a series resistance of 0.2 Ω associated with the wire bonds to the junction, what is the equivalent resistance of the 10 parallel-connected diodes? What connection resistance would a single diode need in order to be totally equivalent? (*Note:* This is why the parallel connection of real diodes can often be used to advantage.)

3.54 In the circuit shown in Fig. P3.54, I is a dc current and v_s is a sinusoidal signal. Capacitors C_1 and C_2 are very large; their function is to couple the signal to and from the diode but block the dc current from flowing into the signal source or the load (not shown). Use the diode small-signal model to show that the signal component of the output voltage is

$$v_o = v_s \frac{nV_T}{nV_T + IR_s}$$

If v_s = 10 mV, find v_o for I = 1 mA, 0.1 mA, and 1 μA. Let R_s = 1 kΩ and n = 2. At what value of I does v_o become one-half of v_s? Note that this circuit functions as a signal attenuator with the attenuation factor controlled by the value of the dc current I.

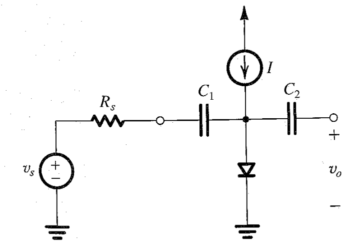

FIGURE P3.54

3.55 In the attenuator circuit of Fig. P3.54, let R_s = 10 kΩ. The diode is a 1-mA device; that is, it exhibits a voltage drop of 0.7 V at a dc current of 1 mA and has n = 1. For small input signals, what value of current I is needed for v_o/v_s = 0.50? 0.10? 0.01? 0.001? In each case, what is the largest input signal that can be used while ensuring that the signal component of the diode current is limited to ±10% of its dc current? What output signals correspond?

3.56 In the capacitor-coupled attenuator circuit shown in Fig. P3.56, I is a dc current that varies from 0 mA to 1 mA, D_1 and D_2 are diodes with n = 1, and C_1 and C_2 are large coupling capacitors. For very small input signals, find the values of the ratio v_o/v_i for I equal to:

(a) 0 μA
(b) 1 μA
(c) 10 μA
(d) 100 μA
(e) 500 μA
(f) 600 μA
(g) 900 μA
(h) 990 μA
(i) 1 mA

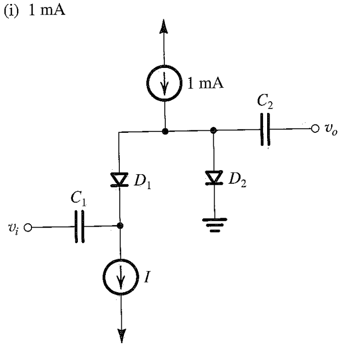

FIGURE P3.56

For the current in each diode in excess of 10 μA, what is the largest input signal for which the critical diode current remains within 10% of its dc value?

***3.57** In the circuit shown in Fig. P3.57, diodes D_1 through D_4 are identical. Each has n = 1 and is a "1-mA diode"; that is, it exhibits a voltage drop of 0.7 V at a 1-mA current.

(a) For small input signals (e.g., 10 mV peak), find values of the small-signal transmission v_o/v_i for various values of I: 0 μA, 1 μA, 10 μA, 100 μA, 1 mA, and 10 mA.