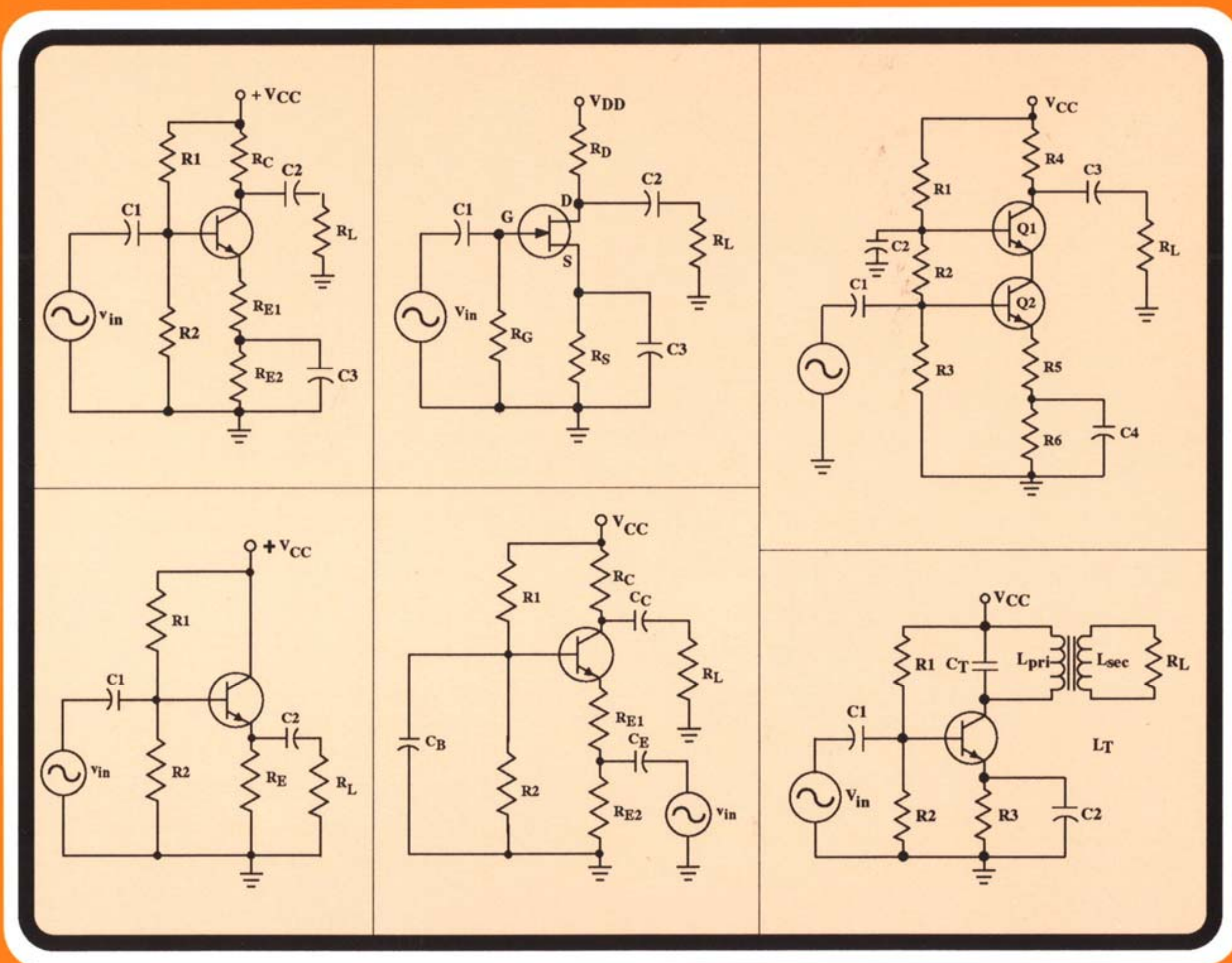
BASIC SOLID STATE ELECTRONIC CIRCUIT ANALYSIS

Through Experimentation

Fourth Edition



Lorne MacDonald

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Preface

BASIC SOLID STATE ELECTRONIC CIRCUIT ANALYSIS THROUGH EXPERIMENTATION has been totally rewritten. The result is a book with better continuity and a more logical topic development than the previous editions. It is easier to read and understand.

The book begins with a review of dc and ac circuits and then introduces solid state diodes. Following the chapter on general purpose diodes, a chapter is devoted to special purpose diodes such as zeners, LEDs, varactors, and Schottkys. The next two chapters are used for an introduction to bipolar transistors and an extensive coverage of biasing. The biasing chapter coverage includes base-biasing, collector-feedback biasing, universal biasing, and two-power-supply biasing.

Common-emitter, single-stage, amplifier circuits are covered in Chapter 6 and common-collector and common-base, single-stage amplifier circuits are covered in Chapter 7. These chapters have been rewritten to include both the approximation and the signal process methods of analysis using graphic techniques and equivalent circuits.

The field effect transistor portion of the book is also totally rewritten. The JFET circuits are analyzed both mathematically and graphically for better accuracy. The ac is solved by using transconductance and (much like bipolar transistor analysis) by using r_s. The straight forward chapters on frequency response and tuned circuit are followed by a chapter on direct-coupled, two-stage cascade and cascode amplifier circuits.

In the power supply chapter bulk supplies are introduced and developed in complexity from the half-wave supply through a series pass regulator with short circuit protection. The last two chapters deal with thyristor switches and latches and semiconductor switching. The thyristor chapter begins with a simple SPST switch and ends with a discussion of a diac-triac phase controller. The switching chapter contains an analysis of TTL and CMOS inverters, NAND gates and NOR gates at the discrete component level.

The theory in the book is complete for the introductory circuit course and the circuit analysis techniques developed for the theory are used in the laboratory exercises. The student analyzes and measures the significant circuit parameters. Since the circuits all work, the measured values will be close to the calculated values. The problems would be miscalculations, poor measurement methods, or incorrectly constructed circuits. The laboratory exercise were written so that they can be used in a standard hardware laboratory or on the computer using simulation programs such as Electronics Workbench® or Micro-Cap.

A debt of gratitude is owed to the hundreds of students who, through feedback and constructive criticism, have helped develop this book to its present form. I am especially indebted to my colleagues John Fitzen of Idaho State University, Wayne Linke of Regency College (Australia), Emile Gaudet and Patrick Mulldoon of British Columbia Institute of Technology, Leon Lucchesi of Truckee Meadows Community College, Jim MacDonald, Ken Manders, Ted Kirsch and Roy Brixen of College of San Mateo, and Steven Boderck and Mark Barrow of Avnet Corporation. Especially, I would like to acknowledge my wife Annette who provided encouragement and typed the manuscript.

Lorne MacDonald
2000

Electronic Circuit Analysis Textbooks
By
Lorne MacDonald

BASIC CIRCUIT ANALYSIS FOR ELECTRONICS
Through Experimentation - 3rd Edition
Lorne MacDonald

BASIC CIRCUIT ANALYSIS FOR ELECTRONICS
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PRACTICAL ANALYSIS OF ADVANCED ELECTRONIC CIRCUITS
Through Experimentation - 2nd Edition
Lorne MacDonald

Contents

CHAPTER 1

DIRECT CURRENT AND ALTERNATING CURRENT CIRCUIT ANALYSIS: A REVIEW

GENERAL DISCUSSION

Basic circuit analysis techniques learned during the study of direct and alternating current circuits are very important in studying active devices in working circuits. They are used again and again. In this chapter, several of these techniques are reviewed.

SECTION I: DIRECT CURRENT CIRCUIT ANALYSIS

Ohm's law and common sense are the basic tools used in analyzing the simplest to the most complex electric circuit. Additionally, Kirchoff's loop equations, the voltage divider equation, and Thevenin's theorem can provide mathematical short cuts, or exactness, where required.

SERIES RESISTORS AND VOLTAGE DIVIDER EQUATION CIRCUIT ANALYSIS

The standard approach for solving voltage drops across two resistors in series is to add the total resistance of the two resistors and divide the applied voltage by the total resistance to solve the circuit current. Then the individual voltage drop across each resistor is solved by multiplying the circuit current by the individual resistor values, as shown in conjunction with the circuit of Figure 1-1.

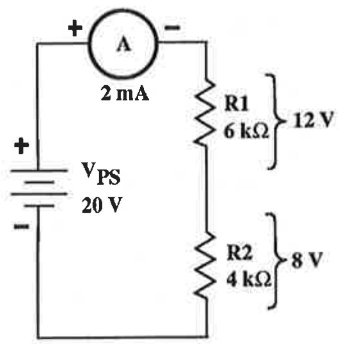


FIGURE 1-1

$$I = \frac{V_{PS}}{R_T} = \frac{V_{PS}}{R1 + R2} = \frac{20\ \text{V}}{6\ \text{k}\Omega + 4\ \text{k}\Omega} = 2\ \text{mA}$$

$$V_{R1} = IR_1 = 2\ \text{mA} \times 6\ \text{k}\Omega = 12\ \text{V}$$

$$V_{R2} = IR_2 = 2\ \text{mA} \times 4\ \text{k}\Omega = 8\ \text{V}$$

$$V_{PS} = V_{R1} + V_{R2} = 12\ \text{V} + 8\ \text{V} = 20\ \text{V}$$

The voltage divider equation is used to solve the voltage drops across series resistors directly, without having to solve for the circuit current. The circuit current I is substituted in the equation for V_{PS}/R_T where: $I = V_{PS}/R_T = V_{PS}/(R1 + R2)$. Therefore:

$$V_{R1} = IR_1 = \frac{V_{PS}}{R_T} \times R1 = \frac{V_{PS} \times R1}{R1 + R2} = \frac{20\ \text{V} \times 6\ \text{k}\Omega}{6\ \text{k}\Omega + 4\ \text{k}\Omega} = \frac{20\ \text{V} \times 6\ \text{k}\Omega}{10\ \text{k}\Omega} = 12\ \text{V}$$

$$V_{R2} = \frac{V_{PS} \times R2}{R1 + R2} = \frac{20\ \text{V} \times 4\ \text{k}\Omega}{6\ \text{k}\Omega + 4\ \text{k}\Omega} = \frac{20\ \text{V} \times 4\ \text{k}\Omega}{10\ \text{k}\Omega} = 8\ \text{V}$$

PARALLEL RESISTOR CIRCUIT ANALYSIS

The total resistance of a parallel combination of two resistors can be solved from:

$$R_T = R1 \parallel R2 = \frac{R1 \times R2}{R1 + R2} \qquad \text{or} \qquad R_T = \frac{1}{1/R1 + 1/R2}$$

If more than two resistors are connected in parallel, the latter equation requires the fewer steps. Also, if the applied voltage is known, further simplification can be made by totaling the current flow in each resistive branch and dividing by the applied voltage.

1. The total resistance of two resistors in parallel can be solved from:

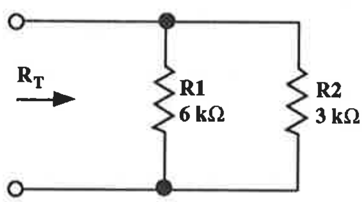


FIGURE 1-2

$$R_T = R1 \parallel R2 = \frac{R1 \times R2}{R1 + R2} = \frac{6\text{ k}\Omega \times 3\text{ k}\Omega}{6\text{ k}\Omega + 3\text{ k}\Omega} = \frac{18\text{ M}\Omega}{9\text{ k}\Omega} = 2\text{ k}\Omega$$

$$R_T = \frac{1}{1/R1 + 1/R2} = \frac{1}{1/6\text{ k}\Omega + 1/3\text{ k}\Omega}$$

$$= \frac{1\,\Omega}{(1.67 \times 10^{-4}) + (3.33 \times 10^{-4})} = \frac{1\,\Omega}{5 \times 10^{-4}}$$

$$= \frac{10^4\,\Omega}{5} = \frac{10 \times 10^3\,\Omega}{5} = 2\text{ k}\Omega$$

2. Total resistance of two resistors in parallel with 6 V of applied voltage is solved from:

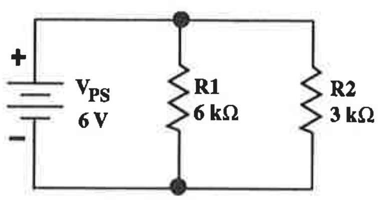


FIGURE 1-3

$$I_{R1} = V_{PS}/R1 = 6\text{ V}/6\text{ k}\Omega = 1\text{ mA}$$

$$I_{R2} = V_{PS}/R2 = 6\text{ V}/3\text{ k}\Omega = 2\text{ mA}$$

$$I_T = I_{R1} + I_{R2} = 1\text{ mA} + 2\text{ mA} = 3\text{ mA}$$

$$R_T = V_{PS}/I_T = 6\text{ V}/3\text{ mA} = 2\text{ k}\Omega$$

3. Total resistance of three resistor in parallel is solved from:

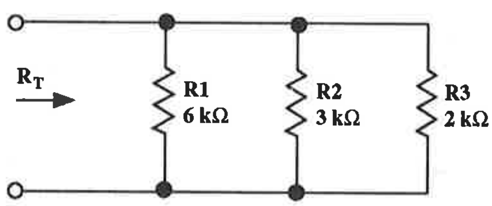


FIGURE 1-4

$$R_T = \frac{1}{1/R1 + 1/R2 + 1/R3} = \frac{1}{1/6\text{ k}\Omega + 1/3\text{ k}\Omega + 1/2\text{ k}\Omega}$$

$$= \frac{1\,\Omega}{(1.67 \times 10^{-4}) + (3.33 \times 10^{-4}) + (5 \times 10^{-4})}$$

$$= \frac{1\,\Omega}{10 \times 10^{-4}} = \frac{1\,\Omega}{10^{-3}} = 1\,\Omega \times 10^3 = 1\text{ k}\Omega$$

4. Total resistance of three resistors in parallel with 6 V of applied voltage is solved from:

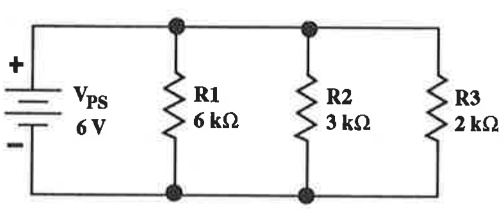


FIGURE 1-5

$$I_{R1} = V_{PS}/R1 = 6\text{ V}/6\text{ k}\Omega = 1\text{ mA}$$

$$I_{R2} = V_{PS}/R2 = 6\text{ V}/3\text{ k}\Omega = 2\text{ mA}$$

$$I_{R3} = V_{PS}/R3 = 6\text{ V}/2\text{ k}\Omega = 3\text{ mA}$$

$$I_T = I_{R1} + I_{R2} + I_{R3} = 1\text{ mA} + 2\text{ mA} + 3\text{ mA} = 6\text{ mA}$$

$$R_T = V_{PS}/I_T = 6\text{ V}/6\text{ mA} = 6\text{ V}/(6 \times 10^{-3}\text{ A}) = 1\text{ k}\Omega$$

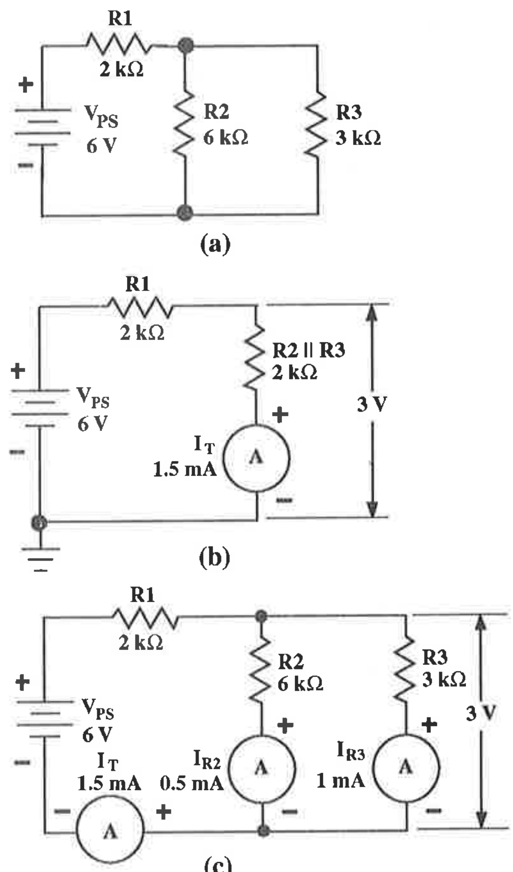
SERIES-PARALLEL RESISTOR CIRCUIT ANALYSIS

Several methods can be used to solve the voltage drops around a series-parallel circuit. If the circuit has only one voltage source, it can be solved by the methods used in the previous examples, or it can be solved using loop equations, nodal equations, or Thevenin's equivalent theorem. In addition, lessor used techniques such as Norton's theorem or the superpostion theorem can be used successfully.

In this section, a single voltage source circuit will be analyzed using Ohm's law, loop equations, nodal equations, and Thevenin's equivalent theorem. Each method of analysis will be used on the same circuit so a comparison can be made.

Ohm's Law Analysis

Ohm's law analysis for the circuit of Figure 1-6 begins by solving for the parallel resistance of R2 and R3. The R2 || R3 value is added to R1 to find R_T. Then, $I_T = V_{PS}/R_T$ is solved enabling the voltage drop across R1 and the voltage drop across the parallel resistors R2 and R3 to be solved. Then, the currents through the R1, R2, and R3 resistors are solved. These steps are shown in conjunctions with the circuit of Figure 1-6.



$$R2 \parallel R3 = \frac{R2 \times R3}{R2 + R3} = \frac{6\ k\Omega \times 3\ k\Omega}{6\ k\Omega + 3\ k\Omega} = 2\ k\Omega$$

$$R_T = R1 + (R2 \parallel R3) = 2\ k\Omega + 2\ k\Omega = 4\ k\Omega$$

$$I_T = V_{PS}/R_T = 6\ V/4\ k\Omega = 1.5\ mA$$

$$V_{R1} = I_T \times R1 = 1.5\ mA \times 2\ k\Omega = 3\ V$$

$$V_{(R2 \parallel R3)} = I_T \times (R2 \parallel R3) = 1.5\ mA \times 2\ k\Omega = 3\ V$$

$$V_{R2} = V_{R3} = 3\ V$$

$$I_{R2} = V_{R2}/R2 = 3\ V/6\ k\Omega = 0.5\ mA$$

$$I_{R3} = V_{R3}/R3 = 3\ V/3\ k\Omega = 1\ mA$$

$$I_{R1} = I_T = I_{R2} + I_{R3} = 0.5\ mA + 1\ mA = 1.5\ mA$$

FIGURE 1-6

Loop Equations Analysis

Loop equations are based on Kirchoff's firsts law which states the sum of the voltage drops around a circuit loop is equal to the applied voltage. They are the most mechanized of the circuit analysis techniques. They can be used on the simplest to the most complex circuit and the structure of the equation does not change when the number of voltage sources is increased. The current flow through each branch, or loop, of the circuit can be solved using either simultaneous equations or determinants.

When solving complex circuits using loop equations it is necessary to follow some basic rules. For example, to solve a two loop circuit such as that of Figure 1-7, it is essential that each I_1 and I_2 mesh circuit be calculated within its own loop and the equations be consistent with the direction of the currents. Also, since there are two equations and two unknowns, the equations are solved using simultaneous equations.

NOTE: It is necessary to designate a current direction to solve loop equations. Since conventional current flow (current flows from the positive to the negative terminals of the voltage source) is used in solid state circuit analysis, that convention will be used in this book. So, in solving the following loop equations, it is assumed that the current in the circuit of Figure 1-7 flows from the positive to the negative terminal of the voltage source.

For the circuit of Figure 1-7, start the loop equations by writing the effective voltage drops around the first loop, where the effect of the 6 V voltage source causes I_1 and I_2 to oppose each other. Therefore:

$$V_{PS} = I_1R_1 + (I_1 - I_2)R_2 = I_1R_1 + I_1R_2 - I_2R_2 = I_1(R_1 + R_2) - I_2R_2$$

While there is no voltage source in the second loop, the I_2 current does cause a voltage drop across the R2 and R3 resistors and, again, since I_1 and I_2 are in opposition, the equation reads:

$$0\text{ V} = I_2R_3 + (I_2 - I_1)R_2 = I_2R_3 + I_2R_2 - I_1R_2 = I_2(R_2 + R_3) - I_1R_2$$

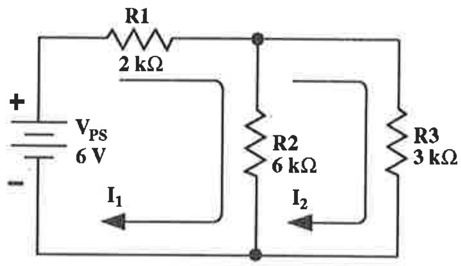


FIGURE 1-7

$$V_{PS} = I_1(R_1 + R_2) - I_2R_2$$
$$0\text{ V} = -I_1R_2 + I_2(R_2 + R_3)$$

$$6\text{ V} = I_1(2\text{ k}\Omega + 6\text{ k}\Omega) - (I_2 \times 6\text{ k}\Omega)$$
$$0\text{ V} = -(I_1 \times 6\text{ k}\Omega) + I_2(6\text{ k}\Omega + 3\text{ k}\Omega)$$

$$6\text{ V} = (I_1 \times 8\text{k}\Omega) - (I_2 \times 6\text{ k}\Omega)$$
$$0\text{ V} = -(I_1 \times 6\text{ k}\Omega) + (I_2 \times 9\text{ k}\Omega)$$

In using simultaneous equations, I_1 is solved by using multiplication and addition to make I_2 drops out of the equation. Thus:

$6\text{ V} = +(I_1 \times 8\text{ k}\Omega) - (I_2 \times 6\text{ k}\Omega)$ multiply by 3: $18\text{ V} = +(I_1 \times 24\text{ k}\Omega) - (I_2 \times 18\text{ k}\Omega)$

$0\text{ V} = -(I_1 \times 6\text{ k}\Omega) + (I_2 \times 9\text{ k}\Omega)$ multilply by 2: $0\text{ V} = -(I_1 \times 12\text{ k}\Omega) + (I_2 \times 18\text{ k}\Omega)$

$$18\text{ V} = I_1 \times 12\text{ k}\Omega$$
$$I_1 = 18\text{ V}/12\text{ k}\Omega = 1.5\text{ mA}$$

Then I_1 is substituted into either equation to solve for I_2.

$$6\text{ V} = (I_1 \times 8\text{ k}\Omega) - (I_2 \times 6\text{ k}\Omega)$$
$$6\text{ V} = (1.5\text{ mA} \times 8\text{ k}\Omega) - (I_2 \times 6\text{ k}\Omega)$$
$$6\text{ V} = 12\text{ V} - (I_2 \times 6\text{ k}\Omega)$$
$$6\text{ V} - 12\text{ V} = -(I_2 \times 6\text{ k}\Omega)$$
$$-6\text{ V} = -(I_2 \times 6\text{ k}\Omega)$$
$$I_2 = 6\text{ V}/6\text{ k}\Omega = 1\text{ mA}$$

$$0\text{ V} = -(I_1 \times 6\text{ k}\Omega) + (I_2 \times 9\text{ k}\Omega)$$
$$0\text{ V} = -(1.5\text{ mA} \times 6\text{ k}\Omega) + (I_2 \times 9\text{ k}\Omega)$$
$$0\text{ V} = -9\text{ V} + (I_2 \times 9\text{ k}\Omega)$$
$$9\text{ V} = I_2 \times 9\text{ k}\Omega$$
$$I_2 = 9\text{ V}/9\text{ k}\Omega = 1\text{ mA}$$

Therefore, since $I_1 = 1.5$ mA and $I_2 = 1$ mA, the voltage drops across the resistors are:

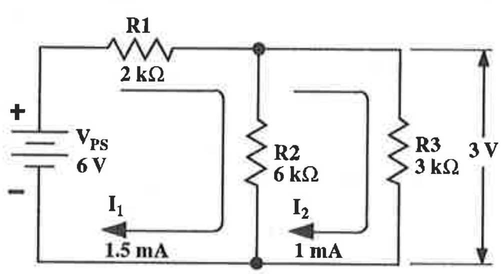


FIGURE 1-8

$$V_{R1} = I_1R_1 = 1.5\text{ mA} \times 2\text{ k}\Omega = 3\text{ V}$$
$$V_{R3} = I_2R_3 = 1\text{ mA x } 3\text{ k}\Omega = 3\text{ V}$$
$$V_{R2} = (I_1 - I_2)R2 = (1.5\text{ mA} - 1\text{ mA})6\text{ k}\Omega$$
$$= 0.5\text{ mA} \times 6\text{ k}\Omega = 3\text{ V}$$

Nodal Equation Analysis

Nodal equation analysis is based on Kirchoffs second law that states the currents into a circuit node are equal to currents out of the node. Thus, in the circuit of Figure 1-9, V_A is the node and $I_{R1} + I_{R2} + I_{R3} = 0$.

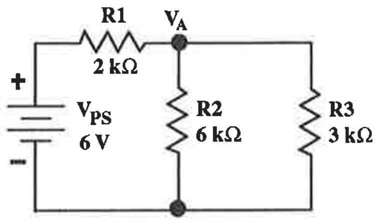


FIGURE 1-9

$$I_{R1} + I_{R2} + I_{R3} = 0$$

$$\frac{V_A - V_{PS}}{R1} + \frac{V_A}{R2} + \frac{V_A}{R3} = 0$$

$$\frac{V_A - 6\text{ V}}{2\text{ k}\Omega} + \frac{V_A}{6\text{ k}\Omega} + \frac{V_A}{3\text{ k}\Omega} = 0$$

$$\frac{V_A}{2\text{ k}\Omega} - \frac{6\text{ V}}{2\text{ k}\Omega} + \frac{V_A}{6\text{ k}\Omega} + \frac{V_A}{3\text{ k}\Omega} \Rightarrow V_A\left(\frac{1}{2\text{ k}\Omega} + \frac{1}{6\text{ k}\Omega} + \frac{1}{3\text{ k}\Omega}\right) = \frac{6\text{ V}}{2\text{ k}\Omega}$$

The equation is then multiplied by 6 kΩ to get rid of the denominator and algebra is used to solve V_A. Thus:

$$V_A\left(\frac{1}{2\text{ k}\Omega} + \frac{1}{6\text{ k}\Omega} + \frac{1}{3\text{ k}\Omega}\right) = \frac{6\text{ V}}{2\text{ k}\Omega}\ (\times 6\text{ k}\Omega) \Rightarrow V_A(3 + 1 + 2) = 18\text{ V}$$

$$V_A\,(6) = 18\text{ V} \Rightarrow V_A = 18\text{ V}/6 = 3\text{ V}$$

Once V_A is know, V_{R1} is solved along with I_{R1}. Then, since $V_A = V_{R2} = V_{R3}$, I_{R2} and I_{R3} are easily solved as shown by the equations in conjuntion with Figure 1-10.

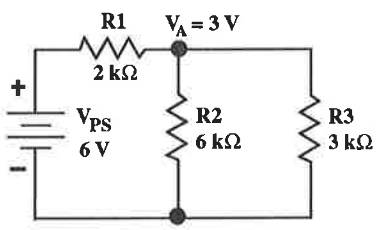


FIGURE 1-10

$$V_{R1} = V_{PS} - V_A = 6\text{ V} - 3\text{ V} = 3\text{ V}$$

$$V_{R2} = V_{R3} = V_A = 3\text{ V}$$

$$I_{R1} = \frac{V_{R1}}{R1} = \frac{3\text{ V}}{2\text{ k}\Omega} = 1.5\text{ mA}$$

$$I_{R2} = \frac{V_{R2}}{R2} = \frac{3\text{ V}}{6\text{ k}\Omega} = 0.5\text{ mA}$$

$$I_{R3} = \frac{V_{R3}}{R3} = \frac{3\text{ V}}{3\text{ k}\Omega} = 1\text{ mA}$$

Thevenin's Theorem Analysis

Thevenin's theorem is a method of analysis used to simplify and solve complex circuits by using an equivalent circuits as the basis for analysis. The theorem states that any linear, two-terminal dc network with the load removed can be replaced by a single source V_{TH} and a single resistance R_{TH}. Therefore, in the circuit of Figure 1-11, the load resistor R3 is removed and the voltage is calculated across the output terminals. The output voltage is labeled V_{TH}. Next, the input resistance (the load removed looking back into the circuit as shown in Figure 1-12) is solved. Since the dc resistance of the dc voltage source is zero ohms (theoretically), $R_{TH} = R1 \parallel R2$. Once the V_{TH} and R_{TH} values are known, they along with R_L can be used to solve the load current $I_{RL} = I_{R3}$, from $I_{RL} = V_{TH}/(R_{TH} + R_L)$ and $V_{RL} = I_{RL} \times R_L$ (Figure (1-13). The remaining voltage drops around the circuit are solved, as shown in the calculations in conjunction with the circuit of Figure 1-14.

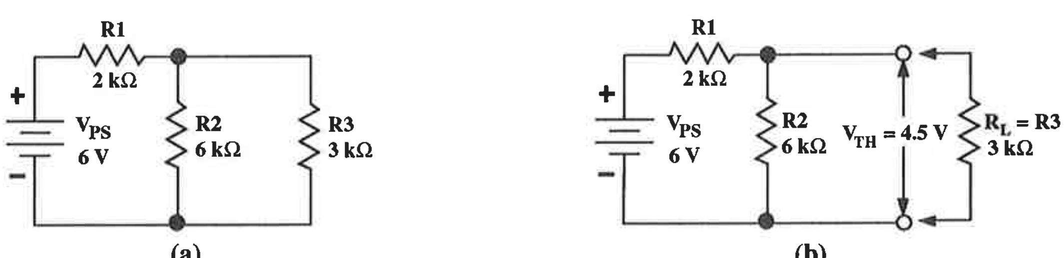
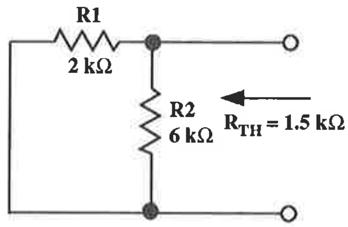


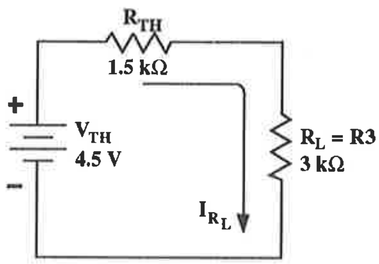
FIGURE 1-11



$$V_{TH} = \frac{V_{PS} \times R2}{R1 + R2} = \frac{6\ V \times 6\ k\Omega}{2\ k\Omega + 6\ k\Omega} = 4.5\ V$$

$$R_{TH} = \frac{R1 \times R2}{R1 + R2} = \frac{2\ k\Omega \times 6\ k\Omega}{2\ k\Omega + 6\ k\Omega} = 1.5\ k\Omega$$

FIGURE 1-12



$$I_{RL} = \frac{V_{TH}}{R_{TH} + R_L} = \frac{4.5\ V}{1.5\ k\Omega + 6\ k\Omega} = 1\ mA$$

$V_{RL} = V_{R3} = I_{RL} \times R_L = 1\ mA \times 3\ k\Omega = 3\ V$, also

$$V_{RL} = \frac{V_{TH} \times R_L}{R_{TH} + R_L} = \frac{4.5\ V \times 3\ k\Omega}{1.5\ k\Omega + 3\ k\Omega} = 3\ V$$

FIGURE 1-13

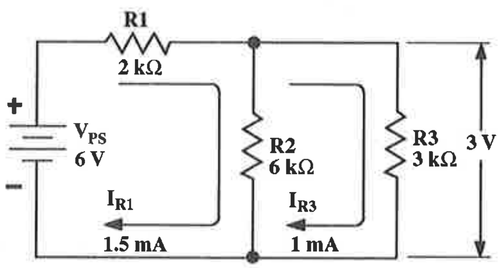


FIGURE 1-14

$I_{RL} = I_{R3} = 1\ mA$

$V_{R3} = I_{R3}R_3 = 1\ mA \times 3\ k\Omega = 3\ V$

$V_{R2} = V_{R3} = 3\ V$

$V_{R1} = V_{PS} - V_{R2} = 6\ V - 3\ V = 3\ V$

$I_{R2} = V_{R2}/R2 = 3\ V/6\ k\Omega = 0.5\ mA$

$I_{R1} = V_{R1}/R1 = 3\ V/2\ k\Omega = 1.5\ mA$

POWER SOURCES

The ideal battery, or power supply, has an internal resistance of zero ohms. Therefore, whether the voltage source is loaded or unloaded, the voltage remains relatively constant. However, if the internal resistance of a power supply is 10 Ω and the open circuit voltage is 6 V, connecting a 10 Ω load resistance will cause the voltage at output to drop to 3 V. Then, if the internal resistance is 0.1 Ω, the voltage drop across the load is only 5.94 V. Obviously, a zero-ohm, internal resistance would maintain the load at 6 V. Figure 1-15 shows the effect of a 10 Ω load on power supplies with 10 Ω and 0.1 Ω of internal resistance.

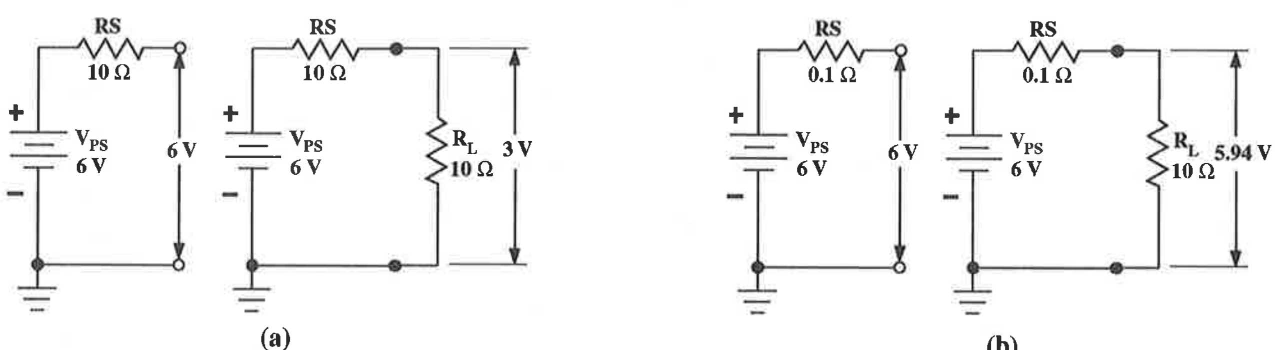


FIGURE 1-15

CIRCUITS WITH TWO POWER SUPPLIES

Connecting two power supplies in a series-aiding connection will produce the sum of the two supply voltages, regardless of where the ground connection is made. For instance, referring to Figure 1-16(a), the total voltage across the two series-aiding 6 V supplies is 12 V. Since the ground connection is made at the negative terminal of the bottom supply (point C), the voltage at the junction of the two supplies (point B), with respect to ground, is 6 V. The voltage at the positive terminal of the top supply (point A), with respect to ground, is 12 V.

However, when the ground is connected to the most positive terminal of the top supply (point A), as shown

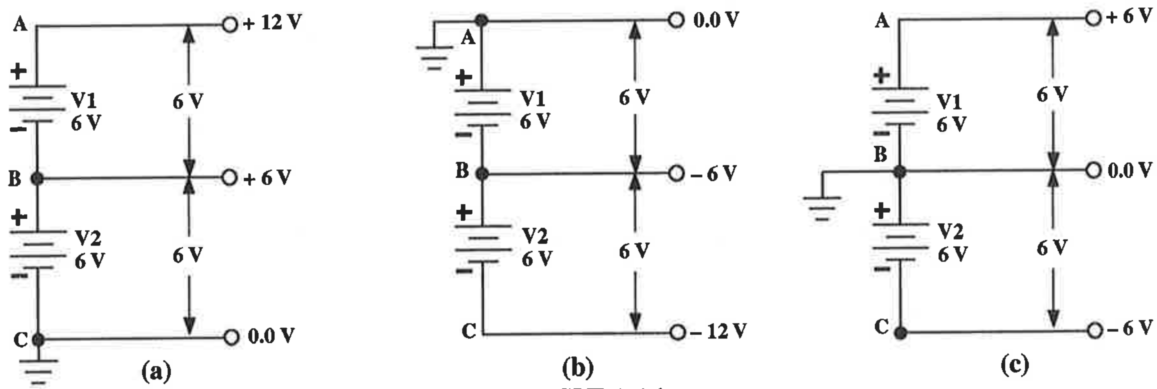


FIGURE 1-16

in Figure 1-16(b), the voltage at point B is – 6 V, with respect to ground, and the voltage at point C is – 12 V, with respect to ground. Then, if the ground is connected at the junction of the two supplies (point B), as shown in Figure 1-16(c), the voltage at point A, with respect to ground, is + 6 V, and the voltage at point C, with respect to ground is – 6 V.

NOTE: In all three connections shown in Figure 1-16, the voltage across the two series supplies remains at 12 V and does not change as the ground is moved from point A to point B to point C. What does change, however, is single point voltages with respect to ground.

CIRCUIT WITH TWO POWER SUPPLIES AND LOAD RESISTORS

When two series resistors are connected across two power supplies in a series-aiding connection, the voltage across the two series load resistors is the same, regardless of where the ground connection is made. However, as shown in Figure 1-17, the single point voltages, with respect to ground, change.

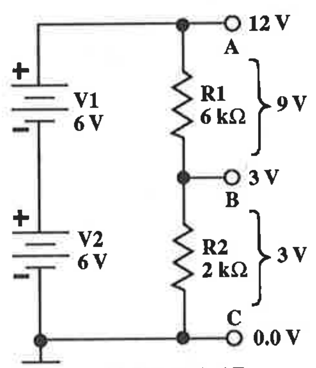


FIGURE 1-17

$$V_T = V1 + V2 = 6\text{ V} + 6\text{ V} = 12\text{ V}$$

$$I = \frac{V_T}{R_T} = \frac{V_T}{R1 + R2} = \frac{12\text{ V}}{6\text{ k}\Omega + 2\text{ k}\Omega} = 1.5\text{ mA}$$

$$V_{R1} = IR_1 = 1.5\text{ mA} \times 6\text{ k}\Omega = 9\text{ V}$$

$$V_{R2} = IR_2 = 1.5\text{ mA} \times 2\text{ k}\Omega = 3\text{ V}$$

$$V_A = V_{R1} + V_{R2} = 9\text{ V} + 3\text{ V} = 12\text{ V}$$

$$V_B = V_A - V_{R1} = 12\text{ V} - 9\text{ V} = 3\text{ V}$$

$$V_C = 0.0\text{ V}$$

When the ground is connected to point A, as shown in Figure 1-18, the voltage drops across RI and R2 remain the same, but the voltage points A, B, and C, with respect to ground, change.

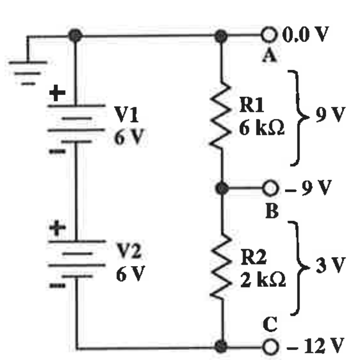


FIGURE 1-18

$$I = \frac{V_T}{R_T} = \frac{V_T}{R1 + R2} = \frac{12\text{ V}}{6\text{ k}\Omega + 2\text{ k}\Omega} = 1.5\text{ mA}$$

$$V_{R1} = IR_1 = 1.5\text{ mA} \times 6\text{ k}\Omega = 9\text{ V}$$

$$V_{R2} = IR_2 = 1.5\text{ mA} \times 2\text{ k}\Omega = 3\text{ V}$$

$$V_A = 0.0\text{ V}$$

$$V_B = V_A - V_{R1} = 0.0\text{ V} - 9\text{ V} = -9\text{ V}$$

$$V_C = V_B - V_{R2} = -9\text{ V} - 3\text{ V} = -12\text{ V}$$

When the ground is connected to the junction of the two power supplies, as shown in Figure 1-19, the voltage drops remain the same again, but the single point voltages, with respect to ground, change.

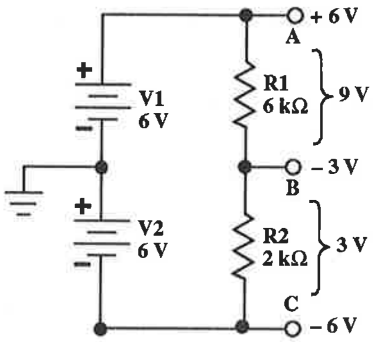


FIGURE 1-19

$$I = \frac{V_T}{R_T} = \frac{V_T}{R1 + R2} = \frac{12\text{ V}}{6\text{ k}\Omega + 2\text{ k}\Omega} = 1.5\text{ mA}$$

$$V_{R1} = IR_1 = 1.5\text{ mA} \times 6\text{ k}\Omega = 9\text{ V}$$

$$V_{R2} = IR_2 = 1.5\text{ mA} \times 2\text{ k}\Omega = 3\text{ V}$$

$$V_A = 6\text{ V}$$

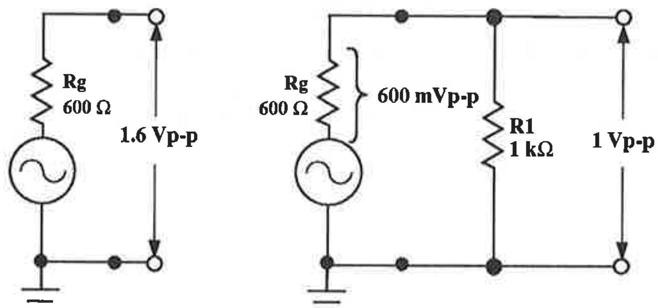
$$V_B = V_A - V_{R1} = 6\text{ V} - 9\text{ V} = -3\text{ V}$$

$$V_C = V_B - V_{R2} = -3\text{ V} - 3\text{ V} = -6\text{ V}$$

SECTION II: ALTERNATING CURRENT CIRCUIT ANALYSIS

INTERNAL RESISTANCE OF SIGNAL GENERATORS

Most laboratory signal generators have internal resistance of either 600 ohms or 50 ohms. This internal resistance, depending on the load the signal generator is driving, causes a certain amount of signal loss. For example, Figure 1-20 shows a circuit with a 1 kΩ load resistor connected across a signal generator with an internal resistance of 600 Ω. If the unloaded voltage is 1.6 Vp-p, the voltage across the 1 kΩ load is 1 Vp-p, since 600 mVp-p is dropped across the signal generator internal resistance of 600 Ω.

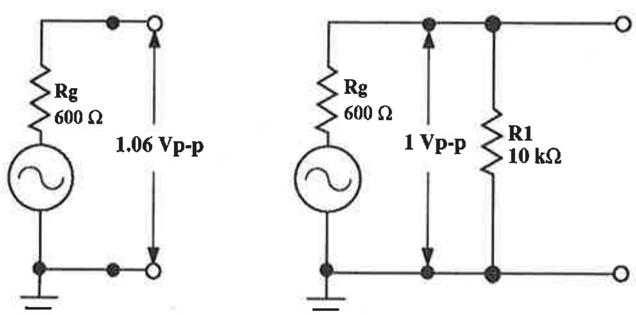


$$V_{R1} = \frac{v_g \times R_L}{R_g + R_L}$$

$$= \frac{1.6\text{ Vp-p} \times 1\text{ k}\Omega}{600\ \Omega + 1\text{ k}\Omega} = 1\text{ Vp-p}$$

FIGURE 1-20

A good laboratory procedure is to connect the signal generator to the circuit before adjusting the signal level of the generator. Then, the internal resistance of the generator does not have to be included in the calculations. For example, if the load resistor is changed to 10 kΩ, as shown in Figure 1-21, then 1.06 Vp-p of open circuit voltage is required to deliver 1 Vp-p to the load, because 60 mVp-p is lost to the internal resistance of 600 Ω. However, the measured V_{in} of the circuit will be 1 Vp-p.



$$v_{in} = v_{R1} = \frac{v_g \times R1}{R_g + R1}$$

$$= \frac{1.06\text{ Vp-p} \times 10\text{ k}\Omega}{600\ \Omega + 10\text{ k}\Omega} = 1\text{ Vp-p}$$

FIGURE 1-21

ALTERNATING CURRENT SIGNAL DISTRIBUTION

The ac signal is distributed much like the dc voltage. If a signal is applied to two series resistors the applied voltage is shared by the two resistors. For example, as shown in Figure 1-22, if 6 Vp-p is applied to R1 and R2, 4 Vp-p is developed across the 6 kΩ resistor R1 and 2 Vp-p is developed across the 3 kΩ resistor R2. The amount of signal voltage absorbed by the internal resistance of the signal generator is 0.4 Vp-p and the open circuit voltage of the generator is calculated at 6.4 Vp-p. So, in the laboratory, it is a good idea to measure V_{in} once the circuit is connected to avoid having to use the internal impedance of the generator in the calculations.

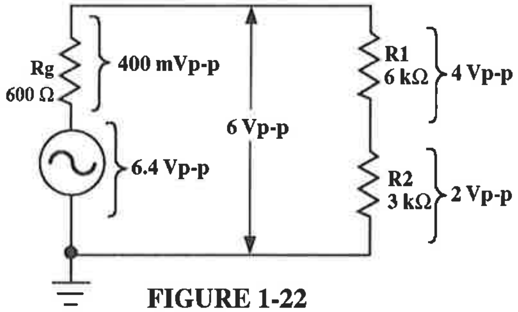


FIGURE 1-22

$$v_{R1} = \frac{v_{in} \times R1}{R1 + R2} = \frac{6\text{ Vp-p} \times 6\text{ k}\Omega}{6\text{ k}\Omega + 3\text{ k}\Omega} = 4\text{ Vp-p}$$

$$v_{R2} = \frac{v_{in} \times R2}{R1 + R2} = \frac{6\text{ Vp-p} \times 3\text{ k}\Omega}{6\text{ k}\Omega + 3\text{ k}\Omega} = 2\text{ Vp-p}$$

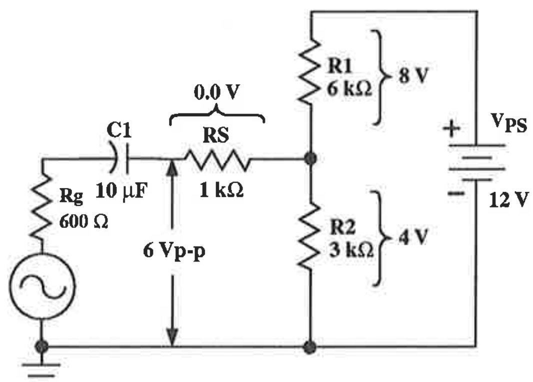
$$i_{RT} = \frac{v_{in}}{R1 + R2} = \frac{6\text{ Vp-p}}{6\text{ k}\Omega + 3\text{ k}\Omega} = 667\ \mu\text{Ap-p}$$

$$v_{Rg} = i_{RT} \times Rg = 667\ \mu\text{Ap-p} \times 600\ \Omega = 400\text{ mVp-p}$$

$$v_g = v_{Rg} + v_{R1} + v_{R2} = 0.4\text{ Vp-p} + 4\text{ Vp-p} + 2\text{ Vp-p} = 6.4\text{ Vp-p}$$

SUPERIMPOSING ALTERNATING CURRENT ON DIRECT CURRENT

Much like oil on water, the ac voltage rides on the dc voltage as long as the dc voltage is not at ac ground. One method of superimposing an ac signal on a dc voltage is by capacitor coupling, as shown in Figure 1-23. In this circuit, the dc voltage is developed across the R1 and R2 resistors and, since the coupling capacitor C1 blocks the flow of dc current through RS, V_{RS} = 0.0 V. The dc voltages of the circuit are shown solved in conjunction with the circuit of Figure 1-23.



$$V_{R1} = \frac{V_{PS} \times R1}{R1 + R2} = \frac{12\text{ V} \times 6\text{ k}\Omega}{6\text{ k}\Omega + 3\text{ k}\Omega} = 8\text{ V}$$

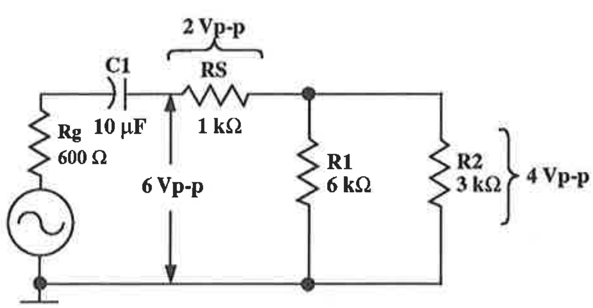
$$V_{R2} = \frac{V_{PS} \times R2}{R1 + R2} = \frac{12\text{ V} \times 3\text{ k}\Omega}{6\text{ k}\Omega + 3\text{ k}\Omega} = 4\text{ V}$$

$$V_{RS} = I_{RS} \times RS = 0.0\text{ mA} \times 1\text{ k}\Omega = 0.0\text{ V}$$

NOTE: Since capacitor C1 is an effective open to dc, no current flows through resistor RS and no dc voltage is dropped across RS.

FIGURE 1-23

In the equivalent ac circuit of Figure 1-24, Resistors R1 and R2 are shown connected to ac ground so that R1 is in parallel with R2, and R1 || R2 is in series with RS. Essentially, since the battery is an effective ac short, both the negative and positive terminals are at ac ground. The ac analysis is shown in conjunction with the equivalent circuit of Figure 1-24.



$$v_{R1} = v_{R2} = \frac{v_{in} \times (R1 \parallel R2)}{RS + (R1 \parallel R2)} = \frac{6\text{ Vp-p }(6\text{ k}\Omega \parallel 3\text{ k}\Omega)}{1\text{ k}\Omega + (6\text{ k}\Omega \parallel 3\text{ k}\Omega)}$$

$$= \frac{6\text{ Vp-p} \times 2\text{ k}\Omega}{1\text{ k}\Omega + 2\text{ k}\Omega} = 4\text{ Vp-p}$$

$$v_{RS} = v_{in} - v_{R1} = 6\text{ Vp-p} - 4\text{ Vp-p} = 2\text{ Vp-p}$$

FIGURE 1-24

FOUR RESISTOR CONNECTION

In the four resistor connection of Figure 1-25, the dc voltage is distributed across resistors R1, R2, and R3. The voltage drops are shown solved in conjunction with the circuit. Again, no dc current flows through the RS resistor, so V_{RS} is 0.0 V.

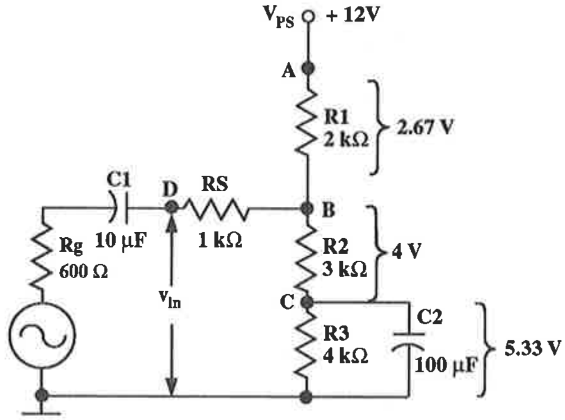


FIGURE 1-25

$$V_{R1} = \frac{V_{PS} \times R1}{R1 + R2 + R3} = \frac{12\text{ V} \times 2\text{ k}\Omega}{2\text{ k}\Omega + 3\text{ k}\Omega + 4\text{ k}\Omega} = 2.67\text{ V}$$

$$V_{R2} = \frac{V_{PS} \times R2}{R1 + R2 + R3} = \frac{12\text{ V} \times 3\text{ k}\Omega}{2\text{ k}\Omega + 3\text{ k}\Omega + 4\text{ k}\Omega} = 4\text{ V}$$

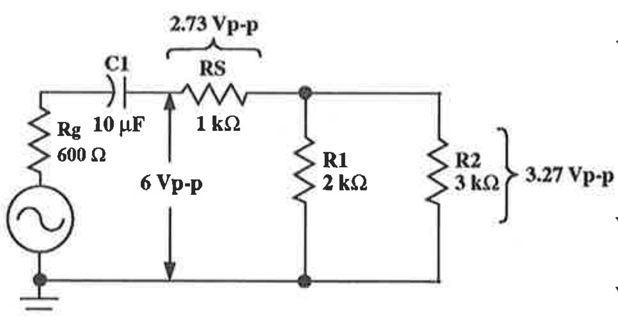
$$V_{R3} = \frac{V_{PS} \times R3}{R1 + R2 + R3} = \frac{12\text{ V} \times 4\text{ k}\Omega}{2\text{ k}\Omega + 3\text{ k}\Omega + 4\text{ k}\Omega} = 5.33\text{ V}$$

$$V_{RS} = I_{RS} \times RS = 0.0\ \mu\text{A} \times 1\text{ k}\Omega = 0.0\text{ V}$$

$$V_{C1} = V_{R2} + V_{R3} = 4\text{ V} + 5.33\text{ V} = 9.33\text{ V}$$

NOTE: Since $V_B = 9.33$ V and $V_{Rg} = 0.0$ V, the voltage dropped across C1 is 9.33 V and the voltage dropped across C2 is 5.33 V.

In the equivalent ac circuit, bypass capacitor C2 effectively causes an ac ground to exist at point C. Hence, the ac signal is distributed only across RS and the parallel resistor connection of R1 and R2, as shown in Figure 1-26. Therefore, if v_{in} equals 6 Vp-p, $v_{RS} = 2.73$ Vp-p and $v_{R1} = v_{R2} = 3.27$ Vp-p, as shown solved in conjunction with the schematic of Figure 1-26.



$$v_{R1} = v_{R2} = \frac{v_{in}\,(R1 \parallel R2)}{RS + (R1 \parallel R2)} = \frac{6\text{ Vp-p }(2\text{ k}\Omega \parallel 3\text{ k}\Omega)}{1\text{ k}\Omega + (2\text{ k}\Omega \parallel 3\text{ k}\Omega)}$$

$$= \frac{6\text{ Vp-p x }1.2\text{ k}\Omega}{1\text{ k}\Omega + 1.2\text{ k}\Omega} = 3.27\text{ Vp-p}$$

$$v_{RS} = v_{in} - v_{R1} = 6\text{ Vp-p} - 3.27\text{ Vp-p} = 2.73\text{ Vp-p}$$

$$v_{R3} = 0.0\text{ Vp-p}$$

FIGURE 1-26

NOTE: Coupling and bypass capacitors look like "opens" to dc voltages and currents, and they look like "shorts" to mid-band 1 kHz ac signals. For example, the capacitive reactance in ohms of a 10 µF capacitor at 1 kHz is 15.9 Ω and that of a 100 µF capacitor is 1.59 Ω.

$$X_{C1} = \frac{1}{2\pi f C_1} = \frac{1}{2\pi \times 1\text{ kHz} \times 10\ \mu\text{F}} = \frac{1}{2\pi \times 10^3 \times 10 \times 10^{-6}} = 15.9\ \Omega$$

$$X_{C2} = \frac{1}{2\pi f C_2} = \frac{1}{2\pi \times 1\text{ kHz} \times 100\ \mu\text{F}} = \frac{1}{2\pi \times 10^3 \times 100 \times 10^{-6}} = 1.59\ \Omega$$

With reference to the equivalent circuit resistance, the reason X_{C1} at 15.9 Ω is considered an ac short is that the C1 capacitor "sees" $R_{eq} = 2.8$ kΩ, which is so much larger than X_{C1}. Thus, $Z \approx R_{eq}$ and is solved from:

$$Z = \sqrt{R_{eq}^2 + X_{C1}^2} = \sqrt{2.8\text{ k}\Omega^2 + 15.9\ \Omega^2} = 2.8\text{ k}\Omega$$

Where: $R_{eq} = R_g + RS + (R1 \parallel R2) = 600\ \Omega + 1\text{ k}\Omega + (2\text{ k}\Omega \parallel 3\text{ k}\Omega) = 2.8\text{ k}\Omega$

CHAPTER PROBLEMS

1. With reference to the circuit of Figure 1-27. Solve for:
   a. I_{R1}
   b. V_{R1}
   c. V_{R2}
   d. V_{R3}
   e. V_{R4}

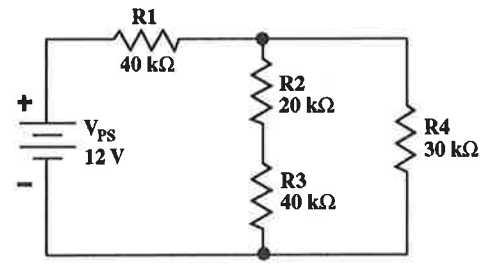


FIGURE 1-27

2. Thevenize the circuit of Figure 1-28. Solve for:
   a. V_{TH} where: $R3 = R_L$
   b. R_{TH}
   c. $I_{RL} = I_{R3}$
   d. Draw the Thevenin equivalent circuit.

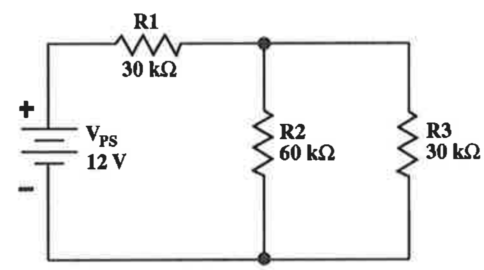


FIGURE 1-28

3. With reference to the circuit of Figure 1-29. Solve for:
   a. V_{R1}
   b. V_{R2}
   c. The voltage at point B, with respect to ground.

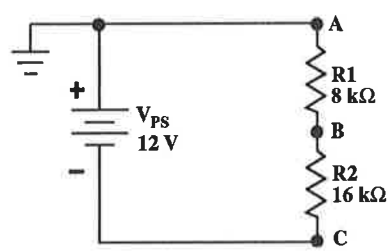


FIGURE 1-29

4. With reference to Figure 1-30. Solve for:
   a. V_{R1}
   b. V_{R2}
   c. V_{R3}
   d. V_A (referenced to ground)
   e. V_B (referenced to ground)
   f. V_C (referenced to ground)

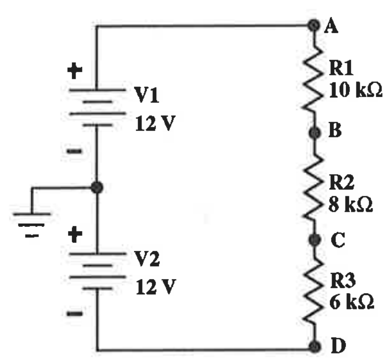


FIGURE 1-30

5. The unloaded 600 Ω signal generator of Figure 1-31 puts out 2 Vp-p. A 1.8 kΩ load resistor is connected across the output terminals.
   a. How much of the signal voltage is developed across the 1.8 kΩ load resistor?
   b. How much of the signal voltage is dropped across the 600 Ω internal resistance of the generator.

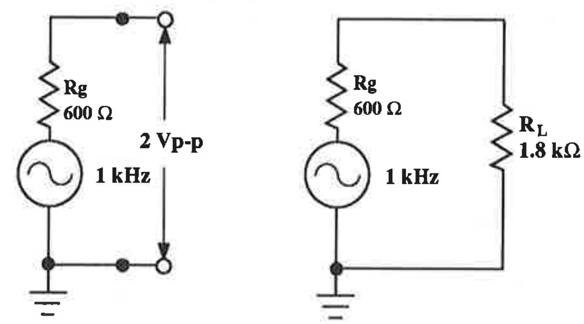


FIGURE 1-31

6. With reference to the circuit of Figure 1-32, the input 1 kHz signal at point B, with reference to ground, is 5 Vp-p.
   a. Calculate the dc voltage drops across R1, R2, R3, and RS.
   b. Draw the equivalent ac circuit and solve for the peak-to-peak signal voltage developed across RS and R1 where: $v_{R1} = v_{(R2+R3)} = v_B$, measured with respect to ground.
   c. Calculate X_{C1} for the 10 μF capacitor C1 at 1 kHz.

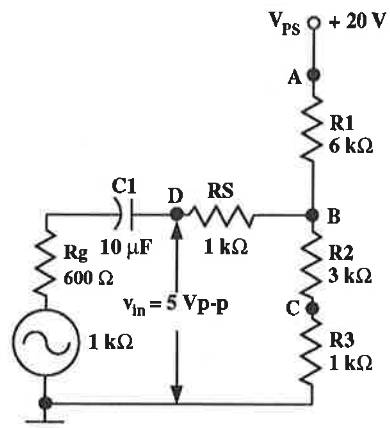


FIGURE 1-32

7. With reference to the circuit of Figure 1-33, the input 1 kHz ac signal at point D, with reference to ground, is 5 Vp-p.
   a. Calculate the dc voltage drops across R1, R2, R3, and RS.
   b. Calculate X_{C2} for the 100 μF capacitor C2 at 1 kHz.
   c. Draw the equivalent ac circuit and solve for the peak-to-peak signal voltage developed across R1, RS, and R3.

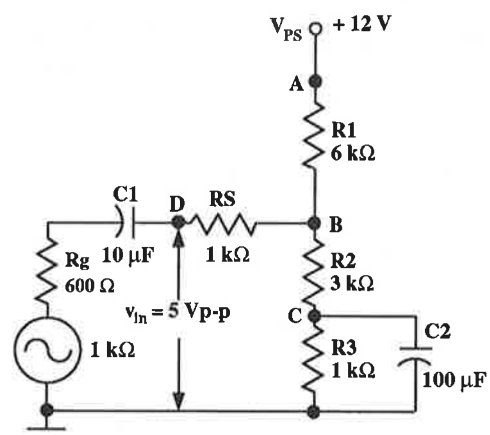


FIGURE 1-33

CHAPTER 2

SOLID STATE DIODES

GENERAL DISCUSSION

Diodes are two terminal devices that allow the free flow of electric current in one direction only. Diodes are used as rectifiers to convert ac to dc in power supply circuits, used as detectors to demodulate the audio signal in radio receivers, and used as high speed switches in digital applications. Most general purpose diodes in use today are solid state devices made from silicon materials.

As late as the 1950's, vacuum tubes were still in use, but were rapidly being replaced by solid state devices. The general acceptance of solid state devices was inevitable because, in comparison to vacuum tubes, they are much smaller, lighter in weight, more rugged, cost less to manufacture, operate at much lower power supply voltage, and dissipate less power.

Germanium solid state diodes were the first to be manufactured, but by the 1960's, silicon had replaced germanium as the industries general purpose diode. This was because, in all but a few parameters, silicon is superior to germanium. Today most general purpose diodes are silicon and silicon is also used in the construction of the zener diode, silicon controlled rectifier (SCR), tunnel diode, four layer diode, and the varicap.

THE IDEAL SOLID STATE DIODE

An ideal diode conducts current in one direction only. The symbol for the diode is an arrow and the two terminals of the device are called the anode and the cathode. The ideal diode acts like a closed switch when the diode is forward biased, as shown in Figure 2-1(a). Forward biasing occurs when the anode voltage is more positive than the cathode voltage and current flows through the diode. The arrow points in the direction of conventional current flow through the diode. When the voltage across the diode is reversed, the cathode voltage is more positive than the anode voltage and the diode acts like an open, as shown in Figure 2-1(b). Ideally, no current flows though a reverse biased diode. To have a full understanding of how diodes work, it is necessary to study the characteristics of semiconductor material.

FIGURE 2-1

NOTE: Conventional current flow is used to analyze solid state devices and it is the convention used in this book. Therefore, current is considered to flow from the positive to the negative terminal of the voltage source.

SEMICONDUCTOR DIODE PACKAGING AND MARKING

Solid state diodes come in a variety of packages. The most widely used general purpose diode comes in a cylindrical package, similar to that shown in Figure 2-2(a). An arrow on the body of the package indicates the direction of conventional current flow through the device. A single band at one end of the package indicates the cathode. For higher current and power applications stud mounted diode packages, such as shown in Figure 2-2(b), are used. The arrow imprinted on the body of the package indicates the anode and cathode of the device.

However, if no marking is present, the thread indicates the cathode for the device and the body is the anode. Also, power devices mounted to the chassis, or to a heat sink, typically need some form of insulator to electrically insulate the anode from the cathode of the device. Thermal grease is then used between the diode, insulator, and chassis to make the surface area between the diode and chassis, or heat sink, more uniform in facilitating the transfer of heat away from the device.

(a) General Purpose Diode (b) Higher Current Diode

FIGURE 2-2

DIODE NUMBERING

Most diodes are identified by 1N preceding a number, such as a 1N914 switching diode or a 1N4001 higher power rectifier diode. These are standardized diode types registered by the Electronics Industry Association (EIA) and the Joint Electron Device Engineering Council (JEDEC). Other diodes that have proprietary company numbers, such as MBR1060 (a Motorola device), can generally be cross referenced to find the 1N number for the purpose of substitution.

DIODE TYPES

Diodes are typically classified as small signal diodes, switching diodes, general purpose diodes, rectifier diodes, and special purpose diodes. For general purpose diodes, the two main parameters are the forward-biased current (I_F) and the peak-reverse (inverse) voltage (PIV). For special purpose diodes, the parameters could be high voltage, high current, or high speed. Selection of a diode is based on the application of the device, and information and specifications can be found in manufacturer data sheets.

SEMICONDUCTOR MATERIALS

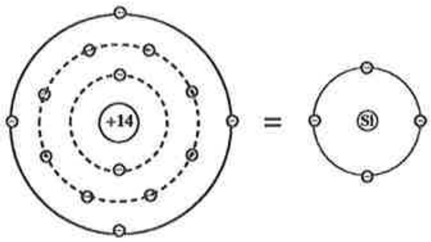
Semiconductors are materials that are rated between conductors and insulators. For example, current flows through a conductor, very little current flows through a semiconductor, and no current flows through an insulator. A good conductor, like copper, has one electron out of a possible eight in its outer ring, semiconductors have four out of a possible eight in the outer ring, and a good insulator has eight electrons in the outer ring, as shown in Figure 2-3. The electrons in the outer ring of atoms are called valence electrons, and the valence electron of the copper atom is easily dislodged with only a small amount of energy. Since copper has million of atoms, millions of free electrons break away from their respective copper atoms to become current carriers and cause current flow. Semiconductor materials, such as carbon, silicon, germanium and tin all have four valence electrons in the outer shell. However, only silicon and germanium are used in solid state diodes because, at room temperature, tin is too conductive and carbon, which is in diamond form, is not conductive enough.

(a) Conductor (b) Semiconductor (c) Insulator

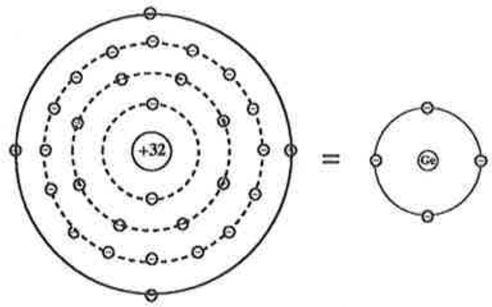
FIGURE 2-3

SILICON AND GERMANIUM ATOMS

In the Bohr model of the silicon and germanium atoms, shown in Figure 2-4, there are only four orbiting electrons in the outer rings out of eight possible. Since the four valence electrons are the farthest removed from the nucleus of their respective atoms, they are the most loosely bound and the easiest to be removed either by thermal or electrical energy. However, because the valence electrons of germanium are much farther removed from the nucleus than those of silicon, the valence electrons of germanium are more easily dislodged by temperature increase than the valence electrons of silicon. So, at room temperature, the flow of current in germanium is much greater than it is in silicon for the same amount of applied voltage.



(a) Silicon Atom

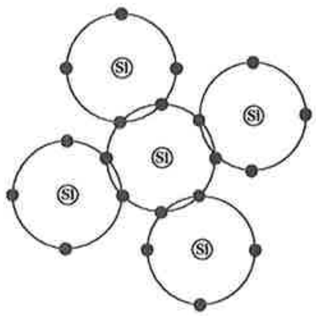


(b) Germanium Atom

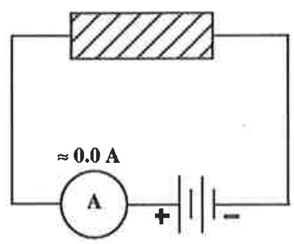
FIGURE 2-4

COVALENT BONDING

Semiconductor crystals are formed by millions of atoms held together by covalent bonding. Covalent bonding occurs because semiconductor atoms have only four valence electrons in their outer ring and they need eight to accomplish a stable crystal. Hence, they share the four available positions with atoms from neighboring atoms. In turn, the neighboring atoms share their valence with four other atoms, and so on. This forms a lattice of millions of atoms bonded together in a pure crystal (intrinsic semiconductor). Covalent bonding of a silicon atom with four neighboring silicon atoms is shown in Figure 2-5(a).



(a) Covalent Bond



(b) Intrinsic Crystal Current Flow

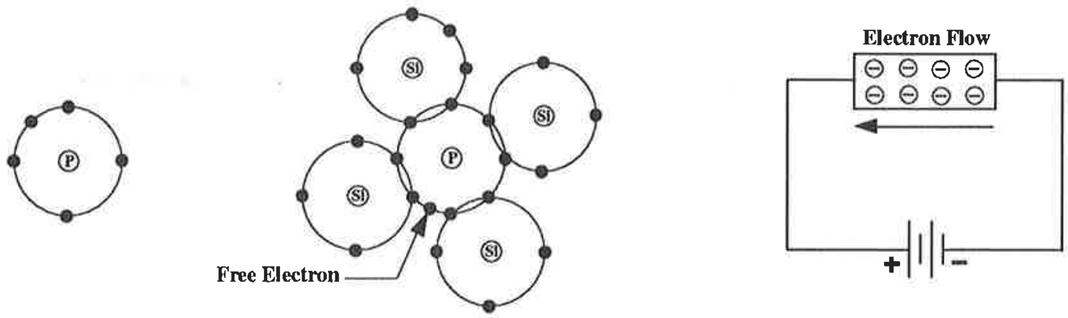
FIGURE 2-5

The current carriers in a semiconductor are thermally generated holes and electrons—electrons flowing in one direction and holes in the other. Negatively charged electrons flow from negative to positive (electron current flow), and positively charged holes flow from positive to negative (conventional current flow). A hole is created when an electron is removed from the bond of the atom and the absence of a negatively charged electron provides a positively charged hole. However, in an intrinsic crystal the number of current carriers is low, even in germanium, which can be 1000 times more conductive than silicon. So, applying a voltage across a pure intrinsic semiconductor, as shown in Figure 2-5(b), will result in almost no current flow. In order to increase the conductivity of an intrinsic crystal, impurities are added by a process called doping.

DOPING THE SEMICONDUCTOR MATERIAL

Doping is accomplished by adding a controlled amount of impurity atoms to the intrinsic (pure) crystal to increase the number of current carriers in the semiconductor. A material that has been doped is called an extrinsic semiconductor and, depending on the impurity used, doping can produce N type or P type semiconductors. Although the mix is approximately one impurity atom to 10 million silicon atoms, the doping greatly increases the number of current carriers and improves the conductivity of the semiconductor material. Electron-hole current carriers in extrinsic material are typically more than one million times more numerous than those in pure (intrinsic) semiconductors.

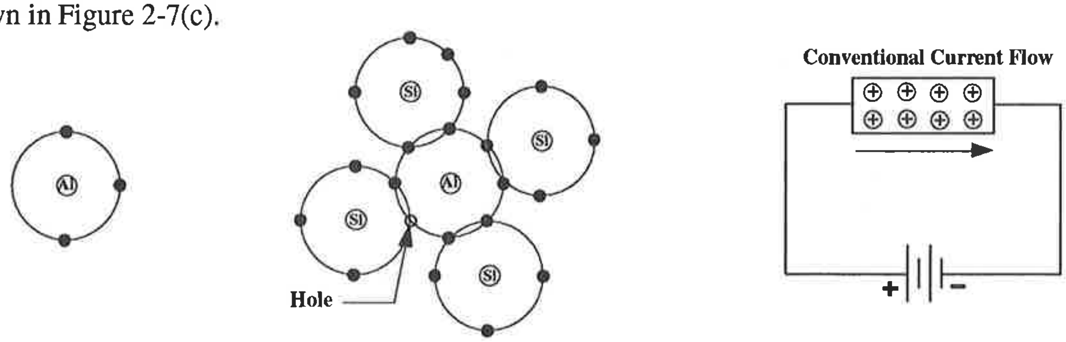
N type semiconductors are obtained by doping an intrinsic crystal with an atom that contains five valence electrons, as shown in Figure 2-6(a). Doping an intrinsic semiconductor with a pentavalent atom creates an excess of an electron, as shown in Figure 2-6(b). Phosphorous, arsenic, and antimony are examples of pentavalent or donor atoms. Since there are millions of pentavalent atoms, there are millions of negatively charged electrons in the N type material. Applying a voltage across a doped N type extrinsic material causes the majority carriers in the material, which are electrons, to flow from negative to positive (electron current flow) as shown in Figure 2-6(c).



(a) Pentavalent Atom (b) Doping with Phosphorous (c) N Type Material

FIGURE 2-6

P type semiconductors are obtained by doping an intrinsic crystal with an atom that contains three valence electrons as shown in Figure 2-7(a). Doping an intrinsic semiconductor with a trivalent atom creates an absence of an electron or a hole, as shown in Figure 2-7(b). Aluminum, gallium, and boron are examples of trivalent or acceptor atoms. Since there are millions of trivalent atoms, there are millions of positively charged holes in the P type material. Applying a voltage across a doped P type extrinsic material causes the majority current carriers in the material, which are holes, to flow from positive to negative (conventional current flow), as shown in Figure 2-7(c).



(a) Trivalent Atom (b) Doping with Aluminum (c) P Type Material

FIGURE 2-7

The PN Junction

Doping both P and N on the same crystal, so the crystal lattice is continuous across the junction, creates a PN junction. Essentially, electrons in the N type region, diffuse towards and into the P region, and in doing so, leave a positive ion on the N side of the junction. However, when an electron enters the P region it falls into a hole making a negative ion out of the hole that captures it. The buildup of negative ions causes a negative ion wall to line the P side and a positive ion wall lining the N side, and the ionized wall prevents the continued flow of current drifting across the junction. Since the region is depleted of current carriers, it is called the depletion region, as shown in Figure 2-8. The space charge between the walls provides an effective barrier voltage (V_B). For germanium diodes the barrier voltage (V_B) is generally between 0.2 V to 0.3 V and typically about 0.25 V. For silicon it is generally between 0.6 V and 0.8 V and typically about 0.7 V.

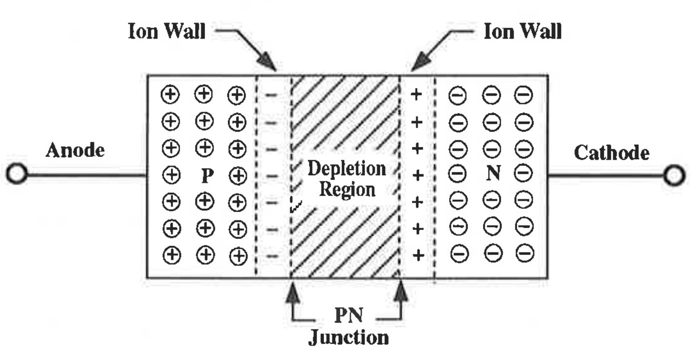


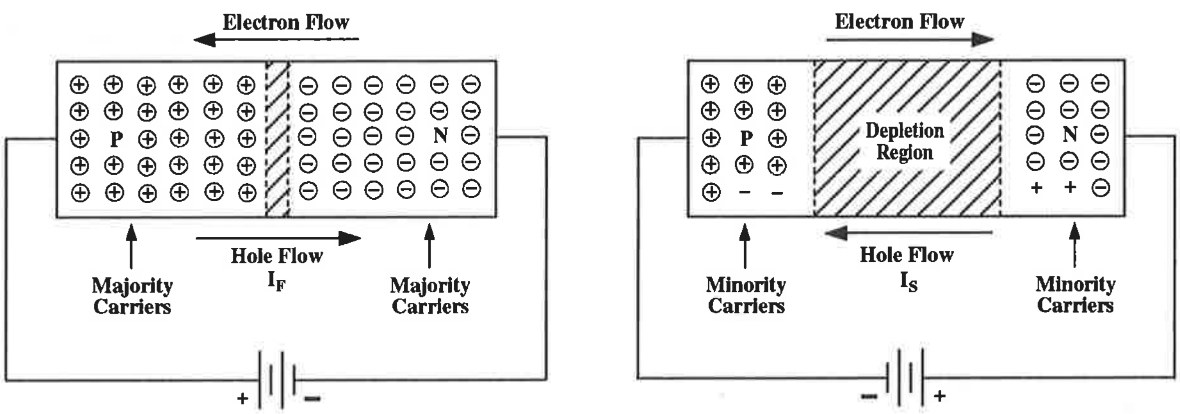
FIGURE 2-8

BIASING THE PN JUNCTION

Applying an external power supply to the PN junction in a forward or reverse direction is called biasing. Forward biasing the PN junction decreases the width of the depletion region and allows current to move easily across the junction— holes in one direction and electrons the other. The current flow through a forward-biased PN junction is typically greater than 1 mA. Reverse biasing the PN junction increases the width of the depletion region and allows very little current to flow through it. Typical current flow through a reverse-biased, silicon PN junction is theoretically less than 1 pA.

Forward Biasing

Forward biasing the PN junction occurs when the positive voltage of the power supply is connected to the anode (P region) and the negative terminal of the power supply is connected to the cathode (N region). Essentially the electrons in the N region are repelled or pushed by the negatively charged terminal of the power supply and move towards and across the junction, and are then attracted by the positively charged terminal of the power supply. Every electron leaving the N region is replaced by another electron from the negatively charged power supply terminal. Likewise, holes as positive charges are repelled by the positively charged terminal of the power supply, move across the junction, into the P region, and are attracted by the negatively charged terminal of the power supply. So current through the forward-biased PN junction is represented by a flow of majority carriers, electrons in one direction and holes in the other. See Figure 2-9(a).



(a) Majority Current Flow (b) Minority Current Flow

FIGURE 2-9

Reverse Biasing

Reverse biasing the PN junction occurs when the positive voltage of the power supply is connected to the cathode (N region) and the negative terminal of the power supply is connected to the anode (P region). When the diode is reverse biased the depletion region is increased, because electrons in the N region are attracted to the positively charges power supply terminal and are effectively pulled away from the junction, and positively charged holes in the P region are attracted to the negatively charged terminal of the power supply and are pulled away from the junction. So, for a reverse-biased diode, no majority carriers cross the junction. However, because crystals are not exactly pure, minority carriers from both sides of the junction drift across the junction, as shown in Figure 2-9(b). So a small amount of current does flow across the reverse biased PN junction. Again holes flow in one direction and electrons in the other. The minority current flow is called the saturation current and designated I_S because, in theory, saturation current only increases with increased temperature. And, once in saturation, increasing the voltage across the PN junction does not have any effect in increasing the I_S current.

IDEAL DIODE SILICON DIODE EQUATION

The Shockley diode equation developed by William Shockley, co-inventor of the transistor, describes mathematically the ideal forward and reverse-biased characteristics of the diode. Although it doesn't show the effect of the bulk resistance of the forward-biased diodes or the breakdown voltage of the reverse-biased diodes, it nevertheless provides a quantitative approach that can be used to graphically explain how and why the PN junction behaves, both in the forward and reverse-biased PN junction conditions.

The Shockley diode equation states:

$I_D = I_S(e^{V_D/V_T} - 1)$ where: V_D is the voltage across the diode
I_S is the saturation current
V_T is the thermal voltage where:

$V_T = kT/q$ where: k is the Boltzmann's constant (k) at 1.38×10^{-23} J/°K,
T is the absolute temperature in degrees Kelvin
q is the charge of an electron at 1.6×10^{-19} C in coulombs.

At absolute zero degree kelvin, the equivalent temperature in Celsius is – 273°C. So, at 0°C the equivalent temperature in kelvin is 273°K. Therefore, if the ambient temperature is 25°C, the temperature in kelvin is (25°C + 273°C) = 298°K. So, using Boltzmann's constant of 1.38×10^{-23}, the temperature T in kelvin at 298°C and the charge of an electron at 1.6×10^{-19} C (coulombs) the thermal voltage V_T is solved from $V_T = kT/q$ at 2.57×10^{-2} J/C, which equals 25.7 mV from:

$$V_T = kT/q = \frac{1.38 \times 10^{-23}\ \text{j/K} \times 298°\text{K}}{1.6 \times 10^{-19}\ \text{C}} = 2.57 \times 10^{-2}\ \text{J/C} \approx 25.7\ \text{mV}$$

Forward Biased

For the forward biased condition $V_D = V_F$ and $I_D = I_F$, so the forward-biased diode current is solved from $I_F = I_S(e^{V_F/V_T} - 1)$. In the following equations, I_F is solved, using the ideal diode equation and a normally saturated current I_S of 1×10^{-13} A for the V_F conditions of 0.5 V, 0.55 V, 0.6 V, and 0.65 V.

$$I_F = I_S(e^{V_F/V_T} - 1) = 1 \times 10^{-13}(e^{0.5/2.57 \times 10^{-2}} - 1) = 1 \times 10^{-13}\ \text{A}\ (2.81 \times 10^{8}) = 28.1\ \mu\text{A}$$

$$I_F = I_S(e^{V_F/V_T} - 1) = 1 \times 10^{-13}(e^{0.55/2.57 \times 10^{-2}} - 1) = 1 \times 10^{-13}\ \text{A}\ (2.14 \times 10^{9}) = 0.214\ \text{mA}$$

$$I_F = I_S(e^{V_F/V_T} - 1) = 1 \times 10^{-13}(e^{0.6/2.57 \times 10^{-2}} - 1) = 1 \times 10^{-13}\ \text{A}\ (1.38 \times 10^{10}) = 1.38\ \text{mA}$$

$$I_F = I_S(e^{V_F/V_T} - 1) = 1 \times 10^{-13}(e^{0.65/2.57 \times 10^{-2}} - 1) = 1 \times 10^{-13}\ \text{A}\ (9.64 \times 10^{10}) = 9.64\ \text{mA}$$

Reverse Biased

In the reverse-biased condition, $I_R = I_S(e^{V_D/V_T} - 1)$, and at low reverse-biased voltages of about – 0.05 V and – 0.1 V it has some significance. However as the reverse-biased voltage is increased to –1 V and –10 V and beyond, the current is effectively in saturation and any further increase in the reverse voltage has no effect in increasing the theoretical $I_R = I_S$ current.

$$I_R = I_S(e^{V_D/V_T} - 1) = 1 \times 10^{-13}(e^{-0.05/2.57 \times 10^{-2}} - 1) = 1 \times 10^{-13}\ \text{A}\ (0.14 - 1) = -0.86 \times 10^{-13}\ \text{A}$$

$$I_R = I_S(e^{V_D/V_T} - 1) = 1 \times 10^{-13}(e^{-0.1/2.57 \times 10^{-2}} - 1) = 1 \times 10^{-13}\ \text{A}\ (0.02 - 1) = -0.98 \times 10^{-13}\ \text{A}$$

$$I_R = I_S(e^{V_D/V_T} - 1) = 1 \times 10^{-13}(e^{-1/2.57 \times 10^{-2}} - 1) = 1 \times 10^{-13}\ \text{A}\ (10^{-17} - 1) = -1 \times 10^{-13}\ \text{A}$$

$$I_R = I_S(e^{V_D/V_T} - 1) = 1 \times 10^{-13}(e^{-10/2.57 \times 10^{-2}} - 1) = 1 \times 10^{-13}\ \text{A}\ (10^{-169} - 1) = -1 \times 10^{-13}\ \text{A}$$

IDEAL DIODE CHARACTERISTIC CURVES

The characteristic of a diode is non-linear, as shown in Figure 2-10. In the forward-biased condition of the silicon diode, no appreciable current flows at 0.4 V and it only begins to flow at about 0.5 V. However, at about 0.6 V the forward current (I_F) begins to increase exponentially. From then on the forward current through the diode rises steeply. In the reverse-biased condition, the curve is initially non-linear from 0.0 V to – 0.1 V and then becomes relatively flat beginning at about – 1 V. After that the current does not increase with increased reverse voltage. The ideal saturation current (I_S) is extremely small at 0.1 pA(1×10^{-13}A).

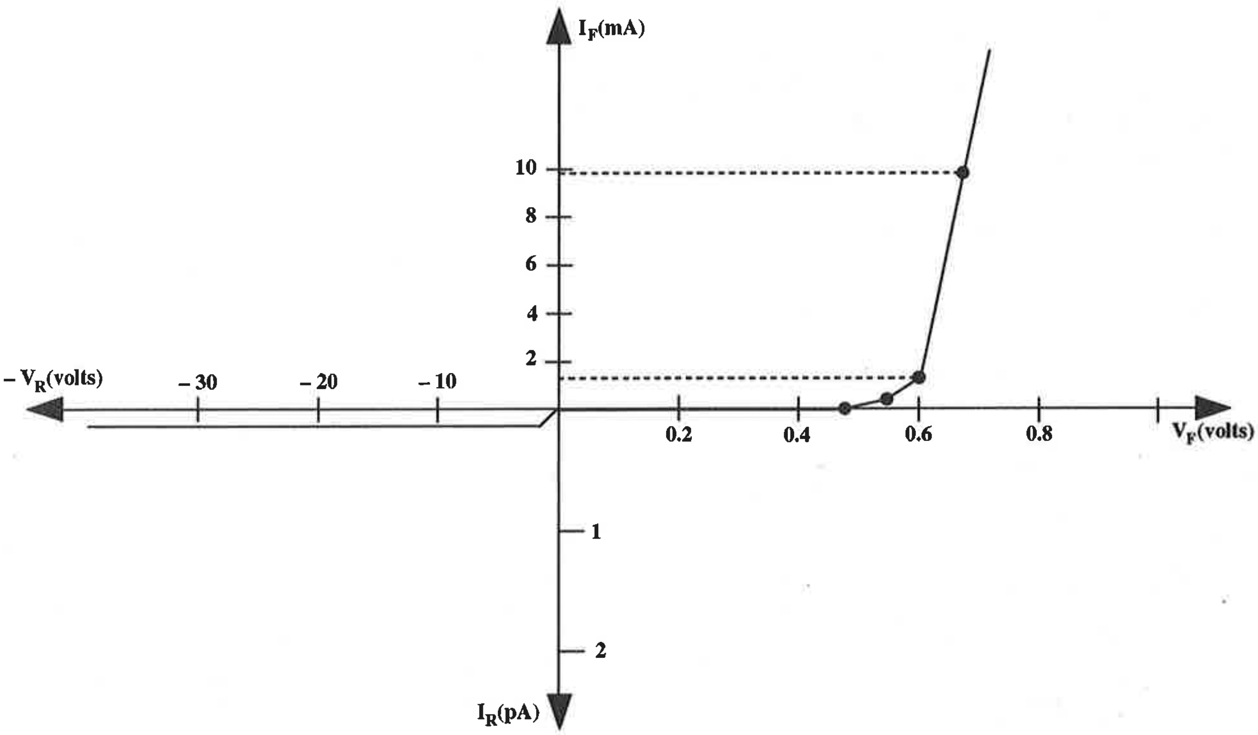


FIGURE 2-10

TEMPERATURE EFFECTS

In theory, the saturation current (I_S) doubles for every 10°C increase in temperature rise and the potential barrier voltage (V_F) decreases 2 millivolts for every 1°C increase in temperature. Therefore, if the current is 1 pA and the temperature rises from 25°C to 75°C, the temperature increases 50°C, or doubles 5 times over from 1 pA to 32 pA. Therefore:

$$I_S\,(75°C) = 2^N I_S\,(25°C) = 2^5 \times 1\text{ pA} = (2 \times 2 \times 2 \times 2 \times 2)1\text{ pA} = 32 \times 1\text{ pA} = 32\text{ pA}$$

Likewise, the potential barrier voltage (V_F) decreases 2 millivolts for every 1°C increase in temperature. So both the I_S and I_F currents increase with temperature rise which, in effect, causes the V_F to decrease, assuming the same current flow through the diode. Therefore, for a 50°C increase in temperature the V_F decreases from about 0.6 V to approximately 0.5 V, where I_F remains the same. Thus:

$$V_F\,(75°C) = V_F\,(25°C) - 2\text{ mV/°C} \times 50°C = 0.6\text{ V} - 0.1\text{ V} = 0.5\text{ V}$$

TEMPERATURE COEFFICIENT OF SEMICONDUCTOR DIODES

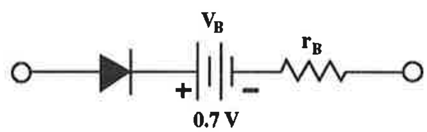
Semiconductor diodes have a negative temperature coefficient (tempco) while metal conductors have a positive tempco. Essentially, increasing the temperature of a metal conductor causes an increase in electrons that collide with atoms and other electrons, impeding the overall electron flow, which has the effect of increasing the resistance of the conductor. However, the opposite is true for diodes where increasing the temperature causes a negative tempco and increased I_S and I_F currents.

PRACTICAL DIODE CHARACTERISTICS

Diodes in circuits have similar characteristics to those of the theoretical model up to the junction voltage of 0.7 V. However, beyond 0.7 V, the forward voltage drops are typically higher than the theoretical model with the same amount of current flow through the diode. Likewise, in the reverse-biased diode connections, leakage currents not previously included cause much higher reverse-biased current to flow than theoretically predicted, except for avalanche (breakdown) voltage which is included in the practical model.

PRACTICAL FORWARD-BIASED DIODE CHARACTERISTICS

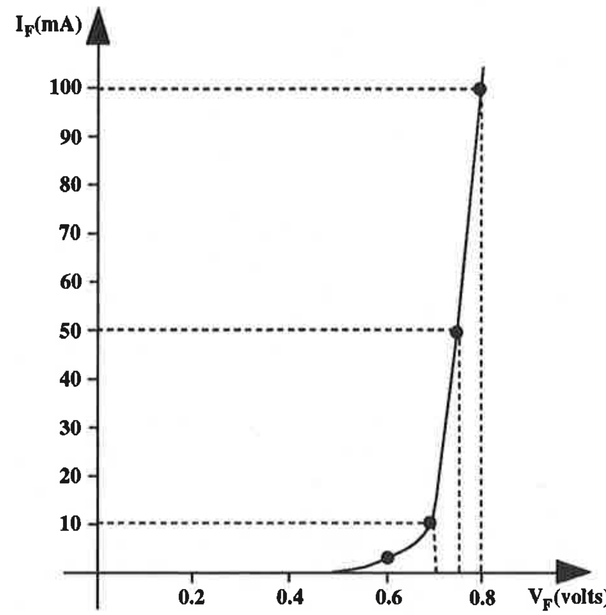
In practical diodes, the bulk resistance of diodes caused by electrons colliding with atoms and other electrons in the crystal, is between 0.1 Ω and 10 Ω. So, the initial forward-biased voltages of 0.6 V at 1 mA and 0.7 V at 10 mA is due to the diodes junction characteristics. However, the forward voltage drop, much beyond 0.7 V, is mainly due to the current through the bulk resistance of the diode. A model of a forward-biased silicon diode that includes the 0.7 V barrier voltage and the in-series bulk resistance is shown in Figure 2-11(a). So, if the bulk resistance of the diode is 1 Ω, and the V_F voltage is 0.7 V at 10 mA, then at 50 mA the V_F voltage is 0.75 V and at 100 mA the V_F is 0.8 V, as shown solved with Figure 2-11(a).



$$V_F(50\text{ mA}) = V_F + (I_F \times r_B)$$
$$= 0.7\text{ V} + (50\text{ mA} \times 1\ \Omega)$$
$$= 0.7\text{ V} + 0.05\text{ V} = 0.75\text{ V}$$

$$V_F(100\text{ mA}) = V_F + (I_F \times r_B)$$
$$= 0.7\text{ V} + (100\text{ mA} \times 1\ \Omega)$$
$$= 0.7\text{ V} + 0.1\text{ V} = 0.8\text{ V}$$

(a) Practical Forward-Biased Model



(b) Practical Forward-Biased Curve

FIGURE 2-11

PRACTICAL REVERSE-BIASED DIODE CHARACTERISTICS

In practical diodes, both the saturation current I_S and the leakage current I_{SL} contribute to the total reverse-biased current of diodes. So, the reverse current, which theoretically is about 0.1 pA, in practice is closer to 1 nA. Essentially, the leakage current occurs because at the surface of the crystal no covalent bonds exists, which effectively exposes holes and allows electrons to flow through the available holes. However, unlike the saturation current, leakage current does increase with increased reverse-bias voltage. So, if the voltage is doubled the leakage current is doubled. Thus, if the reverse-bias current is 1 nA at – 10 V, it could be 2 nA at – 20 V and 3 nA at – 30 V.

Another phenomena of reverse biasing the diode is that at some voltage the diode breaks down. For the 1N4001 the breakdown voltage, or peak inverse voltage (PIV), is 50 V. Essentially, the breakdown (avalanche) condition occurs because increasing the reverse voltage causes the minority carriers to speed up and collide with atoms, which releases free electrons to collide with other atoms, and so on. Large numbers of electrons are freed in this manner, causing large amounts of current to flow. This, coupled with the relatively high reverse voltage, can cause the power dissipation of the device to be exceeded and the device to be destroyed. The V_{BR} response is shown in Figure 2-12.

PRACTICAL FORWARD BIASING OF SILICON DIODES

The knee of the curve of the forward-biased diode occurs when the V_F is about 0.6 V and I_F about 1 mA. Increasing the current through the diode to 10 mA, increases the V_F to about 0.7 V. Further increasing the current through the diode to 100 mA increases the V_F to about 0.8 V. This occurs in working circuits.

For example, a 10 kΩ series resistor in series with a diode and a V_{PS} of 12 V provides a V_F of about 0.6 V and a current of 1.14 mA, as shown in Figure 2-13(a). Then, when a 1 kΩ series resistor is used in series with a diode and a V_{PS} of 12 V, it provides a V_F of about 0.7 V and a current of 11.3 mA, as shown in Figure 2-

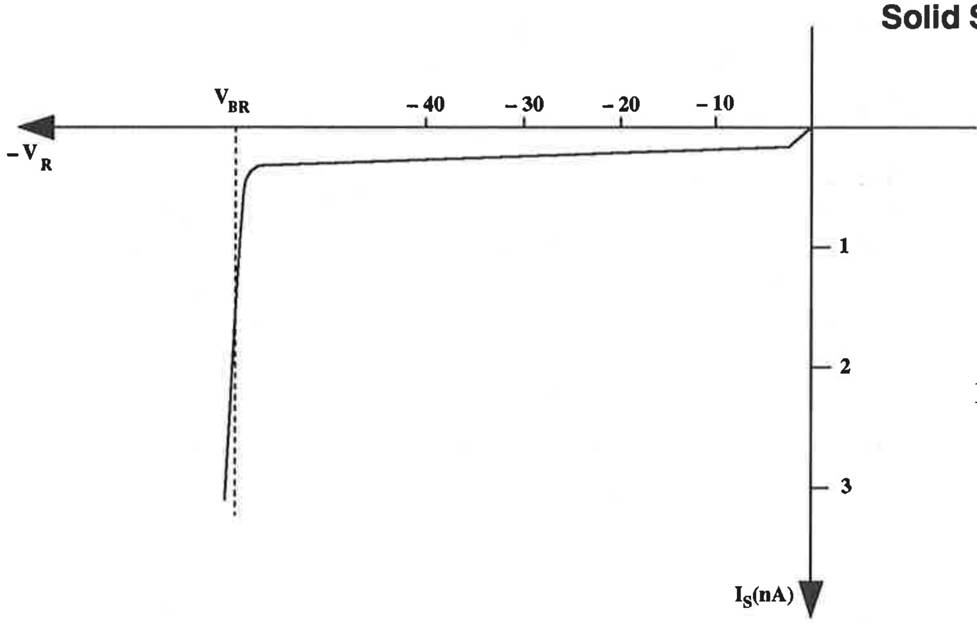
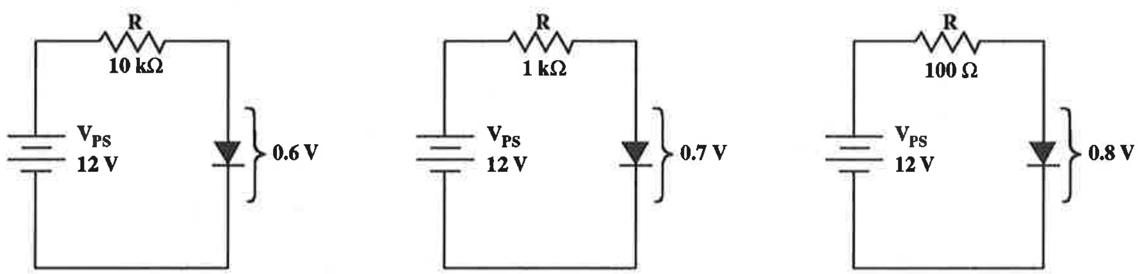


FIGURE 2-12

13(b). Reducing the series resistor further to 100 Ω, in series with a diode and a V_{PS} of 12 V, provides a V_F of about 0.8 V and a current of 112 mA, as shown in Figure 2-13(c).



$$I_F = \frac{V_{PS} - V_F}{R1} = \frac{12\text{ V} - 0.6\text{ V}}{10\text{ k}\Omega} = 1.14\text{ mA}$$

(a) 10 kΩ

$$I_F = \frac{V_{PS} - V_F}{R1} = \frac{12\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega} = 11.3\text{ mA}$$

(b) 1 kΩ

$$I_F = \frac{V_{PS} - V_F}{R1} = \frac{12\text{ V} - 0.8\text{ V}}{100\ \Omega} = 112\text{ mA}$$

(b) 100 Ω

FIGURE 2-13

FORWARD-BIASED DIODE UNDER LOADED CONDITIONS

If a forward-biased diode is loaded by a 500 Ω resistor, as shown in Figure 2-14, the current through the R1 resistor is split between the parallel D and R_L components. Essentially, V_F is assumed at 0.7 V, since the current through the diode is about 10 mA. Therefore, I_{R1} is 11.3 mA and I_{RL} is solved at 1.4 mA. So, the current through the diode is solved at 9.9 mA, as shown in conjunction with Figure 2-14.

$$I_{R1} = \frac{V_{PS} - V_F}{R1} = \frac{12\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega} = 11.3\text{ mA}$$

$$I_{RL} = V_F/R_L = 0.7\text{ V}/500\ \Omega = 1.4\text{ mA}$$

$$I_F = I_{R1} - I_{RL} = 11.3\text{ mA} - 1.4\text{ mA} = 9.9\text{ mA}$$

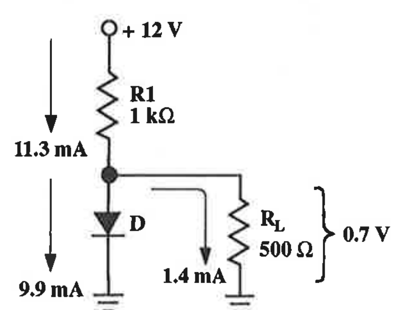


FIGURE 2-14

REVERSE-BIASED SILICON DIODE MEASUREMENTS

The ideal reverse-biased diode voltage of the circuit in Figure 2-15 is 11.99 V. However, in practice, the measured voltage will be slightly lower at 11.87 V. This is because the resistance of a reverse-biased diode is typically about 100 MΩ, and the internal resistance of the meter used to measure the voltage is typically about 10 MΩ. So, effectively, connecting the meter provides loading. The theoretical and expected measured output voltage of a typical reverse-biased diode is shown solved in conjunction with Figure 2-15.

$$\text{Theoretical: } V_D = \frac{V_{PS} \times R_P}{R1 + R_p} = \frac{12\text{ V} \times 100\text{ M}\Omega}{100\text{ k}\Omega + 100\text{ M}\Omega} = 11.99\text{ V}$$

$$\text{Expected: } R_p = R_D \parallel R_M = 100\text{ M}\Omega \parallel 10\text{ M}\Omega = 9.09\text{ M}\Omega$$

$$V_D = \frac{V_{PS} \times R_P}{R1 + R_p} = \frac{12\text{ V} \times 9.09\text{ M}\Omega}{100\text{ k}\Omega + 9.09\text{ M}\Omega} = 11.87\text{ V}$$

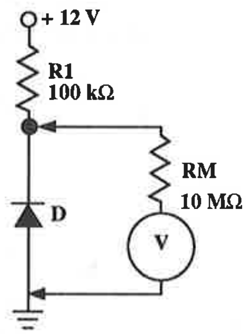


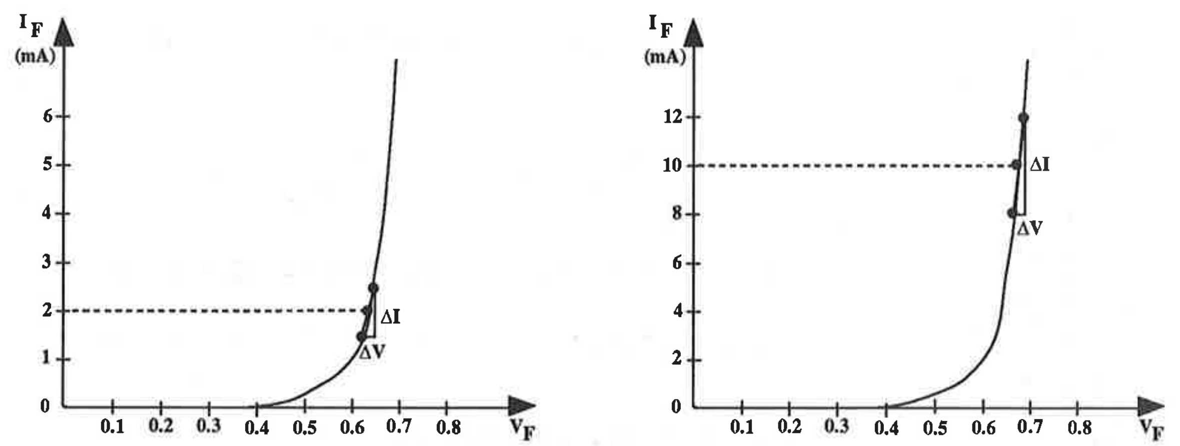
FIGURE 2-15

DYNAMIC (AC) RESISTANCE OF DIODES

In practice, the ac (dynamic) resistance of forward-biased diodes is generally less than 100 Ω, and the reverse-biased ac (dynamic) resistance is generally greater than 100 MΩ. Mathematically, the ac resistance of a forward-biased diode can be solved from $r_{ac} = \Delta V/\Delta I$. However, it typically is solved using the Shockley diode equation which is more direct and generally more accurate. The ac resistance of a reverse-biased diode is linear and solved from $r_{ac} = \Delta V/\Delta I$.

GRAPHICAL ANALYSIS OF FORWARD-BIASED DIODES

The graphical analysis for solving the ac resistance of the diode is to draw a line tangent to the curve at the operating current and measure the ΔV versus ΔI. For example, at an operating point of 2 mA, the ΔV = 40 mV and the ΔI = 2 mA, as shown in Figure 2-16(a), and the $r_{ac} = 20\ \Omega$. However if the operating current is increased to 10 mA as shown in Figure 2-16(b), the ΔV = 20 mV and the ΔI = 4 mA, the $r_{ac} = 5\ \Omega$.



$$r_{ac} = \frac{\Delta V}{\Delta I} = \frac{0.63\text{ V} - 0.61\text{ V}}{2.5\text{ mA} - 1.5\text{ mA}} = \frac{20\text{ mV}}{1\text{ mA}} = 20\ \Omega$$

(a) 2 mA Operating Point

$$r_{ac} = \frac{\Delta V}{\Delta I} = \frac{0.71\text{ V} - 0.69\text{ V}}{12\text{ mA} - 8\text{ mA}} = \frac{20\text{ mV}}{4\text{ mA}} = 5\ \Omega$$

(b) 10 mA Operating Point

FIGURE 2-16

MATHEMATICAL ANALYSIS OF FORWARD BIASED DIODES

The dynamic resistance of forward-biased diodes can also be solved from $r_{ac} = V_T/I_F$ using Shockley's diode equation where: $V_T = nkT/q$ and I_F is the forward-biased current through the diode. Recall that at 25°C the V_T of silicon diodes is equal to 25.7 mV. So for 1 mA of diode current the dynamic ac resistance is 25.7 Ω.

$$V_T = nKT/q = \frac{1 \times 1.38 \times 10^{-23}\ \text{j/K} \times (298°\text{K})}{1.6 \times 10^{-19}\text{C}} = 2.57 \times 10^{-2}\ \text{j/C} = 25.7\ \text{mV}$$

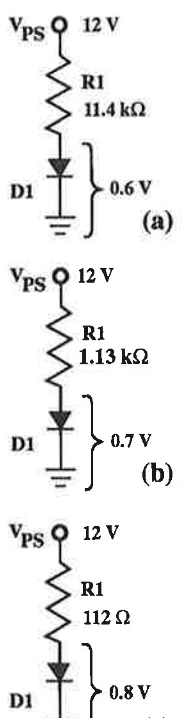
$$r_{ac} = V_T/I_F = V_F/I_F = 25.7\text{mV}/1\text{mA} = 25.7\ \Omega$$

However, the electron density (n) of silicon diodes can be as high as 2. So, if n = 2 is used, V_T = 51.4 mV and the dynamic resistance of diode for an I_F of 1 mA is solved at 51.4 Ω.

$$V_T = nkT/q = \frac{2 \times 1.38 \times 10^{-23}\ \text{j/K} \times (298°\text{K})}{1.6 \times 10^{-19}\text{C}} = 5.14 \times 10^{-2}\ \text{j/C} = 51.4\ \text{mV}$$

$$r_{ac} = V_T/I_F = 51.4\ \text{mV}/1\ \text{mA} = 51.4\ \Omega$$

The above two examples show that ac resistance of the diode can vary over a 2:1 range, and the bulk resistance of the diode was included in the analysis. The effect of the bulk resistance at higher current conditions is most apparent. The minimum and maximum ac resistance at current conditions of 1 mA is shown in Figure 2-17(a), 10 mA in Figure 2-17(b), and 100 mA in Figure 2-17(c).



$$I_F = \frac{V_{PS} - V_F}{R1} = \frac{12\ \text{V} - 0.6\ \text{V}}{11.4\ \text{k}\Omega} = \frac{11.4\ \text{V}}{11.4\ \text{k}\Omega} = 1\ \text{mA}$$

$$r_{ac(min)} = V_T/I_F + r_B = 25.7\ \text{mV}/1\ \text{mA} + 1\ \Omega = 26.7\ \Omega$$

$$r_{ac(max)} = V_T/I_F + r_B = 51.4\ \text{mV}/1\ \text{mA} + 1\ \Omega = 52.4\ \Omega$$

$$I_F = \frac{V_{PS} - V_F}{R1} = \frac{12\ \text{V} - 0.7\ \text{V}}{1.13\ \text{k}\Omega} = \frac{11.3\ \text{V}}{1.13\ \text{k}\Omega} = 10\ \text{mA}$$

$$r_{ac(min)} = V_T/I_F + r_B = 25.7\ \text{mV}/10\ \text{mA} + 1\ \Omega = 3.57\ \Omega$$

$$r_{ac(max)} = V_T/I_F + r_B = 51.4\ \text{mV}/10\ \text{mA} + 1\ \Omega = 6.14\ \Omega$$

$$I_F = \frac{V_{PS} - V_F}{R1} = \frac{12\ \text{V} - 0.8\ \text{V}}{112\ \Omega} = \frac{11.2\ \text{V}}{112\ \Omega} = 100\ \text{mA}$$

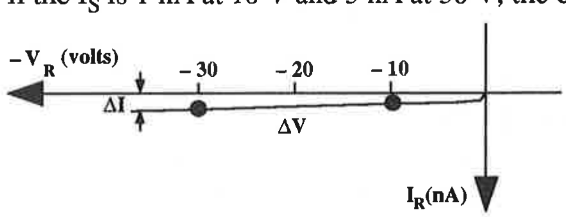
$$r_{ac(min)} = V_T/I_F + r_B = 25.7\ \text{mV}/100\ \text{mA} + 1\ \Omega = 1.26\ \Omega$$

$$r_{ac(max)} = V_T/I_F + r_B = 51.4\ \text{mV}/100\ \text{mA} + 1\ \Omega = 1.51\ \Omega$$

FIGURE 2-17

DYNAMIC RESISTANCE OF REVERSE-BIASED DIODES

Reverse-biased diodes generally operate in the linear region that extends to the breakdown voltage region. In this linear region, shown in Figure 2-18, the dynamic resistance of diodes is extremely high. For example if the I_S is 1 nA at 10 V and 3 nA at 30 V, the dynamic resistance of the reverse-biased diode is 100 MΩ.

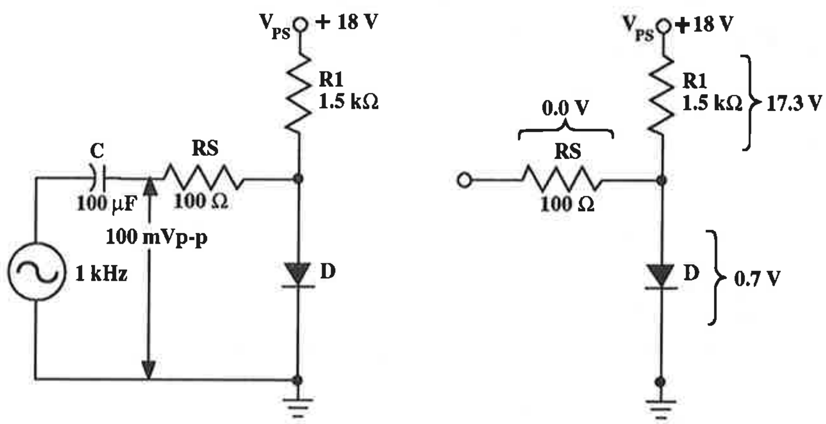


$$r_{ac} = \frac{\Delta V}{\Delta I} = \frac{30\ \text{V} - 10\ \text{V}}{3\ \text{nA} - 1\ \text{nA}} = \frac{20\ \text{V}}{2\ \text{nA}} = 100\ \text{M}\Omega$$

FIGURE 2-18

COMBINED dc AND ac ANALYSIS OF THE FORWARD-BIASED DIODE CIRCUIT

In the circuit of Figure 2-19(a), $V_{PS} = 18$ V, the ac input signal voltage $v_{in} = 100$ mVp-p, $R_S = 100\ \Omega$, R1 = 1.5 kΩ, the bulk resistance is 1 Ω, and V_F is approximately 0.7 V. The equivalent dc circuit and the dc current through the forward-biased diode is solved in conjunction with Figure 2-19(b). Also, since capacitor C is an effective short to the ac signal and an open to the dc, no dc current flows through and no dc voltage is dropped across RS.



(a) Combined Circuit (b) Equivalent Circuit

FIGURE 2-19

$$V_{R1} = V_{PS} - V_F$$

$$= 18\text{ V} - 0.7\text{ V} = 17.3\text{ V}$$

$$I_F = I_{R1} = \frac{V_{R1}}{R1} = \frac{17.3\text{ V}}{1.5\text{ k}\Omega} = 11.5\text{ mA}$$

$$V_{RS} = I_{RS} \times RS = 0.0\text{ mA} \times 100\ \Omega = 0.0\text{ V}$$

Since n is typically between 1 and 2 for silicon diodes, both the minimum and the maximum ac resistance formulas are solved. The ac resistance of the diode is solved using the dc current and includes the assumed bulk resistance of 1 Ω. Then, voltage divider equations are used to solve the ac voltage developed across the dynamic ac resistance of the forward-biased diode.

The ac analysis of the diode at minimum resistance, where 26 mV ≈ 25.7 mV, is shown in conjunction with Figure 2-20. In the circuit R1 is in parallel with the ac resistance of the forward-biased diode and, because R1 is relatively high with respect to the r_{ac}, it has little effect on the output sinewave voltage. Thus, $r_{eq} = r_{ac} \parallel R1 \approx r_{ac}$, so r_{ac} is used in the analysis.

$$r_{ac} = \frac{V_T}{I_F} + r_B = \frac{26\text{ mV}}{11.5\text{ mA}} + 1\ \Omega = 3.26\ \Omega$$

$$r_{eq} = R1 \parallel r_{ac} = 1.5\text{ k}\Omega \parallel 3.26\ \Omega = 3.25\ \Omega$$

$$v_{op\text{-}p} = \frac{v_{in}\, r_{ac}}{RS + r_{ac}} = \frac{100\text{ mVp-p} \times 3.26\ \Omega}{100\ \Omega + 3.26\ \Omega} = 3.16\text{ mVp-p}$$

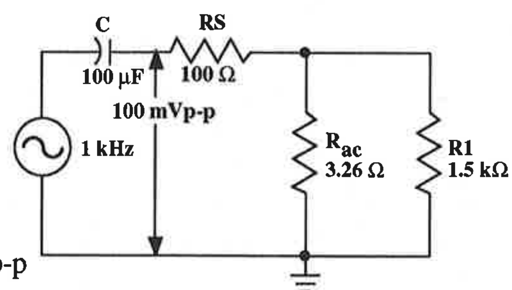


FIGURE 2-20: AC Equivalent Circuit.

Then the ac analysis of the circuit at maximum resistance is solved and 52 mV ≈ 51.4 mV is used as shown in conjunction with the circuit of Figure 2-21.

$$r_{ac} = \frac{V_T}{I_F} + r_B = \frac{52\text{ mV}}{11.5\text{ mA}} + 1\ \Omega = 5.52\ \Omega$$

$$r_{eq} = R1 \parallel r_{ac} = 1.5\text{ k}\Omega \parallel 5.52\ \Omega = 5.50\ \Omega$$

$$v_{op\text{-}p} = \frac{v_{in}\, r_{ac}}{RS + r_{ac}} = \frac{100\text{ mVp-p} \times 5.52\ \Omega}{100\ \Omega + 5.52\ \Omega} = 5.23\text{ mVp-p}$$

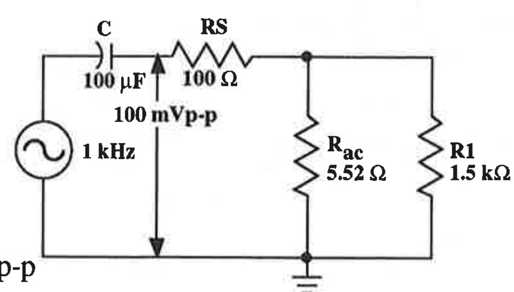


FIGURE 2-21: AC Equivalent Circuit.

SOLVING THE r_{ac} OF THE FORWARD-BIASED DIODE IN THE LAB

In the laboratory, the measured $v_{op\text{-}p}$ and the RS value at 100 Ω are used with algebra to solve the r_{ac}. Essentially, if $v_{op\text{-}p}$ = 5.23 mVp-p, then v_{RS} = 94.77 mVp-p, and r_{ac} is solved at 5.52 Ω, as shown in conjunction with the circuit of Figure 2-22.

$$v_{RS} = v_{in} - v_{op\text{-}p} = 100 \text{ mVp-p} - 5.23 \text{ mVp-p} = 94.77 \text{ Vp-p}$$

Since the ratio of r_{ac}/v_{RS} is equal to the ratio of $v_{op\text{-}p}/v_{RS}$, then r_{ac} is solved from the algebra, where:

$$\frac{r_{ac}}{RS} = \frac{v_{op\text{-}p}}{v_{RS}} \quad \therefore \quad r_{ac} = \frac{v_{op\text{-}p} \times RS}{v_{RS}} = \frac{5.23 \text{ mVp-p} \times 100\ \Omega}{94.77 \text{ Vp-p}} = 5.52\ \Omega$$

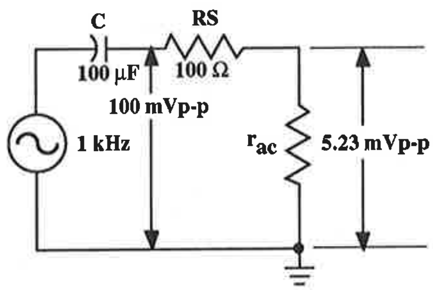
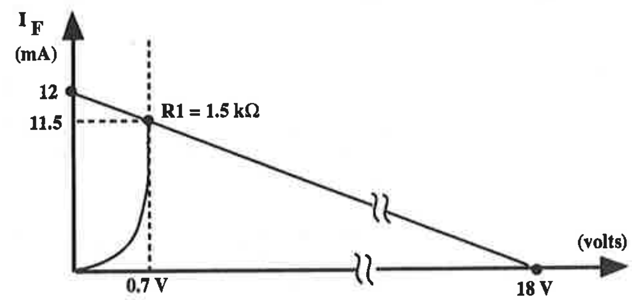


FIGURE 2-22

GRAPHICAL SOLUTIONS USING dc LOAD LINES

The load line of Figure 2-23 provides a graphical solution for the diode circuit of Figure 2-19. On the load line, I_{max} is determined by the V_{PS} voltage and the R1 resistance which intersect the diode curve at the V_F versus I_F operating point. Thus, I_{max} = 12 mA, the V_F of the diode is 0.7 V, and the I_F is 11.5 mA.



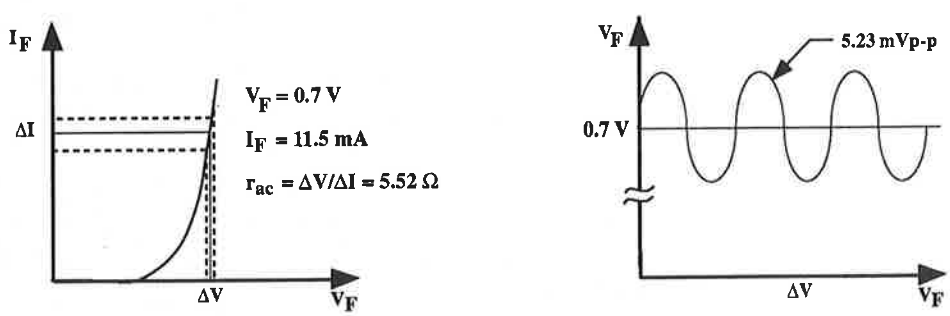
$$I_{max} = \frac{V_{PS}}{R1} = \frac{18 \text{ V}}{1.5 \text{ k}\Omega} = 12 \text{ mA}$$

$$V_{R1} = V_{PS} - V_F = 18 \text{ V} - 0.7 \text{ V} = 17.3 \text{ V}$$

$$I_F = \frac{V_{R1}}{R1} = \frac{17.3 \text{ V}}{1.5 \text{ k}\Omega} = 11.5 \text{ mA}$$

FIGURE 2-23

Since the ac sinewave signal rides on the dc voltage, two conditions should exist in order to obtain a clean sinewave voltage across the diode output. The first condition is that the operating point should be located on the linear portion of the curve as shown in Figure 2-24(a). Secondly, the amplitude of the output wave should be much smaller than the dc voltage it rides on. In this example, the operating point is on the linear portion of the curve and the output sine wave at 5.23 mVp-p rides on a much higher 700 mV dc voltage, as shown in Figure 2-24(b). So the output signal should be free of distortion.



(a) Operating Point

(b) 5.23 mVp-p ac riding on 0.7 V dc

FIGURE 2-24

OHMMETER TROUBLESHOOTING OF DIODES

Testing a diode with an ohmmeter provides a simple check of whether or not the diode is good. A working diode will show a low resistance in one direction and a high resistance in the other. However, if the diode is low in both directions, the diode is probably shorted. If the diode is high in both directions, the diode is probably open.

The measurement of diodes using an ohmmeter is, at best, a go or no-go check. So, select an ohmmeter setting, typically with a multiplier of × 100 or so, and make the measurement without regard to the actual resistive value. Essentially, an ohmmeter provides a different current flow through the diode with each setting change. Therefore, a different resistance reading will occur at each setting. However, what is important when measuring a diode with an ohmmeter is not the actual measured values, but the relative low and high resistive values (go or no-go conditions) obtained on the ohmmeter for the forward and reverse-biased diodes.

LABORATORY EXERCISE

EXERCISE OBJECTIVES

To become familiar with:

The dc analysis and measurement of silicon diode circuits.

The forward characteristic curve of silicon diodes.

The ac analysis and measurement of silicon diode circuits.

LIST OF MATERIALS AND EQUIPMENT

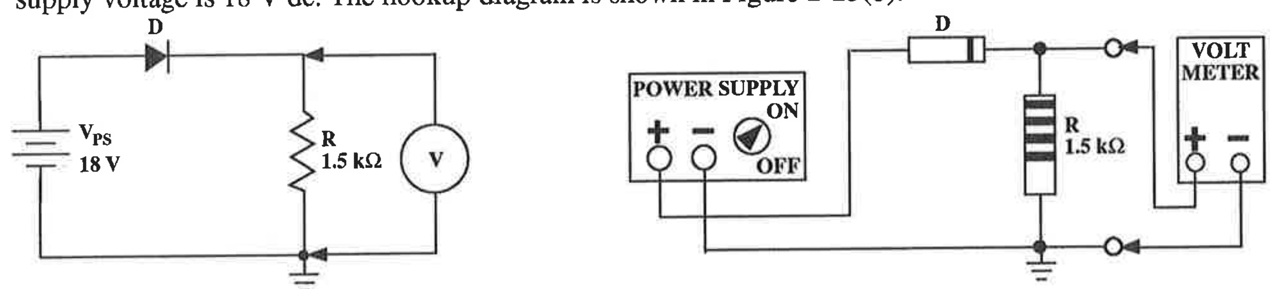
1. Diode: 1N4001-1N4007, or equivalent device
2. Resistors (one each): 100 Ω, 1 kΩ, 1.5 kΩ, 3.3 kΩ, 10 kΩ, 15 kΩ, 33 kΩ, 1 MΩ
3. Capacitor: 100 μF
4. Multimeter
5. Power Supply
6. Oscilloscope

PROCEDURE

SECTION I: Basic Diode Circuits

PART A: Forward-Biased Diode

1. In the circuit of Figure 2-25(a), the diode is forward-biased in series with the 1.5 kΩ resistor R, and the power supply voltage is 18 V dc. The hookup diagram is shown in Figure 2-25(b).



(a) Forward Biased Diode

(b) Hookup Diagram

FIGURE 2-25

2. Pre-laboratory calculations:
   a. Calculate the dc voltage drop across resistor R where: $V_R = V_{PS} - V_F$ and $V_F \approx 0.7$ V.
   b. Calculate the dc current through the series R and diode D where: $I_F = I_R = V_R/R$.

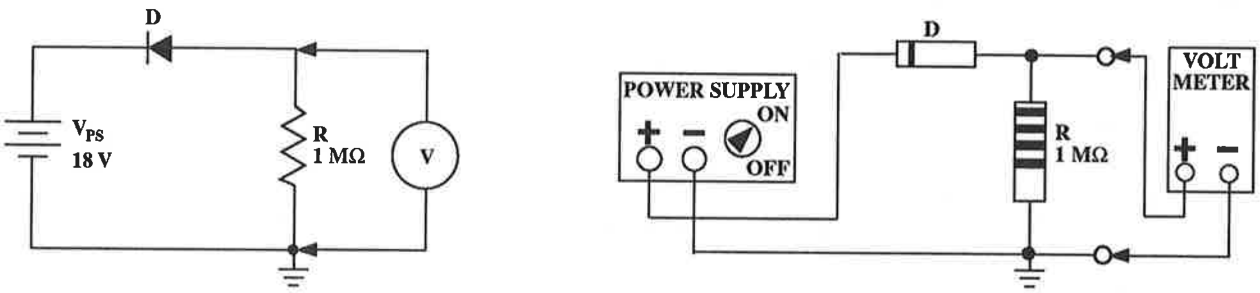
NOTE: Forward-biased diode voltages typically range from about 0.6 V to about 0.8 V, where the higher the current flow through the diode, the higher the V_F of the diode.

3. Circuit measurements:
   a. Connect the circuit of Figure 2-25(b) and measure V_{PS} and V_R.
   b. Use the measured V_{PS} and V_R values to find V_F where: $V_F = V_{PS} - V_R$.
   c. Use the measured V_R value to find I_F where: $I_F = I_R = V_R/R$.

4. Insert the calculated and measured values, as indicated, into Table 2-1.

PART B: Reverse-Biased Diode Circuit

1. In the circuit of Figure 2-26(a), the diode is reverse biased in series with the 1 MΩ resistor R and the power supply voltage is 18 V dc. The hookup diagram is shown in Figure 2-26(b)



(a) Reverse-Biased Diode

(b) Hookup Diagram

FIGURE 2-26

2. Pre-laboratory calculations:
   a. Calculate the dc voltage drop across resistor R where: $V_R = I_S \times R$, and $I_S \approx 1$ nA.
   b. Calculate the dc voltage drop across reverse-biased diode D where: $V_D = V_{PS} - V_R$.
   c. Calculate the reverse-biased diode resistance from: $R_D = V_D/I_S$.

NOTE: For reverse-biased diodes, the I_S current is very low, typically 1 nA or lower. So the voltage drop across R should be very low, the reverse-biased diode voltage high, and the resistance of the reverse-biased diode resistance extremely high.

3. Circuit measurements:
   a. Connect the circuit of Figure 2-26(b) and measure V_{PS} and V_R.
   b. Use the measured V_{PS} and V_R values to find V_D where: $V_D = V_{PS} - V_R$.
   c. Use the measured V_R value to find I_S where: $I_S = V_R/R$.
   d. Use the measured V_D value to find I_S where: $R_D = V_D/I_s$.

4. Insert the calculated and measured values, as indicated, into Table 2-1.

NOTE: Meter loading will occur, but it is less than 10% if the input resistance of the meter is 10 MΩ.

TABLE 2-1	Forward-Biased Circuit				Reverse-Biased Circuit				
	V_{PS}	V_R	V_F	I_F	V_{PS}	V_R	V_D	I_S	R_D
CALC.									
MEAS.									

SECTION II : Loading the Forward-Biased Diode Circuits

PART A: Unloaded Circuit Conditions

1. In the unloaded circuit of Figure 2-27(a), the R resistor is in series with diode D and the output is across the diode. In the circuit of Figure 2-27(b), a 1 kΩ load resistor is connected across the output and forward-biased diode. In both connections the V_{PS} is 18 V dc.

2. Pre-laboratory calculations:
   a. Calculate the dc voltage drop across resistor R where: $V_R = V_{PS} - V_F$, and $V_F \approx 0.7$ V.
   b. Calculate the dc current through the series R and diode D where: $I_F = I_R = V_R/R$.

NOTE: Forward-biased diode voltages typically range from about 0.6 V to about 0.8 V, where the higher the current flow through the diode, the higher the V_F of the diode.

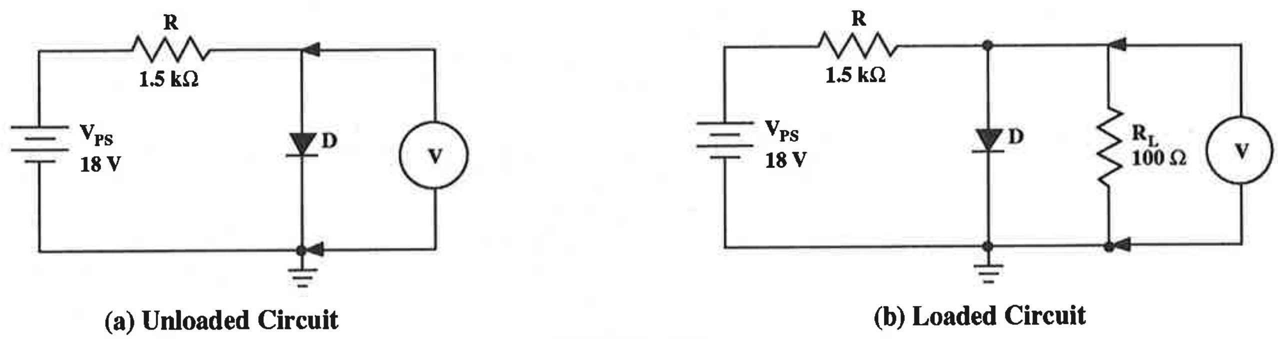


FIGURE 2-27

3. Circuit measurements:
   a. Connect the circuit of Figure 2-27(a) and measure V_{PS} and V_F.
   b. Use the measured V_{PS} and V_F values to find V_R where: $V_R = V_{PS} - V_F$.
   c. Use the measured V_R value to find I_F where: $I_F = I_R = V_R/R$.

PART B: Loaded Circuit Conditions

1. In the circuit of Figure 2-27(b), a 100 Ω load resistor is connected across the output, in parallel with the forward-biased diode.

2. Pre-laboratory calculations:
   a. Calculate the dc voltage drop across resistor R where: $V_R = V_{PS} - V_F$, and $V_F \approx 0.7$ V.
   b. Calculate the dc current through the series R where: $I_R = V_R/R$.
   c. Calculate the dc current through the series R_L where: $I_{RL} = V_{RL}/R_L$ and $V_{RL} = V_F$.

3. Circuit measurements:
   a. Connect the circuit of Figure 2-27(b) and measure the V_{PS} and V_{RL}.
   b. Then find the voltage drop across R where: $V_R = V_{PS} - V_{RL}$ and $V_F = V_{RL}$.
   c. Find the current flow through R where: $I_R = V_R/R$.
   d. Find the current flow through R_L where: $I_{RL} = V_{RL}/R_L$.
   e. Find the current flow through D where: $I_F = I_R - I_{RL}$.

4. Insert the calculated and measured values, as indicated, into Table 2-2.

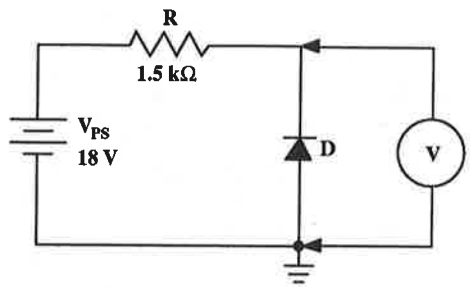
TABLE 2-2	Forward-Biased Circuit				Loaded Forward-Biased Circuit				
	V_{PS}	V_R	V_F	I_F	V_{RL}	V_R	I_R	I_{RL}	I_F
CALC.									
MEAS.									

SECTION III : Loading the Reverse-Biased Diode Circuits

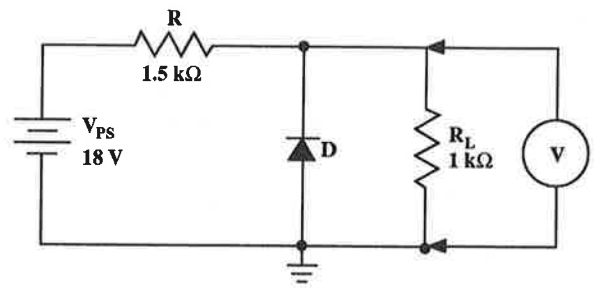
PART A: Unloaded Circuit Conditions

1. In the unloaded circuit of Figure 2-28(a), the reverse-biased diode D is in series with R and the output voltage is taken across the reverse-biased diode. In the circuit of Figure 2-28(b), a 1 kΩ load resistor is connected across the reverse-biased diode. In both connections the V_{PS} is 18 V dc.

2. Pre-Laboratory calculations:
   a. Calculate the dc voltage drop across resistor R where: $V_R = I_S \times R$ and $I_S \approx 1$ nA.
   b. Calculate the dc voltage drop across reverse-biased diode D where: $V_D = V_{PS} - V_R$.



(a) Unloaded Circuit



(b) Loaded Circuit

FIGURE 2-28

3. Circuit measurements:
   a. Connect the circuit of Figure 2-28(a). and measure V_{PS} and V_D.
   b. Use the measured V_{PS} and V_D values to find V_R where: $V_R = V_{PS} - V_D$.
   c. Use the measured V_R value to find I_S where: $I_S \approx V_R/R$.

NOTE: Since R is 1.5 kΩ, the effect of meter loading can be safely ignored because the meter resistance of approximately 10 MΩ is in parallel with the high reverse-biased diode resistance, which is still extremely high with regard to R. So, $V_o \approx V_{PS}$, and I_S should be measured at ≈ 0.0 mA.

PART B: Loaded Circuit Conditions

1. Connect the circuit of Figure 2-28(b), where a 1 kΩ load resistor is connected across the output and in parallel with the reverse-biased diode.

2. Pre-laboratory calculations:
   a. Calculate the voltage drop across R_L where: $V_{RL} = V_{PS} \times R_L/(R + R_L)$.
   b. Calculate the voltage drop across R where: $V_R = V_{PS} - V_{RL}$.
   c. Calculate the current through R where: $I_R = V_R/R$.
   d. Calculate the current through R_L where: $I_{RL} = V_{RL}/R_L$.

3. Circuit measurements:
   a. Measure the V_{PS} and V_{RL} the voltage across the 1 kΩ load resistor.
   b. Find the voltage drop across R where: $V_R = V_{PS} - V_{RL}$.
   c. Find the current flow through R where: $I_R = V_R/R$.
   d. Find the current flow through R_L where: $I_{RL} = V_{RL}/R_L$.
   e. Find the current flow through D where: $I_S = I_R - I_{RL}$.

NOTE: I_S is extremely low and approaches 0.0 mA, so it is very difficult to measure I_S accurately.

4. Insert the calculated and measured values, as indicated, into Table 2-3.

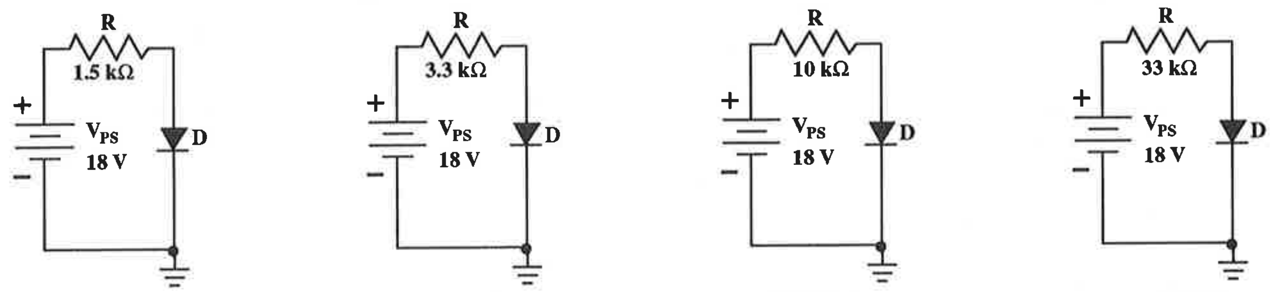
TABLE 2-3	Reverse-Biased Circuit				Loaded Reverse-Biased Circuit				
	V_{PS}	V_R	V_D	I_S	V_{RL}	V_R	I_R	I_{RL}	I_S
CALC.									
MEAS.									

SECTION IV: Forward-Biased Diode Characteristic Curve

The forward-biased characteristic curve of a diodes can be obtained either by using bench measurements, or by using the curve tracer. With bench measurements the measured V_F and associated I_F currents are used to plot the diode characteristic curve, while the curve tracer displays the characteristic curve from which the I_F current and associated V_F voltages are obtained. Neither bench measurements or the curve tracer do an adequate job of measuring and displaying the reverse-biased current (I_S) of silicon diodes, so only the forward-biased characteristic curve of the diode is analyzed.

PART A: Bench Techniques—Forward-Biased Condition.

1. Connect the circuits, as shown in Figure 2-29. For each circuit measure the V_{PS} and V_F. Then use the measured values to find V_R and the associated I_F current.



(a) 1.5 kΩ (b) 3.3 kΩ (c) 10 kΩ (d) 33 kΩ

FIGURE 2-29

2. R = 1.5 kΩ:
   a. Connect the circuit of Figure 2-29(a), where the R resistor is 1.5 kΩ, and measure V_{PS} and V_F.
   b. Use the measured V_{PS} and V_F values to find V_R where: $V_R = V_{PS} - V_F$.
   c. Then use the V_R value to find I_F where: $I_F = I_R = V_R/R$.

3. R = 3.3 kΩ, R = 10 kΩ, and R = 33 kΩ:
   a. Reconnect the circuit shown in Figure 2-29(b), where R is now 3.3 kΩ. Measure V_{PS} and V_F and repeat the measurements and calculations for V_R and I_F.
   b. Next, reconnect and repeat the measurements and calculations for V_R and I_F using the resistor values of 10 kΩ, as shown in Figure 2-29(c), and then 33 kΩ, as shown in Figure 2-29(d) .

4. Insert the measured V_F and the associated I_F current, for each of the R values, into Table 2-4.

TABLE 2-4	1.5 kΩ		3.3 kΩ		10 kΩ		33 kΩ	
	V_F	I_F	V_F	I_F	V_F	I_F	V_F	I_F
CALCULATED								
MEASURED								

PART B: (Optional Laboratory) Curve Tracer Techniques

1. Forward-biased diode characteristics: The forward-biased characteristic curve displayed on a curve tracer can be used to visually measure the I_F current and the associated V_F voltage.
   a. Begin by connecting the diode across the (marked) collector and emitter terminals, or use the diode test fixture, which is electrically connected to the terminals.
   b. Set the horizontal scale initially to 0.1 V/div and the vertical scale to 1 mA/div. The polarity switch is set to display forward-biased conditions.
   c. Begin with the horizontal voltage at about 0.0 V and slowly increase, typically left to right, the horizontal voltage to 0.3 V, 0.4 V, 0.5 V, 0.6 V and so on, until the characteristic curve of the forward-biased diode is displayed.
   d. Measure the voltage drops across the forward-biased diode at an I_F current of 1 mA, and measure the associated V_F voltage.

e. Measure the remaining V_F voltages at the associated I_F currents of 2 mA, 5 mA, and 10 mA.

2. Insert the measured voltage drops for each of the associated currents, as indicated, into Table 2-5.

TABLE 2-5	1 mA	2 mA	5 mA	10 mA
	V_F	V_F	V_F	V_F
MEASURED				

NOTE: It may be necessary to set the horizontal scale to 0.05 V/div or lower in order to obtain a better visual measurement of the forward-biased diode response. Also, the reverse-biased measurement is not taken on the curve tracer for two reasons. One, the extremely low I_S current is not detectable on the curve tracer. Secondly, once breakdown is reached the device may be destroyed, and it will happen so fast it will be without benefit of visual discovery.

PART C: Plotting the Characteristic Curve of the Forward-Biased Diode

Use the data obtained from either the bench measurements or the curve tracer visual measurements to plot the characteristic curve of the forward-biased diode on the graph of Figure 2-30.

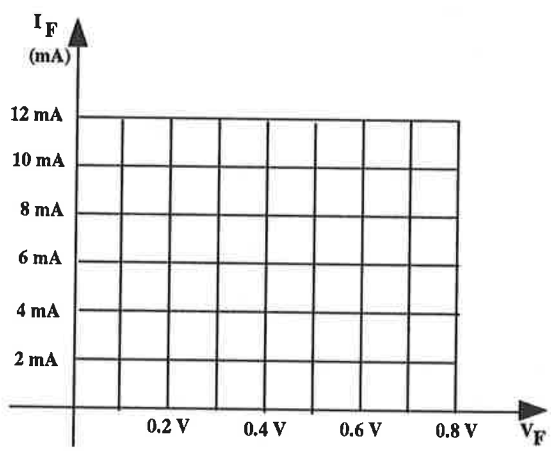


FIGURE 2-30

SECTION V: Dynamic Resistance Of Forward-Biased Diodes

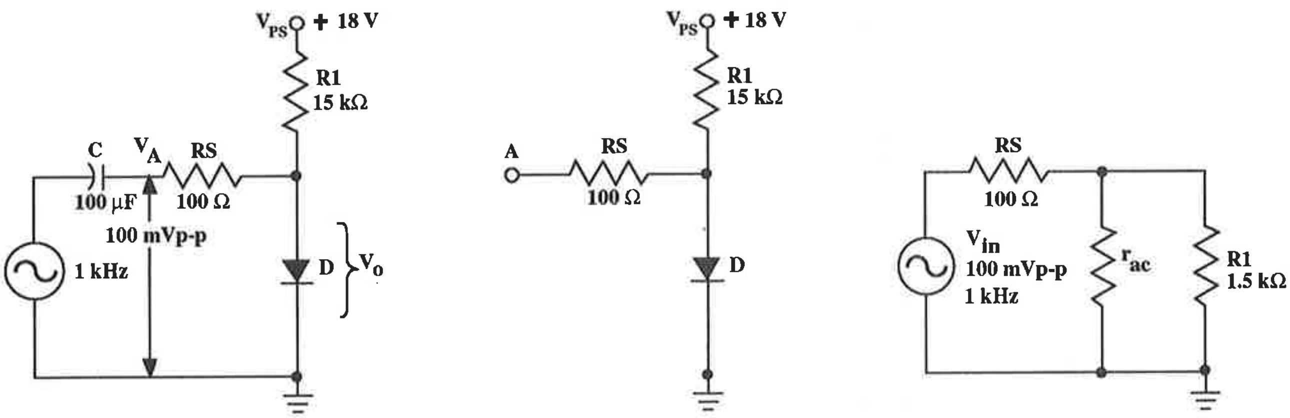
The dynamic resistance of the diode will be analyzed at two current conditions: slightly higher than 1 mA and slightly higher than 10 mA.

PART A: R1 = 15 kΩ

1. In the circuit of Figure 2-31, a sine wave signal of 100 mVp-p at 1 kHz is applied to a forward-biased diode circuit. The dc measurements of the circuit are made using a voltmeter and the ac measurements of the circuit are made using a scope.

2. Direct current considerations—pre-laboratory calculations:
   a. Calculate the dc voltage drop across R1 where: $V_{R1} = V_{PS} - V_F$ and $V_F \approx 0.7$ V.
   b. Calculated I_F where: $I_F = I_{R1} = V_{R1}/R1$.
   c. Calculate the dc voltage drop across RS where: $I_{RS} \approx 0.0$ mA.

3. Direct current measurements:
   a. Connect the circuit of Figure 2-31(a) and use a voltmeter to measure V_{PS} and V_F.
   b. Then find V_{R1} where: $V_{R1} = V_{PS} - V_F$.
   c. Find I_F where: $I_F = I_{R1} = V_{R1}/R1$.



(a) Forward-Biased Diode **(b) The dc Equivalent Circuit** **(c) The ac EquivalentCircuit**

FIGURE 2-31

d. Measure V_A and V_F and find V_{RS} where: $V_{RS} = V_A - V_F$.

4. Insert the calculated and measured dc values, as indicated, into Table 2-6.

5. Alternating current calculations—pre-laboratory calculations:
   a. Minimum r_{ac} calculations:
      1. Calculate the minimum dynamic resistance of the diode from: $r_{ac(min)} \approx 26\ mV/I_F$.
      2. Calculate the minimum output signal voltage v_o where: $v_{o(min)} \approx v_{in} \times r_{ac}/(r_{ac} + RS)$.
   b. Maximum r_{ac} calculations:
      1. Calculate the maximum dynamic resistance of the diode from: $r_{ac(max)} \approx 52\ mV/I_F$.
      2. Calculate the maximum output signal voltage v_o where: $v_{o(max)} \approx v_{in} \times r_{ac}/(r_{ac} + RS)$.

6. Alternating current measurements:
   a. Connect the circuit of Figure 2-31(a) and use a oscilloscope to measure v_{in} at 100 mVp-p and at 1 kHz, and measure v_o. Calculate v_{RS} from: $v_{RS} = v_{in} - v_o$.
   b. Find r_{ac} where: $r_{ac} = v_o \times RS/v_{RS}$.

NOTE: Dynamic resistance of diodes (r_{ac}) can range over a 2 : 1 ratio, typically between $r_{ac} = 26\ mV/I_F$ and $r_{ac} = 52\ mV/I_F$. Also, $r_{ac} \parallel R1 \approx r_{ac}$, since R1 is much larger than r_{ac}. The bulk resistance r_B, which is typically 1 Ω or less, is not included in the r_{ac} calculations.

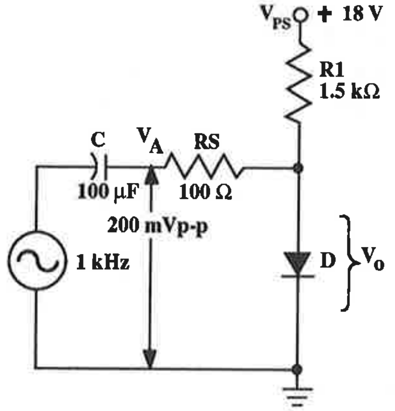
7. Insert the calculated and measured ac values, as indicated, into Table 2-6.

TABLE 2-6	dc Considerations					ac Considerations			
	V_{PS}	V_F	V_{R1}	I_F	V_{RS}	$v_{o(min)}$	$v_{o(max)}$	$r_{ac(min)}$	$r_{ac(max)}$
CALC.									
MEAS.									

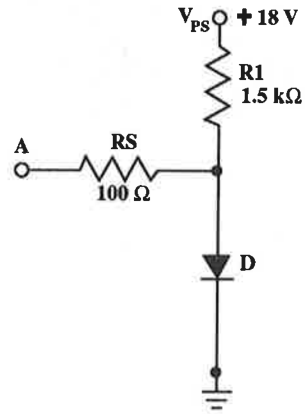
PART B: R1 = 1.5 kΩ

1. In the circuit of Figure 2-32(a), a sine wave signal of 200 mVpp at 1 kHz is applied to a forward-biased diode circuit. The dc measurements of the circuit using a voltmeter is shown in Figure 2-32(b), and the ac measurements of the circuit using a scope is shown in Figure 2-32(c).

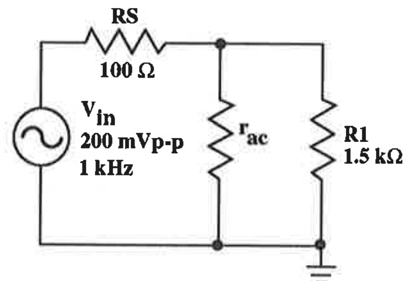
2. Direct current considerations—pre-laboratory calculations:
   a. Calculate the dc voltage drop across R1 where: $V_{R1} = V_{PS} - V_F$, where $V_F \approx 0.7$ V.



(a) Forward-Biased Diode



(b) The dc Equivalent Circuit



(c) The ac EquivalentCircuit

FIGURE 2-32

b. Calculated I_F where: $I_F = I_{R1} = V_{R1}/R1$.
c. Calculate the dc voltage drop across RS where: $V_{RS} \approx 0.0$ V.

3. Direct current measurements:
   a. Connect the circuit of Figure 2-32(a) and use a voltmeter to measure V_{PS} and V_F.
   b. Then find V_{R1} where: $V_{R1} = V_{PS} - V_F$.
   c. Find I_F where: $I_F = I_{R1} = V_{R1}/R1$.
   d. Measure V_A and V_F and find V_{RS} where: $V_{RS} = V_A - V_F$.

4. Insert the calculated and measured dc values, as indicated, into Table 2-7.

5. Alternating current calculations—pre-laboratory calculations:
   a. Minimum r_{ac} calculations:
      1. Calculate the minimum dynamic resistance of the diode from: $r_{ac(min)} \approx 26\ \text{mV}/I_F$.
      2. Calculate the minimum output signal voltage v_o where: $v_{o(min)} \approx v_{in} \times r_{ac}/(r_{ac} + RS)$.
   b. Maximum r_{ac} calculations:
      1. Calculate the maximum dynamic resistance of the diode from: $r_{ac(max)} \approx 52\ \text{mV}/I_F$.
      2. Calculate the maximum output signal voltage v_o where: $v_{o(max)} \approx v_{in} \times r_{ac}/(r_{ac} + RS)$.

6. Alternating current measurements:
   a. Connect the circuit of Figure 2-32(a) and use an oscilloscope to measure V_{in} at 200 mVp-p and 1 kHz and measure v_o. Calculate v_{RS} from: $v_{RS} = v_{in} - v_o$.
   b. Find r_{ac} where: $r_{ac} = v_o \times R_S/v_{RS}$.

NOTE: The dynamic resistance of diodes (r_{ac}) can range over a 2:1 ratio, typically between $r_{ac} = 26\ \text{mV}/I_F$ and $52\ \text{mV}/I_F$. Also, $r_{ac} \parallel R1 \approx r_{ac}$, since R1 is much larger than r_{ac}. The bulk resistance r_B which is typically 1 Ω or less, is not included to help simplify the r_{ac} calculations.

7. Insert the calculated and measured ac values into Table 2-7.

TABLE 2-7	dc Considerations					ac Considerations			
	V_{PS}	V_F	V_{R1}	I_F	V_{RS}	$v_{o(min)}$	$v_{o(max)}$	$r_{ac(min)}$	$r_{ac(max)}$
CALC.									
MEAS.									

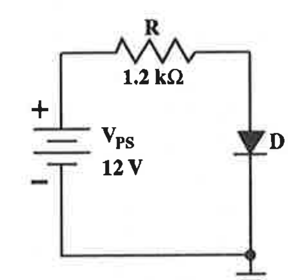
CHAPTER QUESTIONS

1. What is the definition of an intrinsic semiconductor?
2. What is the definition of an extrinsic semiconductor?
3. Why are pure semiconductors doped?
4. If aluminum is used to dope an intrinsic semiconductor, will it produce an N type or P type semiconductor material.
5. Is a donar atom a trivalent or pentavalent atom? Explain!
6. Is an acceptor atom a trivalent or pentavalent atom?
7. Does increasing or decreasing the I_F current through a forward biased diode increase the V_F voltage?
8. Do semiconductors have positive or negative temperature coefficients?
9. Does increasing the temperature increase the current flow through a diode? How about the V_F?
10. Does increasing the current flow through a forward biased diode increase or decrease the r_{ac} of the diode?
11. Is a reverse-biased diode more of an open or a short? Explain!
12. Why are the ohmmeter measurement of diodes relagated to go or no-go testing?

CHAPTER PROBLEMS

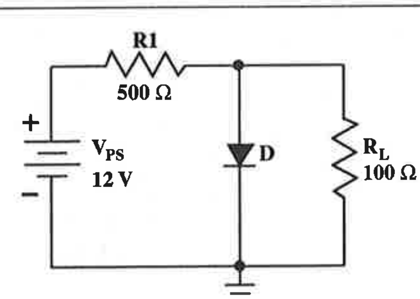
1. With reference to the circuit of Figure 2-33:
   $V_F = 0.7$ V.
   Solve for:
   a. V_R
   b. I_F

FIGURE 2-33



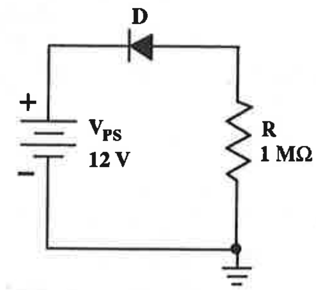
2. With reference to the circuit of Figure 2-34:
   $V_F = 0.8$ V.
   Solve for:
   a. V_{R1}
   b. I_{RL}
   c. I_F

FIGURE 2-34



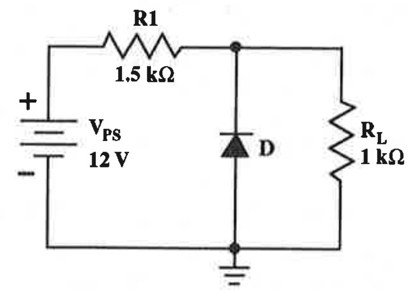
3. With reference to the circuit of Figure 2-35:
   $I_S = 10$ nA.
   Solve for:
   a. V_R
   b. V_D
   c. R_D

FIGURE 2-35



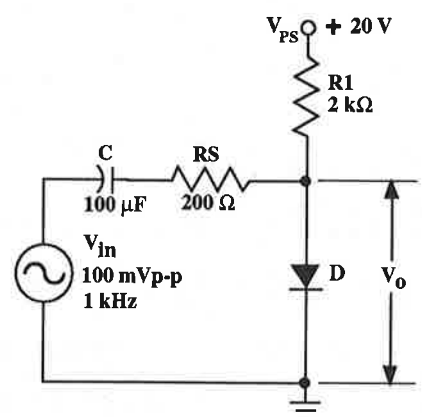
4. With reference to the circuit of Figure 2-36:
   Solve for:
   a. V_{R1}
   b. I_{RL}
   c. I_D

FIGURE 2-36



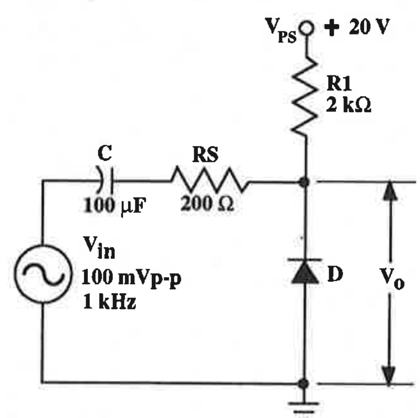
5. With reference to the circuit of Figure 2-37:
   $r_B = 1\ \Omega$ and $V_F = 0.7$ V.
   Solve for:
   a. I_F
   b. r_{ac}
   c. v_o

FIGURE 2-37



6. With reference to the circuit of Figure 2-38:
   $I_S = 10$ nA.
   Solve for:
   a. V_{R1}
   b. V_D
   c. v_o

FIGURE 2-38



CHAPTER 3

ZENERS AND SPECIAL PURPOSE DIODES

GENERAL DISCUSSION

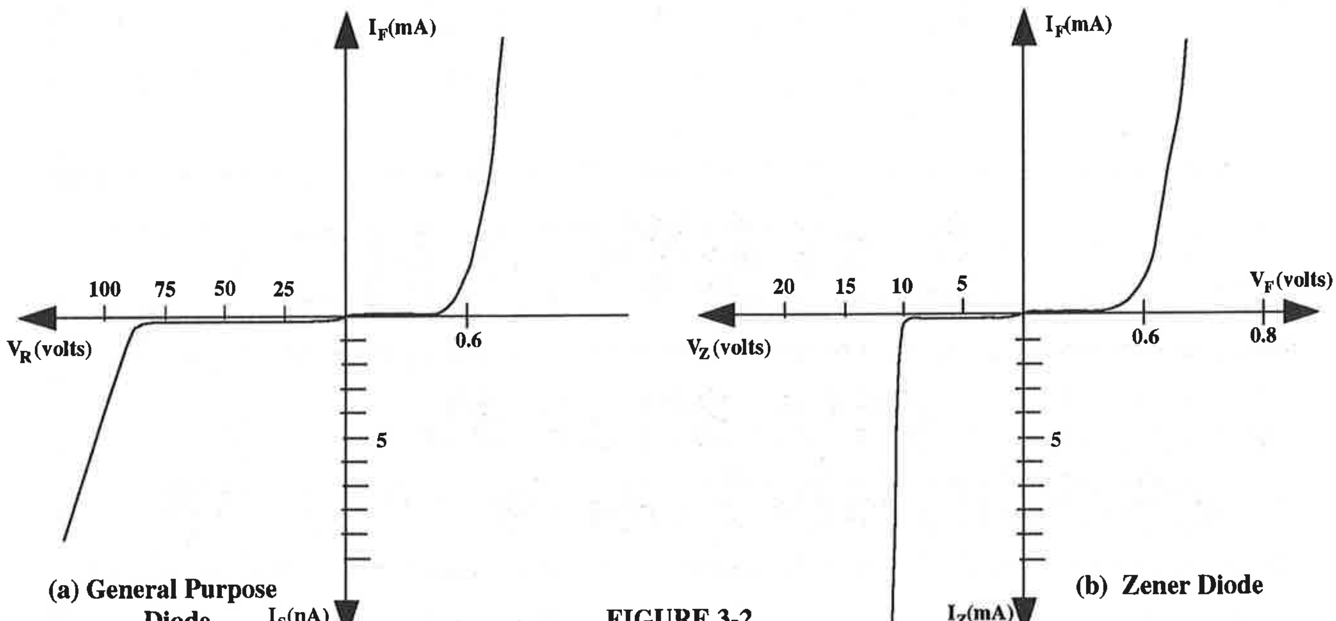
Diodes are categorized as general purpose or special purpose diodes. General purpose diodes are small signal and rectifier diodes, while zener diodes, light emitting diodes, varactors, and Schottky diodes are considered special purpose diodes. Among other special purpose diodes are the tunnel diode, the PIN diode and the step-recovery diode. Zener diodes are generally used as the voltage reference in power supplies, light emitting diodes (LED) give off light when forward biased and typically are used as indicators, varactor diodes are used as dc controlled variable capacitors that vary the frequency in radio and televisions, and the Schottky diode is a fast switching diode typically used in switching regulator circuits. Symbols for the zener diode, the light emitting diode, the varactor, and the Schottky diode are shown in Figure 3-1.

(a) Zener Diode (b) LED (c) Varactor (d) Schottky Diode

FIGURE 3-1

ZENER DIODES

General purpose diodes and zener diodes have similar forward biased characteristics curves. However, when reverse biased, the characteristic curves are quite different. For instance, the reverse biased breakdown voltages of general purpose diodes can exceed 100 V, as shown in Figure 3-2(a), while zener diodes are purposely doped so that the breakdown occurs at lower voltages. Once in the breakdown region, the voltage remains relatively constant over a wide current range, as shown in Figure 3-2(b).



(a) General Purpose Diode

(b) Zener Diode

FIGURE 3-2

When both the general purpose and zener diodes are forward biased, they will both drop about 0.7 V. The forward-biased general purpose diode is shown in Figure 3-3(a), and the forward biased zener diode is shown in Figure 3-3(b).

(a) General Purpose Diode (b) Zener Diode

FIGURE 3-3

However, if both the general purpose and zener diodes are reverse biased, the general purpose diode will drop about 19.999 V, as shown in Figure 3-4(a), and the reverse-biased 10 V zener diode will drop about 10 V, as shown in Figure 3-4(b).

(a) General Purpose Diode (b) Zener Diode

FIGURE 3-4

ZENER DIODE PACKAGING AND MARKING

Zener diodes, like general purpose diodes, come in a variety of packages with power ratings from below 200 mW to above 50 watts. Also, like general purpose diodes, zener diodes are identified by 1N preceding a series of numbers, such as 1N4742. However, the marking of general purpose diodes and zener diodes are similar, so unless the zener number is known, telling whether the device is a zener or a general purpose diode can be difficult. The best method of selecting the proper zener diode is to consult a data book. Data sheets not only provide the nominal reference voltage, but parameters such as percent tolerance, temperature range, and power dissipation rating.

THE ZENER EFFECT

The reverse-biased breakdown voltage of a zener diode is subject to two breakdown phenomena: zener breakdown and avalanche breakdown. Zener breakdown occurs at low breakdown voltages, typically less than 5 V, while avalanche breakdown occurs at higher breakdown voltages, typically greater than 8 V.

Lower zener breakdown voltage zener diodes are fabricated by heavily doping both sides of the PN junction. This causes a narrow depletion region, so only a small external voltage, slightly beyond the breakdown voltage, is needed to cause electrons to flow across the junction from the P side and directly into the conduction band on the N side. Lower breakdown voltage zener diodes of less than 5 V, such as the 4 V breakdown voltage shown in Figure 3-5(a), have soft breakdown characteristics.

Higher avalanche breakdown voltage zener diodes are fabricated when the doping level on the P side of the junction is reduced. This causes both the depletion region and the reverse breakdown voltage to increase. Higher voltage zener diodes of greater than 8 V, such as the 10 V breakdown voltage shown in Figure 3-5(a), have sharp breakdown characteristics.

TEMPERATURE EFFECTS

Low voltage zener diodes below 5 V have a negative tempco, so an increase in temperature causes the zener voltage to decrease. High voltage zener diodes above 8 V have a positive tempco, so an increase in the temperature causes the zener voltage to increase.

In between 4 V and 8 V, both zener and avalanche breakdown phenomena occurs and, ideally, can approach a zero tempco. However, since most reference voltages are typically higher voltages, a practical solution is to use a forward-biased diode in series with a zener diode, as shown in Figure 3-5(b). In this connection, the positive tempco of the general purpose diode combines with the negative tempco of the higher voltage (10 V) zener to provide a tempco that closely approaches zero tempco conditions. So, not only does the circuit provide the sharp breakdown that allows for a fixed voltage over a larger range of current change, but the reference voltage should remain steady despite increases or decreases in ambient temperature.

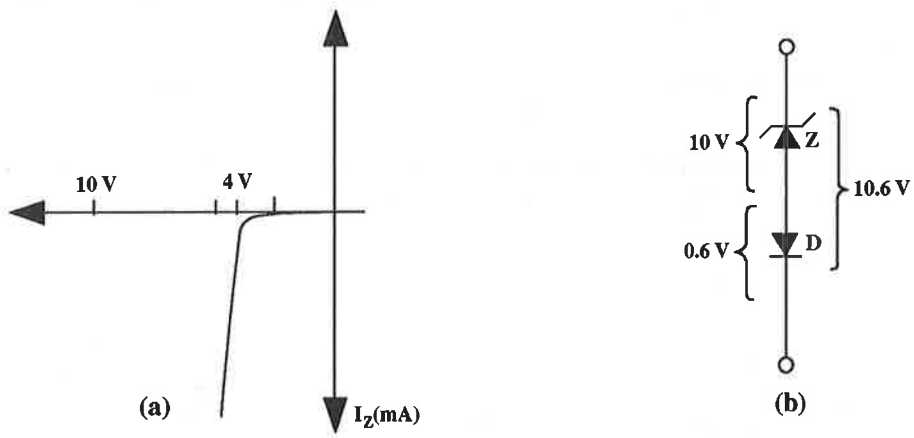


FIGURE 3-5

CONDITIONS OF ZENER REGULATIONS

Varying the power supply of the circuit of Figure 3-6(a) from 5 V to 30 V will bring the zener diode from a non-regulated to fully regulated condition, as shown in the graph of Figure 3-6(b).

NON- REGULATED CONDITIONS

With V_{PS} at 5 V, the zener diode is not in regulation (point d) and acts like any general purpose reverse-biased diode, so the current flow through the device is extremely low and the voltage drop across the device is about 5 V. Then, as the power supply voltage approaches 10 V the zener remains out of regulation (point c), little or no current flows through R and the zener, and the voltage drop across the zener diode is approximately equal to the power supply voltage.

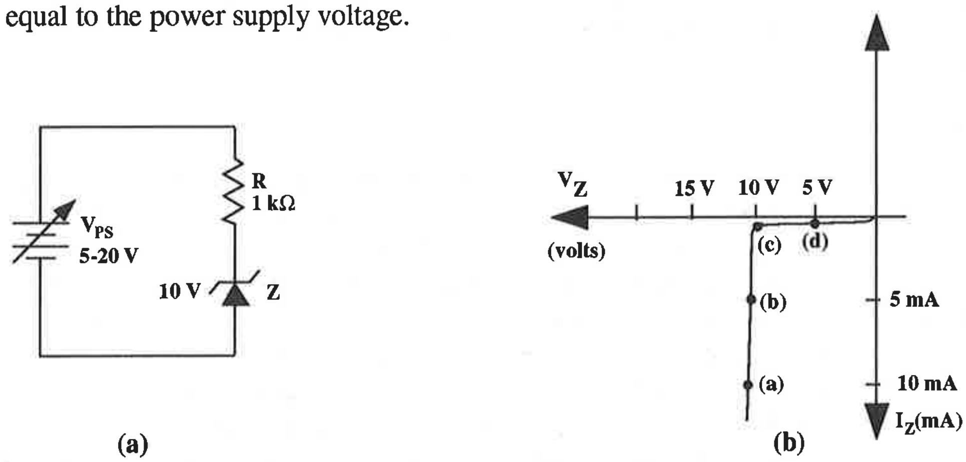
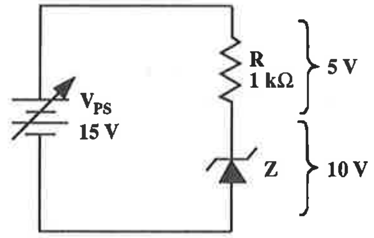


FIGURE 3-6

REGULATED CONDITIONS

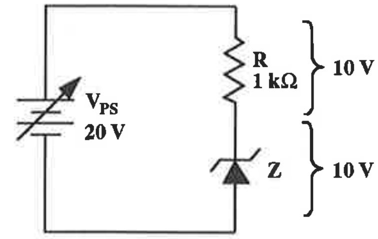
When the power supply voltage is increased to 15 V, current flows in the zener. It is in regulation and operates at 10 V and 5 mA (point b). The power dissipated is 50 mW. When the current through the diode is increased to 10 mA (point a), the power dissipated by the device is 100 mW. The calculations are shown solved in conjunction with the circuits of Figure 3-7.



$$I_{R1} = \frac{V_{PS} - V_Z}{R} = \frac{15\text{ V} - 10\text{ V}}{1\text{ k}\Omega} = 5\text{ mA}$$

$$P_Z = I_R V_Z = 5\text{ mA} \times 10\text{ V} = 50\text{ mW}$$

(a) V_{PS} = 15 V



$$I_{R1} = \frac{V_{PS} - V_Z}{R} = \frac{20\text{ V} - 10\text{ V}}{1\text{ k}\Omega} = 10\text{ mA}$$

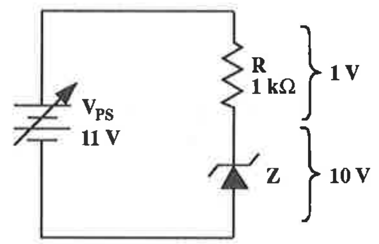
$$P_Z = I_R V_Z = 10\text{ mA} \times 10\text{ V} = 100\text{ mW}$$

(b) V_{PS} = 20 V

FIGURE 3-7

ZENER DIODE LIMITATIONS

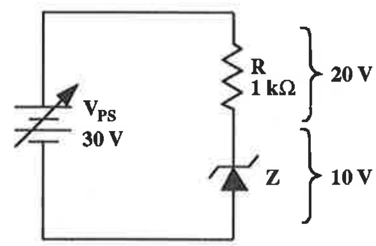
The limitations of zener diodes is determined by the minimum current (≈1 mA) that keeps the device in regulation and its maximum power. For example, if the zener voltage is 10 V and the series resistor 1 kΩ, then the power supply voltage can be as low as 11 V to maintain at least 1 mA of current flow through the device, as shown solved in conjunction with the circuit Figure 3-8(a). However, if the maximum power dissipation of the device is 200 mW, then the maximum current through the zener diode is 20 mA, which limits the power supply voltage to 30 V, as shown solved in conjunction with the circuit of Figure 3-8(b).



$$I_R = \frac{V_{PS} - V_Z}{R} = \frac{11\text{ V} - 10\text{ V}}{1\text{ k}\Omega} = 1\text{ mA}$$

$$P_Z = I_R V_Z = 1\text{ mA} \times 10\text{ V} = 10\text{ mW}$$

(a) V_{PS} = 11 V



$$I_R = \frac{V_{PS} - V_Z}{R} = \frac{30\text{ V} - 10\text{ V}}{1\text{ k}\Omega} = 20\text{ mA}$$

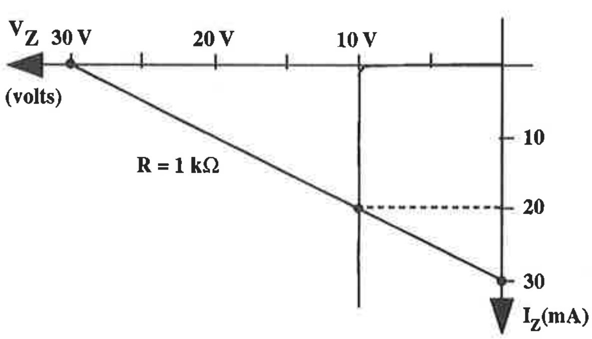
$$P_Z = I_R V_Z = 20\text{ mA} \times 10\text{ V} = 200\text{ mW}$$

(b) V_{PS} = 30 V

FIGURE 3-8

GRAPHICAL SOLUTION USING DC LOAD LINES

The load line of Figure 3-9 provides a graphical solution for the zener diode circuit of Figure 3-8(b). On the load line, $I_{(max)}$ is determined by the V_{PS} voltage and the R resistance which intersects the diode curve at the V_Z versus I_Z operating point. Thus, $I_{(max)}$ = 30 mA and the V_Z of the zener diode is 10 V. So the load line intersects the 10 V reference voltage at the $I_R = I_Z$ current condition of 20 mA, as shown in Figure 3-9.



$$I_{(max)} = \frac{V_{PS}}{R} = \frac{30\text{ V}}{1\text{ k}\Omega} = 30\text{ mA}$$

$$V_R = V_{PS} - V_F = 30\text{ V} - 10\text{ V} = 20\text{ V}$$

$$I_Z = I_R = \frac{V_R}{R} = \frac{20\text{ V}}{1\text{ k}\Omega} = 20\text{ mA}$$

FIGURE 3-9

PERCENT REGULATION OF ZENER DIODES

Zener diodes like all components have a percent tolerance and the percent tolerance is typically in the 5% to 20% range. Therefore, if a 10 V zener has a 5% tolerance, the reference voltage can be between 9.5 V and 10.5 V and still be within the tolerance limits of the device.

LOADED CONDITIONS OF THE ZENER DIODE CIRCUIT

Placing a 2 kΩ load resistor across the zener diode, as shown in the circuit of Figure 3-10, causes the current through the R1 resistor to be shared by both the diode and the load resistor. In this connection, I_{R1} = 20 mA and the I_{RL} = 5 mA. So, I_Z = 15 mA, as shown solved in conjunction with the circuit of Figure 3-10.

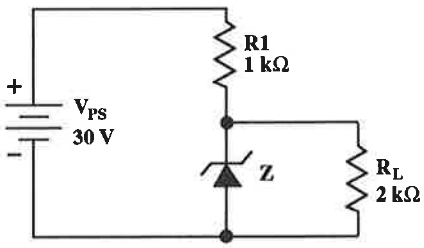


FIGURE 3-10

$$R_L = 2\text{ k}\Omega$$

$$I_{R1} = \frac{V_{PS} - V_Z}{R1} = \frac{30\text{ V} - 10\text{ V}}{1\text{ k}\Omega} = 20\text{ mA}$$

$$I_{RL} = V_{RL}/R_L = 10\text{ V}/2\text{ k}\Omega = 5\text{ mA}$$

$$I_Z = I_{R1} - I_{RL} = 20\text{ mA} - 5\text{ mA} = 15\text{ mA}$$

$$P_Z = I_Z V_Z = 15\text{ mA} \times 10\text{ V} = 150\text{ mW}$$

Lowering load resistor across the zener diode to 1 kΩ causes the current through the R1 resistor to remain at 20 mA and I_{RL} to increase to 10 mA. So, I_Z = 10 mA, as shown solved in conjunction with the circuit of Figure 3-11.

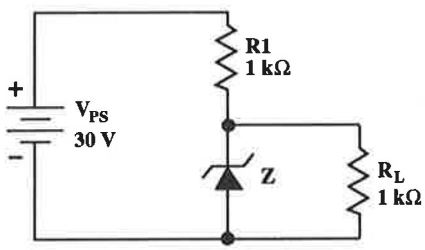


FIGURE 3-11

$$R_L = 1\text{ k}\Omega$$

$$I_{R1} = \frac{V_{PS} - V_Z}{R1} = \frac{30\text{ V} - 10\text{ V}}{1\text{ k}\Omega} = 20\text{ mA}$$

$$I_{RL} = V_{RL}/R_L = 10\text{ V}/1\text{ k}\Omega = 10\text{ mA}$$

$$I_Z = I_{R1} - I_{RL} = 20\text{ mA} - 10\text{ mA} = 10\text{ mA}$$

$$P_Z = I_Z V_Z = 10\text{ mA} \times 10\text{ V} = 100\text{ mW}$$

OUT OF REGULATION CONDITIONS

Reducing the load resistor value across the zener diode to 500 Ω causes the current through the R1 resistor to remain at 20 mA. However, I_{RL} = 20 mA, so I_Z = 0.0 mA and the zener is out of regulation, as shown in the calculation in conjunction with the circuit of Figure 3-12

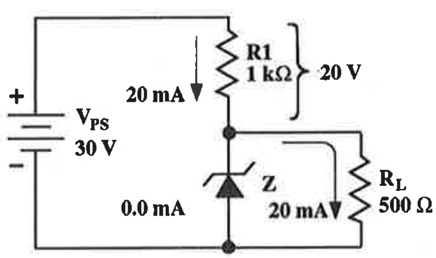


FIGURE 3-12

$$R_L = 500\ \Omega$$

$$I_{R1} = \frac{V_{PS} - V_Z}{R1} = \frac{30\text{ V} - 10\text{ V}}{1\text{ k}\Omega} = 20\text{ mA}$$

$$I_{RL} = V_{RL}/R_L = 10\text{ V}/500\ \Omega = 20\text{ mA}$$

$$I_Z = I_{R1} - I_{RL} = 20\text{ mA} - 20\text{ mA} = 0.0\text{ mA}$$

Further reducing the load resistor lowers the output voltage, where the zener diode has no effect on the circuit. Essentially, once out of regulation, the zener diode acts like any reverse biased general purpose diode with a resistance of 1 MΩ or higher. So the zener resistance can be safely ignored in the calculations. Therefore voltage divider equations can be used to solved V_{RL} using the values of R1 and R_L, and V_{PS}. Then I_{R1} and I_{RL} are solved at 24 mA and I_Z at 0.0 ma, as shown solved in conjunction with Figure 3-13.

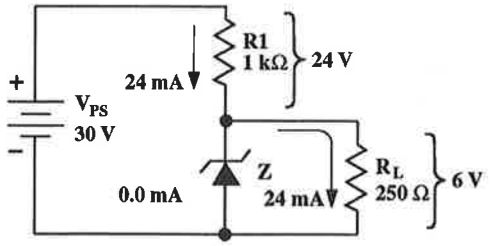


FIGURE 3-13

$$R_L = 250\ \Omega$$

$$V_{RL} = \frac{V_{PS} \times R_L}{R1 + R_L} = \frac{30\ V \times 250\ \Omega}{1\ k\Omega + 250\ \Omega} = 6\ V$$

$$I_{RL} = V_{RL}/R_L = 6\ V/250\ \Omega = 24\ mA$$

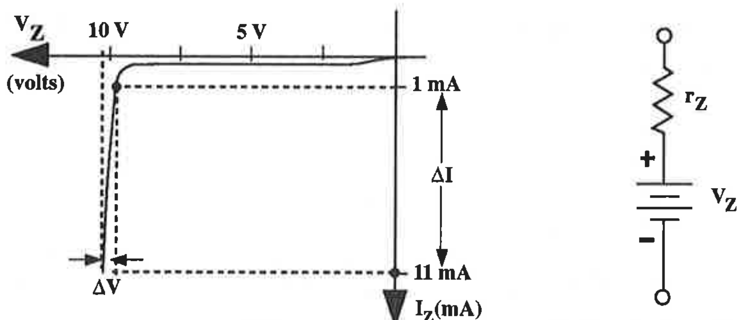
$$I_{R1} = \frac{V_{PS} - R_L}{R1} = \frac{30\ V - 6\ V}{250\ \Omega} = 24\ mA$$

$$I_Z = I_{R1} - I_{RL} = 24\ mA - 24\ mA = 0.0\ mA$$

DYNAMIC (ac) RESISTANCE OF ZENER DIODES

In practice, the ac (dynamic) resistance of reverse-biased zener diodes is generally less than 100 Ω, and mathematically is solved from $r_{ac} = \Delta V/\Delta I$. For ideal zener diodes the voltage remains the same for all current conditions. However, in practice, zener diodes have bulk resistance. So, as the current through the zener is increased, the voltage developed across the bulk resistance increases, causing the overall voltage of the zener to increase. The increase in the overall zener voltage is noted in the slope of the zener breakdown response of Figure 3-14(a).

The equivalent circuit of a zener diode circuit is shown in Figure 3-14(b). In this circuit, if the zener diode voltage is 9.9 V at 1 mA and 10 V at 11 mA, the dynamic resistance of the zener diode is 10 Ω, as shown solved in conjunction with Figure 3-14(b).



$$r_Z = \frac{\Delta V}{\Delta I} = \frac{10\ V - 9.9\ V}{11\ mA - 1\ mA}$$

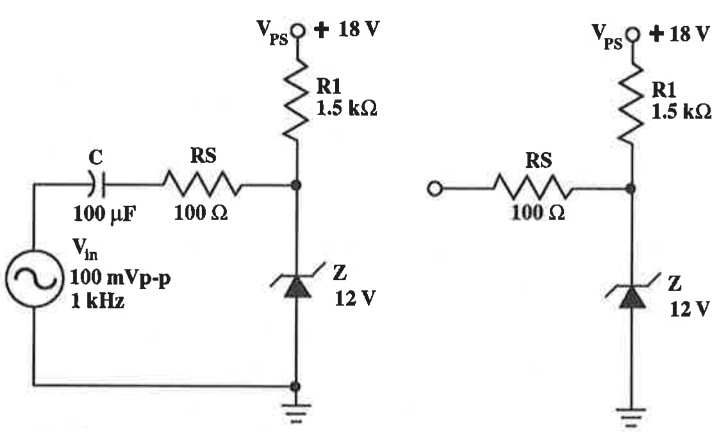
$$= \frac{0.1\ V}{10\ mA} = \frac{100\ mV}{10\ mA} = 10\ \Omega$$

(a) (b) Equivalent Circuit for the Zener

FIGURE 3-14: Dynamic resistance of the zener.

COMBINED dc-ac ANALYSIS OF REVERSE-BIASED ZENER CIRCUIT

In the circuit of Figure 3-15(a), V_{PS} = 18 V, the ac input signal voltage v_{in} = 100 mVp-p, RS = 100 Ω, and R1 = 1.5 kΩ. The dynamic resistance is 10 Ω and V_Z is 12 V. The equivalent dc circuit and the dc current through the zener diode is solved in conjunction with Figure 3-15(b). Also, capacitor C is an effective short to the ac signal and an open to the dc. So, no dc current flows through and no voltage is dropped across RS.



$$V_{R1} = V_{PS} - V_Z = 18\ V - 12\ V = 6\ V$$

$$I_Z = I_{R1} = V_{R1}/R1 = 6\ V/1.5\ k\Omega = 4\ mA$$

$$V_{RS} = I_{RS} \times RS = 0.0\ mA \times 100\ \Omega = 0.0\ V$$

$$X_C = \frac{1}{2\pi fC}$$

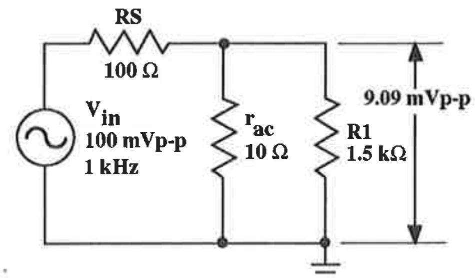
$$= \frac{1}{2\pi \times 1\ kHz \times 100\ \mu F} = 1.59\ \Omega$$

(a) Combined Circuit (b) DC equivalent circuit

FIGURE 3-15

AC CONSIDERATIONS

The ac resistance of the zener was solved at 10 Ω and, although R1 is in parallel with the ac resistance of the forward biased diode, it is relatively high in value with respect to the r_{ac} and has little effect on the output sinewave voltage. So, $r_{eq} = r_{ac} \parallel R1$, which is approximately equal to r_{ac}. So, r_{ac} is used in the analysis and is shown solved in conjunction with Figure 3-16.



AC Equivalent Circuit

$$r_{ac} = 10\ \Omega$$

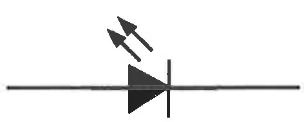
$$R_{eq} = R1 \parallel r_{ac} = 1.5\ k\Omega \parallel 10\ \Omega = 9.99\ \Omega \approx 10\ \Omega$$

$$v_{op\text{-}p} = \frac{v_{in} \times r_{ac}}{RS + r_{ac}} = \frac{100\ mVp\text{-}p \times 10\ \Omega}{100\ \Omega + 10\ \Omega} \approx 9.09\ mVp\text{-}p$$

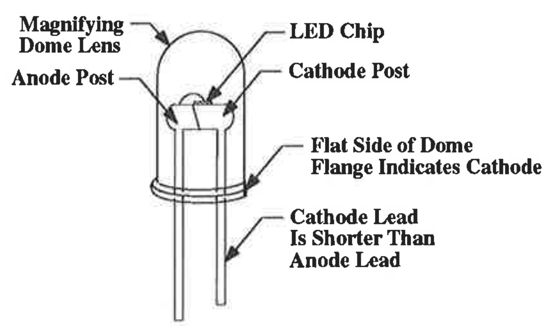
FIGURE 3-16

LIGHT EMITTING DIODES (LEDS)

Light emitting diodes (LEDs) are solid state devices that are small, lightweight, rugged, and operate at low voltages. They generally are used as indicator lights on the panels of electronic equipment. Commercially, LEDs are available in red, yellow, orange, green and blue and, because they are solid state, they have an operating life in excess of 100,000 hours. The symbol for the LED is shown in Figure 3-17(a) and the basic construction of a common LED is shown in Figure 3-17(b). Like silicon diodes, LEDs have an anode and a cathode. The anode is the longer of the two leads and the cathode is located closest to the flat edge of the dome flange.



(a) LED Symbol



(b) Plastic LED

FIGURE 3-17

LED CHARACTERISTICS

Forward-biased, general-purpose diodes convert energy into heat when electrons combine with a holes, but light emitting diodes convert energy into light when electrons combine with holes. The LED characteristic curve is similar to that of PN-junction diodes, but LEDs require a higher forward bias voltages (V_F), typically in excess of 1.6 V. The forward biased currents are typically in excess of 15 mA. Red has the lowest forward voltage, followed by yellow, green, and blue as shown in Figure 3-19(b). However, the reverse voltage breakdown (V_{BR}) of LEDs is low, typically lower than 5 V and exceeding the reverse breakdown voltage can damage the device.

Light emitting diodes are constructed from various mixes of trivalent (three valence) and pentavalent (five valence) electron elements to produce a PN semiconductor that emits energy in the form of light. Depending on the mix, an LED can emit light that ranges between infrared to ultraviolet. Examples of three valence electron elements are gallium (Ga) and aluminum (Al). Examples of five valence electron elements are phosphorous (P) and arsenic (As).

Typical combinations in the construction the LEDs chips are gallium arsenide(GaAs) that produces an infrared diode which is not visible to the human eye. However, mixes visible to the human eye are gallium phosphide (GaP) that produces red and green light, and gallium arsenide phosphide (GaAsP) that produces