Canadian Edition, Prentice Hall, 1999, Pages 1-17

Electronic Devices and Circuit Theory, Bolyestad and Nashelsky, Canadian Edition, Prentice-Hall, 1999, pg. 1-17

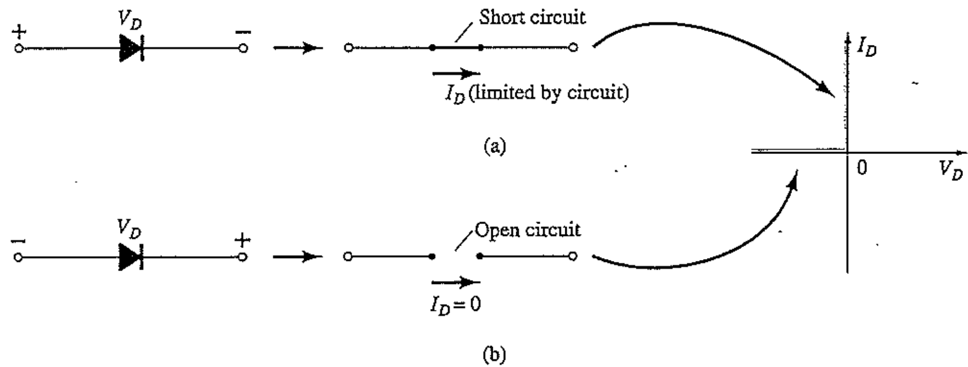

Figure 1.2 (a) Conduction and (b) nonconduction states of the ideal diode as determined by the applied bias.

In general, it is relatively simple to determine whether a diode is in the region of conduction or nonconduction simply by noting the direction of the current I_D established by an applied voltage. For conventional flow (opposite to that of electron flow), if the resultant diode current has the same direction as the arrowhead of the diode symbol, the diode is operating in the conducting region as depicted in Fig. 1.3a. If the resulting current has the opposite direction, as shown in Fig. 1.3b, the open-circuit equivalent is appropriate.

Remember that the characteristics of an ideal device are used for comparison with the characteristics of the commercial variety. As you progress through the next few sections, keep the following questions in mind:

How close will the forward or "on" resistance of a practical diode be to the desired 0-Ω level?

Is the reverse-bias resistance sufficiently large to permit an open-circuit approximation?

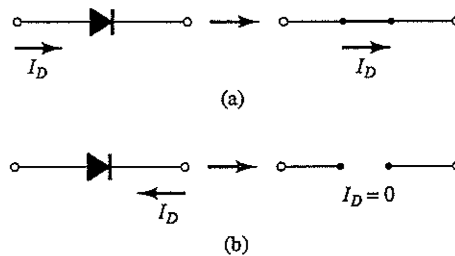

Figure 1.3 (a) Conduction and (b) nonconduction states of the ideal diode as determined by the direction of conventional current established by the network.

1.3 Semiconductor Materials

semiconductor

The label **semiconductor** itself provides a hint as to its characteristics. The prefix *semi-* is normally applied to a range of levels midway between two limits.

The term conductor is applied to any material that will support a generous flow of charge when a voltage source of limited magnitude is applied across its terminals.

An insulator is a material that offers a very low level of conductivity under pressure from an applied voltage source.

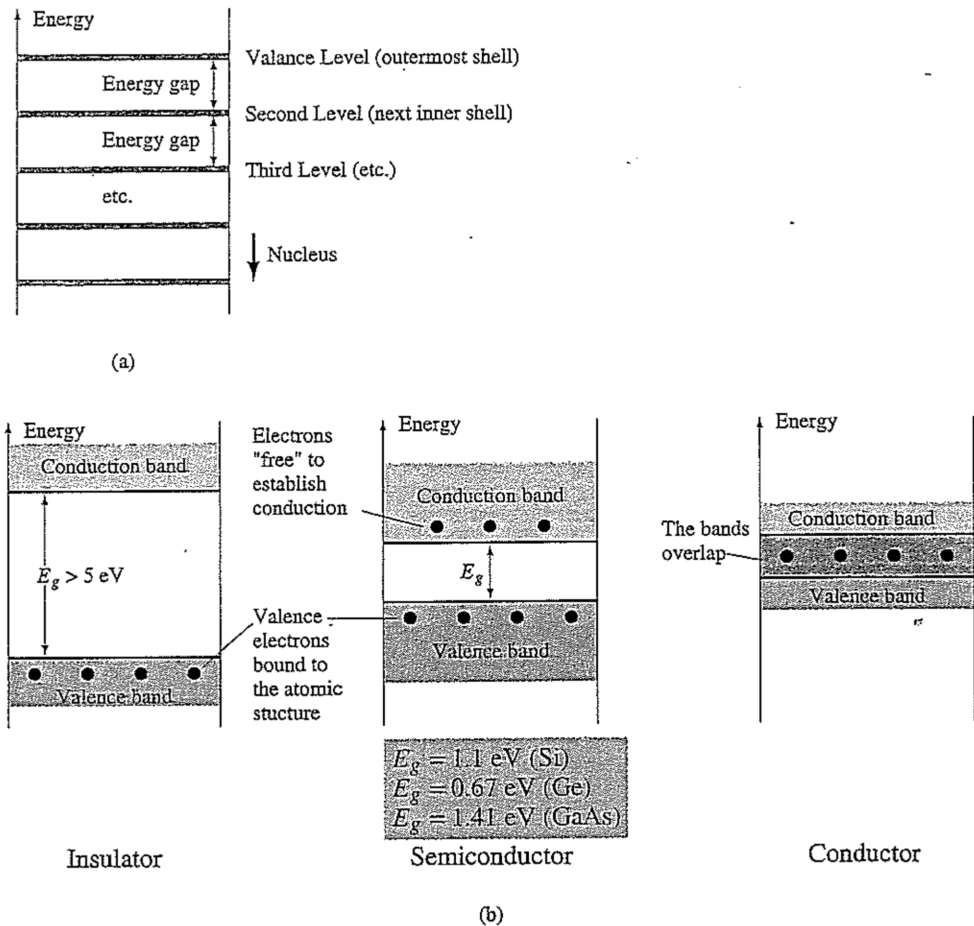

Figure 1.8 Energy levels: (a) discrete levels in isolated atomic structures; (b) conduction and valence bands of an insulator, semiconductor, and conductor.

as derived from the defining equation for voltage $V = W/Q$. The charge Q is the charge associated with a single electron.

electron volt

Substituting the charge of an electron and a potential difference of 1 volt into Eq. (1.2) will result in an energy level referred to as **one electron volt**. Since energy is also measured in joules and the charge of one electron = 1.6×10^{-19} coulomb,

$$W = QV = (1.6 \times 10^{-19}\ \text{C})(1\ \text{V})$$

and

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J} \tag{1.3}$$

At 0 K or absolute zero (−273.15°C), all the valence electrons of semiconductor materials find themselves locked in their outermost shell of the atom with energy levels associated with the valence band of Fig. 1.8b. However, at room temperature (300 K, 25°C) a large number of valence electrons have acquired sufficient energy to leave the valence band, cross the energy gap defined by E_g in Fig. 1.8b and enter the conduction band. For silicon E_g is 1.1 eV, for germanium 0.67 eV, and for gallium arsenide 1.41 eV. The obviously lower E_g for germanium accounts for the increased number of carriers in that material as compared to silicon at room temperature. Note for the insulator that the energy gap is typically 5 eV or more, which severely limits the number of electrons that can enter the conduction band at room temperature. The conductor has electrons in the conduction band even at 0 K. Quite obviously, therefore, at room temperature there are more than enough free carriers to sustain a heavy flow of charge, or current.

Intrinsic materials are those semiconductors that have been carefully refined to reduce the impurities to a very low level — essentially as pure as can be made available through modern technology.

intrinsic carriers

The free electrons in the material due only to natural causes are referred to as **intrinsic carriers**. At the same temperature, intrinsic germanium material will have approximately 2.5×10^{13} free carriers per cubic centimeter. The ratio of the number of carriers in germanium to that of silicon is greater than 10^3 and would indicate that germanium is a better conductor at room temperature. This may be true, but both are still considered poor conductors in the intrinsic state. Note in Table 1.1 that the resistivities also differ by a ratio of about 1000:1, with silicon having the larger value. This should be the case, of course, since resistivity and conductivity are inversely related.

An increase in temperature of a semiconductor can result in a substantial increase in the number of free electrons in the material.

As the temperature rises from absolute zero (0 K), an increasing number of valence electrons absorb sufficient thermal energy to break the covalent bond and contribute to the number of free carriers as described above. This increased number of carriers will increase the conductivity index and result in a lower resistance level.

Semiconductor materials such as Ge and Si that show a reduction in resistance with increase in temperature are said to have a *negative* **temperature coefficient**.

temperature coefficient

You will probably recall that the resistance of most *conductors* will increase with temperature. This is due to the fact that the numbers of carriers in a conductor will not increase significantly with temperature, but the vibrations of the atoms about relatively fixed locations will make it increasingly difficult for electrons to pass through. An increase in temperature therefore results in an increased resistance level and a *positive* **temperature coefficient**. In semiconductors, increased conduction from breaking bonds exceeds the effect of increased atomic vibration.

1.4 Energy Levels

In the isolated atomic structure there are discrete (individual) energy levels associated with each orbiting electron, as shown in Fig. 1.8a. Each material will, in fact, have its own set of permissible energy levels for the electrons in its atomic structure.

The more distant the electron from the nucleus, the higher the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure.

Between the discrete energy levels are gaps in which no electrons in the isolated atomic structure can appear. As the atoms of a material are brought closer together to form the crystal lattice structure, there is an interaction between atoms that will result in the electrons in a particular orbit of one atom having slightly different energy levels from electrons in the same orbit of an adjoining atom. The net result is an expansion of the discrete levels of possible energy states for the valence electrons to that of bands as shown in Fig. 1.8b. Note that there are boundary levels and maximum energy states in which any electron in the atomic lattice can find itself, and there remains a *forbidden region* between the valence band and the ionization level. Recall that ionization is the mechanism whereby an electron can absorb sufficient energy to break away from the atomic structure and enter the conduction band. You will note that the energy associated with each electron is measured in *electron volts* (eV). The unit of measure is appropriate, since

$$W = QV \tag{1.2}$$

We will find in Section 1.5 that if certain impurities are added to the intrinsic semiconductor materials, energy states in the forbidden bands will occur which will cause a net reduction in E_g for both semiconductor materials—consequently, increased carrier density in the conduction band at room temperature.

1.5 Extrinsic Materials — *n*- and *p*-Type

The characteristics of semiconductor materials can be altered significantly by the addition of certain impurity atoms into the relatively pure semiconductor material. These impurities, although only added to perhaps 1 part in 10 million, can alter the band structure sufficiently to totally change the electrical properties of the material.

extrinsic material

A semiconductor material that has been subjected to the doping process is called an **extrinsic material**.

There are two extrinsic materials of great importance in fabricating semiconductor devices: *n*-type and *p*-type. Each is described in detail in the following paragraphs.

n-Type Material

Both the *n*- and *p*-type materials are formed by adding a predetermined number of impurity atoms into a germanium or silicon base. The *n*-type is created by introducing those impurity elements that have *five* valence electrons (*pentavalent*), such as *antimony, arsenic,* and *phosphorus.* The effect of such impurity elements is indicated in Fig. 1.9 (using antimony as the impurity in a silicon base). Note that the four covalent bonds are still present. There is, however, an additional fifth electron from the impurity atom, which is *unassociated* with any particular covalent bond. This remaining electron, loosely bound to its parent (antimony) atom, is relatively free to move within the newly formed *n*-type material. Since the inserted impurity atom has donated a relatively free electron to the structure:

donor atom

Diffused impurities with five valence electrons are called **donor atoms.**

It is important to realize that even though a large number of free carriers have been established in the *n*-type material, it is still electrically *neutral* since the number of positively charged protons in the nuclei is still equal to the number of free and orbiting negatively charged electrons in the structure.

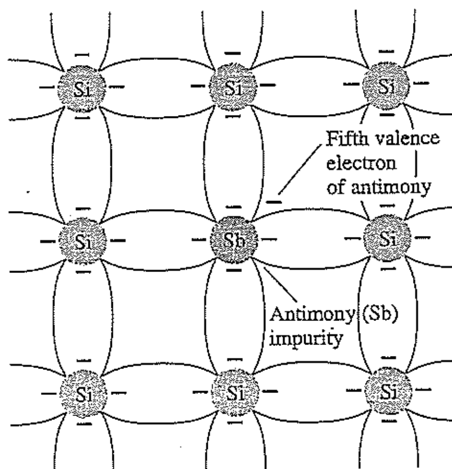

Figure 1.9 Antimony impurity in *n*-type material.

donor level

The effect of this doping process on the relative conductivity can best be described through the use of the energy-band diagram of Fig. 1.10. Note that a discrete energy level (called the **donor level**) appears in the forbidden band with an E_g significantly less than that of the intrinsic material. Those free electrons due to the added impurity sit at this energy level and have less difficulty absorbing a sufficient measure of thermal energy to move into the conduction band at room temperature. The result is that at room temperature, there are a large number of carriers (electrons) in the conduction level and the conductivity of the material increases significantly. At room temperature in an intrinsic Si material there is about one free electron for every 10^{12} atoms (1 to 10^9 for Ge). If the dopage level were 1 in 10 million (10^7), the ratio ($10^{12}/10^7 = 10^5$) would indicate that the carrier concentration has increased by a ratio of 100 000:1.

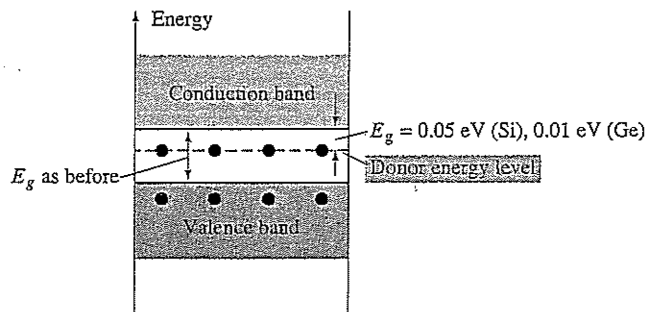

Figure 1.10 Effect of donor impurities on the energy band structure.

p-Type Material

The *p*-type material is formed by doping a pure germanium or silicon crystal with impurity atoms having *three* valence electrons. The elements most frequently used for this purpose are *boron, gallium,* and *indium.* The effect of one of these elements, boron, on a base of silicon is indicated in Fig. 1.11.

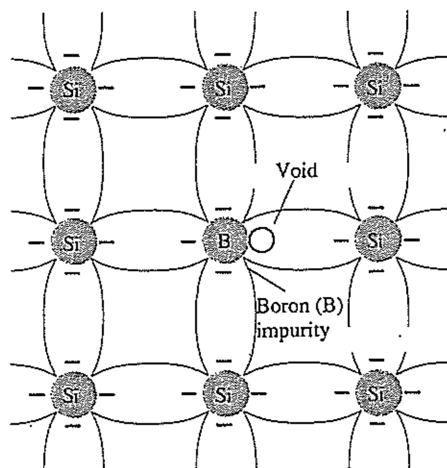

Figure 1.11 Boron impurity in *p*-type material.

hole

Note that there is now an insufficient number of electrons to complete the covalent bonds of the newly formed lattice. The resulting vacancy is called a **hole** and is

represented by a small circle or positive sign due to the absence of a negative charge. Since the resulting vacancy will readily *accept* a free electron:

acceptor atom

The diffused impurities with three valence electrons are called **acceptor atoms**.

The resulting *p*-type material is electrically neutral, for the same reasons described for the *n*-type material.

Electron versus Hole Flow

The effect of the hole on conduction is shown in Fig. 1.12. If a valence electron acquires sufficient kinetic energy to break its covalent bond and fills the void created by a hole, then a vacancy, or hole, will be created in the covalent bond that released the electron. There is, therefore, a transfer of holes to the left and electrons to the right, as shown in Fig. 1.12. The direction to be used in this text is that of *conventional flow,* which is indicated by the direction of hole flow.

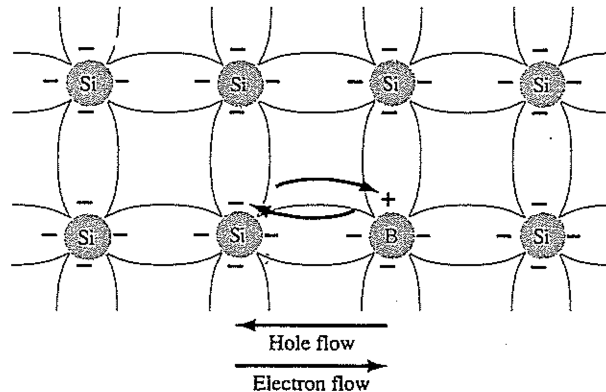

Figure 1.12 Electron versus hole flow.

Majority and Minority Carriers

In the intrinsic state, the number of free electrons in Ge or Si is due only to those few electrons in the valence band that have acquired sufficient energy from thermal or light sources to break the covalent bond or to the few impurities that could not be removed. The vacancies left behind in the covalent bonding structure represent our very limited supply of holes. In an *n*-type material, the number of holes has not changed significantly from this intrinsic level. The net result, therefore, is that the number of electrons far outweighs the number of holes. For this reason:

majority carrier
minority carrier

In an *n*-type material (Fig. 1.13a) the electron is called the **majority carrier** and the hole the **minority carrier**.

For the *p*-type material the number of holes far outweighs the number of electrons, as shown in Fig. 1.13b. Therefore:

In a *p*-type material the hole is the majority carrier and the electron is the minority carrier.

When the fifth electron of a donor atom leaves the parent atom, the atom remaining acquires a net positive charge: hence the positive sign in the donor-ion representation. For similar reasons, the negative sign appears in the acceptor ion.

The *n*- and *p*-type materials represent the basic building blocks of semiconductor devices. We will find in the next section that the joining of a single *n*-type material with a *p*-type material will result in a semiconductor element of considerable importance in electronic systems.

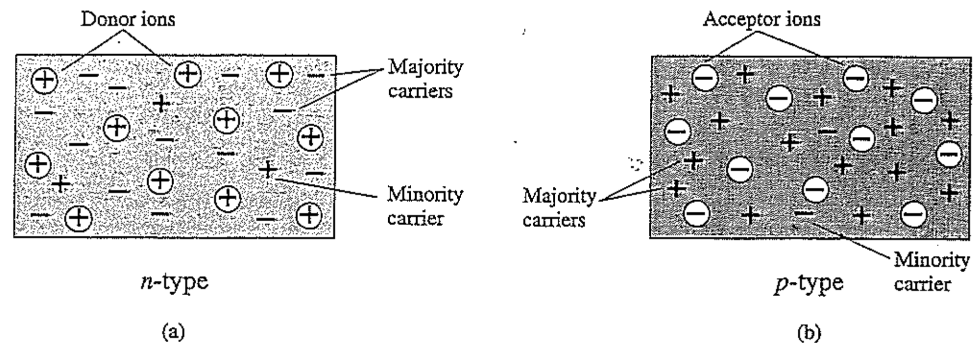

Figure 1.13 (a) n-type material; (b) p-type material.

1.6 Semiconductor Diode

In Section 1.5 both the n- and p-type materials were introduced. The semiconductor diode is formed by simply bringing these materials together (constructed from the same base—Ge or Si), as shown in Fig. 1.14, using techniques to be described in Chapter 13. At the instant the two materials are joined the electrons and holes in the region of the **junction** will combine, resulting in a lack of carriers in the region near the junction.

junction

This region of uncovered positive and negative ions is called the **depletion region** due to the depletion of carriers in this region.

depletion region

Since the diode is a two-terminal device, the application of a voltage across its terminals leaves three possibilities: *no bias* ($V_D = 0$ V), *forward bias* ($V_D > 0$ V), and *reverse bias* ($V_D < 0$ V). Each condition will result in a particular response that you must clearly understand to use the device effectively.

No Applied Bias ($V_D = 0$ V)

no-bias

Under **no-bias** (no applied voltage) conditions, any minority carriers (holes) in the n-type material that find themselves within the depletion region will pass directly into the p-type material. The closer the minority carrier is to the junction, the greater the attraction for the layer of negative ions and the less the opposition of the positive ions in the depletion region of the n-type material. For the purposes of future discussions we shall assume that all the minority carriers of the n-type material that find themselves in the depletion region due to their random motion will pass directly into the p-type material. Similar discussion can be applied to the minority carriers (electrons) of the p-type material. This carrier flow has been indicated in Fig. 1.14 for the minority carriers of each material.

The majority carriers (electrons) of the n-type material must overcome the attractive forces of the layer of positive ions in the n-type material and the shield of negative ions in the p-type material to migrate into the area beyond the depletion region of the p-type material. However, the number of majority carriers is so large in the n-type material that there will invariably be a small number of majority carriers with sufficient kinetic energy to pass through the depletion region into the p-type material. Again, the same type of discussion can be applied to the majority carriers (holes) of the p-type material. The resulting flow due to the majority carriers is also shown in Fig. 1.14.

A close examination of Fig. 1.14 will reveal that the relative magnitudes of the flow vectors are such that the net flow in either direction is zero. This cancellation of vectors has been indicated by crossed lines. The length of the vector representing hole

ionization

As the voltage across the diode increases in the reverse-bias region, the velocity of the minority carriers responsible for the reverse saturation current I_s will also increase. Eventually, their velocity and associated kinetic energy ($W_K = \frac{1}{2}mv^2$) will be sufficient to release additional carriers through collisions with otherwise stable atomic structures. That is, an **ionization** process will result whereby valence electrons absorb sufficient energy to leave the parent atom. These additional carriers can then aid the ionization process to the point where a high *avalanche* current is established and the *avalanche breakdown* region determined.

Zener region

The avalanche region (V_Z) can be brought closer to the vertical axis by increasing the doping levels in the p- and n-type materials. However, as V_Z decreases to very low levels, such as -5 V, another mechanism, called *Zener breakdown,* will contribute to the sharp change in the characteristic. It occurs because there is a strong electric field in the region of the junction that can disrupt the bonding forces within the atom and generate carriers. Although the Zener breakdown mechanism is a significant contributor only at lower levels of V_Z, this sharp change in the characteristic at any level is called the **Zener region** and diodes employing this unique portion of the characteristic of a p-n junction are called *Zener diodes.* They are described in detail in Section 1.14.

The Zener region of the semiconductor diode described must be avoided if the response of a system is not to be completely altered by the sharp change in characteristics in this reverse-voltage region.

peak inverse voltage (PIV)

The maximum reverse-bias potential that can be applied before entering the Zener region is called the **peak inverse voltage** (referred to simply as the PIV rating) or the peak reverse voltage (denoted by PRV rating).

If an application requires a PIV rating greater than that of a single unit, a number of diodes of the same characteristics can be connected in series. Diodes are also connected in parallel to increase the current-carrying capacity.

Silicon versus Germanium

offset potential

Silicon diodes have, in general, higher PIV and current ratings and wider temperature ranges than germanium diodes. PIV ratings for silicon can be in the neighborhood of 1000 V, whereas the maximum value for germanium is closer to 400 V. Silicon can be used for applications in which the temperature may rise to about 200°C (400°F), whereas germanium has a much lower maximum rating (100°C). The disadvantage of silicon, however, as compared to germanium, as indicated in Fig. 1.23, is the higher forward-bias voltage required to reach the region of upward swing. It is typically of the order of magnitude of 0.7 V for commercially available silicon diodes and 0.3 V for germanium diodes when rounded off to the nearest tenths. The increased offset for silicon is due primarily to the factor η in Eq. (1.4). This factor plays a part in determining the shape of the curve only at very low current levels. Once the curve starts its vertical rise, the factor η drops to 1 (the continuous value for germanium). This is evidenced by the similarities in the curves once the **offset potential** is reached. The potential at which this rise occurs is commonly referred to as the *offset, threshold,* or *firing potential.* Frequently, the first letter of a term that describes a particular quantity is used in the notation for that quantity. However, to ensure a minimum of confusion with other terms, such as output voltage (V_o) and forward voltage (V_F), the notation V_T has been adopted for this book, from the word "threshold."

In review:

$$V_T = 0.7 \text{ (Si)}$$
$$V_T = 0.3 \text{ (Ge)}$$

Obviously, the closer the upward swing is to the vertical axis, the more ideal the device. However, the other characteristics of silicon as compared to germanium still make it the choice in the majority of commercially available units.

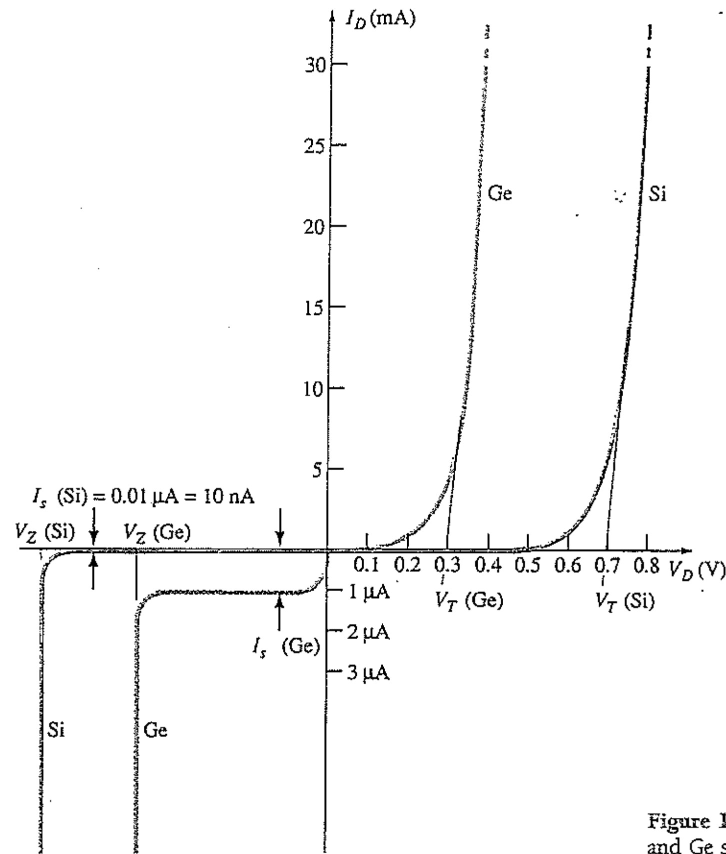

Figure 1.23 Comparison of Si and Ge semiconductor diodes.

Temperature Effects

Temperature can have a marked effect on the characteristics of a silicon semiconductor diode as witnessed by a typical silicon diode in Fig. 1.24. It has been found experimentally that:

> The reverse saturation current I_s will just about double in magnitude for every 10°C increase in temperature.

It is not uncommon for a germanium diode with an I_s in the order of 1 or 2 μA at 25°C to have a leakage current of 100 μA = 0.1 mA at a temperature of 100°C. Current levels of this magnitude in the reverse-bias region would certainly compromise our desired open-circuit condition in the reverse-bias region. Typical values of I_s for silicon are much lower than those of germanium for similar power and current levels as shown in Fig. 1.23. The result is that even at high temperatures the levels of I_s for silicon diodes do not reach the same high levels obtained for germanium—a very important reason that silicon devices enjoy a significantly higher level of development and use in design. Fundamentally, the open-circuit equivalent in the reverse-bias region is better realized at any temperature with silicon than with germanium.

The increasing levels of I_s with temperature account for the lower levels of threshold voltage, as shown in Fig. 1.24. Simply increase the level of I_s in Eq. (1.4) and note the earlier rise in diode current. Of course, the level of T_K also will be increasing in the same equation, but the increasing level of I_s will overpower the smaller percent change in T_K. As the temperature increases, the forward characteristics are actually becoming more ideal. We will find, however, when we review the specifications sheets that temperatures beyond the normal operating range can have a very detrimental effect on the diode's maximum power and current levels. In the reverse-bias region the breakdown voltage is increasing with temperature, but note the undesirable increase in reverse saturation current.