C3HAPTER ONE:

Basic Semiconductor Theory

1.1. Introduction

A study of modern electronic devices like diodes, transistors and integrated circuits must begin with a study of the materials from which those devices are constructed. Knowledge of the principles of material composition at the level of the fundamental structure of matter is an important prerequisite in the field of electronics. The vital concern of this field is *predicting and controlling the flow of the atomic charge*. The study of electronic devices is now almost synonymous with the study of *semiconductor devices*. 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. So a ***Semiconductor*** is a material that has conductivity level somewhere between the extremes of an insulator and conductor. ***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. ***Insulator*** is a material that offers a very low level of conductivity under pressure from an applied voltage source.

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Resistivity

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.

$$\rho = \frac{RA}{l} = \frac{(\Omega)(\text{cm}^2)}{\text{cm}} \Rightarrow \Omega\text{-cm} \qquad \textbf{(1.1)}$$

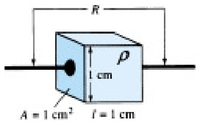

Figure 1.1 defining the metric units of resistivity

TABLE 1.1 Typical Resistivity Values

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

Note in Table 1.1 the extreme range between the conductor and insulating materials for the 1-cm length (1-cm^2 area) of the material. 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).

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.

1.2. Atomic Theory

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. 1.2

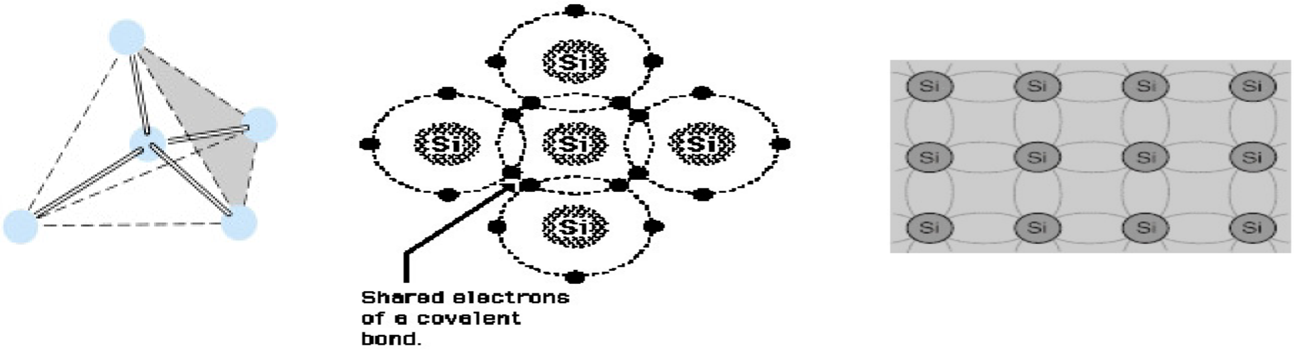

Figure.1.2. Ge and Si (Single-crystal structure Silicon Lattice)

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 single-crystal feature exists, and, in addition, the periodicity of the structure does not change significantly with the addition of impurities in the **doping process.**

How the structure of the atom 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. 1.3

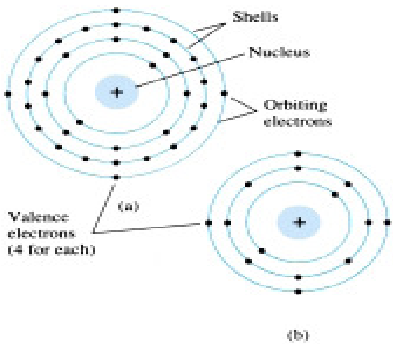

Figure 1.3 Atomic structures: (a) germanium; (b) Silicon

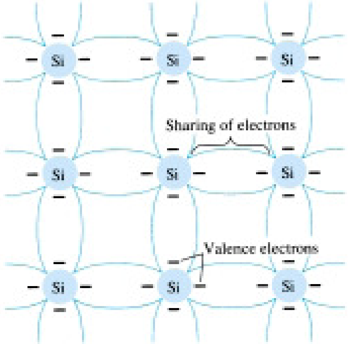

Figure 1.4 Covalent bonding of the silicon atom

As indicated by Fig. 1.3a, 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. 1.4 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 valence electrons, is called covalent bonding.

ENERGY LEVELS

In the isolated atomic structure there are discrete (individual) energy levels associated with each orbiting electron, as shown in Fig. 1.5. 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.

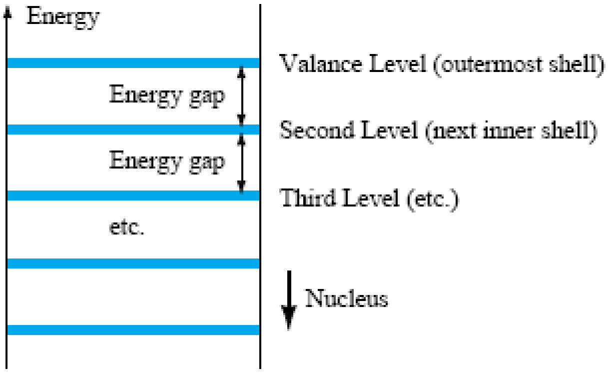

Figure 1.5 Energy levels: discrete levels in isolated atomic structures;

The energy associated with each electron is measured in *electron volts* (eV). The unit of measure is appropriate, since

$$\boxed{W = QV} \qquad \text{eV} \qquad (1.2)$$

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,

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

$$\boxed{1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}} \qquad (1.3)$$

Energy Band Model

One method of characterizing an electrical material is based up on a diagram that represents electron energy in that material. In the general case, electronic energy is divided among three bands that are designated as the valence band (bonding electrons with lowest energy), forbidden gap or band (electrons do not occupy energy states), and conduction band (conduction electrons with highest energy). In metallic conductors the forbidden gap is absent. In insulators, the forbidden gap is very large, and in semiconductors it is relatively small. Energy band diagrams for these three classes of materials are illustrated in figure 1.6.

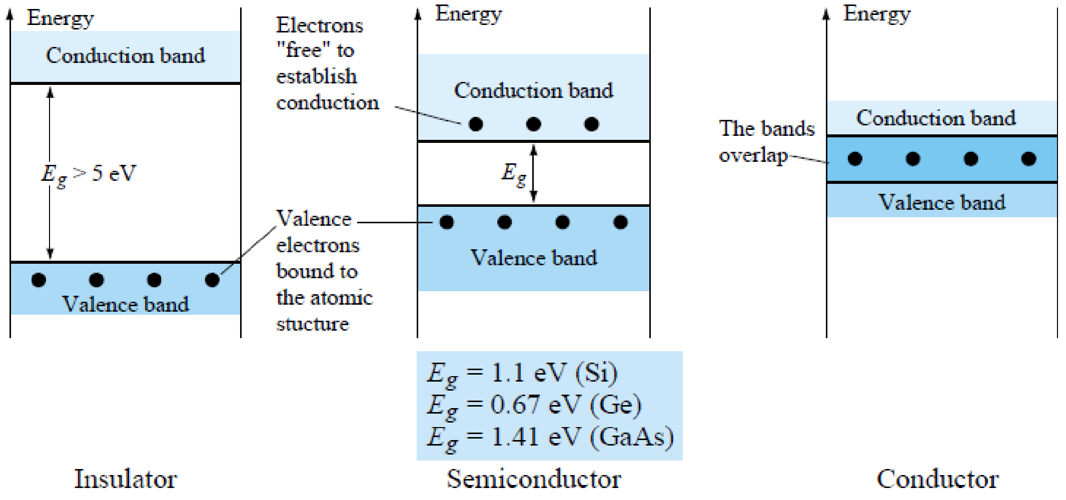

Fig.1.6. Conduction and valence bands of an Insulator, Semiconductor and Conductor

Electrons occupy specific energy states, or levels, in the conduction and valence bands, but they may not occupy energy states located in the band gap, which is why it is frequently called the *forbidden gap*. Relative to figure 1.6, to achieve electrical conduction, electrons must transfer from energy states in the valence band to energy states in the conduction band. The valence band represents low energy states of the electrons, in which the electrons are tightly bound to the atoms of the material. The forbidden band is not a physical void, but rather an energy gap. To cross the band gap, an electron must attain energy equal to or greater than the lowest allowed energy state in the conduction band; otherwise it cannot cross the gap.

In metals once temperature rises above absolute zero (0K), electrons acquire sufficient thermal energy to transfer from the valence band to the conduction band, thus making electrical conduction possible in the form of that described by Ohm's law.

In semiconductors, the term ohmic condition is applied to this phenomenon. Atoms are ionized (electrons are torn loose), and free (conduction) electrons are released to establish an electric current.

The forbidden gap regions associated with insulators and semiconductors represent energy levels that electrons may not assume. The only way that an electron can move from the valence band to the conduction band in these materials is by acquiring sufficient energy to cross the gap. Because of the large forbidden band in insulators, the material is usually damaged or destroyed.

In the pure (intrinsic) state, semiconducting materials manifest a forbidden gap that is less than that found in insulators. These materials are basically insulators, but not particularly good ones. When intrinsic semiconductors are modified by the addition of certain impurities, new (allowed) valence electrons states are created high in the forbidden gap, so that electrons can jump relatively easily into the conduction band

Example

1. How much energy in joules is required to move a charge of 6 C through a difference in potential of 3 V?

   Solution

   $$W = QV = (6C)(3V) = \underline{18J}$$

2. If 48 eV of energy is required to move a charge through a potential difference of 12V, determine the charge involved.

   Solution

   $$48eV = 48(1.6\times10^{-19}J) = 76.8\times10^{-19}J$$

   $$Q = \frac{W}{V} = \frac{76.8\times10^{-19}J}{12V} = \underline{6.40\times10^{-19}C}$$

   $6.4\times10^{-19}C$ is the charge associated with 4 electrons

1.3. Semiconductor Materials

Semiconductor materials are basically *Intrinsic* and *Extrinsic* semiconductor

1.3.1. Intrinsic Semiconductor

An intrinsic semiconductor is one, which is pure enough that impurities do not appreciably affect its electrical behaviour. In this case, all carriers are created due to thermally or optically excited electrons from the full valence band into the empty 9conduction band. Thus equal numbers of electrons and holes are present in an intrinsic semiconductor. Electrons and holes flow in opposite directions in an electric field, though they contribute to current in the same direction since they are oppositely charged.

Hole current and electron current are not necessarily equal in an intrinsic semiconductor, however, because electrons and holes have different effective masses (crystalline analogues to free inertial masses).The concentration of carriers is strongly dependent on the temperature. At low temperatures, the valence band is completely full making the material an insulator. Increasing the temperature leads to an increase in the number of carriers and a corresponding increase in conductivity. This characteristic shown by intrinsic semiconductor is different from the behaviour of most metals, which tend to become less conductive at higher temperatures due to increased phonon scattering.

Negative temperature coefficient:

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.

1.3.2. Extrinsic Semiconductor

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.

1.4. Types of Extrinsic Semiconductor Materials

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.

1.4.1. 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. 1.7 (using antimony as the impurity in a silicon base).

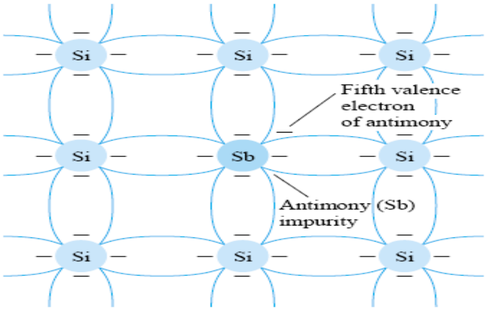

Figure 1.7 Antimony impurity in *n*-type material.

Note that the four covalent bonds are still present. There is, however, an additional fifth electron due to the impurity atom, which is *not associated* 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. 1.8. Note that a discrete energy level (called the *donor level*) appears in the forbidden band with an *Eg* 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} atom (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.

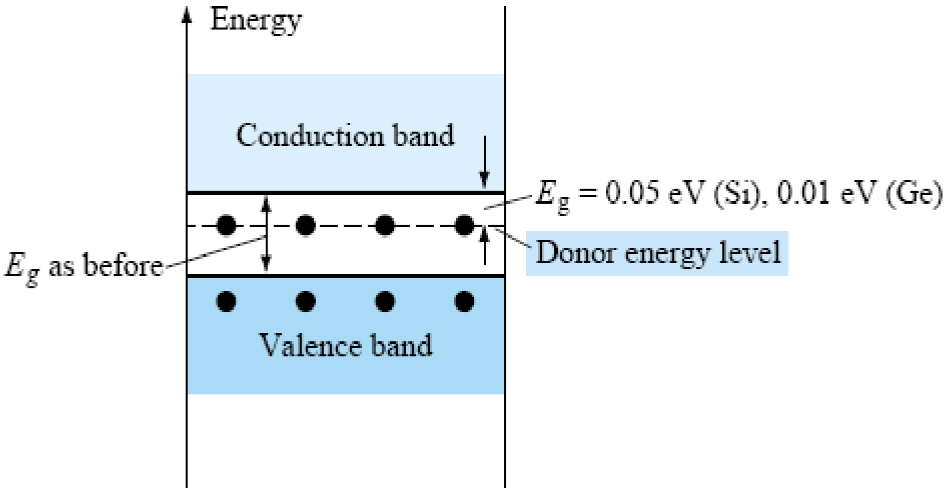

Figure 1.8 Effect of donor impurities on the energy band structure

1.4.2. ***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. 1.9.

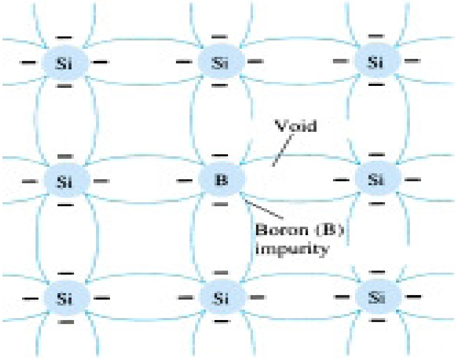

Figure 1.9 Boron impurities in *p*-type material.

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. 1.10. 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. 1.10. The direction to be used in this text is that of *conventional flow,* which is indicated by the direction of hole flow.

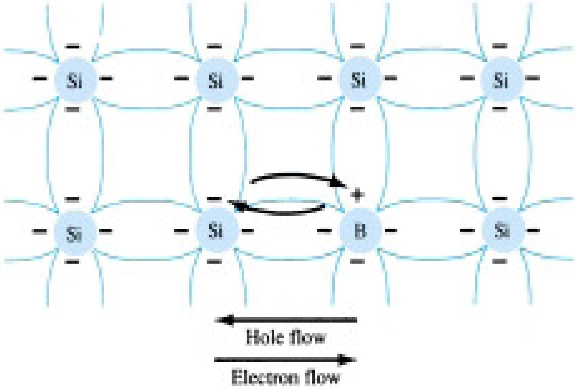

Figure 1.10 Electron versus hole flow.

Diffusion and drift current

The diffusion is a flow of charge carriers from a region of high density to a region of low density due to non uniform distribution of it. Diffusion current is the transport of charge carriers in a semiconductor.

Drift is charged particle motion in response to an applied electric field. When an electric field is applied across a semiconductor, the carriers start moving, producing a current. The positively charged holes move with the electric field, whereas the negatively charged electrons move against the electric field.

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 has 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. 1.11a) 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. 1.11b. 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.

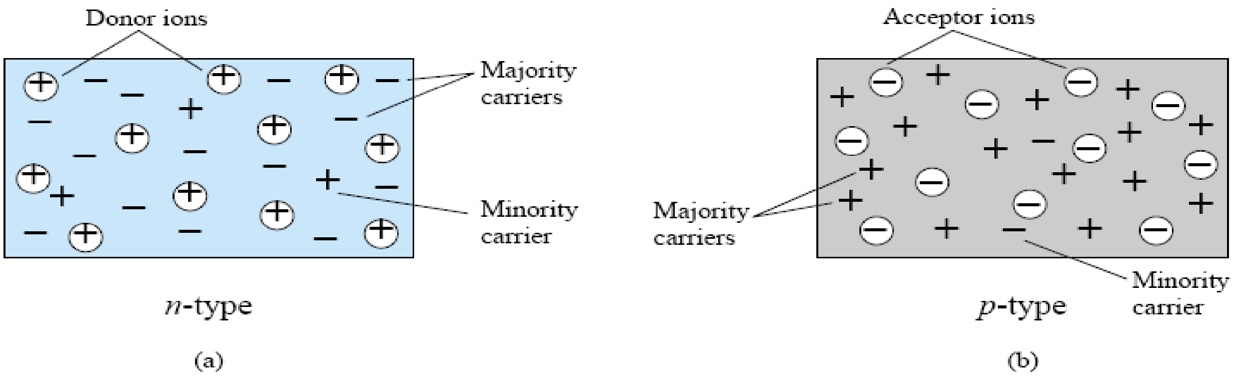

Figure 1.11 (a) *n*-type material; (b) *p*-type material

Regeneration and Recombination of Electron-Hole Pair

Free electrons and holes are generated by thermal energy, which causes covalent bonds to break at a rate depending strongly on temperature. The higher the temperature, the higher will be the rate of rege**neration**. On the other hand, for every '*liberated*' electron a '*hole*' remains in valence band. The atom with the 'hole' now has bonding 'deficiency' that demands filling. *Please note that, for the deficient silicon atom, a net positive charge has resulted. Also note that in a pure semiconductor, that is an intrinsic semiconductor, the number of liberated electrons equals the number of holes*. The liberated electrons to the conduction band give up energy and drop into a hole in the valence band. This does not contribute to the current; rather it is cancellation of charge carriers. And we say that **recombination** has occurred.

Thus, in semiconductors, the process of recombination and generation of electron-hole pairs establishes equilibrium at a particular temperature.

Therefore at any particular temperature there exists a certain number of electron-hole pairs that will govern the conductivity and the resistance of the material. Increasing the temperature of silicon will increase its conductivity and thus decrease its resistance. Thus semiconductors have a negative *Temperature Coefficient of Resistance*.

1.5. PN- Junction Theory

1.5.1. Unbiased PN-Junction

We have just seen that a crystal of pure silicon can be turned into a relatively good electrical conductor by adding an impurity such as Arsenic or Phosphorus (for an n-type semiconductor) or Aluminium or Gallium (for a p-type semiconductor).

By itself, a single type of semiconductor material is not very useful. But, something interesting happens when a single semiconductor crystal contains both p-type and n-type regions.

Hereafter, we examine the properties of a single silicon crystal which is half n-type and half p-type. Consider the silicon crystal represented below.

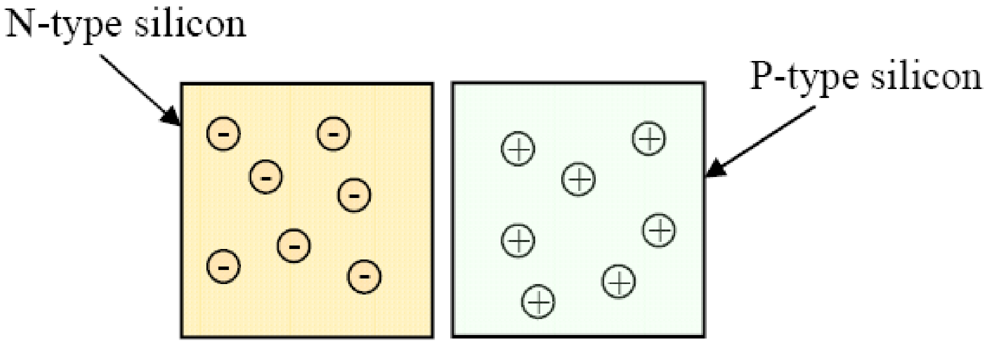

Fig.1.12.PN - Junction

Half is n-type while the other half is p-type. The two types are shown slightly separated, as if they were two separate crystals. In the real world, two such crystals cannot be joined together usefully. Therefore, a practical pn junction can only be created by inserting different impurities into different parts of a single crystal.

When we join the n- and p-type crystals together, an interesting interaction occurs at the junction. The extra electrons in the n region will seek to lose energy by filling the holes in the p region. This leaves an empty zone, or *depletion region*, around the junction. This action also leaves a small electrical imbalance inside the crystal. The n region is missing some electrons so it has a positive charge. Those electrons have migrated to fill holes in the p region, which therefore has a negative charge.

This electrical imbalance amounts to about 0.3 volt in a germanium crystal, and about 0.65 to 0.7 volt in a silicon crystal, known as a *barrier potential*. This will vary somewhat depending on the concentration of the impurities on either side of the junction.

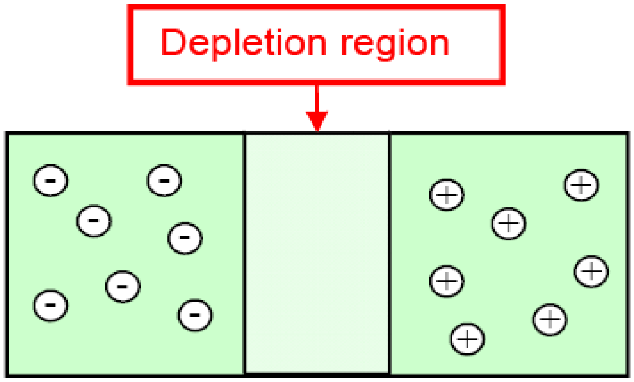

Fig.1.13.PN – Junction (unbiased)

1.5.2. PN – Junction Biasing

Forward Biasing

Suppose now we apply a voltage to the outside ends of our pn-crystal. In the forward biasing case, the negative terminal of the supply voltage is connected to the N-type end and the positive terminal is connected to the P-type material. The negative voltage applied to the N-type end pushes electrons towards the junction, while the positive voltage at the P-type end pushes holes towards the junction. This has the effect of shrinking the depletion region. As the applied voltage exceeds the internal electrical imbalance, current carriers of both types can cross the junction into the opposite ends of the crystal. Now, electrons in the p-type end are attracted to the positive applied voltage, while holes in the n-type end are attracted to the negative applied voltage. This is the condition of ***forward bias***.

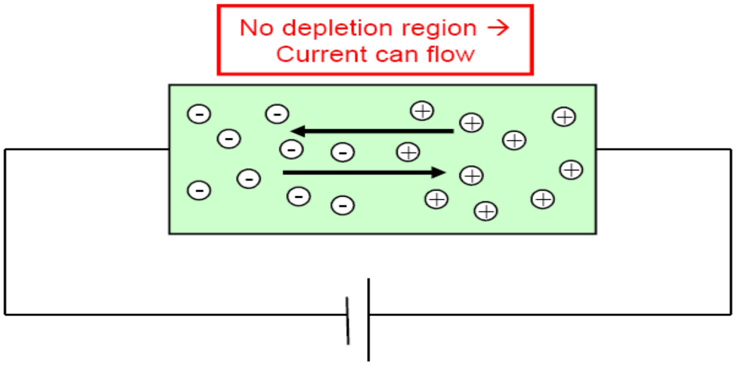

Fig.1.15. PN – Junction (Forward biased)

The conclusion is that due to the decrease of depletion region resistance, an electrical current can flow through the junction in the forward direction, but not in the reverse direction. This is the basic property of a semiconductor diode acting as a closed switch.

It is important to realize that holes exist only within the crystal.

A hole reaching the negative terminal of the crystal is filled by an electron from the power source and simply disappears. At the positive terminal, the power supply attracts an electron out of the crystal, leaving a hole behind to move through the crystal toward the junction again.

Reverse Biasing

Assume that the applied voltage polarities are reversed. In the reverse biasing case, the positive terminal of the external voltage is applied to the n-type material and the negative terminal of the supply voltage is connected to the p-type end.

In such a case, the positive voltage applied to the n-type material attracts free electrons towards the end of the crystal and away from the junction, while the negative voltage applied to the p-type end attracts holes away from the junction on this end.

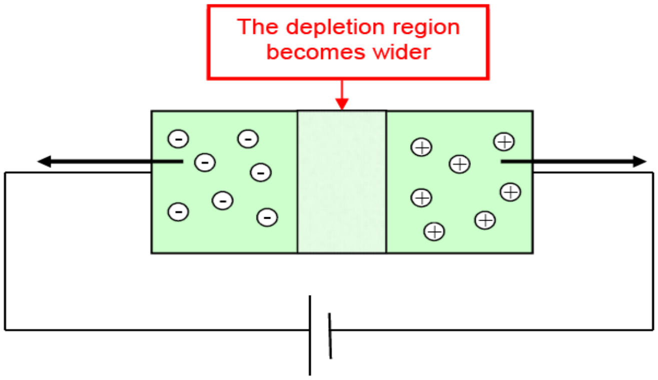

Fig.1.14.PN – Junction (Reverse biased)

The result is that all available current carriers are attracted away from the junction, and the depletion region grows correspondingly larger and its resistance increases.

Therefore, there is no current flow through the crystal because no current carriers can cross the junction (in practice, some tiny leakage current can still flow).

This is known as ***reverse bias*** applied to the semiconductor crystal, which is another basic property of a semiconductor diode acting as an open switch