

SEMICONDUCTOR MATERIALS :-

The label semiconductor itself provides a hint as to its characteristics. The prefix semis 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. A semiconductor, therefore, is a material that has a conductivity level somewhere between the extremes of an insulator and a conductor.

Inversely related to the conductivity of a material is its resistance to the flow of charge, or current. That is, the higher the conductivity level, the lower the resistance level. In tables, the term resistivity (ρ , Greek letter rho) is often used when comparing the resistance levels of materials. In metric units, the resistivity of a material is measured in $\Omega\text{-cm}$ or $\Omega\text{-m}$. The units of $\Omega\text{-cm}$ are derived from the substitution of the units for each quantity of Fig. 1.4 into the following equation (derived from the basic resistance equation $R = \rho l/A$):

$$\rho = \frac{RA}{l} = \frac{(\Omega)(\text{cm}^2)}{\text{cm}} \Rightarrow \Omega\text{-cm}$$

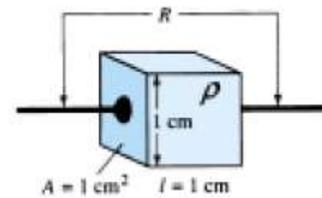


Figure 1.4 Defining the metric units of resistivity.

In fact, if the area of Fig. 1.4 is 1 cm^2 and the length 1 cm , the magnitude of the resistance of the cube of Fig. 1.4 is equal to the magnitude of the resistivity of the material as demonstrated below:

$$|R| = \rho \frac{l}{A} = \rho \frac{(1 \text{ cm})}{(1 \text{ cm}^2)} = |\rho| \text{ohms}$$

This fact will be helpful to remember as we compare resistivity levels in the discussions to follow. In Table 1.1, typical resistivity values are provided for three broad categories of materials. Although you may be familiar with the electrical properties of copper and mica from your past studies, the characteristics of the semiconductor materials of germanium (Ge) and silicon (Si) may be relatively new. As you will find in the chapters to follow, they are certainly not the only two semiconductor materials.

TABLE 1.1 Typical Resistivity Values

| Conductor | Semiconductor | Insulator |
|---|--|---|
| $\rho \cong 10^{-6} \Omega\text{-cm}$ (copper) | $\rho \cong 50 \Omega\text{-cm}$ (germanium) $\rho \cong 50 \times 10^3 \Omega\text{-cm}$ (silicon) | $\rho \cong 10^{12} \Omega\text{-cm}$ (mica) |

They are, however, the two materials that have received the broadest range of interest in the development of semiconductor devices. In recent years the shift has been steadily toward silicon and away from germanium, but germanium is still in modest production. Note in Table 1.1 the extreme range between the conductor and insulating materials for the 1-cm length (1-cm² area) of the material. Eighteen places separate the placement of the decimal point for one number from the other. Ge and Si have received the attention they have for a number of reasons. One very important consideration is the fact that they can be manufactured to a very high purity level. In fact, recent advances have reduced impurity levels in the pure material to 1 part in 10 billion (1:10,000,000,000). One might ask if these low impurity levels are really necessary.

They certainly are if you consider that the addition of one part impurity (of the proper type) per million in a wafer of silicon material can change that material from a relatively poor conductor to a good conductor of electricity. We are obviously dealing with a whole new spectrum of comparison levels when we deal with the semiconductor medium. The ability to change the characteristics of the material significantly through this process, known as “doping,” is yet another reason why Ge and Si have received such wide attention. Further reasons include the fact that their characteristics can be altered significantly through the application of heat or light—an important consideration in the development of heat- and light-sensitive devices.

Some of the unique qualities of Ge and Si noted above are due to their atomic structure. The atoms of both materials form a very definite pattern that is periodic in nature (i.e., continually repeats itself). One complete pattern is called a crystal and the periodic arrangement of the atoms a lattice. For Ge and Si the crystal has the three-dimensional diamond structure of Fig. 1.5. Any material composed solely of repeating crystal structures of the same kind is called a single-crystal structure. For semiconductor materials of practical application in the electronics field, this singlecrystal feature exists, and, in addition, the periodicity of the structure does not change significantly with the addition of impurities in the doping process.

Let us now examine the structure of the atom itself and note how it might affect the electrical characteristics of the material. As you are aware, the atom is composed of three basic particles: the electron, the proton, and the neutron. In the atomic lattice, the neutrons and protons form the nucleus, while the electrons revolve around the nucleus in a fixed orbit. The Bohr models of the two most commonly used semiconductors, germanium and silicon, are shown in Fig. 1.6.

As indicated by Fig. 1.6a, the germanium atom has 32 orbiting electrons, while silicon has 14 orbiting electrons. In each case, there are 4 electrons in the outermost (valence) shell. The potential (ionization potential) required to remove any one of these 4 valence electrons is lower than that required for any other electron in the structure.

In a pure germanium or silicon crystal these 4 valence electrons are bonded to 4 adjoining atoms, as shown in Fig. 1.7 for silicon. Both Ge and Si are referred to as tetravalent atoms because they each have four valence electrons. A bonding of atoms, strengthened by the sharing of electrons, is called covalent bonding.

Although the covalent bond will result in a stronger bond between the valence

electrons and their parent atom, it is still possible for the valence electrons to absorb

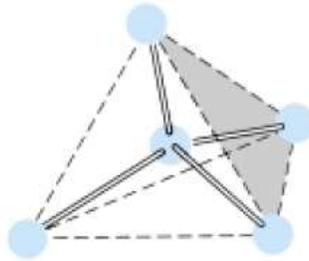


Figure 1.5 Ge and Si single-crystal structure.

sufficient kinetic energy from natural causes to break the covalent bond and assume the “free” state. The term free reveals that their motion is quite sensitive to applied electric fields such as established by voltage sources or any difference in potential. These natural causes include effects such as light energy in the form of photons and thermal energy from the surrounding medium.

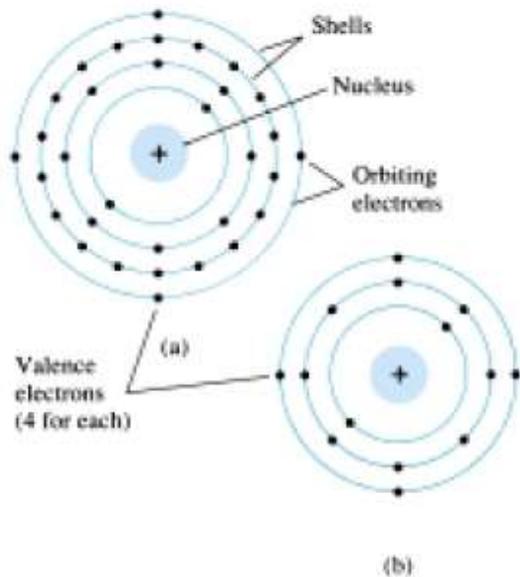


Figure 1.6 Atomic structure: (a) germanium; (b) silicon.

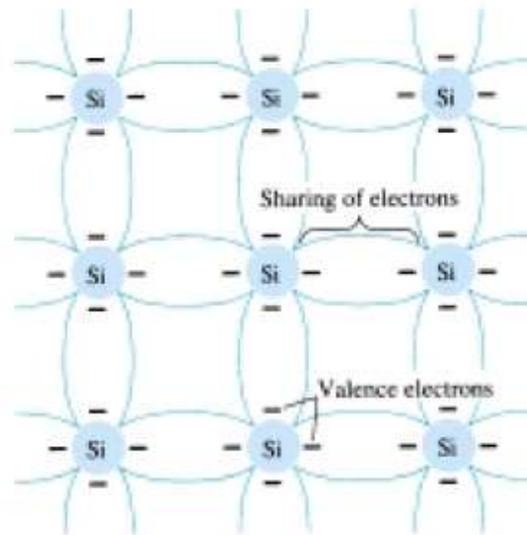


Figure 1.7 Covalent bonding of the silicon atom.

At room temperature there are approximately (1.5×10^{10}) free carriers in a cubic centimeter of intrinsic silicon material.

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.

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 103 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 resistivity also differs 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.

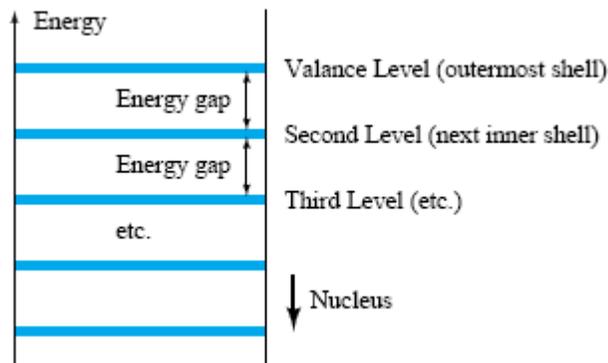
As the temperature rises from absolute zero (0 K), an increasing number of valence electrons absorb sufficient thermal energy to break the covalent bond and contribute to the number of free carriers as described above. This increased number of carriers will increase the conductivity index and result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

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 their vibration pattern about a relatively fixed location 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.

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.



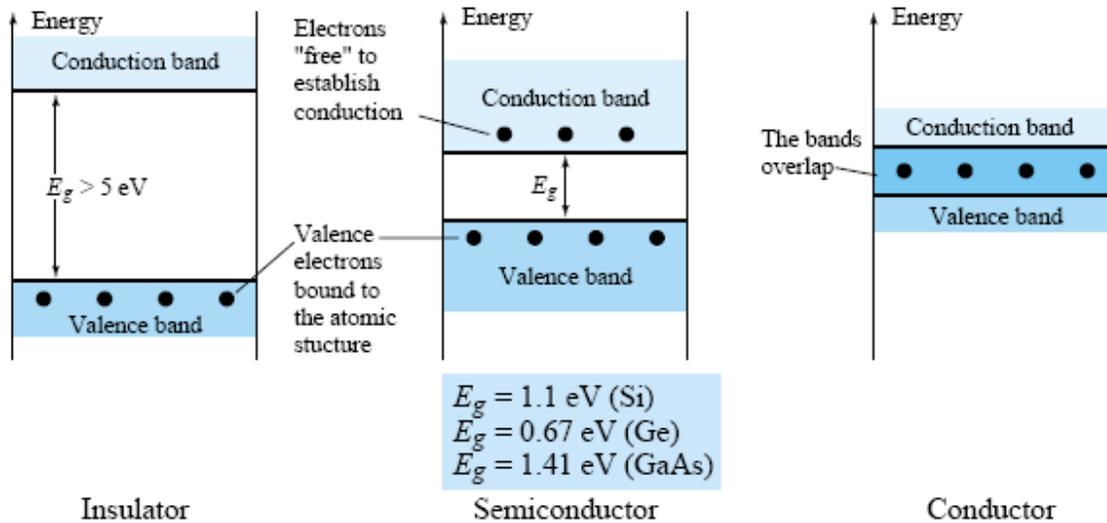


Figure 1.8 Energy levels: (a) discrete levels in isolated atomic structures; (b) conduction and valence bands of an insulator, semiconductor, and conductor.

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

$$W = QV \quad \text{eV} \tag{1.2}$$

as derived from the defining equation for voltage ($V = W/Q$). The charge Q is the charge associated with a single electron. 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 $1 \text{ eV} = 1.6 \times 10^{19} \text{ J}$ (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.

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!

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

There are two extrinsic materials of immeasurable importance to semiconductor device fabrication: n-type and p-type. Each will be described in some 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 due to 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:

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 ideally 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.

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

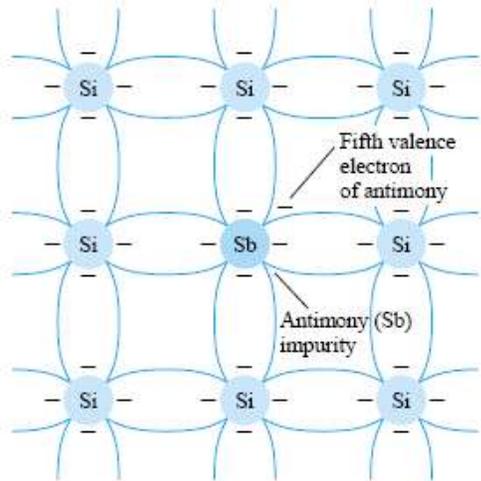


Figure 1.9 Antimony impurity in n-type material.

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 our dosage 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.

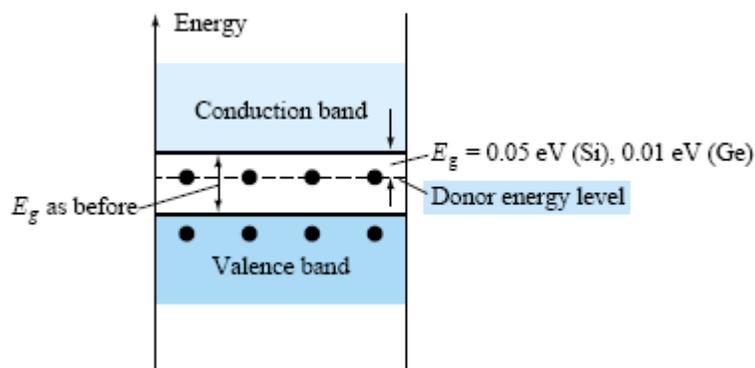


Figure 1.10 Effect of donor impurities on the energy band structure.

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.

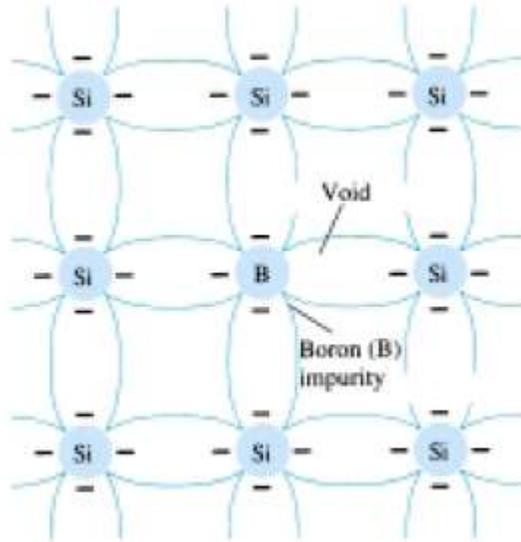


Figure 1.11 Boron impurity in p-type material.

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: 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.

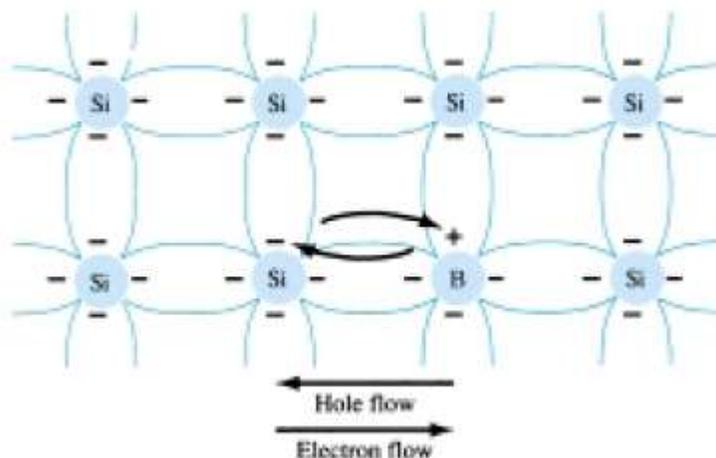


Figure 1.12 Electron versus hole flow.

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:

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.

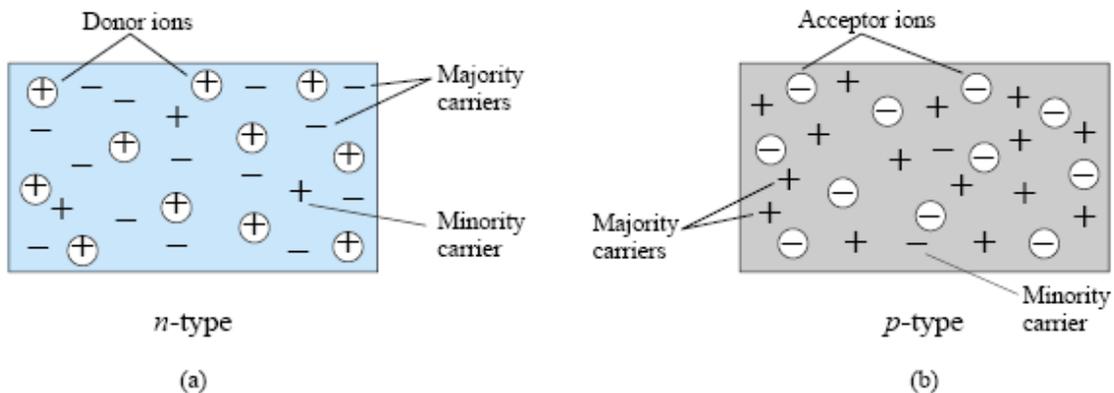


Figure 1.13 (a) n-type material; (b) p-type material.

SEMICONDUCTOR DIODE:-

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,. 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. This region of uncovered positive and negative ions is called the depletion region due to the depletion of carriers in this 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 is a condition that will result in a response that the user must clearly understand if the device is to be applied effectively.

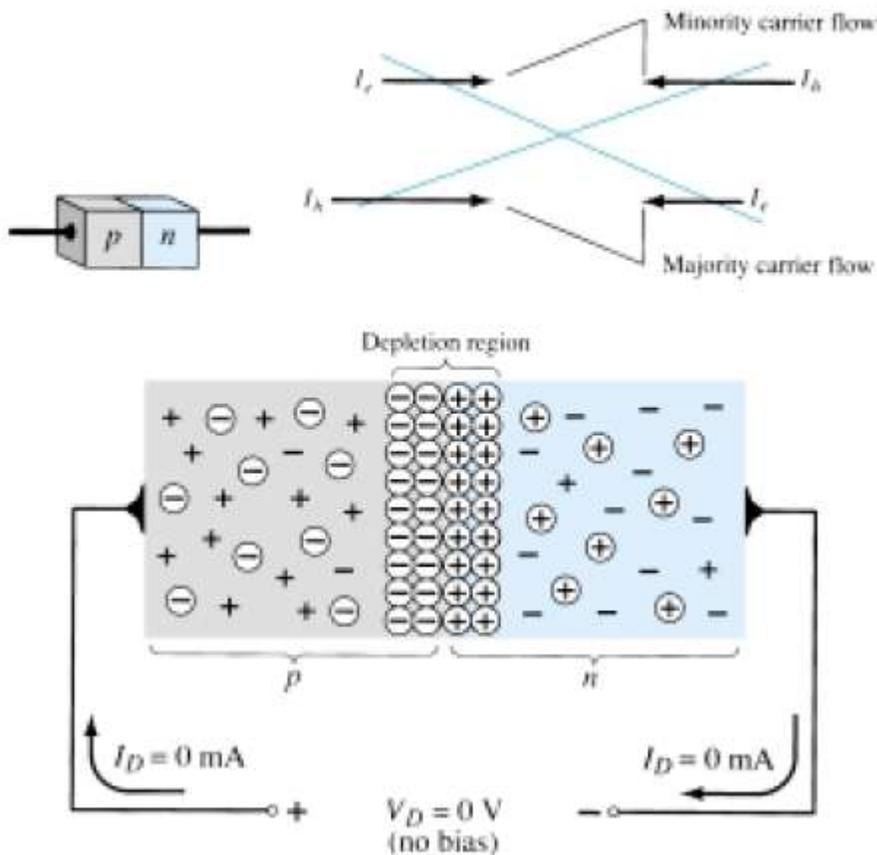


Figure 1.14 p-n junction with no external bias.

No Applied Bias ($V_D = 0$ V):-

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 flow has been drawn longer than that for electron flow to demonstrate that the magnitude of each need not be the same for cancellation and that the doping levels for each material may result in an unequal carrier flow of holes and electrons. In summary,

therefore: In the absence of an applied bias voltage, the net flow of charge in any one direction for a semiconductor diode is zero. The symbol for a diode is repeated in Fig. 1.15 with the associated n- and p-type regions. Note that the arrow is associated with the p-type component and the bar with the n-type region. As indicated, for $V_D = 0$ V, the current in any direction is 0 mA.

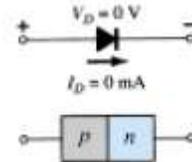


Figure 1.15 No-bias conditions for a semiconductor diode.

Reverse-Bias Condition ($V_D = 0$ V):-

If an external potential of V volts is applied across the p-n junction such that the positive terminal is connected to the n-type material and the negative terminal is connected to the p-type material as shown in Fig. 1.16, the number of uncovered positive ions in the depletion region of the n-type material will increase due to the large number of “free” electrons drawn to the positive potential of the applied voltage. For similar reasons, the number of uncovered negative ions will increase in the p-type material. The net effect, therefore, is a widening of the depletion region. This widening of the depletion region will establish too great a barrier for the majority carriers to overcome, effectively reducing the majority carrier flow to zero as shown in Fig. 1.16.

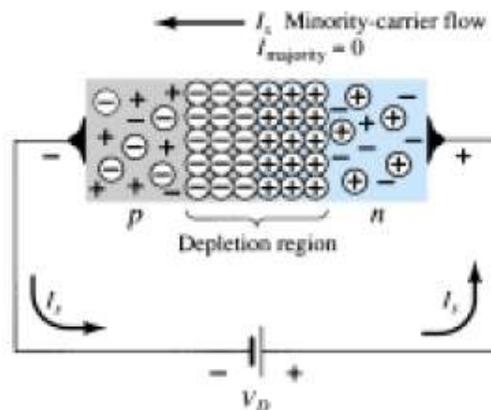


Figure 1.16 Reverse-biased p-n junction.

The number of minority carriers, however, that find themselves entering the depletion region will not change, resulting in minority-carrier flow vectors of the same magnitude indicated in Fig. 1.14 with no applied voltage.

The current that exists under reverse-bias conditions is called the reverse saturation current and is represented by I_s .

The reverse saturation current is seldom more than a few microamperes except for high-power devices. In fact, in recent years its level is typically in the nanoampere range for silicon devices and in the low-microampere range for germanium. The term saturation comes from the fact that it reaches its maximum level quickly and does not change significantly with increase in the reverse-bias potential, as shown on the diode characteristics of Fig. 1.19 for $V_D < 0$ V. The reverse-biased conditions are depicted in Fig. 1.17 for the diode symbol and p-n junction. Note, in particular, that the direction of I_s is against the arrow of the symbol. Note also that the negative potential is connected to the p-type material and the positive potential to the n-type material—the difference in underlined letters for each region revealing a reverse-bias condition.



Figure 1.17 Reverse-bias conditions for a semiconductor diode.

Forward-Bias Condition ($V_D > 0$ V):-

A forward-bias or “on” condition is established by applying the positive potential to the p-type material and the negative potential to the n-type material as shown in Fig.1.18. For future reference, therefore:

A semiconductor diode is forward-biased when the association p-type and positive and n-type and negative has been established.

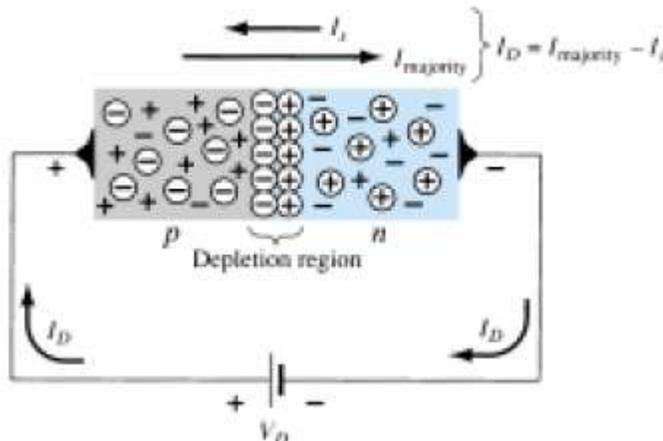


Figure 1.18 Forward-biased p-n junction.

The application of a forward-bias potential V_D will “pressure” electrons in the n-type material and holes in the p-type material to recombine with the ions near the boundary and reduce the width of the depletion region as shown in Fig. 1.18. The resulting minority-carrier flow of electrons from the p-type material to the n-type material (and of holes from the n-type material to the p-type material) has not changed in magnitude (since the conduction level is controlled primarily by the limited number of impurities in the material), but the reduction in the width of the

depletion region has resulted in a heavy majority flow across the junction. An electron of the n-type material now “sees” a reduced barrier at the junction due to the reduced depletion region and a strong attraction for the positive potential applied to the p-type material. As the applied bias increases in magnitude the depletion region will continue to decrease in width until a flood of electrons can pass through the junction, resulting in an exponential rise in current as shown in the forward-bias region of the characteristics of Fig. 1.19. Note that the vertical scale of Fig. 1.19 is measured in milliamperes (although some semiconductor diodes will have a vertical scale measured in amperes) and the horizontal scale in the forward-bias region has a maximum of 1 V

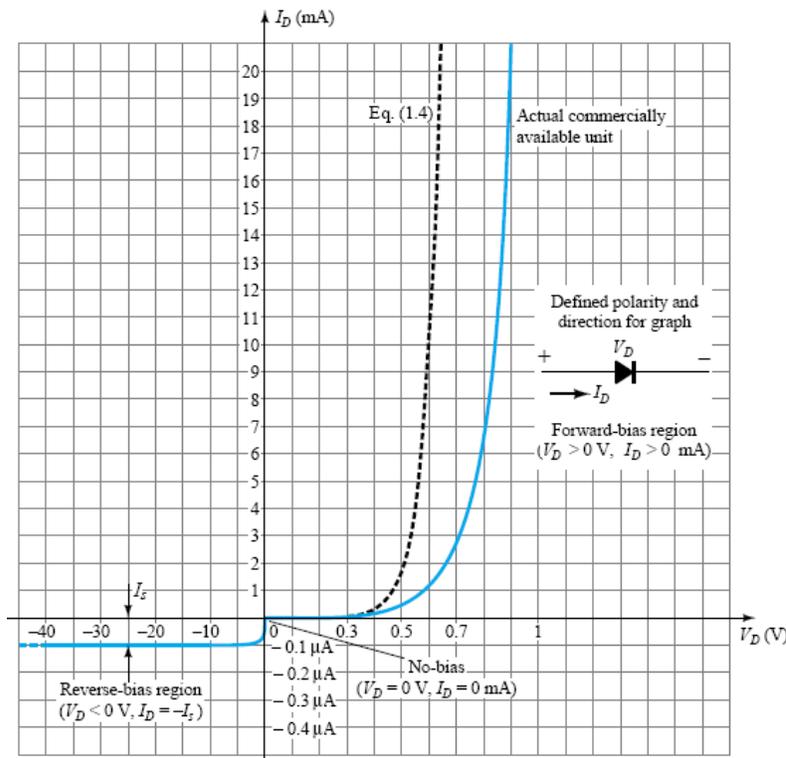


Figure 1.19 Silicon semiconductor

Typically, therefore, the voltage across a forward-biased diode will be less than 1 V. Note also, how quickly the current rises beyond the knee of the curve. It can be demonstrated through the use of solid-state physics that the general characteristics of a semiconductor diode can be defined by the following equation for the forward- and reverse-bias regions:

$$I_D = I_s(e^{kV_D/T_k} - 1) \tag{1.4}$$

where I_s = reverse saturation current

$k = 11,600/\eta$ with $\eta=1$ for Ge and $\eta= 2$ for Si for relatively low levels of diode current (at or below the knee of the curve) and $\eta= 1$ for Ge and Si for higher levels of diode current (in the rapidly increasing section of the curve)

$$T_K = T_C + 273^\circ$$

A plot of Eq. (1.4) is provided in Fig. 1.19. If we expand Eq. (1.4) into the following form, the contributing component for each region of Fig. 1.19 can easily be described:

$$I_D = I_s e^{kV_D/T_K} - I_s$$

For positive values of V_D the first term of the equation above will grow very quickly and overpower the effect of the second term. The result is that for positive values of V_D , I_D will be positive and grow as the function $y = e^x$ appearing in Fig. 1.20. At $V_D = 0$ V, Eq. (1.4) becomes $I_D = I_s(e^0 - 1) = I_s(1 - 1) = 0$ mA as appearing in Fig. 1.19. For negative values of V_D the first term will quickly drop off below I_s , resulting in $I_D = -I_s$, which is simply the horizontal line of Fig. 1.19. The break in the characteristics at $V_D = 0$ V is simply due to the dramatic change in scale from mA to A.

Note in Fig. 1.19 that the commercially available unit has characteristics that are shifted to the right by a few tenths of a volt. This is due to the internal “body” resistance and external “contact” resistance of a diode. Each contributes to an additional voltage at the same current level as determined by Ohm’s law ($V = IR$). In time, as production methods improve, this difference will decrease and the actual characteristics approach those of Eq. (1.4).

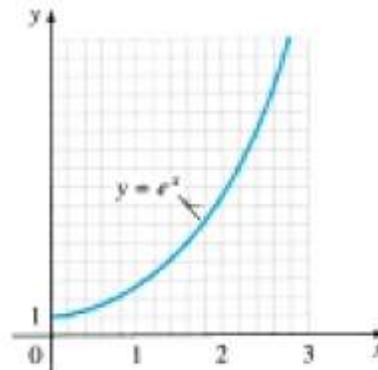


Figure 1.20 Plot of e^x .

It is important to note the change in scale for the vertical and horizontal axes. For positive values of I_D the scale is in milliamperes and the current scale below the axis is in microamperes (or possibly nanoamperes). For V_D the scale for positive values is in tenths of volts and for negative values the scale is in tens of volts.

Initially, Eq. (1.4) does appear somewhat complex and may develop an unwarranted fear that it will be applied for all the diode applications to follow. Fortunately, however, a number of approximations will be made in a later section that will negate the need to apply Eq. (1.4) and provide a solution with a minimum of mathematical difficulty.

Before leaving the subject of the forward-bias state the conditions for conduction (the “on” state) are repeated in Fig. 1.21 with the required biasing polarities and the resulting direction of majority-carrier flow. Note in particular how the direction of



Figure 1.21 Forward-bias conditions for a semiconductor diode.

conduction matches the arrow in the symbol (as revealed for the ideal diode).

Zener Region:-

Even though the scale of Fig. 1.19 is in tens of volts in the negative region, there is a point where the application of too negative a voltage will result in a sharp change

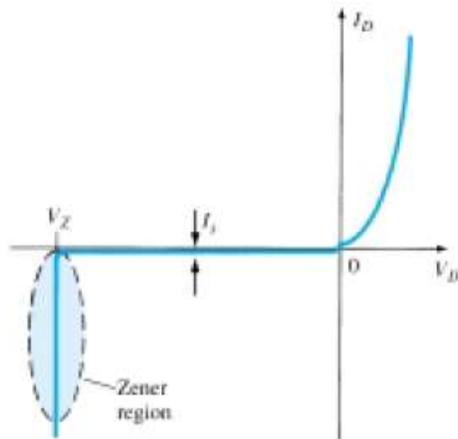


Figure 1.22 Zener region.

in the characteristics, as shown in Fig. 1.22. The current increases at a very rapid rate in a direction opposite to that of the positive voltage region. The reverse-bias potential that results in this dramatic change in characteristics is called the Zener potential and is given the symbol V_Z .

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 ($WK = 1/2mv^2$) 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.

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.

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.

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:-

Silicon diodes have, in general, higher PIV and current rating 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.

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 A at 25°C to have a leakage current of 100 A = 0.1 mA at a temperature of 100°C.

Current levels of this magnitude in the reverse-bias region would certainly question our desired open-circuit condition in the reverse-bias region. Typical values of I_s for silicon are much lower than that of germanium for similar power and current levels

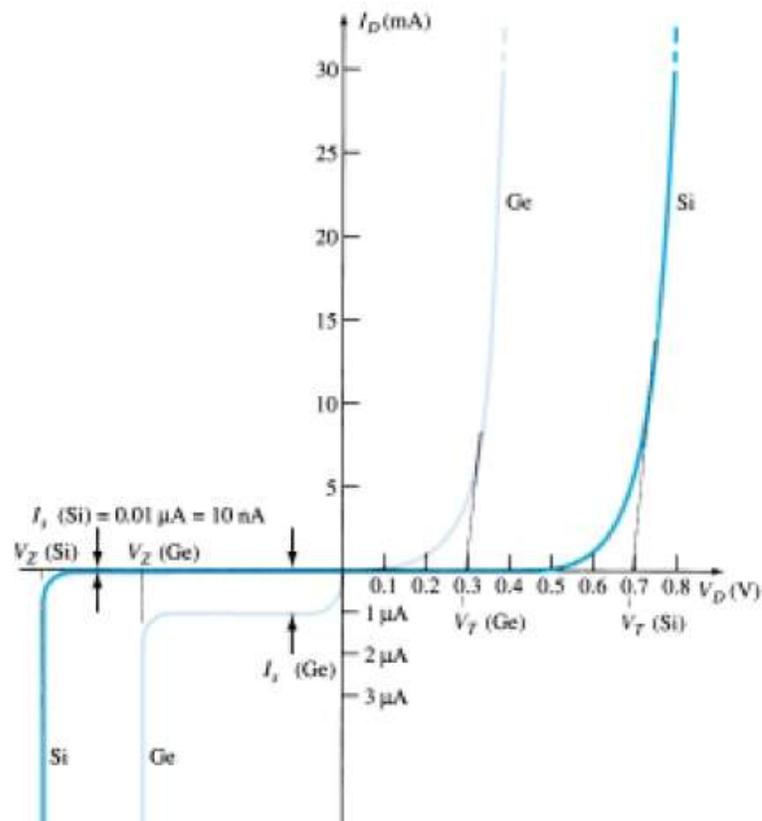


Figure 1.23 Comparison of Si and Ge semiconductor diodes.

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 utilization 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,” but we will find 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.

RESISTANCE LEVELS:-

As the operating point of a diode moves from one region to another the resistance of the diode will also change due to the nonlinear shape of the characteristic curve. It will be demonstrated in the next few paragraphs that the type of applied voltage or signal will define the resistance level of interest. Three different levels will be introduced in this section that will appear again as we examine other devices. It is therefore paramount that their determination be clearly understood.

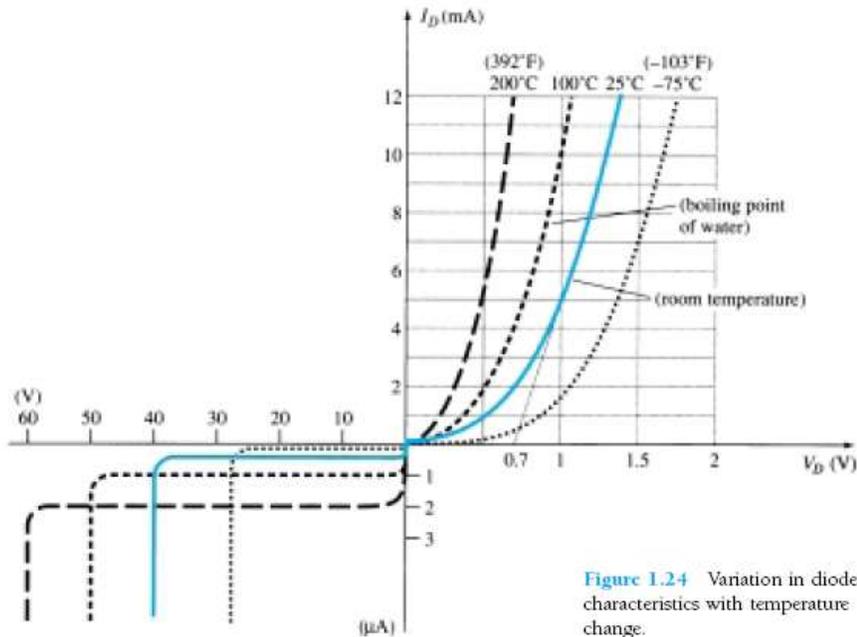


Figure 1.24 Variation in diode characteristics with temperature change.

DC or Static Resistance:-

The application of a dc voltage to a circuit containing a semiconductor diode will result in an operating point on the characteristic curve that will not change with time. The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D as shown in Fig. 1.25 and applying the following equation:

$$R_D = \frac{V_D}{I_D} \quad (1.5)$$

The dc resistance levels at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics. The resistance levels in the reverse-bias region will naturally be quite high. Since ohmmeters typically employ a relatively constant-current source, the resistance determined will be at a preset current level (typically, a few milliamperes).

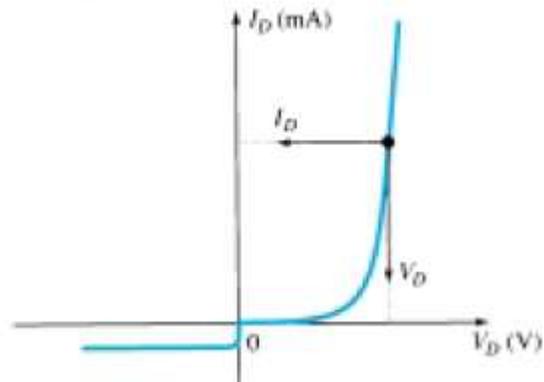


Figure 1.25 Determining the dc resistance of a diode at a particular operating point.

In general, therefore, the lower the current through a diode the higher the dc resistance level.

EXAMPLE 1.1

Determine the dc resistance levels for the diode of Fig. 1.26 at (a) $I_D = 2 \text{ mA}$
 (b) $I_D = 20 \text{ mA}$, (c) $V_D = 10 \text{ V}$

Solution

(a) At $I_D = 2 \text{ mA}$, $V_D = 0.5 \text{ V}$ (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.5 \text{ V}}{2 \text{ mA}} = 250 \ \Omega$$

(b) At $I_D = 20 \text{ mA}$, $V_D = 0.8 \text{ V}$ (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.8 \text{ V}}{20 \text{ mA}} = 40 \ \Omega$$

(c) At $V_D = 10 \text{ V}$, $I_D = -I_s = -1 \ \mu\text{A}$ (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{10 \text{ V}}{1 \ \mu\text{A}} = 10 \ \text{M}\Omega$$

clearly supporting some of the earlier comments regarding the dc resistance levels of a diode.

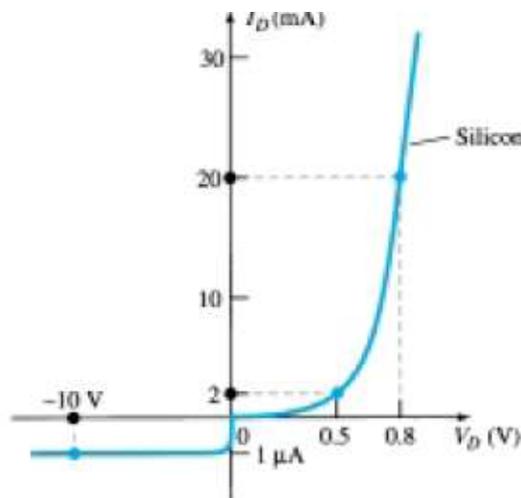


Figure 1.26 Example 1.1

AC or Dynamic Resistance:-

It is obvious from Eq. 1.5 and Example 1.1 that the dc resistance of a diode is independent of the shape of the characteristic in the region surrounding the point of interest. If a sinusoidal rather than dc input is applied, the situation will change completely. The varying input will move the instantaneous operating point up and down a region

of the characteristics and thus defines a specific change in current and voltage as shown in Fig. 1.27. With no applied varying signal, the point of operation would be the Q-point appearing on Fig. 1.27 determined by the applied dc levels. The designation Q-point is derived from the word quiescent, which means “still or unvarying.”

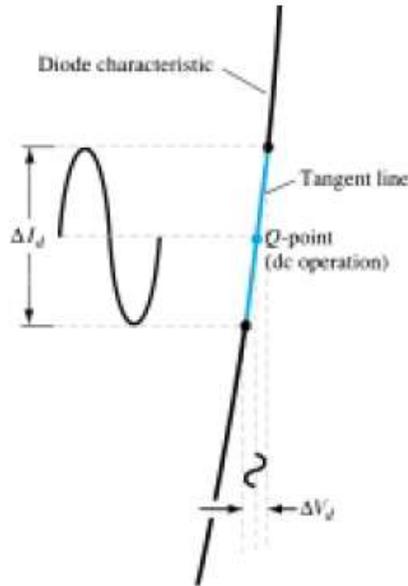


Figure 1.27 Defining the dynamic or ac resistance.

A straight line drawn tangent to the curve through the Q-point as shown in Fig. 1.28 will define a particular change in voltage and current that can be used to determine the ac or dynamic resistance for this region of the diode characteristics. An effort should be made to keep the change in voltage and current as small as possible and equidistant to either side of the Q-point. In equation form,

$$r_d = \frac{\Delta V_d}{\Delta I_d} \quad \text{where } \Delta \text{ signifies a finite change in the quantity.} \quad (1.6)$$

The steeper the slope, the less the value of ΔV_d for the same change in ΔI_d and the less the resistance. The ac resistance in the vertical-rise region of the characteristic is therefore quite small, while the ac resistance is much higher at low current levels. In general, therefore, the lower the Q-point of operation (smaller current or lower voltage) the higher the ac resistance.

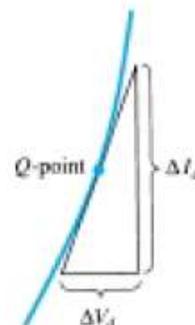


Figure 1.28 Determining the ac resistance at a Q-point.