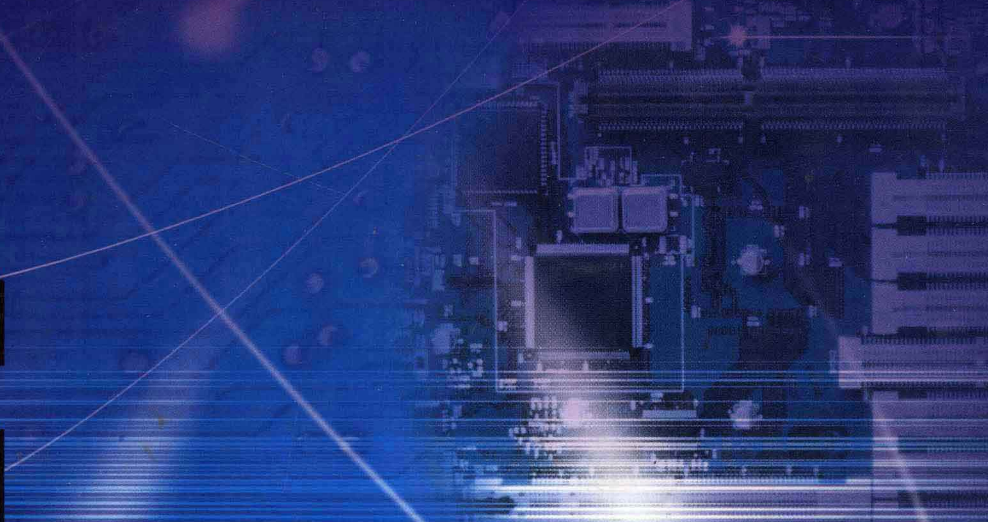

ELECTRONIC TECHNOLOGY FUNDAMENTALS

电子技术基础

高有堂 朱清慧 主编

XADTCBS 西安地图出版社

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前　　言

本书为高校电子信息及工科类双语教学使用教材，同时也可作为一般工程技术人员自学和参考用书。全书分为上、下两部分，1～8 章为模拟电子技术部分，9～21 章为数字部分。第一部分讲述了半导体基本知识及电子电路分析基础，在讲解基本理论的同时，偏重介绍实用元器件及电路分析方法；第二部分讲述了数字电路的基本常识和分析方法，最后还介绍了数字计算机的系统组成和工作原理，强调集成元器件的使用及实际应用系统举例。本书的特点是深入浅出，语言流畅，知识点全面，有丰富的例子和习题，学习起来容易上手，并且对提高电子类专业英语水平有很大帮助。

全书由朱清慧老师统稿，高有堂、王志奎老师为英语顾问，张戈、闫海鹏、刘亚卓老师校稿。具体章节的编写安排如下：朱清慧老师编写了第1、10 章；高有堂老师编写了第2章的2.1～2.4 节、第7、9、20 章；王志奎老师编写了第11、12 章；张戈老师编写了第17、18 章；闫海鹏老师编写了第13、14 章；刘亚卓老师编写了第15、16 章；牛军老师编写了第8 章；胡瑞华老师编写了第4 章的4.0～4.3 节、第5 章；唐晓燕老师编写了第19、21 章；李鉴老师编写了第4 章的4.4～4.5 节、第6 章；曹若云老师编写了第2 章的2.5～2.14 节；马志刚老师编写了第3 章。

本书是在以上各位老师繁忙的教学工作中加班加点完成的。在编写中，阅读了大量的相关外语教材和优秀中文教材，去伪存真，为本书的出版付出了艰辛的劳动。但由于时间仓促，水平有限，书中难免存在错误和不足，敬请读者批评指正！

编　者

内容简介

本书为电子技术类专业基础课程《电子技术》所用教材。全书共分21章，内容涵盖模拟电子技术和数字电子技术两部分，其中1～8章为模拟电子技术部分，9～21章为数字电子技术部分。主要介绍了：半导体二极管和三极管；基本放大电路；功率放大电路；运算放大电路；逻辑门电路；组合逻辑电路；时序逻辑电路；数字集成电路等电子学基础内容。本书选用了大量实用性电路作为例题进行讲解，具有较强的指导性和实践性。

本书可作为工科大专院校有关课程教学用书，对从事电子设计、数据处理和家电维修的科技人员和广大电子技术爱好者具有一定的参考价值。

CONTENTS

CHAPTER 1
SEMICONDUCTOR MATERIALS, DIODES AND TRANSISTORS

1.0 PREVIEW

This text deals with the analysis and design of circuits containing of circuits containing electronic devices, such as diodes and transistors. These electronic devices are fabricated using semiconductor materials, so we begin Chapter 1 with a brief discussion of the properties and characteristics of semiconductors. The intent of this brief discussion is to become familiar with some of the semiconductor material terminology.

A basic electronic device is the pn junction diode. One of the more interesting characteristics of the diode is its nonlinear current –voltage properties. The resistor, for example, has a linear relation between the current through it and the voltage across the element. The diode is also a two-terminal device, but the *i-v* relationship is nonlinear. The current is an exponential function of voltage in one direction and is essentially zero in the other direction. As we will see, this nonlinear characteristic makes possible the generation of a dc voltage from an ac voltage source and the design of digital logic circuits, for example.

Since the diode is a nonlinear element, the analysis of circuits containing diodes is not as straightforward as is the analysis of simple resistor circuits. A mathematical model of the diode, describing the nonlinear $i-v$ properties, is developed. However, the circuit cannot be analyzed, in general, by direct mathematical calculations. In many engineering problems, approximate "bace-of the envelope" solutions replace difficult complex solutions. We develop one such approximation technique using the piecewise linear model of the diode. In this case, we replace the nonlinear diode properties by linear characteristics that are approximately valid over a limited region of operation. This concept is used throughout the study of electronics.

Besides the pn junction diode, we consider five other types of diodes that are used in specialized electronic applications. These include the solar cell, photodiode, light-emitting diode, Schottky barrier diode, and the Zener diode.

The general properties of the diode are considered in this chapter. Simple diode circuits are analyzed with the intent of developing a basic understanding of analysis techniques and diode circuit characteristics.

Then the techniques and concepts developed are used to analyze and design electronic circuits containing diodes. A general goal of this chapter is to develop the ability to use the piecewise linear model and approximation techniques in the hand analysis and design of various diode circuits.

Each circuit to be considered accepts an input signal at a set of input terminals and produces an output signal at a set of input terminal and produces an output signal at a set of output terminals. This process is called signal processing. The circuit "processes" the input signal and produces an output signal that is a different shape or a different function compared to the input signal. We will see in this chapter how diodes are used to perform these various signal processing functions.

Circuits to be considered perform functions such as rectification, clipping, and clamping. These functions are possible only because of the nonlinear properties of the pn junction diode. The conversion of an ac voltage to a dc voltage, such as for a dc power supply, is called rectification. Clipper diode circuits clip portions of a signal that are above or below some reference level. Clamper circuits shift the entire signal by some dc value.

Zener diodes, which operate in the reverse-bias breakdown region, have the advantage that the voltage across the diode in this region is nearly constant over a wide range of currents. Such diodes are used in voltage reference or voltage regulator circuits. Finally, we look at the circuits of two special diodes: the light-emitting diode (LED) and the photodiode. An LED circuit is used in visual display, such as the seven-segment numerical display. The photodiode circuit is used to detect the presence or absence of light and convert this information into an electrical signal.

In this chapter we still introduce the physical structure and operation of the bipolar transistor, mainly dealing with the transistor characteristics. The dc analysis and ac analysis of bipolar circuits will discuss in chapter 2.

1.1 SEMICONDUCTOR MATERIALS AND PROPERTIES

Most electronic devices are fabricated by using semiconductor materials along with conductors and insulators. To gain a better understanding of the behavior of the electronic devices in circuits, we must first understand a few of the characteristics of the semiconductor material. Silicon is by far the most common semiconductor material used for semiconductor devices and integrated circuits. Other semiconductor materials are used for specialized applications. For example, gallium arsenide and related compounds are used for very-high-speed devices and optical devices.

1.1.1 Intrinsic Semiconductors

An atom is composed of a nucleus, which contains positively charged protons and neutrons, and negatively charged electrons that, in the classical sense, orbit the nucleus. The electrons are distributed in various "shells" at different distances from the nucleus, and electron energy increases as shells radius. Electrons in the outermost shells are called **valence electrons**, and the chemical activity of a material is determined primarily by the number of such electrons.

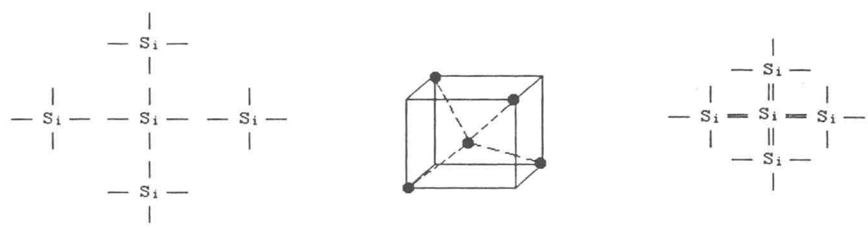
Elements in the period Tablecan be grouped according to the number of valence electrons. Table1-1 shows a portion of the periodic Tablein which the more common semiconductors are found. Silicon (Si) and germanium (Ge) are in group IV and **elemental semiconductors**. In contrast, gallium arsenide is a group ITT-V **compound semiconductors**. We will show that the elements in group III and group V are also I, important in semiconductors.

Table 1-1 A portion of the periodic table

III	IV	V
B	C	
Al	Si	P
Ga	Ge	As

Figure 1-1 (a) shows five noninteracting silicon atoms, with the four valence electrons of each atom shown as dashed lines emanating from the atom. As silicon atoms come into close proximity to each other, the valence electrons interact to form a crystal. The final crystal structure is a tetrahedral configuration in which each silicon atom has four nearest neighbors, as shown in Figure 1-1 (b). The valence electrons are shared between atoms, forming what are called covalent bonds. Germanium, gallium arsenide, and many other semiconductor materials have the same tetrahedral configuration.

Figure 1-1 (c) is a two-dimensional representation of the lattice formed by the five silicon atoms in Figure 1-1 (a). An important property of such a lattice is that valence electrons are always available on the outer edge of the silicon crystal so that additional atoms can be added to form very large single-crystal structures.



(a) Five noninteracting silicon atoms, each with four valence electrons (b) The tetrahedral configuration (c) A two-dimensional representation showing the covalent bonding

Figure 1-1 Silicon atoms in a crystal matrix

A two-dimensional representation of a silicon single crystal is shown in Figure 1.2, for $T = 0^\circ K$, where T = temperature. Each line between atoms represents a valence electron. At $T = 0^\circ K$, each electron is in its lowest possible energy state, so each covalent bonding position is filled. If a small electric field is applied to this material, the electrons will not move, because they will still be bound to their individual atoms. Therefore, at $T = 0^\circ K$, silicon is an **insulator**; that is, no charge flows through it.

If the temperature increases, the valence electrons will gain thermal energy. Any such electron may gain enough thermal energy to break the covalent bond and move away from its original position (Figure 1-3). The electron will then be free to move within the crystal.

Since the net charge of the material is neutral, if a negatively charged electron breaks its covalent bond and moves away from its original position, a positively charged "empty state" is created at that position (Figure 1-3). As the temperature increases, more covalent bonds are broken and more free electrons and positive empty states are created.

In order to break the covalent bond, a valence electron must gain a minimum energy, E_g, called the **bandgap energy**. Materials that have large bandgap energies, in the range of 3 to 6 electron-volts (eV)(An electron-volt is the energy of an electron that has been accelerated through a potential difference of a volt, and a 1 eV = 1.6×10^{-19} joules), are insulators because, at room temperature, essentially no free electrons exist in these materials. In contrast, materials that contain very large numbers of free electrons at room temperature are **conductors.**

In a semiconductor, the bandgap energy is on the order of 1 eV. The not flow of free electrons in a semiconductor causes a current. In addition, a valence electron that has a certain thermal energy and is adjacent to an empty state may move into that position, as shown in Figure 1.4 making it appear as if a positive charge is moving through the semiconductor. This positively charge "particle" is called a **hole.** In semiconductors, then, two types of charged particles contribute to the current: the negatively charged free electron, and the positively charged hole.

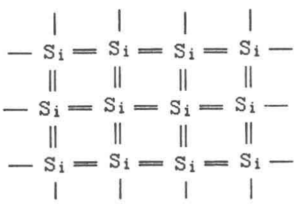


Figure 1-2 Two-dimensional representation of the silicon crystal at T=0 °K

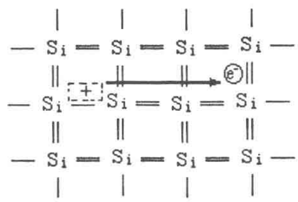


Figure 1-3 The breaking of a covalent bond for T >0 °K

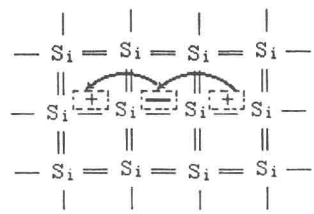


Figure 1-4 A two-dimensional representation of the silicon crystal showing the mov- ement of the positively charged hole

The concentrations (#/cm^3) of electrons and holes are important parameters in the characteristics of a semiconductor material, because they directly influence the magnitude of the current. An **intrinsic semiconductor** is a single-crystal semiconductor material with no other types of atoms within the crystal. In an intrinsic semiconductor, the densities of electrons and holes are equal, since the thermally generated electrons and holes are the only source of such particles. Therefore, we use the notation n_i as the **intrinsic carrier concentration** for the concentration of the free electrons, as well as that of the holes. The equation for n_i is as follows:

$$n_i = BT^{3/2}e^{\left(\frac{-E_g}{2kT}\right)} \qquad \textbf{(1-1)}$$

where B is a constant related to the specific semiconductor material. E_g is the bandgap energy (eV). T is the temperature (°K), and k is Boltzmann's constant (86×10^{-6}eV/°K). The values for B and E_g for several semiconductor materials are given in Table1-2. The bandgap energy is not a strong function of temperature.

Table 1-2 Semiconductor constants

Material	E_g (eV)	B(cm^{-3} ° $K^{-3/2}$)
Silicon (Si)	1.1	5.23×10^{15}
Gallium arsenide (GaAs)	1.4	2.10×10^{14}
Germanium (Ge)	0.66	1.66×10^{15}

EXAMPLE 1-1 Calculate the intrinsic carrier concentration in silicon at $T = 300$ °K.

Solution For silicon at $T = 300$ °K, we can write

$$n_i = BT^{3/2}e^{\left(\frac{-E_g}{2kT}\right)} = (5.23\times10^{15})(300)^{3/2}e^{\left(\frac{-1.1}{2(86\times10^{-6})(300)}\right)} = 1.5\times10^{10}\text{cm}^{-3}$$

Comment An intrinsic electron concentration of 1.5×10^{10}cm^{-3} may appear to be large, but it is relatively small compared to the concentration of silicon atoms, which is 5×10^{22} cm^{-3}.

The intrinsic concentration n_i is an important parameter that appears often in the current-voltage equations for semiconductor devices.

1.1.2 Extrinsic Semiconductors

Because the electron and hole concentrations in an intrinsic semiconductor are relatively small, only very small currents are possible. However, these concentrations can be greatly increased by adding controlled amounts of certain impurities. A desirable impurity is one that enters the crystal lattice and replaces (i.e., substitutes for) one of the semiconductor atoms, even though the impurity atom does not have the same valence electron structure. For silicon, the desirable substitutional impurities are form the group **III** and **V** element (see Table1-1).

The most common group **V** elements used for this purpose are phosphorus and arsenic. For example, when a phosphorus atom substitutes for a silicon atom, as shown in Figure 1-5, four of its valence electrons are used to satisfy the covalent bond requirements. The fifth valence electron is more loosely bound to the phosphorus atom. At room temperature, this electron has enough thermal energy to break the bond, thus being free to move through the crystal and contribute to the electron current in the semiconductor.

The phosphorus atom is called a **donor impurity**, since it donates an electron that is free to move. Although the remaining phosphorus atom has a net positive charge, the atom is immobile in the crystal and cannot contribute to the current. Therefore, when a donor impurity is added to a semiconductor, free electrons are created without generating holes. This process is called **doping**, and it allows us to control the concentration of free electrons in a semiconductor.

A semiconductor that contains donor impurity atoms is called an **n-type semiconductor** (for the negatively charged electrons).

The most common group **III** element used for silicon doping is boron. When a boron atom replaces a silicon atom, its three valence electrons are used to satisfy the covalent bond requirements for three of the four nearest silicon atoms (Figure 1-6). This leaves one bond position open. At room temperature, adjacent silicon valence electrons have sufficient thermal energy to move into this position, thereby creating a hole. The boron atom then has a net negative charge, but cannot move, and a hole is created that can contribute to a hole current.

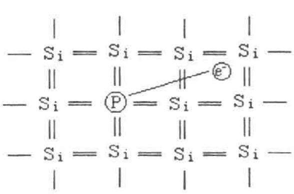


Figure 1-5 Two dimensional Representation of a silicon lattice Doped with a phosphorus atom

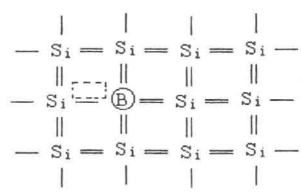


Figure 1-6 Two-dimensional repre- sentation of a silicon lattice doped with a boron atom

Because the boron atom has accepted a valence electron, the boron is therefore called an acceptor impurity. Acceptor atoms lead to the creation of holes without electrons being generated. This process, also called doping, can be used to control the concentration of holes in a semiconductor.

A semiconductor that contains acceptor impurity atoms is called a **p-type semiconductor** (for the positively charged holes created).

The materials containing impurity atoms are called **extrinsic semiconductors**, or **doped semiconductors**. The doping process, which allows us to control the concentrations of free electrons and holes, determines the conductivity and currents in the material.

In an n-type semiconductor, electrons are called the majority carrier because they far outnumber the holes, which are termed the minority carrier. In contrast, in a p-type semiconductor, the holes are the majority carrier and the electrons are the minority carrier.

1.1.3 Drift and Diffusion Currents

The two basic processes which cause electrons and holes to move in a semiconductor are: (a) **drift**, which is the movement caused by electric fields; and (b) **diffusion**, which is the flow caused by variations in the concentration, that is, concentration gradients. Such gradients can be caused by a nonhomogeneous doping distribution, or by the injection of a quantity of electrons or holes into a region, using methods to be discussed later in this chapter.

To understand drift, assume an electric field is applied to a semiconductor. The field produces a force that acts on free electrons and holes, which then experience a net drift velocity and net movement. Consider an n-type semiconductor with a large number of free electrons (Figure 1-7 (a)). An electric field E applied in one direction produces a force on the electrons in the *opposite* direction, because of the electrons' negative charge. The electrons acquire a drift velocity which is opposite to that of the applied electric field as shown in Figure 1-7 (a). The electron drift produces a drift current density. The conventional drift current is in the opposite direction from the flow of negative charge, which means that the drift current in an n-type semiconductor is in the same direction as the applied electric field.

Next consider a p-type semiconductor with a large number of holes (Figure 1-7(b)). An electric field E applied in one direction produces a force on the holes in the *same* direction, because of the positive charge on the holes. The holes also acquire a drift velocity which is in the same direction as the applied electric field as shown in Figure 1-7(b). The hole drift produces a drift current density. The conventional drift current is in the same direction as the flow of positive charge, which means that the drift current in a p-type material is also in the same direction as the applied electric field.

Figure 1-7 Applied electric field, carrier drift velocity, and drift current density in (a) an n-type semiconductor and (b) a p-type semiconductor

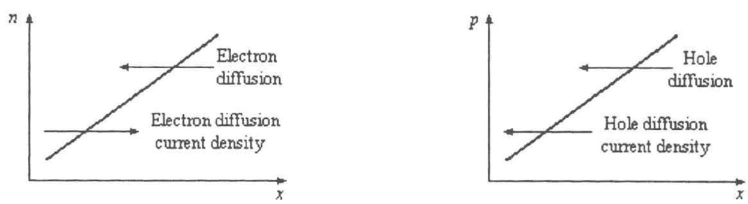
Since a semiconductor contains both electrons and holes, the total drift current density is the sum of the electron and hole components. If the electric field is the result of applying a voltage to the semiconductor, a linear relationship between current and voltage is one form of Ohm's law.

With diffusion, particles flow from a region of high concentration to a region of lower concentration. This is a statistical phenomenon related to kinetic theory. To explain, the electrons and holes in a semiconductor are in continuous motion, with an average speed determined by the temperature, and with the directions randomized by interactions with the lattice atoms. Statistically, we can assume that, at any particular instant, approximately half of the particles in the high-concentration region are moving *away* from that region toward the lower-concentration region. We can also assume that, at the same time, approximately half of the particles in the lower-concentration region are moving *toward* the high-concentration region. However, by definition, there are fewer particles in the lower-concentration region than there are in the high-concentration region. Therefore, the net result is a flow of particles away from the high-concentration region and toward the lower-concentration region. This is the basic diffusion process.

For example. Consider an electron concentration that varies as a function of distance x, as shown in Figure 1-8 (a). The diffusion of electrons from a high-concentration region to a low-concentration region produces a flow of electrons in the negative x direction. Since electrons are negatively charged, the conventional current direction is in the positive x direction.

In Figure 1-8 (b), the hole concentration is a function of distance. The diffusion of holes from a high-concentration region to a low-concentration region produces a flow of holes in the negative x direction.

The total current density is the sum of the drift and the diffusion components. Fortunately, in most cases only one component dominates the current at any one time in a given region of a semiconductor.



(a) Electron diffusion and corresponding current density (b) Hole diffusion and corresponding current density

Figure 1-8 Current density caused by concentration gradients

1.2 THE pn JUNCTION

In the preceding sections, we looked at characteristics of semiconductor materials. The real power of semiconductor electronics occurs when p- and n-regions are directly adjacent to each other, forming a **pn junction**. One important concept to remember is that in most integrated circuit applications, the entire semiconductor material is a single crystal, with one region doped to be p-type and the adjacent region doped to be n-type.

1.2.1 The Equilibrium pn Junction

Figure 1-9(a) is a simplified block diagram of a pn junction assuming uniform the minority carrier concentrations in each region, assuming thermal equilibrium.

The interface at $x = 0$ is called the **metallurgical junction**. A large density gradient in both the hole and electron concentrations occurs across this junction. Initially, then there is a diffusion of holes from the p-region into the n-region, and a diffusion of electrons form the n-region into the p-region (Figure 1-9(b)). The flow of holes from the p-region uncovers negatively charged acceptor ions, and the flow of electrons from the n-region uncovers positively charged donor ions. This action creates a charge separation (Figure 1-10(a)), which sets up an electric field oriented in the direction from the positive charge to the negative charge.

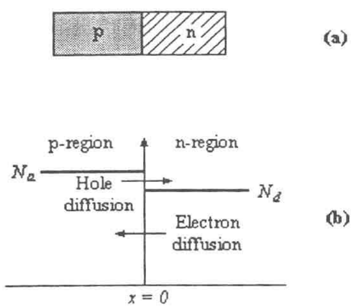


Figure 1-9 (a) simplified geometry of a pn junction and (b) Initial diffusion of electrons and holes at the Metallurgical junction, establishing thermal equilibrium

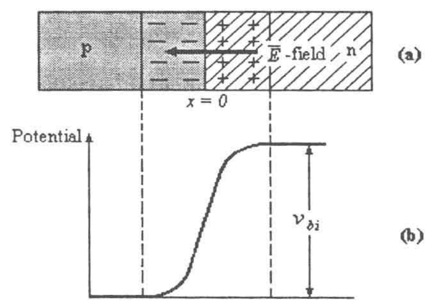


Figure 1-10 The pn junction in thermal equilibrium: (a) the space-charge region and electric field and (b) the potential through the junction

If no voltage is applied to the pn junction, the diffusion of holes and electrons must eventually cease. The direction of the induced electric field will cause the resulting force to repel the diffusion of holes from the p-region and the diffusion of electrons from the n-region. Thermal equilibrium occurs when the force produced by the electric field and the "force" produced by the density gradient exactly balance.

The Positively charge region and the negatively charged region comprise the **space-charge** region, or **depletion region**, of the pn junction, in which there are essentially no mobile electrons or holes. Because of the electric field in the space-charge region, there is a potential difference across that region (Figure 1-10(b)). This potential difference V_{bi} is called the **built-in potential barrier**, or built-in voltage, and is about 0.7V for a Si pn junction, and 0.2V for a Ge pn junction.

The potential difference across the space-charge region cannot be measured by a voltmeter because new potential barriers form between the probes of the voltmeter and the semiconductor, canceling the effects of V_{bi}. In essence, V_{bi} maintains equilibrium, so no current is produced by this voltage. However, the magnitude of V_{bi} becomes important when we apply a forward-bias voltage, as discussed later in this chapter.