# Contents

# 1

# *Introduction*

Electronic circuits utilize a multitude of components in a variety of interconnections to perform important and useful processes on electrical signals. A low-pass filter, for instance, removes the high-frequency components from a signal by an appropriate combination of passive elements, that is, resistors, capacitors, and inductors. An amplifier usually converts energy from a d.c. source into a large a.c. signal that reproduces a smaller a.c. reference signal. Amplifier circuits employ an appropriate combination of passive elements and at least one *active* element such as a transistor. In every case, circuits, whether they be discrete or integrated, are made up of passive and/or active components. Each element or device in an electronic circuit is characterized by its conductive property, a relationship that describes the current that flows through it in response to the voltage that is applied across it. The current-voltage relationship of a component or device can be used to develop models describing its characteristic behavior. Other models can be developed based on an understanding of the physical processes that underlie the conduction effects in the device. It is an understanding of the models of circuit elements that permits the engineer to analyze and to design circuits for specific applications. In many instances, as, for example, in integrated circuits, the terminals of a device may not be accessible for the measurement of a current-voltage characteristic. In these cases modeling of the device depends totally on a knowledge of the physics of the conduction processes. And competence in analysis or design in all cases depends on the accuracy and effectiveness of the models.

This book is an introduction to the physical processes in nature that have been and will continue to be utilized by engineers to create useful electronic devices. Our study will emphasize the relationships among the fundamental processes and the conduction properties of common devices so that the engineer may better understand not only the characteristic operation of devices but also their inherent capabilities and limitations.

Of the many components of electronic circuits, this book will not be very much concerned with the linear passive elements of resistors, capacitors, and inductors. These elements, characterized by their properties of resistance, capacitance, and inductance, respectively, are familiar to students who have studied an introductory course in circuits. The relationship between current and voltage for each of these components can be expressed analytically in the form of a linear differential equation. For a resistor, for example, the relationship is $I = (V/R)$, where $I$ is the current through the resistor, $V$ is the voltage drop across it, and $R$ is the resistance. The behavior of networks of these elements can be analyzed using highly developed techniques that utilize linear mathematics. Application of Kirchhoff's current and voltage laws are two such techniques. The properties of capacitance and inductance are usually studied in an introductory course in electricity and magnetism. The property of resistance, or its inverse, conductance, is of importance not only in resistors but also in all other devices. Therefore we shall study this property in some detail.

The primary emphasis in this book will be on the operational characteristics of nonlinear devices that include passive diode switches and active amplifiers such as junction and field-effect transistors. It is the nonlinear devices that make possible the fascinating variety of signal-processing techniques that characterize modern electronics. For these elements the relationships between current and voltage are complex and depend critically on internal physical processes. Usually the current-voltage relationships are too complicated to express even in terms of a nonlinear equation. And if it were possible to write equations, their analytical solution would probably not be possible because nonlinear mathematics is not well developed. In lieu of nonlinear equations and analytical solutions, engineers have developed graphical displays and techniques of solution. A graphical display of a current-to-voltage relationship is called a *current-voltage characteristic curve* or $I$-$V$ characteristic. Each element has its own $I$-$V$ characteristic. In addition, computers can be employed to analyze and to design nonlinear networks by manipulating numerical data.

In this chapter we shall consider examples of ideal and real $I$-$V$ characteristics as well as common methods of analysis of circuit problems with nonlinear elements. We shall also introduce the concept of an integrated circuit. The objective in this chapter is to place in perspective the work of the remainder of the book and to indicate why an understanding of the physical processes of electronics is important not only to those engineers who build devices but also to those who use them. The need for such an understanding becomes apparent when we compare idealized and realistic characteristics of devices and when we attempt to model their behavior in both discrete and integrated circuits.

## 1.1 MODELING ELECTRONIC ELEMENTS AND DEVICES

A nonlinear element in a simple circuit that otherwise would be linear is shown in Fig. 1-1. The relationship, either analytical or graphical, between

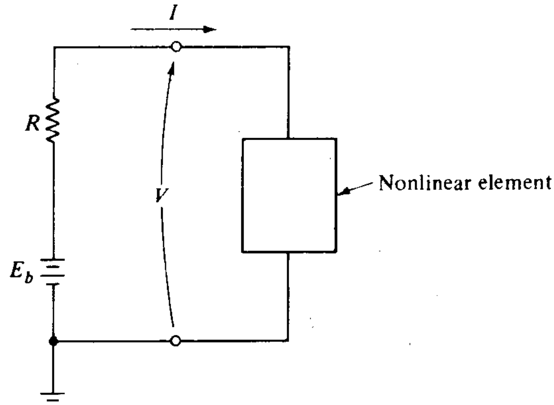


**Fig. 1-1** Nonlinear element in a simple circuit.

the current flowing into the terminals of the device and the voltage difference between the terminals is called its *terminal characteristic*. Hypothetical devices that perform specialized functions in circuits can be described by idealized characteristics. How useful a real device is depends, after economic considerations, largely on how its $I$-$V$ characteristic resembles or differs from the ideal and over what range of a parameter such as frequency or power level the device maintains that characteristic behavior.

### A Switch

In an electronic circuit a switch is a device that is either opened or closed. When closed the ideal switch short-circuits its terminals; that is, any current can flow with no potential drop evident. When open, the ideal switch prohibits current flow for whatever voltage might be applied. An ideal diode is a switch that is open when the voltage across its terminals is negative in the sense of Fig. 1-1 and that is closed otherwise. The $I$-$V$ characteristic of an idealized diode switch and its conventional circuit representation are shown in Fig. 1-2. A variety of real devices have terminal characteristics sufficiently like the ideal diode to be useful. Among these are vacuum diodes, gaseous diodes, *p-n* junction semiconductor diodes, Schottky barrier diodes, and silicon-controlled rectifiers (SCRs). The current-voltage characteristic of a typical *p-n* junction diode is sketched in Fig. 1-3. Notice how this character-

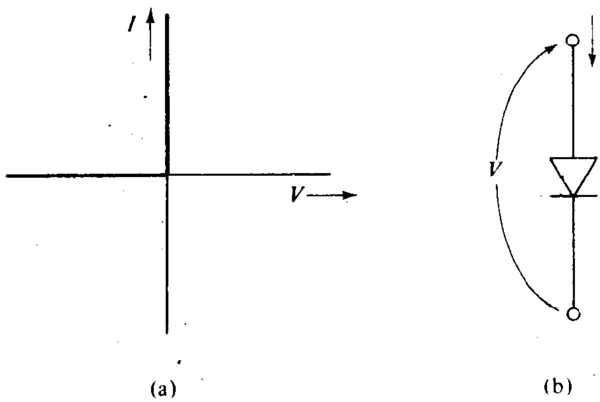


**Fig. 1-2** Ideal diode: (a) *I-V* characteristic, (b) circuit representation.

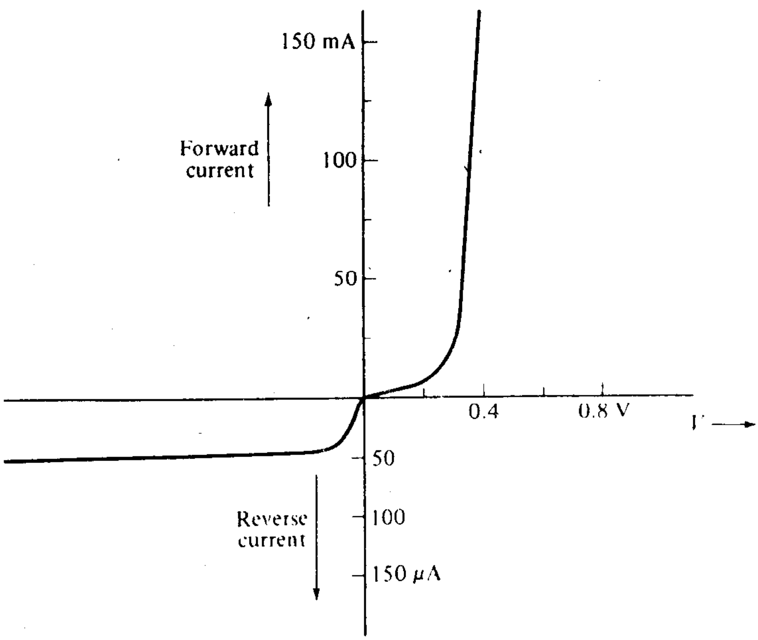


**Fig. 1-3** Characteristic of a typical real *p-n* junction diode (note change in scale for reverse current).

istic differs from the ideal. For negative voltages, called the *reverse direction*, some current does flow: The device is not a perfect open circuit. The device is not a perfect short circuit either since a finite potential drop appears between the terminals for a given forward current. Just what internal processes give rise to these characteristics, how they determine the nonideality of the device, and how they effect the range and limitations of the performance of the device are the questions we plan to answer in our study.

#### An Amplifier

Another useful functional operation in circuits is amplification. An ideal amplifier is a device the output of which is a magnified reproduction of some reference signal. Since amplifiers must have a reference or input signal and an output signal, they can be represented as a two-port device as in Fig. 1-4(a). In practice, two of the terminals of the two-port device are frequently common so that the three-terminal representation of Fig. 1-4(b) is also used.

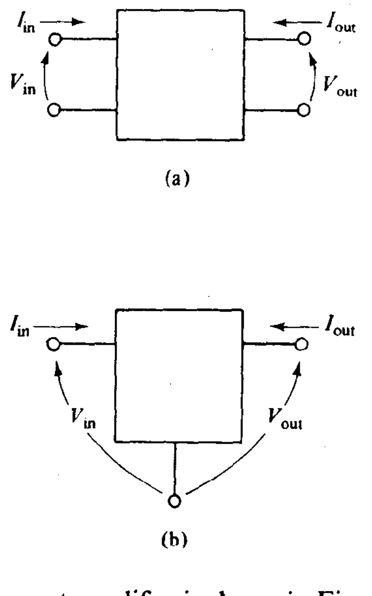


Fig. 1-4 Amplifier: (a) two-port representation, (b) three-terminal representation.

The ideal *I-V* characteristic of a current amplifier is shown in Fig. 1-5(a). The output current-voltage relationship is plotted for selected values of input current. By contrast, Fig. 1-5(b) indicates the output or collector characteristic of a typical transistor in what is called the *common-emitter configuration*. Notice that the characteristics of the real device do not extend to very low values of output voltage. Notice, also, that each curve has a nonzero slope everywhere, in contrast to the idealized curves. Last, notice that an output exists with no input. The terminal characteristics of this real device, as with the diode, arise as the result of internal properties and processes. We can

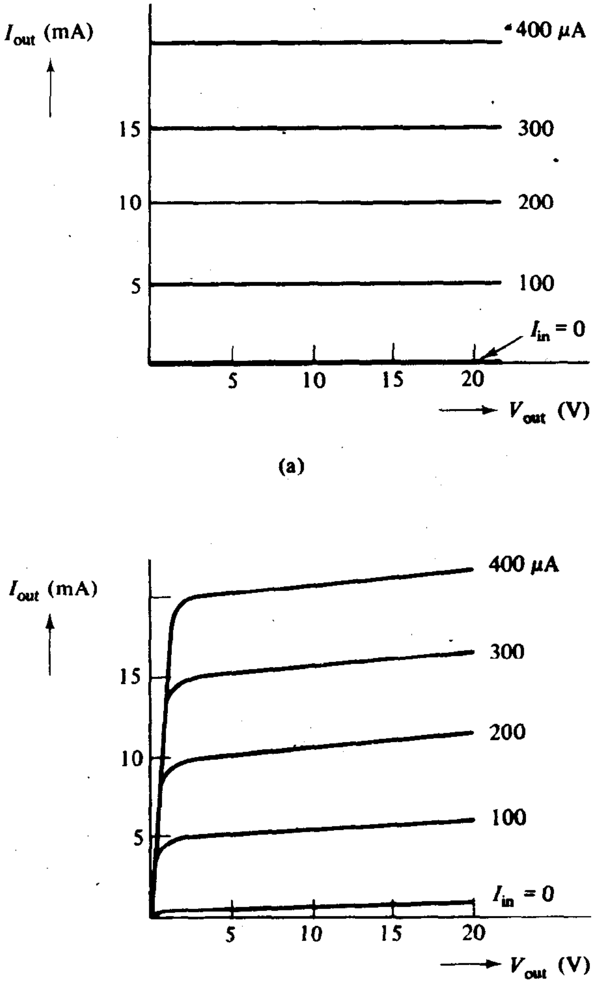


**Fig. 1-5** Characteristics of a current amplifier: (a) ideal, (b) typical transistor in a common-emitter configuration.

understand the characteristic and the circuit models developed from them only by an examination of these properties and processes.

As an example of models of a familiar circuit element, consider the resistor. The terminal characteristic of an idealized resistor can be expressed analytically as $I = (V/R)$ or graphically as in Fig. 1-6(a). Three equivalent models of a practical resistor are shown in Fig. 1-6(b). One of these is that of the idealized circuit element and is valid at low frequencies. Depending on

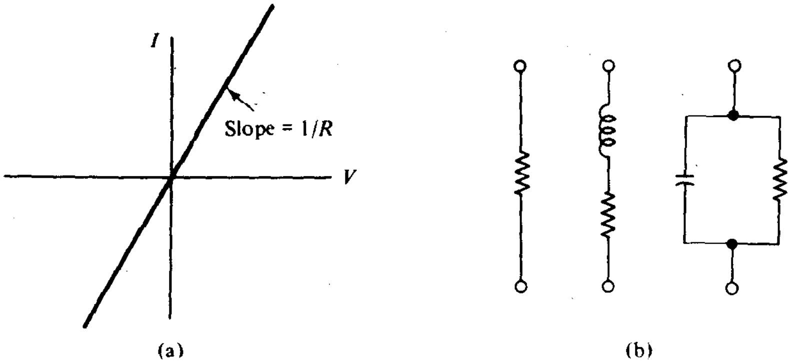


**Fig. 1-6** Resistor: (a) low-frequency terminal characteristics, (b) circuit models.

the physical construction of the resistor, one of the other two models may be required if the signal frequencies are sufficiently high. For example, a resistor may be made from a long piece of resistive wire coiled into a small package in which case the inductance of the coil becomes important at high frequencies. Alternatively, a low-inductance resistor can be made, but it may evidence capacitive effects at high frequencies.

And so it is with every circuit element. The model used to represent its behavior in a circuit depends on its physical construction and the application to which it is put.

## 1.2 NONLINEAR DEVICES IN D.C. CIRCUITS

Analysis of circuits using nonlinear elements with d.c. currents and voltages can be accomplished by using a graphical technique known as *load line analysis.* The technique consists of determining the current-voltage characteristic of the linear part of the circuit and superimposing that curve on the *I-V* characteristic of the nonlinear element. The current-voltage curve of the linear part of the circuit will always be a straight line. Since the linear part represents a load on the nonlinear element, its characteristic is called the load line. The state of the circuit is determined by the point at which the two curves intersect, the point of intersection being the simultaneous solution of the equations that represent both parts of the circuit.

As an example of the technique, let us consider the simple circuit of Fig. 1-1 with a *p-n* junction diode as the nonlinear element. In such a series circuit, the current is of primary interest because the same current flows through each element.

The current-voltage relationship for the diode is given in Fig. 1-3. The current-voltage relationship for the rest of the circuit is a straight line since the resistor is a linear device. All that is required to sketch the load line are two points on the line. The easiest conditions to determine are the one for which no current flows through the circuit and the one for which no voltage appears across the terminals of the diode, that is, the one for which sufficient current flows so that the $IR$ drop across the resistor equals the battery voltage. These two points are shown in Fig. 1-7. The linear characteristic is the

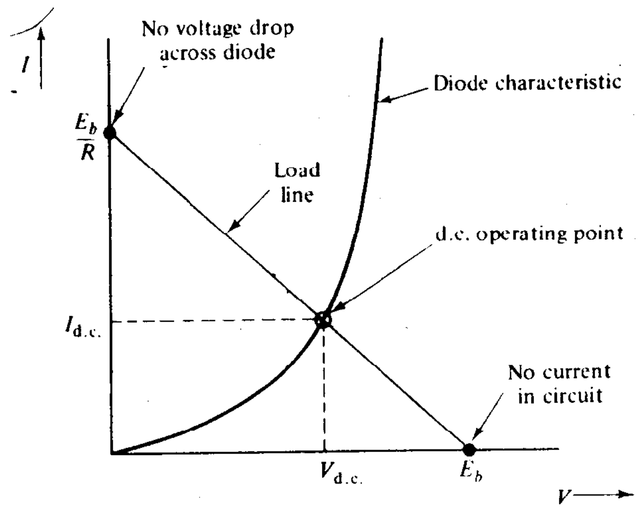


Fig. 1-7 Load line analysis for the circuit of Fig. 1-1 using the characteristics of the diode of Fig. 1-3.

line joining these two points and is shown superimposed on the forward characteristic of the diode. The load line represents all possible terminal current-voltage combinations for the battery in series with the resistor. It is the graphical representation of the relationship $V = E_b - IR$. But only one operating condition for the battery and resistor corresponds to a possible operating condition for the diode. The operating condition for the whole circuit is the intersection of the two curves and is called the *d.c. operating point* or the *quiescent operating point*. The current that flows in the circuit is $I_{d.c.}$ and the voltage drop across the diode is $V_{d.c.}$, as indicated in Fig. 1-7.

## 1.3 NONLINEAR DEVICES IN A.C. CIRCUITS

The currents and voltages in electronic circuits have both d.c. and a.c. components in general. A circuit, then, will have a quiescent operating condition corresponding to the average currents and voltages. But the currents and voltages will deviate from their averages as the a.c. components of the signals. Analysis of the response of a circuit with nonlinear elements to a.c. signals depends on the $I$-$V$ characteristics of the devices, the internal processes that give rise to the characteristics, and the magnitude and frequency of the a.c. signal.

The quiescent operating conditions of the output circuit of an amplifier of the type represented in Fig. 1-4 can be determined using the load line technique, where the load line in this instance is the current-voltage relationship for the linear circuit loading the output terminals of the amplifier. An example of such a load line analysis is shown in Fig. 1-8(a), where the nonlinear device is the common-emitter transistor of Fig. 1-5(b). Notice that in this case there are very many possible d.c. operating conditions for the output circuit, depending on the value of the d.c. component of the input current. Figure 1-8 indicates, for example, that if the input current is 250 $\mu$A, the d.c. output current and voltage are the coordinates of the point $Q$.

### Low-Frequency Signals

When a low-frequency a.c. signal is added to the d.c. input current the operating condition of the output circuit changes in response to the instantaneous value of the input current. The instantaneous operating point is confined to the load line for a resistive output circuit. Figure 1-8(b) shows a magnified view of the region around the quiescent operating point $Q$. The shaded bars indicate the ranges of input current and output current and voltage for an a.c. input current of amplitude 20 $\mu$A.

If the amplitude of the a.c. input signal is sufficiently small, the instantaneous operating point for the output may sample only a small portion of the $I$-$V$ characteristic, which can be approximated by equally spaced parallel straight lines. Under these conditions the a.c. output current will be linearily related to the a.c. input, and the device operates as a linear element for the a.c. signal. Just such a condition is represented in Fig. 1-8(b). By analyzing the $I$-$V$ characteristic in the vicinity of $Q$, it is possible to devise a small-signal linear equivalent circuit composed of an ideal amplifier and resistors that simulates the behavior of the real circuit in response to the incremental a.c. signals. The validity of an incremental equivalent circuit analysis is restricted to small perturbations about the quiescent point, where *small* is determined by the linearity of the $I$-$V$ characteristic in the vicinity of the quiescent operating point. For a larger signal the instantaneous operating point samples regions of the characteristic where a linear relationship no longer holds and the analysis is much more complicated.

### High-Frequency Signals

The response of a circuit with a nonlinear element such as an amplifier to a.c. signals at high frequencies is complicated in two ways. First, the load line characteristic of the linear portion of the circuit will depend on frequency

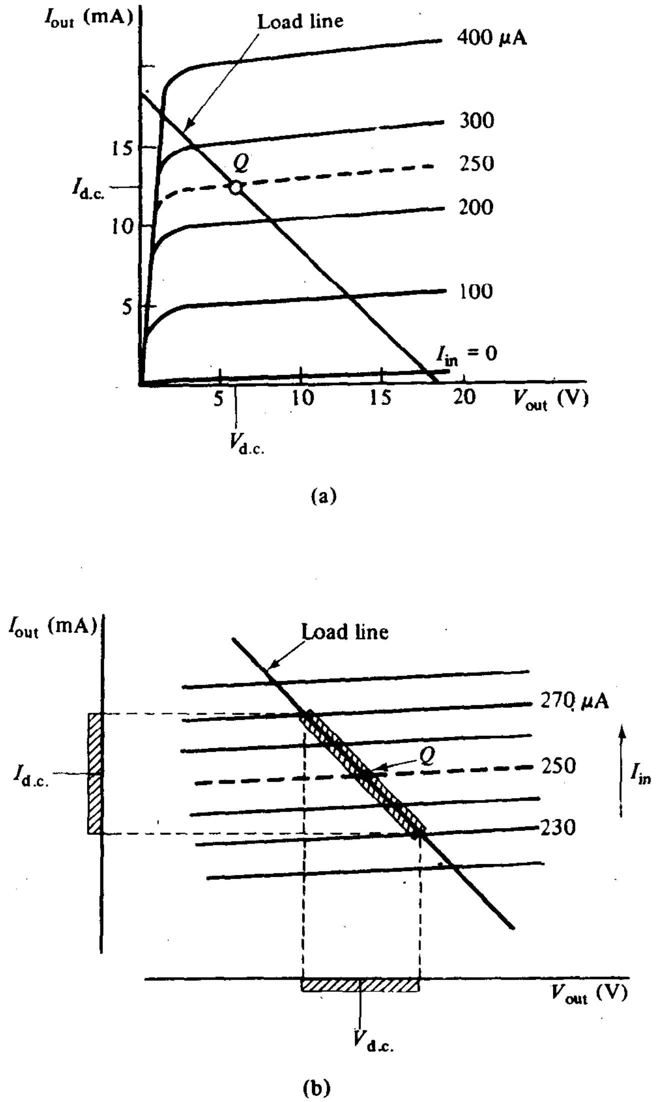


**Fig. 1-8** *Load line analysis for the output circuit of a common-emitter transistor: (a) determination of the quiescent operating point, (b) magnified view of the vicinity of Q.*

if there are capacitors and inductors in the circuit. Second, the relationship between the current and voltage of the nonlinear device at high frequency differs from the d.c. or low-frequency $I$-$V$ characteristic. In fact, what we mean by high frequencies are those frequencies at which deviations from low-frequency behavior occur. All is not lost, however, provided we understand what phenomena within the device itself cause the high-frequency deviations. If we understand the device physics, we shall still be able to devise a high-frequency incremental equivalent circuit by adding frequency-dependent elements to the low-frequency incremental circuit. An example of such a high-frequency circuit is the hybrid-$\pi$ model, which will be introduced in Chapter 10. The added elements must be properly chosen to reflect the physical behavior of the device. An example of a high-frequency effect is the delay caused by the finite time required for electrons to traverse the device. This effect can be simulated in a circuit model by a capacitance called the *transit-time capacitance*.

Clearly, an understanding of the internal processes within a device is of great importance in the development and utilization of small-signal a.c. models for electronic devices. The internal physical processes determine not only the parameters of such an equivalent circuit model but also, and very importantly, the limitations of the device itself. The rest of this book, then, is devoted to the development of an understanding of the physical processes that determine the electrical properties of devices. While the emphasis will be on modern devices in widespread use, the underlying physical principles that we shall study are valid and are applicable to present-day devices that we shall not be able to study because of space limitations and to future conduction devices that have yet to be invented.

## 1.4 INTEGRATED CIRCUITS

A simple picture of an integrated circuit (IC) is a single piece of solid-state material such as a crystal of a semiconductor in which very many passive and active circuit elements have been formed. A detailed discussion of integrated circuits is presented in Chapter 12 based on the material on solid-state electronics of Chapters 6–11. Commonly, resistors, capacitors, diodes, and transistors occupy well-defined adjacent regions of the integrated device. The IC also includes as part of the structure interconnecting leads between the regions where the various circuit functions are performed on signals. Thus an IC is a complicated network constructed as a whole and is essentially indivisible. Because of the very small size of integrated circuits, only a limited number of connections can be made to an external circuit. In contrast, a discrete circuit is composed of individual elements manufactured separately and thereafter connected together in some fashion. The elements of a discrete circuit are individually available for testing and for measurement of their terminal characteristics. This is not true of integrated circuits.

Yet an integrated circuit is more than a discrete circuit transposed and manufactured in integrated form. Practical problems arise that are not confronted by the designer of discrete circuits. For example, inductors are difficult to make in integrated form so that generally they must be avoided in the design or their circuit function must be simulated by networks of active and passive elements. Additional examples of complications in integrated circuits are the problems of isolating neighboring regions of the device from one another electrically and of providing interconnecting conductive paths between the proper elements. In both cases the techniques used to accomplish isolation and interconnection introduce effects that complicate the behavior of the system as a whole. Modeling these effects depends on an understanding of physical processes since specific portions of the IC may not be available for measurement. It is important to recognize these complications and their effects on the performance of the IC both in design and in application. For example, an IC utilizing reversed-biased *p-n* junctions for isolation will not perform as well at high frequencies as one that employs a beam-lead isolation technique. A discussion of details of IC fabrication and techniques of isolation and interconnection is presented in Chapter 12.

In addition to restrictions and complications in design, integrated circuits offer new opportunities to the circuit designer. First, very large numbers of elements, active and passive, can be fabricated in a very small volume of the solid-state material. Furthermore, many identical integrated circuits can be produced at the same time; that is, they may be batch-processed. Thus the equivalent network of devices can be extremely complicated at very modest cost. For example, filters can be constructed without using inductors by simulating their function using active elements in conjunction with resistors and capacitors. Second, circuit elements exist in integrated form that have no practical counterparts in discrete form. Among these are multi-emitter, lateral, and thin-film devices.

It is clear from the foregoing discussion that integrated circuits present problems of understanding and modeling that are difficult if not impossible to surmount without a clear picture of what physical processes contribute to the conductive properties of such devices. On the other hand, the fundamental physical processes of conduction occur in all electronic systems including vacuum and gaseous devices as well as the solid-state forms. We shall therefore first develop the principal concepts that we shall need for an understanding of all electronic devices in simple classical systems before proceeding to the more complicated quantum mechanical problems of solid-state electronics.

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## PROBLEMS

**1-1.** (a) An approximation to the forward *I-V* characteristic of the *p-n* junction diode of Fig. 1-3 can be made by drawing segments of straight lines so that they resemble the real curve. Sketch such an approximate characteristic using two straight lines.

(b) Devise an equivalent circuit composed of a battery, a resistor, and an ideal diode that has this approximate *I-V* characteristic. Indicate the values of the battery voltage and the resistance.

**1-2.** A voltage-controlled current source is a two port device whose output current depends on its input voltage. Sketch an ideal *I-V* characteristic for such a device.

**1-3.** A voltage-controlled voltage source is a two port device whose output voltage depends on its input voltage. Sketch an ideal *I-V* characteristic for such a device.

**1-4.** The current gain is defined as the ratio of the change in output current to the change in input current. What is its value for the ideal amplifier of Fig. 1-5?

**1-5.** Write an equation for the voltage at the terminal of the nonlinear element in Fig. 1-1 in terms of the current flowing through the resistor. From this expression, plot the current as a function of voltage.

**1-6.** Modify the circuit of Fig. 1-1 to include a low-frequency sinusoidal voltage source $e(t)$ in series with the battery. Take the nonlinear element to be the diode of Fig. 1-3. Use graphical techniques to indicate the instantaneous diode current and voltage.

**1-7.** For the device of Fig. 1-8(a), find the maximum value of the output current that is possible for large values of the a.c. component of the input current. This effect is known as *saturation*. Assume a low-frequency sinusoidal a.c. component of the input current of sufficient amplitude to drive the device into saturation. Sketch the input current and what the corresponding output current looks like.

# 2

# Elements of Equilibrium Statistical Mechanics

All electronic devices, just like all physical systems, are composed of incredibly large numbers of very small atoms. Just as the behavior of any system can be explained in terms of the behavior of all of its various parts, the properties of physical systems can be understood in terms of the aggregate behavior of its constituent atoms. In some cases the atoms or molecules may be in an ionized state, meaning that they are split up into electrically charged particles, negative electrons and positive ions. For instance, 1 $cm^3$ (one cubic centimeter) of air is actually comprised of about $2.5 \times 10^{19}$ molecules of which about 78% are nitrogen and 20% oxygen. In unpolluted air at sea level and over land, between 500 and 600 of these molecules are ionized, the principal ionizing agent being terrestrial radioactivity. The semiconductor germanium contains about $5 \times 10^{22}$ atoms/$cm^3$, and, at room temperature, about $10^{13}$ of these are ionized as a consequence of the nature of the material that will be discussed in a later chapter.* In any event, it is the behavior of these ions and electrons under the stimulus of forces, usually electromagnetic forces, that determines the ultimate electronic properties of the whole system. For example, the uniform motion of ions or

*In semiconductors the objects that carry positive charge and hence are analogous to positive ions are called *holes*. In this and the following two chapters we shall refer to positive charge carriers by the more general term *ions*. Since most of the ideas developed in these chapters are applicable to both gases and solids, the more general context emphasizes that the fundamental concepts are widely applicable.