Transit time
Turn-on voltage
Voltage regulator
Voltage transfer characteristic (VTC)
Zener breakdown
Zener diode
Zero bias
Zero-bias junction capacitance

REFERENCE

1. G. W. Neudeck, *The PN Junction Diode,* 2d ed. Pearson Education, Upper Saddle River, NJ: 1989.

ADDITIONAL READING

PSPICE, ORCAD, now owned by Cadence Design Systems, San Jose, CA.
LTspice available from Linear Technology Corp.
Tina-TI SPICE-based analog simulation program available from Texas Instruments.
T. Quarles, A. R. Newton, D. O. Pederson, and A. Sangiovanni-Vincentelli, *SPICE3 Version 3f3 User's Manual.* UC Berkeley: May 1993.
A. S. Sedra, and K. C. Smith. *Microelectronic Circuits.* 5th ed. Oxford University Press, New York: 2004.

PROBLEMS

3.1 The *pn* Junction Diode

3.1. A diode is doped with $N_A = 10^{19}/\text{cm}^3$ on the p-type side and $N_D = 10^{18}/\text{cm}^3$ on the n-type side. (a) What is the depletion-layer width w_{do}? (b) What are the values of x_p and x_n? (c) What is the value of the built-in potential of the junction? (d) What is the value of E_{MAX}? Use Eq. (3.3) and Fig. 3.5.

3.2. A diode is doped with $N_A = 10^{18}/\text{cm}^3$ on the p-type side and $N_D = 10^{15}/\text{cm}^3$ on the n-type side. (a) What are the values of p_p, p_n, n_p, and n_n? (b) What are the depletion-region width w_{do} and built-in voltage?

3.3. Repeat Prob. 3.2 for a diode with $N_A = 10^{16}/\text{cm}^3$ on the p-type side and $N_D = 10^{19}/\text{cm}^3$ on the n-type side.

3.4. Repeat Prob. 3.2 for a diode with $N_A = 10^{18}/\text{cm}^3$ on the p-type side and $N_D = 10^{18}/\text{cm}^3$ on the n-type side.

3.5. Repeat Prob. 3.2 for a diode with $N_D = 10^{20}/\text{cm}^3$ on the n-type side and $N_A = 10^{18}/\text{cm}^3$ on the p-type side.

3.6. A diode has $w_{do} = 0.4\ \mu\text{m}$ and $\phi_j = 0.85$ V. (a) What reverse bias is required to triple the depletion-layer width? (b) What is the depletion region width if a reverse bias of 7 V is applied to the diode?

3.7. A diode has $w_{do} = 1\ \mu\text{m}$ and $\phi_j = 0.6$ V. (a) What reverse bias is required to double the depletion-layer width? (b) What is the depletion region width if a reverse bias of 12 V is applied to the diode?

3.8. Suppose a drift current density of 2000 A/cm^2 exists in the neutral region on the n-type side of a diode that has a resistivity of 0.5 $\Omega \cdot$ cm. What is the electric field needed to support this drift current density?

3.9. Suppose a drift current density of 5000 A/cm^2 exists in the neutral region on the p-type side of a diode that has a resistivity of 2.5 $\Omega \cdot$ cm. What is the electric field needed to support this drift current density?

3.10. The maximum velocity of carriers in silicon is approximately 10^7 cm/s. What is the maximum drift current density that can be supported in a region of p-type silicon with a doping of $4 \times 10^{17}/\text{cm}^3$?

3.11. The maximum velocity of carriers in silicon is approximately 10^7 cm/s. What is the maximum drift current density that can be supported in a region of n-type silicon with a doping of $5 \times 10^{15}/\text{cm}^3$?

**3.12. Suppose that $N_A(x) = N_o \exp(-x/L)$ in a region of silicon extending from $x = 0$ to $x = 12\ \mu\text{m}$, where N_o is a constant. Assume that $p(x) = N_A(x)$. Assuming that j_p must be zero in thermal equilibrium, show that a built-in electric field must exist and find its value for $L = 1\ \mu\text{m}$ and $N_o = 10^{18}/\text{cm}^3$.

3.13. What carrier gradient is needed to generate a diffusion current density of $j_n = 2000\ \text{A/cm}^2$ if $\mu_n = 500\ \text{cm}^2/\text{V}\cdot\text{s}$?

3.14. Use the solver routine in your calculator to find the solution to Eq. (3.25) for $I_S = 10^{-16}$ A.

3.15. Use a spreadsheet to iteratively find the solution to Eq. 3.25 for $I_S = 10^{-13}$ A.

3.16. (a) Use MATLAB or MATHCAD to find the solution to Eq. 3.25 for $I_S = 10^{-13}$ A. (b) Repeat for $I_S = 10^{-15}$ A.

3.2–3.4 The *i*-*v* Characteristics of the Diode; The Diode Equation: A Mathematical Model for the Diode; and Diode Characteristics Under Reverse, Zero, and Forward Bias

3.17. To what temperature does $V_T = 0.025$ V actually correspond? What is the value of V_T for temperatures of −55°C, 0°C, and +85°C?

3.18. (a) Plot a graph of the diode equation similar to Fig. 3.8 for a diode with $I_S = 10^{-12}$ A and $n = 1$. (b) Repeat for $n = 2$. (c) Repeat (a) for $I_S = 10^{-14}$ A.

3.19. A diode has $n = 1.05$ at $T = 320$ K. What is the value of $n \cdot V_T$? What temperature would give the same value of $n \cdot V_T$ if $n = 1.00$?

3.20. Plot the diode current for a diode with $I_{SO} = 11$ fA and $\phi_j = 0.8$ for $-10\ \text{V} \le v_D \le 0$ V using Eq. 3.19.

*3.21. What are the values of I_S and n for the diode in the graph in Fig. P3.21? Assume $V_T = 0.025$ V.

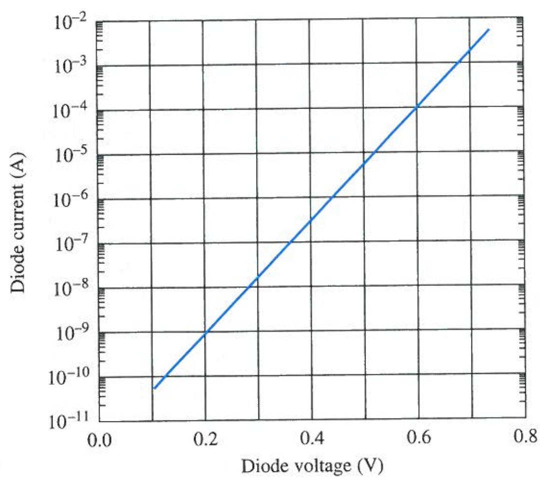


Figure P3.21

3.22. A diode has $I_S = 10^{-17}$ A and $n = 1.07$. (a) What is the diode voltage if the diode current is 70 μA? (b) What is the diode voltage if the diode current is 5 μA? (c) What is the diode current for $v_D = 0$ V? (d) What is the diode current for $v_D = -0.075$ V? (e) What is the diode current for $v_D = -5$ V?

3.23. A diode has $I_S = 10^{-18}$ A and $n = 1$. (a) What is the diode voltage if the diode current is 100 μA? (b) What is the diode voltage if the diode current is 10 μA? (c) What is the diode current for $v_D = 0$ V? (d) What is the diode current for $v_D = -0.06$ V? (e) What is the diode current for $v_D = -4$ V?

3.24. A diode has $I_S = 10^{-16}$ A and $n = 1$. (a) What is the diode current if the diode voltage is 0.675 V? (b) What will be the diode voltage if the current increases by a factor of 3?

3.25. A diode has $I_S = 10^{-10}$ A and $n = 2$. (a) What is the diode voltage if the diode current is 40 A? (b) What is the diode voltage if the diode current is 100 A?

3.26. A diode is operating with $i_D = 300$ μA and $v_D = 0.75$ V. (a) What is I_S if $n = 1$? (b) What is the diode current for $v_D = -3$ V?

3.27. A diode is operating with $i_D = 2$ mA and $v_D = 0.82$ V. (a) What is I_S if $n = 1$? (b) What is the diode current for $v_D = -5$ V?

3.28. The saturation current for diodes with the same part number may vary widely. Suppose it is known that $10^{-14}\ \text{A} \le I_S \le 10^{-12}$ A. What is the range of forward voltages that may be exhibited by the diode if it is biased with $i_D = 1$ mA?

3.29. A diode is biased by a 0.9-V dc source, and its current is found to be 100 μA at $T = 315$ K. (a) At what temperature will the current double? (b) At what temperature will the current be 50 μA?

**3.30. The *i*-*v* characteristic for a diode has been measured under carefully controlled temperature conditions ($T = 307$ K), and the data are in Table P3.30.

TABLE P3.30
Diode *i*-*v* Measurements

DIODE VOLTAGE	DIODE CURRENT
0.500	6.591×10^{-7}
0.550	3.647×10^{-6}
0.600	2.158×10^{-5}
0.650	1.780×10^{-4}
0.675	3.601×10^{-4}
0.700	8.963×10^{-4}
0.725	2.335×10^{-3}
0.750	6.035×10^{-3}
0.775	1.316×10^{-2}

Use a spreadsheet or MATLAB to find the values of I_S and n that provide the best fit of the diode equation to the measurements in the least-squares sense. [That is, find the values of I_S and n that minimize the function $M = \sum_{m=1}^{n}(i_D^m - I_{Dm})^2$, where i_D is the diode equation from Eq. (3.1) and I_{Dm} are the measured data.] For your values of I_S and n, what is the minimum value of $M = \sum_{m=1}^{n}(i_D^m - I_{Dm})^2$?

3.5 Diode Temperature Coefficient

3.31. What is the value of V_T for temperatures of -40°C, 0°C, and +50°C?

3.32. A diode has $I_S = 10^{-15}$ A and $n = 1$. (a) What is the diode voltage if the diode current is 100 μA at $T = 25$°C? (b) What is the diode voltage at $T = 50$°C? Assume the diode voltage temperature coefficient is -1.8 mV/K at 0°C.

3.33. A diode with $I_S = 2.5 \times 10^{-16}$ A at 30°C is biased at a current of 1 mA. (a) What is the diode voltage? (b) If the diode voltage temperature coefficient is -2 mV/K, what will be the diode voltage at 50°C?

3.34. A diode has $I_S = 10^{-15}$ A and $n = 1$. (a) What is the diode voltage if the diode current is 250 μA at $T = 25$°C? (b) What is the diode voltage at $T = 85$°C? Assume the diode voltage temperature coefficient is -2 mV/K at 55°C.

*3.35. The temperature dependence of I_S is described approximately by

$$I_S = CT^3 \exp\left(-\frac{E_G}{kT}\right)$$

What is the diode voltage temperature coefficient based on this expression and Eq. (3.15) if $E_G = 1.21$ eV, $V_D = 0.7$ V, and $T = 300$ K?

3.36. The saturation current of a silicon diode is described by the expression in Prob. 3.35. (a) What temperature change will cause I_S to double? (b) To increase by 10 times? (c) To decrease by 100 times?

3.6 Diodes Under Reverse Bias

3.37. A diode has $w_{do} = 1$ μm and $\phi_j = 0.8$ V. (a) What is the depletion layer width for $V_R = 5$ V? (b) For $V_D = -10$ V?

3.38. A diode has a doping of $N_D = 10^{20}/\text{cm}^3$ on the n-type side and $N_A = 10^{18}/\text{cm}^3$ on the p-type side. What are the values of w_{do} and ϕ_j? What is the value of w_d at a reverse bias of 5 V? At 25 V?

3.39. A diode has a doping of $N_D = 10^{15}/\text{cm}^3$ on the n-type side and $N_A = 10^{16}/\text{cm}^3$ on the p-type side. What are the values of w_{do} and ϕ_j? What is the value of w_d at a reverse bias of 10 V? At 100 V?

*3.40. A diode has $w_{do} = 1$ μm and $\phi_j = 0.6$ V. If the diode breaks down when the internal electric field reaches 300 kV/cm, what is the breakdown voltage of the diode?

*3.41. Silicon breaks down when the internal electric field exceeds 300 kV/cm. At what reverse bias do you expect the diode of Prob. 3.2 to break down?

3.42. What are the breakdown voltage V_Z and Zener resistance R_Z of the diode depicted in Fig. P3.42?

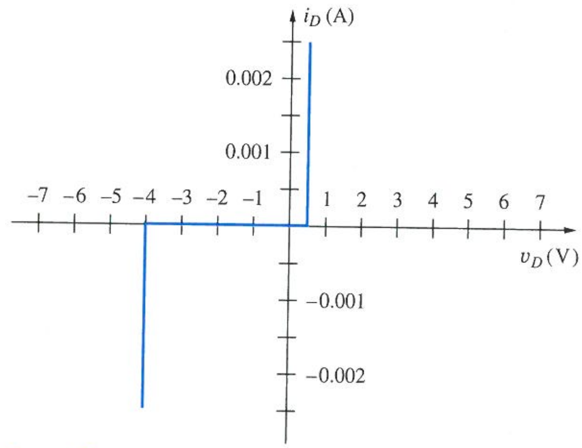


Figure P3.42

**3.43. A diode is fabricated with $N_A \gg N_D$. What value of doping is required on the lightly doped side to achieve a reverse-breakdown voltage of 1000 V if the semiconductor material breaks down at a field of 300 kV/cm?

3.7 *pn* Junction Capacitance

3.44. What is the zero-bias junction capacitance per cm² for a diode with $N_A = 10^{18}/\text{cm}^3$ on the p-type side and $N_D = 10^{15}/\text{cm}^3$ on the n-type side. What is the diode capacitance with a 9 V reverse bias if the diode area is 0.02 cm²?

3.45. What is the zero-bias junction capacitance/cm² for a diode with $N_A = 10^{15}/\text{cm}^3$ on the p-type side and $N_D = 10^{20}/\text{cm}^3$ on the n-type side? What is the diode capacitance with a 3-V reverse bias if the diode area is 0.05 cm²?

3.46. A diode is operating at a current of 200 μA. (a) What is the diffusion capacitance if the diode transit time is 100 ps? (b) How much charge is stored in the diode? (c) Repeat for $i_D = 5$ mA.

3.47. A diode is operating at a current of 1 A. (a) What is the diffusion capacitance if the diode transit time is 10 ns? (b) How much charge is stored in the diode? (c) Repeat for $i_D = 100$ mA.

3.48. A square *pn* junction diode is 5 mm on a side. The *p*-type side has a doping concentration of $10^{19}/\text{cm}^3$ and the *n*-type side has a doping concentration of $10^{16}/\text{cm}^3$. What is the zero-bias capacitance of the diode? What is the capacitance at a reverse bias of 4 V?

3.49. A *pn* junction diode has a cross-sectional area of 10^4 μm^2. The *p*-type side has a doping concentration of $10^{19}/\text{cm}^3$ and the *n*-type side has a doping concentration of $10^{17}/\text{cm}^3$. What is the zero-bias capacitance of the diode? What is the capacitance at a reverse bias of 5 V?

3.50. A variable capacitance diode with $C_{jo} = 39$ pF and $\phi_j = 0.80$ V is used to tune a resonant LC circuit as shown in Fig. P3.50. The impedance of the RFC (radio frequency choke) can be considered infinite. What are the resonant frequencies ($f_o = \frac{1}{2\pi\sqrt{LC}}$) for $V_{DC} = 1$ V and $V_{DC} = 9$ V?

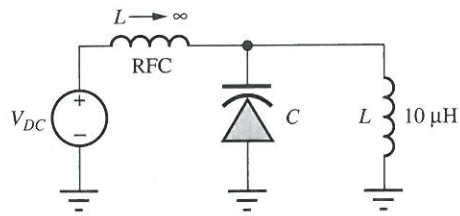


Figure P3.50

3.8 Schottky Barrier Diode

3.51. A Schottky barrier diode is modeled by the diode equation in Eq. (3.11) with $I_S = 10^{-11}$ A. (a) What is the diode voltage at a current of 4 mA? (b) What would be the voltage of a *pn* junction diode with $I_S = 10^{-14}$ A operating at the same current?

3.52. Suppose a Schottky barrier diode can be modeled by the diode equation in Eq. (3.11) with $I_S = 10^{-7}$ A. (a) What is the diode voltage at a current of 50 A? (b) What would be the voltage of a *pn* junction diode with $I_S = 10^{-15}$ A and $n = 2$?

3.9 Diode SPICE Model and Layout

3.53. (a) A diode has $I_S = 5 \times 10^{-16}$ A and $R_S = 10\ \Omega$ and is operating at a current of 1 mA at room temperature. What are the values of V_D and V_D'? (b) Repeat for $R_S = 100\ \Omega$.

3.54. A *pn* diode has a resistivity of 2 Ω · cm on the *p*-type side and 0.01 Ω · cm on the *n*-type side. What is the value of R_S for this diode if the cross-sectional area of the diode is 0.01 cm^2 and the lengths of the *p*- and *n*-sides of the diode are each 250 μm?

*3.55. A diode fabrication process has a specific contact resistance of 10 Ω · μm^2. If the contacts are each 1 μm × 1 μm in size, what are the total contact resistances associated with the anode and cathode contacts to the diode in Fig. 3.21(a).

3.56. (a) Estimate the area of the diode in Fig. 3.21(a) if the contact dimensions are 1 μm × 1 μm. (b) Repeat for 0.13 μm × 0.13 μm contacts.

3.10 Diode Circuit Analysis Load-Line Analysis

3.57. (a) Plot the load line and find the Q-point for the diode circuit in Fig. P3.57 if $V = 10$ V and $R = 5$ kΩ. Use the *i*-*v* characteristic in Fig. P3.42. (b) Repeat for $V = -10$ V and $R = 5$ kΩ. (c) Repeat for $V = -2$ V and $R = 2$ kΩ.

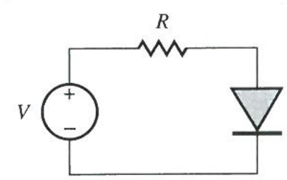


Figure P3.57

3.58. (a) Plot the load line and find the Q-point for the diode circuit in Fig. P3.57 if $V = 5$ V and $R = 10$ kΩ. Use the *i*-*v* characteristic in Fig. P3.42. (b) Repeat for $V = -6$ V and $R = 3$ kΩ. (c) Repeat for $V = -3$ V and $R = 3$ kΩ.

3.59. Simulate the circuit in Prob. 3.57 with SPICE and compare the results to those in Prob. 3.57. Use $I_S = 10^{-15}$ A.

3.60. Use the *i*-*v* characteristic in Fig. P3.42. (a) Plot the load line and find the Q-point for the diode circuit in Fig. P3.57 if $V = 6$ V and $R = 4$ kΩ. (b) For $V = -6$ V and $R = 3$ kΩ. (c) For $V = -3$ V and $R = 3$ kΩ. (d) For $V = 12$ V and $R = 8$ kΩ. (e) For $V = -25$ V and $R = 10$ kΩ.

3.61. (a) Plot the load line and find the Q-point for the diode circuit in Fig. P3.57 if $V = -10$ V and $R = 10$ kΩ. Use the *i*-*v* characteristic in Fig. P.3.42. (b) Repeat for $V = 10$ V and $R = 10$ kΩ. (c) Repeat for $V = -4$ V and $R = 2$ kΩ.

Iterative Analysis and the Mathematical Model

3.62. (a) Use direct trial and error to find the solution to the diode circuit in Fig. 3.22 using Eq. (3.27).

3.63. Repeat the iterative procedure used in the spreadsheet in Table 3.2 for initial guesses of 1 μA, 5 mA, and 5 A and 0 A. How many iterations are required for each case? Did any problem arise? If so, what is the source of the problem?

3.64. A diode has $I_S = 0.1$ fA and is operating at $T = 300$ K. (a) What are the values of V_{DO} and r_D if $I_D = 100$ μA? (b) If $I_D = 2.5$ mA? (c) If $I_D = 20$ mA?

3.65. (a) Use the iterative procedure in the spreadsheet in Table 3.2 to find the diode current and voltage for the circuit in Fig. 3.22 if $V = 7.5$ V and $R = 3$ kΩ. (b) Repeat for $V = 2.5$ V and $R = 15$ kΩ.

3.66. (a) Use the iterative procedure in the spreadsheet in Table 3.2 to find the diode current and voltage for the circuit in Fig. 3.22 if $V = 3$ V and $R = 15$ kΩ. (b) Repeat for $V = 1$ V and $R = 6.2$ kΩ.

3.67. Use MATLAB or MATHCAD to numerically find the Q-point for the circuit in Fig. 3.22 using the equation in the exercise on page 100.

Ideal Diode and Constant Voltage Drop Models

*3.68. Find the Q-point for the circuit in Fig. 3.22 using the same four methods as in Sec. 3.10 if the voltage source is 1 V. Compare the answers in a manner similar to Table 3.3.

3.69. Find the Q-point for the diode in Fig. P3.69 using (a) the ideal diode model and (b) the constant voltage drop model with $V_{on} = 0.6$ V. (c) Discuss the results. Which answer do you feel is most correct? (d) Use iterative analysis to find the actual Q-point if $I_S = 1$ fA.

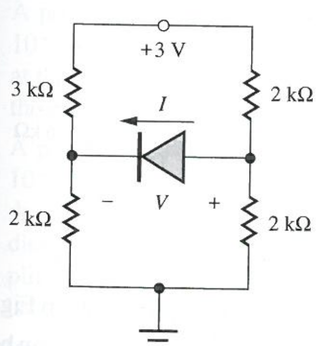


Figure P3.69

3.70. (a) Find the worst-case values of the Q-point current for the diode in Fig. P3.69 using the ideal diode model if the resistors all have 10 percent tolerances. (b) Repeat using the CVD model with $V_{on} = 0.6$ V.

3.71. Simulate the circuit of Fig. P3.69 and find the diode Q-point. Compare the results to those in Prob. 3.69.

3.72. (a) Find I and V in the four circuits in Fig. P3.72 using the ideal diode model. (b) Repeat using the constant voltage drop model with $V_{on} = 0.7$ V.

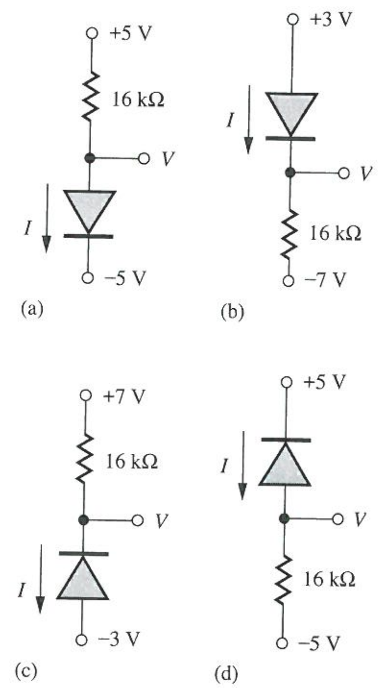


Figure P3.72

3.73. (a) Find I and V in the four circuits in Fig. P3.72 using the ideal diode model if the resistor values are changed to 100 kΩ. (b) Repeat using the constant voltage drop model with $V_{on} = 0.6$ V.

3.11 Multiple Diode Circuits

3.74. Find the Q-points for the diodes in the four circuits in Fig. P3.74 using (a) the ideal diode model and (b) the constant voltage drop model with $V_{on} = 0.65$ V.

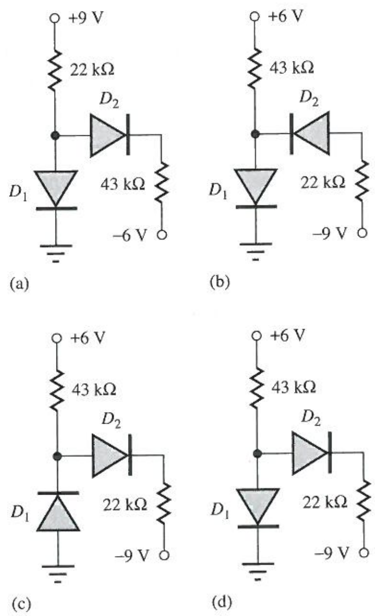
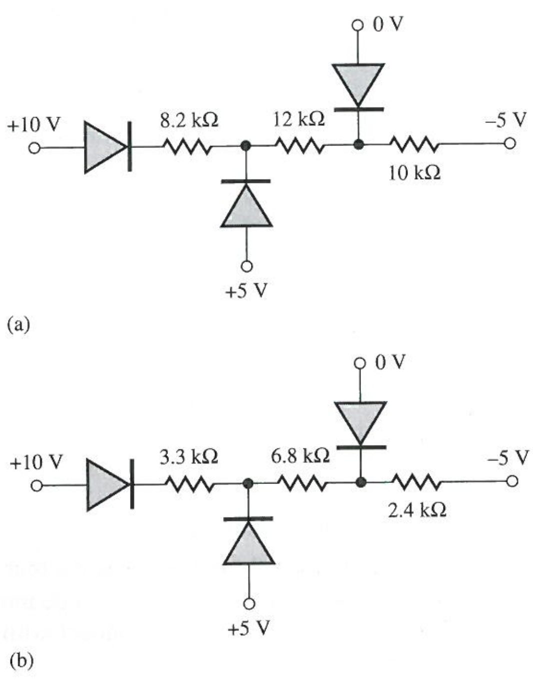


Figure P3.74

3.75. Find the Q-points for the diodes in the four circuits in Fig. P3.74 if the values of all the resistors are changed to 15 kΩ using (a) the ideal diode model and (b) the constant voltage drop model with $V_{on} = 0.65$ V.

3.76. Find the Q-point for the diodes in the circuits in Fig. P3.76 using the ideal diode model.



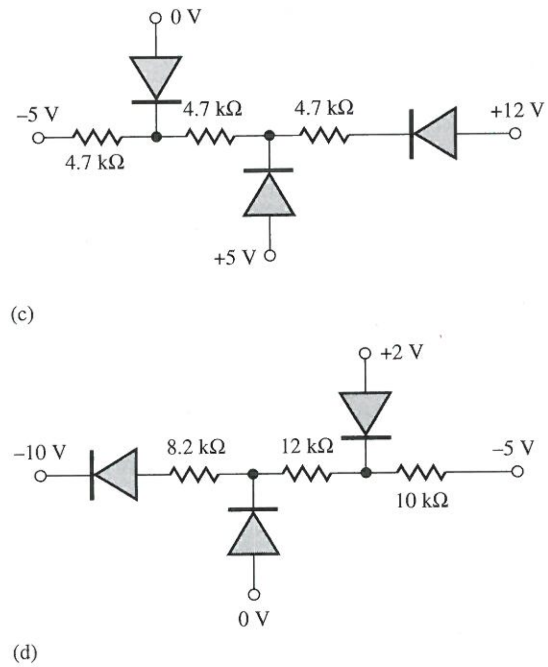


Figure P3.76

3.77. Find the Q-point for the diodes in the circuits in Fig. P3.76 using the constant voltage drop model with $V_{on} = 0.65$ V.

3.78. Simulate the diode circuits in Fig. P3.76 and compare your results to those in Prob. 3.76.

3.79. Verify that the values presented in Ex. 3.8 using the ideal diode model are correct.

3.80. Simulate the circuit in Fig. 3.33 and compare to the results in Ex. 3.8.

3.12 Analysis of Diodes Operating in the Breakdown Region

3.81. Draw the load line for the circuit in Fig. P3.81 on the characteristics in Fig. P3.42 and find the Q-point.

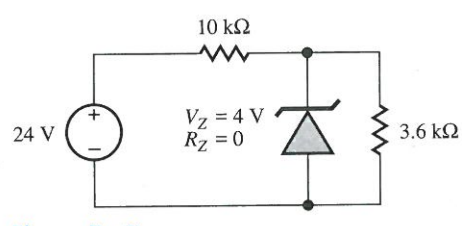


Figure P3.81

3.82. Find the Q-point for the Zener diode in Fig. P3.81.

3.83. What is maximum load current I_L that can be drawn from the Zener regulator in Fig. P3.83 if it is to maintain a regulated output? What is the minimum value of R_L that can be used and still have a regulated output voltage?

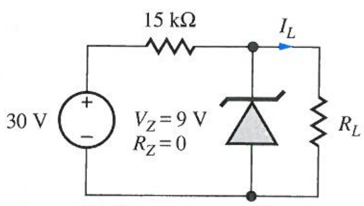


Figure P3.83

3.84. What is power dissipation in the Zener diode in Fig. P3.83 for $R_L = \infty$?

3.85. Load resistor R_L in Fig. P3.83 is 10 kΩ. What are the nominal and worst-case values of Zener diode current and power dissipation if the power supply voltage, Zener breakdown voltage and resistors all have 5 percent tolerances?

3.86. What is power dissipation in the Zener diode in Fig. P3.86 for (a) $R_L = 100\ \Omega$? (b) $R_L = \infty$?

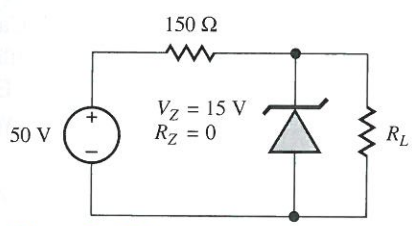


Figure P3.86

3.87. Load resistor R_L in Fig. P3.86 is 100 Ω. What are the nominal and worst-case values of Zener diode current and power dissipation if the power supply voltage, Zener breakdown voltage, and resistors all have 10 percent tolerances?

3.13 Half-Wave Rectifier Circuits

3.88. A power diode has a reverse saturation current of 10^{-9} A and $n = 2$. What is the forward voltage drop at the peak current of 48.6 A that was calculated in the example in Sec. 3.13.5?

3.89. A power diode has a reverse saturation current of 10^{-8} A and $n = 1.6$. What is the forward voltage drop at the peak current of 100 A? What is the power dissipation in the diode in a half-wave rectifier application operating at 60 Hz if the series resistance is 0.01 Ω and the conduction time is 1 ms?

*3.90. (a) Use a spreadsheet or MATLAB or write a computer program to find the numeric solution to the conduction angle equation for a 60 Hz half-wave rectifier circuit that uses a filter capacitance of 100,000 μF. The circuit is designed to provide 5 V at 5 A. {That is, solve $[(V_P - V_{on})\exp(-t/RC) = V_P \cos\omega t - V_{on}]$. Be careful! There are an infinite number of solutions to this equation. Be sure your algorithm finds the desired answer to the problem.} Assume $V_{on} = 1$ V. (b) Compare to calculations using Eq. (3.57).

3.91. What is the actual average value (the dc value) of the rectifier output voltage for the waveform in Fig. P3.91 if V_r is 5 percent of $V_P - V_{on} = 18$ V?

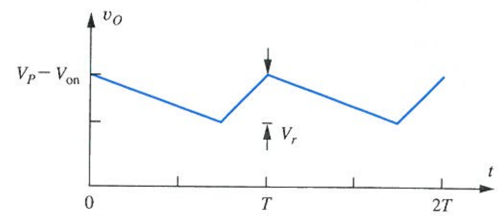


Figure P3.91

3.92. Draw the voltage waveforms, similar to those in Fig. 3.53, for the negative output rectifier in Fig. 3.57(b).

*3.93. Show that evaluation of Eq. (3.61) will yield the result in Eq. (3.62).

3.94. The half-wave rectifier in Fig. P3.94 is operating at a frequency of 60 Hz, and the rms value of the transformer output voltage v_I is 12.6 V ± 10%. What are the nominal and worst case values of the dc output voltage V_O if the diode voltage drop is 1 V?

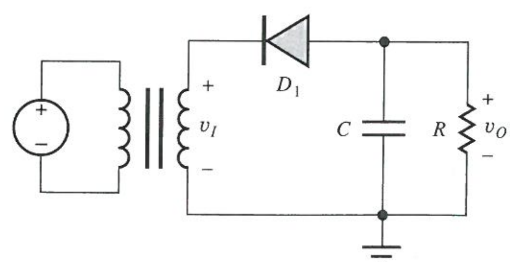


Figure P3.94

3.95. The half-wave rectifier in Fig. P3.94 is operating at a frequency of 60 Hz, and the rms value of the transformer output voltage is 6.3 V. (a) What is the value of the dc output voltage V_O if the diode voltage drop is 1 V? (b) What is the minimum value of C required to maintain the ripple voltage to less than 0.25 V if $R = 0.5\ \Omega$? (c) What is the PIV rating of the diode in this circuit? (d) What is the surge current when power is first applied? (e) What is the amplitude of the repetitive current in the diode?

3.96. Simulate the behavior of the half-wave rectifier in Fig. P3.94 for $v_I = 10\sin 120\pi t$, $R = 0.025\ \Omega$ and $C = 0.5$ F. (Use IS $= 10^{-10}$ A, RS $= 0$, and RELTOL $= 10^{-6}$.) Compare the simulated values of dc output voltage, ripple voltage, and peak diode current to hand calculations. Repeat simulation with $R_S = 0.02\ \Omega$.

3.97. (a) Repeat Prob. 3.95 for a frequency of 400 Hz. (b) Repeat Prob. 3.95 for a frequency of 70 kHz.

3.98. For the Zener regulated power supply in Fig. P3.98, the rms value of v_I is 15 V, the operating frequency is 60 Hz, $R = 100\ \Omega$, $C = 1000\ \mu$F, the on-voltage of diodes D_1 and D_2 is 0.75 V, and the Zener voltage of diode D_3 is 15 V. (a) What type of rectifier is used in this power supply circuit? (b) What is the dc voltage at V_1? (c) What is the dc output voltage V_O? (d) What is the magnitude of the ripple voltage at V_1? (e) What is the minimum PIV rating for the rectifier diodes? (f) Draw a new version of the circuit that will produce an output voltage of -15 V.

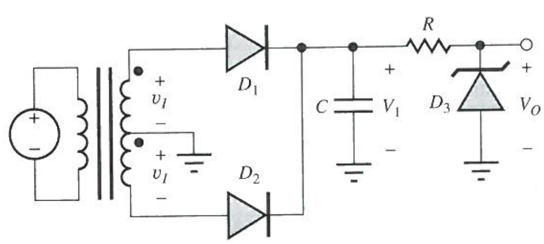


Figure P3.98

3.99. A 3.3-V, 30-A dc power supply is to be designed with a ripple of less than 2.5 percent. Assume that a half-wave rectifier circuit (60 Hz) with a capacitor filter is used. (a) What is the size of the filter capacitor C? (b) What is the PIV rating for the diode? (c) What is the rms value of the transformer voltage needed for the rectifier? (d) What is the value of the peak repetitive diode current in the diode? (e) What is the surge current at $t = 0^+$?

3.100. A 2800-V, 2-A, dc power supply is to be designed with a ripple voltage ≤ 0.5 percent. Assume that a half-wave rectifier circuit (60 Hz) with a capacitor filter is used. (a) What is the size of the filter capacitor C? (b) What is the minimum PIV rating for the diode? (c) What is the rms value of the transformer voltage needed for the rectifier? (d) What is the peak value of the repetitive current in the diode? (e) What is the surge current at $t = 0^+$?

*3.101. Draw the voltage waveforms at nodes v_O and v_1 for the "voltage-doubler" circuit in Fig. P3.101 for the first two cycles of the input sine wave. What is the steady-state output voltage if $V_P = 17$ V?

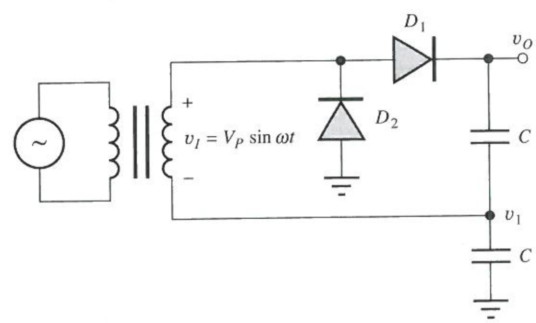


Figure P3.101

3.102. Simulate the voltage-doubler rectifier circuit in Fig. P3.101 for $C = 500\ \mu$F and $v_I = 1500\sin 2\pi(60)t$ with a load resistance of $R_L = 3000\ \Omega$ added between v_O and ground. Calculate the ripple voltage and compare to the simulation.

3.103. Simulate the AM demodulator in the EIA on page 122. Compare the spectra of the voltages across the two capacitors.

3.14 Full-Wave Rectifier Circuits

3.104. The full-wave rectifier in Fig. P3.104 is operating at a frequency of 60 Hz, and the rms value of the transformer output voltage is 18 V. (a) What is the value of the dc output voltage if the diode voltage drop is 1 V? (b) What is the minimum value of C required to maintain the ripple voltage to less than 0.25 V if $R = 0.5\ \Omega$? (c) What is the PIV rating of the diode in this circuit? (d) What is the surge current when power is first applied? (e) What is the amplitude of the repetitive current in the diode?

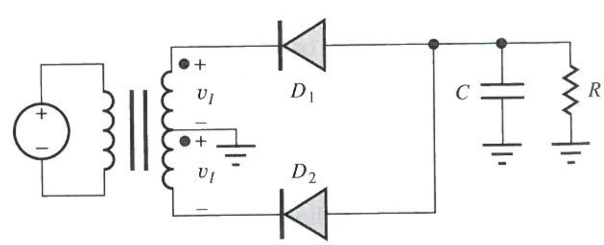


Figure P3.104

3.105. Repeat Prob. 3.104 if the rms value of the transformer output voltage v_I is 10 V.

3.106. Simulate the behavior of the full-wave rectifier in Fig. P3.104 for $R = 3\ \Omega$ and $C = 22{,}000\ \mu\text{F}$. Assume that the rms value of v_I is 10.0 V and the frequency is 400 Hz. (Use IS $= 10^{-10}$ A, RS $= 0$, and RELTOL $= 10^{-6}$.) Compare the simulated values of dc output voltage, ripple voltage, and peak diode current to hand calculations. Repeat simulation with $R_S = 0.25$.

3.107. Repeat Prob. 3.99 for a full-wave rectifier circuit.

3.108. Repeat Prob. 3.100 for a full-wave rectifier circuit.

*3.109. The full-wave rectifier circuit in Fig. P3.109(a) was designed to have a maximum ripple of approximately 1 V, but it is not operating properly. The measured waveforms at the three nodes in the circuit are shown in Fig. P3.109(b). What is wrong with the circuit?

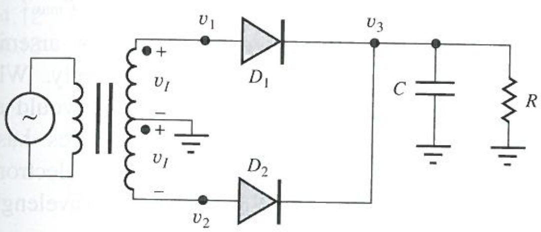


Figure P3.109(a)

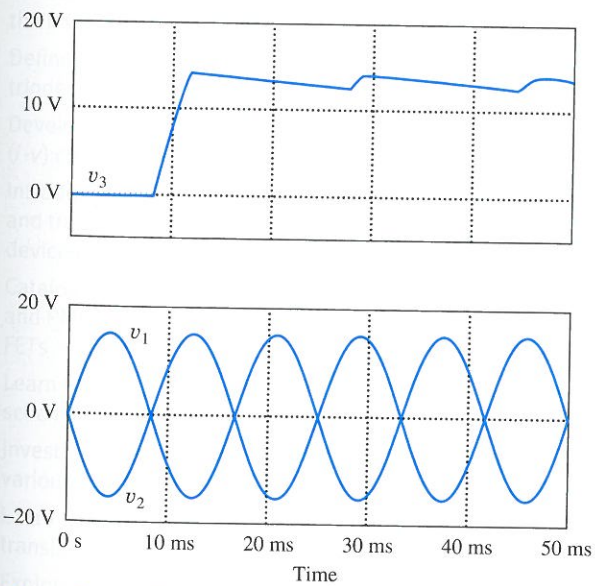


Figure P3.109(b) Waveforms for the circuit in Fig. P3.109(a).

3.15 Full-Wave Bridge Rectification

3.110. Repeat Prob. 3.104 for a full-wave bridge rectifier circuit. Draw the circuit.

3.111. Repeat Prob. 3.99 for a full-wave bridge rectifier circuit. Draw the circuit.

3.112. Repeat Prob. 3.100 for a full-wave bridge rectifier circuit. Draw the circuit.

*3.113. What are the dc output voltages V_1 and V_2 for the rectifier circuit in Fig. P3.113 if $v_I = 40 \sin 377t$ and $C = 20{,}000\ \mu\text{F}$?

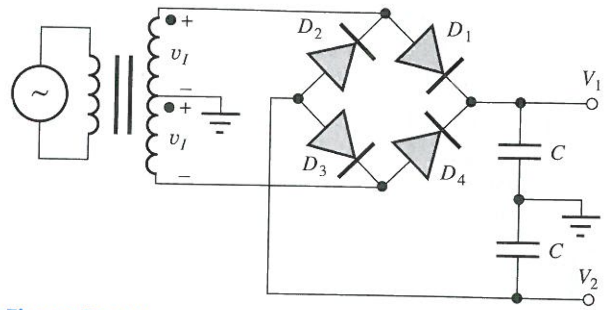


Figure P3.113

3.114. Simulate the rectifier circuit in Fig. P3.113 for $C = 100$ mF and $v_I = 40 \sin 2\pi(60)t$ with a 500-Ω load connected between each output and ground.

3.115. Repeat Prob. 3.104 if the full-wave bridge circuit is used instead of the rectifier in Fig. P3.104. Draw the circuit!

3.16 Rectifier Comparison and Design Tradeoffs

3.116. A 3.3-V, 15-A dc power supply is to be designed to have a ripple voltage of no more the 10 mV. Compare the pros and cons of implementating this power supply with half-wave, full-wave, and full-wave bridge rectifiers.

3.117. A 200-V, 3-A dc power supply is to be designed with less than a 2 percent ripple voltage. Compare the pros and cons of implementing this power supply with half-wave, full-wave, and full-wave bridge rectifiers.

3.118. A 3000-V, 1-A dc power supply is to be designed with less than a 4 percent ripple voltage. Compare the pros and cons of implementing this power supply with half-wave, full-wave, and full-wave bridge rectifiers.

3.17 Dynamic Switching Behavior of the Diode

*3.119. (a) Calculate the current at $t = 0^+$ in the circuit in Fig. P3.119. (b) Calculate I_F, I_R, and the storage time expected when the diode is switched off if $\tau_T = 7$ ns.

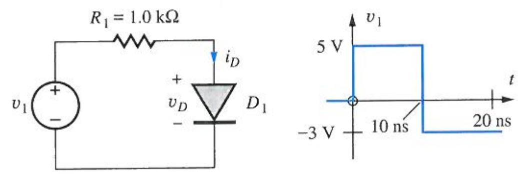


Figure P3.119

3.120. (a) Simulate the switching behavior of the circuit in Fig. P3.119. (b) Compare the simulation results to the hand calculations in Prob. 3.119.

*3.121. (a) Calculate the current at $t = 0^+$ in the circuit in Fig. P3.119 if R_1 is changed to 5 Ω. (b) Calculate I_F, I_R, and the storage time expected when the diode is switched off at $t = 10\ \mu s$ if $\tau_T = 250$ nS.

**3.122. The simulation results presented in Fig. 3.68 were performed with the diode transit time $\tau_T = 5$ ns. (a) Repeat the simulation of the diode circuit in Fig. 3.122(a) with the diode transit time changed to $\tau_T = 50$ ns. Does the storage time that you observe change in proportion to the value of τ_T in your simulation? Discuss. (b) Repeat the simulation with the input voltage changed to the one in Fig. P3.122(b), in which it is assumed that v_I has been at 1.5 V for a long time, and compare the results to those obtained in (a). What is the reason for the difference between the results in (a) and (b)?

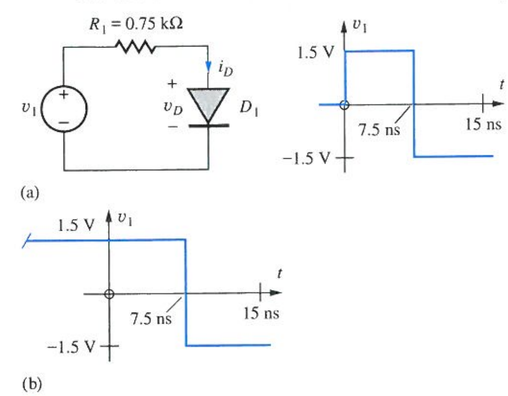


Figure 3.122

3.18 Photo Diodes, Solar Cells, and LEDs

*3.123. The output of a diode used as a solar cell is given by

$$I_C = 1 - 10^{-15}[\exp(40V_C) - 1] \text{ amperes}$$

What operating point corresponds to P_{max}? What is P_{max}? What are the values of I_{SC} and V_{OC}?

*3.124. Three diodes are connected in series to increase the output voltage of a solar cell. The individual outputs of the three diodes are given by

$$I_{C1} = 1.05 - 10^{-15}[\exp(40V_{C1}) - 1] \text{ A}$$
$$I_{C2} = 1.00 - 10^{-15}[\exp(40V_{C2}) - 1] \text{ A}$$
$$I_{C3} = 0.95 - 10^{-15}[\exp(40V_{C3}) - 1] \text{ A}$$

(a) What are the values of I_{SC} and V_{OC} for the series connected cell? (b) What is the value of P_{max}?

**3.125. The bandgaps of silicon and gallium arsenide are 1.12 eV and 1.42 eV, respectively. What are the wavelengths of light that you would expect to be emitted from these devices based on direct recombination of holes and electrons? To what "colors" of light do these wavelengths correspond?

**3.126. Repeat Prob. 3.125 for Ge, GaN, InP, InAs, BN, SiC and CdSe.