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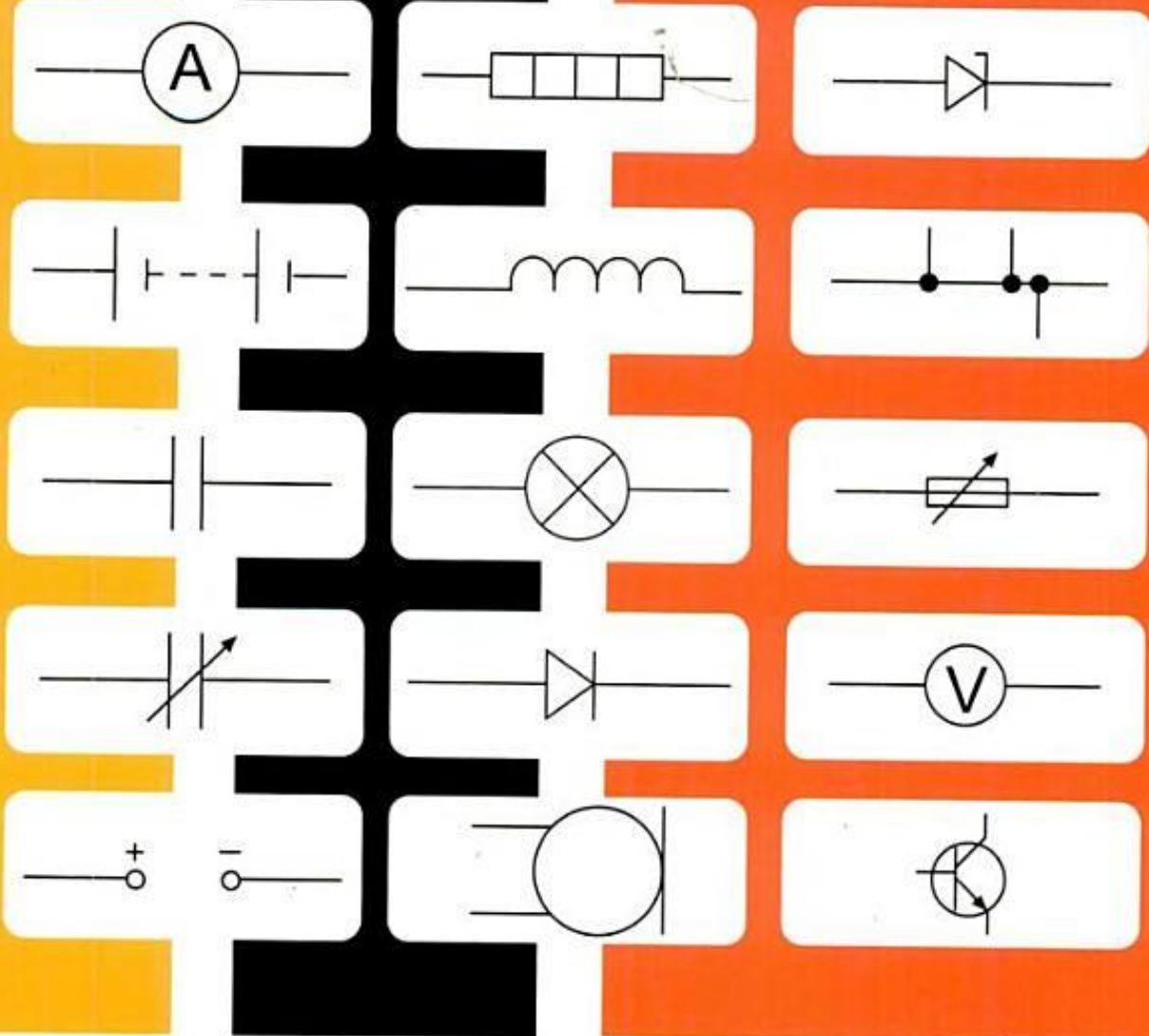


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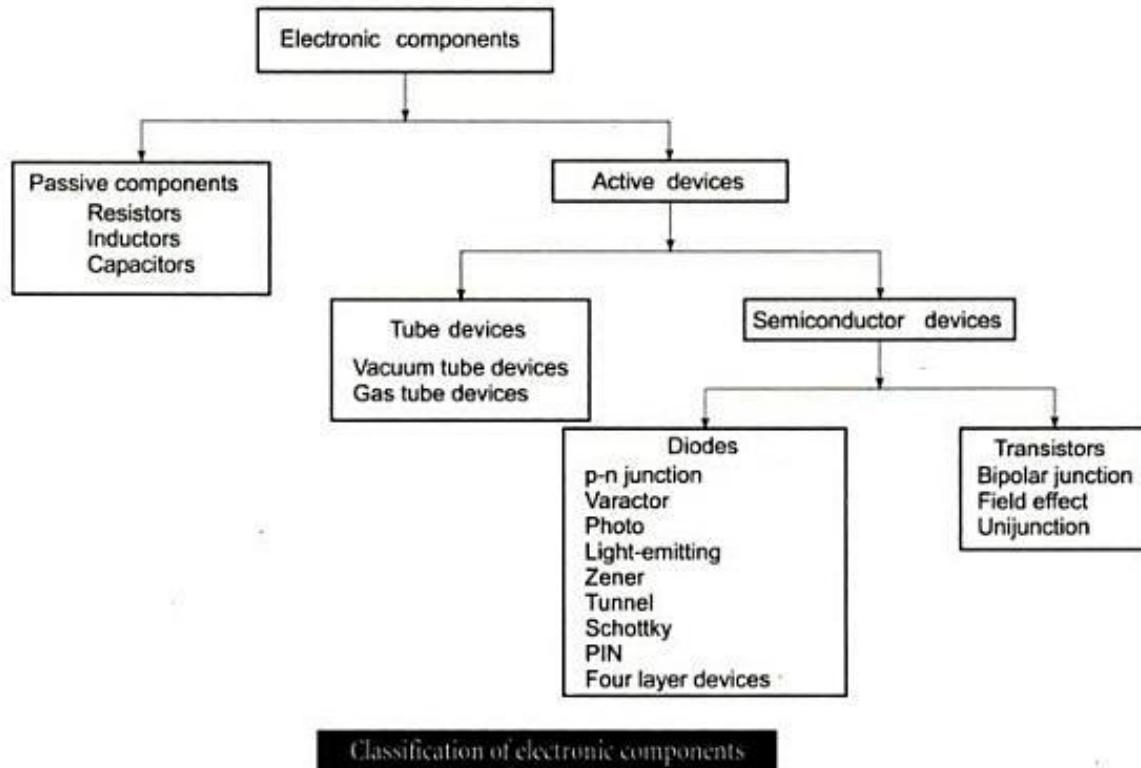


Electronic Devices and Circuits



Dharma Raj Cheruku ||| Battula Tirumala Krishna

Introduction



Chapter Outline

This introductory chapter outlines the fundamental terms related to electronics and its applications while delving briefly into the concepts of electronic components. These are essentially awareness stimulation techniques before going into the serious thoughtful topics. One may call this the appetizer before the feast—‘Electronic Warming Up’.

1.1 WHAT IS ELECTRONICS?

The word *electronics* is derived from *electron mechanics*, which means the study of the behaviour of an electron under different conditions of externally applied fields. Electronics can also be defined as physics of electrons and their utilisation. It is the study of how electrons behave and how they can be controlled so that they can do useful jobs. Electronics can also be referred to as '*the field of science and engineering, which deals with electronic devices and their utilisation*'. An *electronic device* is a device in which conduction takes place by the movement of electrons through vacuum, gas or semiconductor.

A tiny electronic component requires very minute power in the range of milliwatts or microwatts to function, but it can control or do works involving kilowatts or megawatts of power. Thus, it is not surprising to find the fundamentals of electronics being the core subject in all branches of engineering nowadays.

Nearly all the machines we use in our everyday lives from radios, calculators and television remote controls to telephones, computers and cars contain electronic circuits that make them work. Electronics is the backbone of information technology and communications. Although each of these areas represents a remarkable advance in technology, underlying the field of electronics are basically the general principles of electricity. All the applications of electronics make use of the fundamental laws of electricity and magnetism.

The study of electronics began at the end of the nineteenth century and had its first practical use in the early twentieth century in the development of radio communications. The first electronic devices were called thermionic valves. These included the diode valve, which allowed the flow of current in one direction but not in the other and triode in which a small current could be used to control a much larger current. These valves were either vacuum type or gas filled. In 1950s, semiconductor devices quickly replaced valves.

The invention of semiconductor transistor revolutionised every field of human life. Compared to the conventional tubes, these semiconductor devices are very compact, simple, more reliable and efficient. Since the size of the components reduced to a very large extent, electronic circuits were fabricated on Printed Circuit Boards (PCBs), which are very small and simple. The semiconductor devices are mounted on the board and the interconnections between the components are established easily by etching the conducting tracks on the board. These electronic circuits are very compact and are capable of doing almost any job.

The development of the Integrated Circuits (ICs) made electronics occupy all possible fields in domestic, industrial, medical and defence applications. An IC is an electronic circuit that is much more compact compared to PCB circuits in that the components as well as the total circuits are fabricated on a single substrate. Very complex circuits could be fabricated on a single simple substrate, reducing the size of the electronic circuits to microscopic level. The growth of the IC fabrication techniques is tremendously high—these days millions of transistors are fabricated on to a single microscopic-sized IC. With these drastic developmental changes in IC fabrication, the growth of IC applications is extremely rapid and has occupied all walks of life. Ultra-high-speed electronic devices were possible due to miniature-sized components. The speed with which an electronic gadget can operate is of the order of gigacycles per second. This tremendous speed of

operation has enabled the electronic engineer to devise new gadgets to meet all possible human requirements. These minute electronic components can control extremely large cargo ships at sea, gigantic steel mills, small robots and so on. It is no wonder today that these tiny electronic components do the most wondrous things in this wonderful world of ours.

The evolution of digital logic and digital electronics is the basic boost to the developments in the fields of computer science, information technology, communications and allied fields.

1.2 APPLICATIONS OF ELECTRONICS

The field of electronics is so broad that all human endeavours involve some form of electronics application. The following are a few of the innumerable areas that are dependent on electronics.

Home: Every nook and corner of a modern house is stacked with electronic gadgets. Electronic devices have simplified and speeded up mundane tasks of cleaning, cooking, lighting and security. Recreation at home is essentially the electronic way. Microwave oven, telephone, answering machine, home security, personal computer, light dimmers, appliances, toys, air conditioners, refrigerators, watches, clocks, washing machines, grinders, vacuum cleaners, electronic regulators, digital cameras, movie and video cameras and so on are few of the electronic devices used in the present day homes.

Information, communications and entertainment: The progress of a country depends upon the availability of economical and rapid means of communication. During the early part of twentieth century, the main application of electronics was in the field of telephony and telegraphy. This utilises a pair of wires. However, mobile communication using wireless communication systems gained wide popularity due to ease of communication between any two remote points on the globe. The wireless communication took shape and it has rapidly advanced in the last two or three years so much so that mobile communication is the buzzword of the day. Communication between any two remote places on the globe is possible, thereby shrinking the size of the globe. The other communication media these days are fax, Internet and so on, where any form of information (data, audio and video) travels with the speed of light. Entertainment has also drastically changed its face after the tremendous advancement of electronics. TV, radio, VCD, tape recorders, movie and so forth are part and parcel of domestic life these days. Electronic toys and games have revolutionised the field of entertainment to a very large extent. Each and every stage in the big screen and small screen makes endless use of electronics. Music synthesising, music recording, music enhancement, amplifying, special effects, stage special effects, public address system, digital images, graphics and so on are few stages involved in this field.

Transportation: In this jet age of travel, electronics is used in supersonic aircrafts to bullet trains to even a musical horn in a bicycle. Navigation of ships, space shuttles, air and auto traffic control, global positioning systems and so on are all electronic.

Business: Business transaction across the seas, buying and selling of not only commodities but also shares and stocks are all electronic these days.

Medicine: Bereft of electronics, medical sciences are severely handicapped. It is not very surprising to note that the functions of the medical field would be severely

hampered these days without electronics. One cannot think of diagnostics, surgery or treatment these days without the use of electronics in the medical field. Really, one has to think how these might have been possible without electronics in the good old days. Electronics and biomedical instrumentation have a huge role in this key field of medicine. Amazing advances in diagnosis, surgery, and pharmacy have been possible due to aid of electronics. Medical transcription and coding have made it possible to share medical information the electronic way. Diagnostics such as ECG, MRI and X-ray; electronic microscope, scanning, cancer treatment, surgery, patient monitoring, treatment; therapies such as laser, ultrasound and electronic puncture; rehabilitation aids and technique such as pacemakers, drug delivery, physical therapy and biofeedback; patient aids such as artificial limbs and hearing aids; biomedical instrumentation, telemedicine and many more are all electronic.

Instrumentation: Automation in industries is the order of the day. Quality control, standardisation of techniques, time and cost saving methods are possible only due to the application of electronics. Electronic gadgets control the process of production in an industry, whatever may be the type of product. For example, control of thickness, quality, weight, moisture, temperature and so on. Automatic door openers, lighting systems, power systems and safety devices, are used in establishments and shops. Industrial heating, welding, power device controls, and so on are also electronic. Cathode-ray oscilloscopes, ammeters, voltmeters, digital and analog multimeters, flux meters, pH meters, strain gauge, and precision measuring equipment are a few more examples of electronic instrumentation.

Scientific research: Electronics make scientific research simple by means of simulations, modelling and so on.

Environmental protection: Electronics find application in the protection of environment also. Electronic alarms can be employed which alert when a specified level of pollution is exceeded. Electric car, the recent invention, emits minimum or no pollutants into air. Waste treatment or waste water recycling are all controlled by electronic gadgets.

Athletics and sports: Optimisation of performance through electronic analysis of motion, control exercise equipment and so on depend on electronics. Live coverage, analysis and umpiring of any type of sporting action are with the help of electronic equipment.

Military: Defence operations currently are largely electronic. The radar gives the exact coordinates and tracks the target with extreme precision. The missiles are guided by electronic equipment. Global positioning systems give exact enemy location. Secrecy of information is achieved these days with the help of digital communications. To maintain the secrecy of base military camps and stations, electronic countermeasures, electronic jammers and so on are employed.

Computers: All hardware circuits and modules of digital computers such as CPU, monitors, keyboard, printers, scanners, CD writers, players, floppy drives, memory—RAM or ROM, uninterrupted power supplies and web cams are all electronic. Hardware components of LAN, MAN, WAN of various computing systems, e-mail, e-chat, all networking modems, modules, robots, computer communications, data communications, e-commerce, e-business, e-transcription, e-manufacturing and e-banking (for example, credit cards and ATMs) make use of the principles of electronics.

Education: Education at present employs large amount of electronics. E-learning and satellite TV form an integral part of distance-mode education system. Even for classroom teaching one requires LCD projectors, slide projectors, PA systems and so on, which are all electronic.

Astronomy: The space shuttle and its control, the communication gadgets employed in the study of extra terrestrial features of space, other planets, moon and so on are all electronic.

1.3 ELECTRONIC COMPONENTS

An electronic circuit may appear to be complex but is capable of performing innumerable functions. The electronic circuit is built with a few basic components of electronics.

The *electronic components* may be classified broadly as *passive* and *active* as shown in Fig. 1.1. Passive components are those components that cannot by themselves amplify or generate electric signals. They need no external biasing for their operation. Under this category, *resistors*, *inductors* and *capacitors* can be listed. Resistors are dissipative elements and they offer resistance to the flow of electric current through them. They dissipate energy in the form of heat. There are many types of resistors. They may be classified based on the applications, material composition, power rating and so on. Inductors and capacitors are energy storage device. They store electric energy and release as and when required. An inductor is a current-controlled device whereas a capacitor is a voltage-controlled device. These components can be classified based on the make, material used in

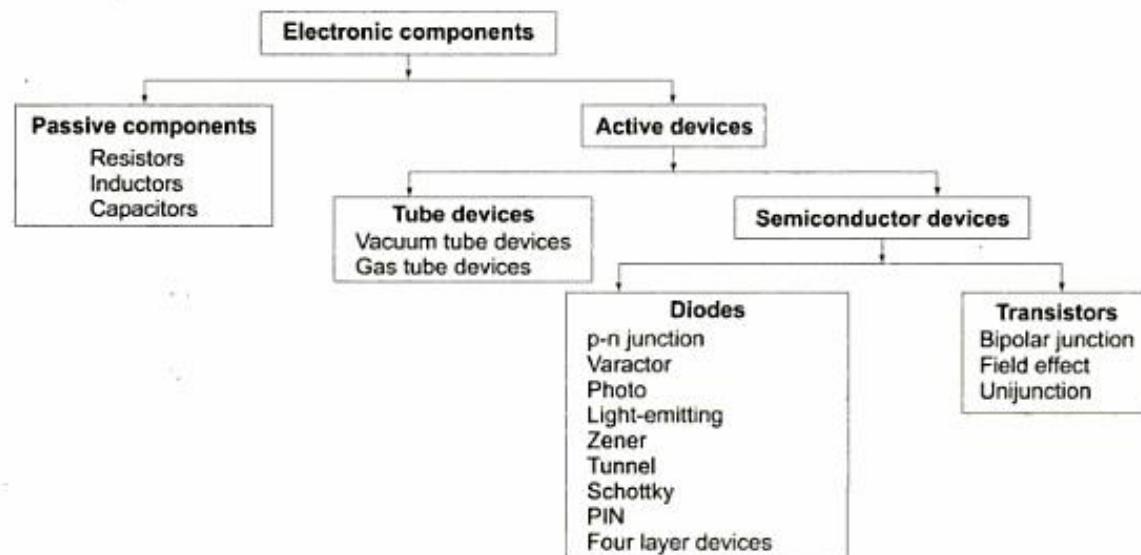


Fig. 1.1 Classification of electronic components

fabrication, power rating and so on. Variable resistors, capacitors or inductors are also possible.

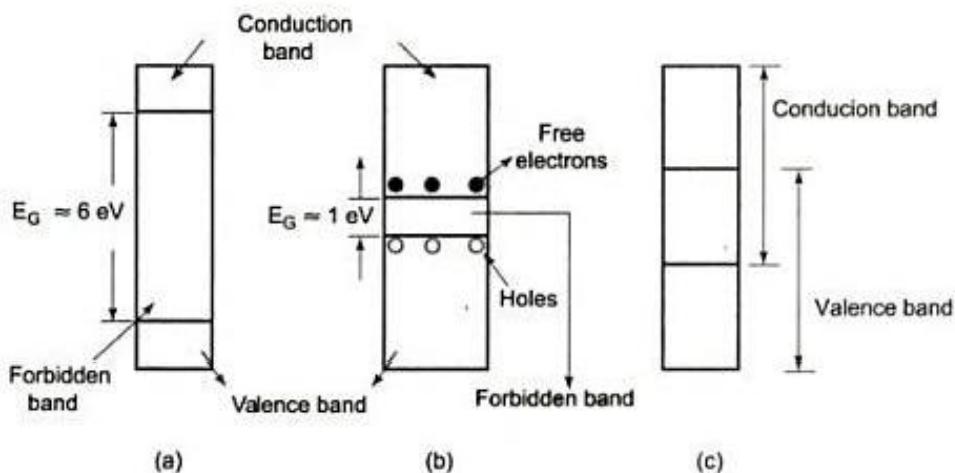
Active devices are the subject of this present work. Active devices are classified into *tube devices* and *semiconductor devices*. Tube devices are not dealt with here since they are almost obsolete. Tube devices are classified once again into *vacuum tubes* and *gas tubes*. The examples of vacuum tubes are vacuum diodes, vacuum triodes, vacuum pentodes and so on. The examples of gas tubes are gas diodes, thyratrons and so on. With the invention of compact and more efficient semiconductor devices, these tube devices find no place these days in electronics.

Semiconductor devices are the subject of treatment in the present work. There are various components in the field of electronics. The first and foremost is the *p-n semiconductor junction*. All subsequent developments in the electronic components are based on the principle of this semiconductor junction. The *junction diode* and the *transistor* are the broad classification of these devices. There are large numbers of diodes possible, depending on the application. They can be *p-n junction diode*, *varactor diode*, *photodiode*, *light-emitting diode*, *Zener diode*, *tunnel diode*, *Schottky diode*, *PIN diode* and so on. These diodes are tailored for a given application. These diodes can rectify, detect, switch, regulate, amplify or oscillate. Under the transistor classification, there are *bipolar junction transistors*, *field-effect transistors*, *unijunction transistors*, and so on. These devices can amplify, oscillate, control power, switch and so on.

The construction, structure, characteristics, equivalent circuits and applications of these semiconductor devices are presented in total in this book. Few important circuits built with these devices, namely, rectifiers, amplifiers and oscillators are also presented and analysed in this work. Before leaping into the details of the electronic components, one has to have an understanding of the semiconductor materials and their use in the fabrication of the electronic devices. These are introduced in Chapter 2. Various types of diodes and their characteristics along with their applications are discussed in Chapter 3. The construction of regulated power supply is also equally important for an electronic engineer. This is dealt with in the fourth chapter of the book. Chapters 5 and 8 introduce the transistor and field-effect transistor respectively, giving their characteristics, modes of operation and so on. The biasing methods and stability of transistors are discussed in Chapter 6. Chapter 7 deals with the analysis of amplifier circuits. Four-layer devices, unijunction transistors and other devices used in power electronics are presented in Chapter 9. Types of amplifiers and sinusoidal oscillators are discussed in Chapters 10, 11 and 12. Chapter 13 deals with one more electronic component which is widely and popularly used, namely, the Operational Amplifier, (OP-Amp). Cathode-ray oscilloscope (CRO) is one of the important measuring devices in electronics. The construction, features and applications of CRO are presented in Chapter 14, the last chapter of the book.

Semiconductors

2



Energy-band structure of (a) insulator, (b) semiconductor, and (c) metal

Chapter Outline

The concepts introduced in this chapter are:

- ◆ *Conductors and semiconductors*
- ◆ *Different types of semiconductors*
- ◆ *Current components in a semiconductor*
- ◆ *The behaviour of minority carriers in semiconductors*
- ◆ *Concept of semiconductor junction*

2.1 INTRODUCTION

The physics of the materials used in the construction of various electronic devices is very important to understand the basic operation of the device. The materials used in the electronic devices are *semiconductors*. These are the materials which neither fall in the category of conductors nor insulators. Unlike the dielectric materials, they have some conductivity, which can be controlled by external agents. This advantage of controlling the conductivity of the material at designers' requirements makes the material most suitable for electronic devices. In other words, the electron, the basic entity, is to be made to do work as per the requirement. The tiny energy associated with the tiny particle is contributed in the direction that is useful for a given application. The electrons, which are free and are not bound to any particular atom or molecule, are the charges that contribute to the conduction. In a semiconductor, unlike a conductor, there are positively charged holes that contribute conduction. So, in a semiconductor, there are two types of charge carriers, that contribute to conduction. They are negatively charged electrons and positively charged holes. Along with conduction current in a semiconductor, there is also a possibility of one more type of current known as *diffusion current*. This diffusion current may be once again due to electrons or holes. This type of current is not possible in a conductor. So, in a conductor, the current is only due to conduction of electrons. Whereas, in a semiconductor, the current consists of four components, namely, conduction current due to electrons, conduction current due to holes, diffusion current due to electrons and diffusion current due to holes. The behaviour of all these components of the current is to be known in detail to understand the electrical characteristics of the material that is used in the electronic devices. The most popularly used materials used in fabrication of the active devices are *silicon* and *germanium*.

The charge of negative electricity and the mass of the *electron* are known to be 1.6×10^{-19} C and 9.11×10^{-31} kg, respectively. Since 1 A of current is flow of 1 C/s, 1×10^{-12} A (1 pA) represents the motion of approximately 6000000 electrons per second. But, 1 pA of current is in general, very minute. The radius of the electron is estimated to be 10^{-15} m. This being a very small value, the electron is assumed to be point in all the discussion to follow.

A semiconductor material has two types of charge carriers. They are electrons and holes. Holes are formed when an electron is missing from the covalent bond that is formed between neighbouring atoms of the semiconductor material. Since an electron is missing from the stable covalent bond, the empty space in the bond structure is referred to as *hole*. The electron is negatively charged and so, the hole is positively charged. The magnitude of the charge of a hole is same as that of the electron. These holes also contribute to conduction and the details of all of the current components will be taken up in detail later in the chapter.

The unit of energy, Joule, is in general used in mks system. Depending on the magnitude of the energy, the joule can be expressed in kilo, mega, micro, or pico in the discussion of basic electronic theory; since the energies associated with the electron are very small, expressing them in joules is difficult. Thus, a new unit of energy is used for such tiny magnitudes of energies.

One *electron volt* (eV) can be defined as

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J} \quad \dots(2.1)$$

If an electron falls through a potential of 1 V, its kinetic energy will increase with decrease in potential energy. Thus,

$$qV = (1.6 \times 10^{-19} \text{ C}) \times (1 \text{ V}) = 1.6 \times 10^{-19} \text{ J} = 1 \text{ eV} \quad \dots(2.2)$$

This unit is unit of energy and can be used for any type of energy.

2.2 POTENTIAL BARRIER

The concept of *potential barrier* finds a very interesting and most useful application in semiconductor junctions. To understand this concept, consider two parallel electrodes *A* and *B* separated by distance *d*, with *B* at a negative potential V_d with respect to *A* as shown in Fig. 2.1.

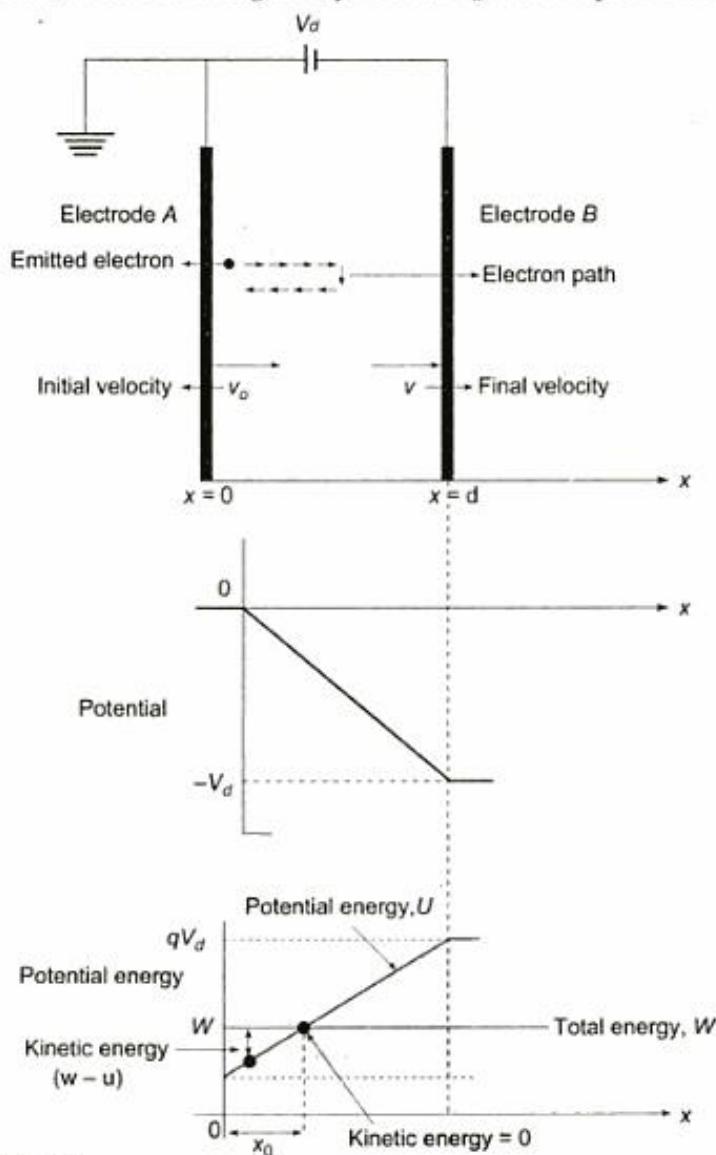


Fig. 2.1 Potential Barrier

The force f on charge q in presence of electric field is defined as charge times the electric field intensity ϵ . The same force may be expressed in terms of Newton's second law of motion as its mass m times acceleration if the charge moves with a velocity v .

$$f = q\epsilon = m(dv/dt) \quad \dots(2.3)$$

The work done per unit charge in moving a point charge from point A to point B is known as the *potential* V of the point B .

$$\epsilon = -dV/dx \quad \dots(2.4)$$

And, the *potential energy* U is *charge times the potential*,

$$U = qV \quad \dots(2.5)$$

According to the law of conservation of energy the total energy in a system remains constant. Thus, the two components of energy available in this system are potential energy U [Eq.(2.5)] and the kinetic energy associated with moving charge ($\frac{1}{2} mv^2$).

$$W = U + \frac{1}{2} mv^2 = \text{constant} \quad \dots(2.6)$$

Referring to Fig. 2.1, consider an electron leaving the surface of A with an initial velocity v_0 in the direction towards B . Since the potential of A is zero, the potential energy at this electrode is zero and the total energy is entirely due to kinetic energy and is equal to

$$W = \frac{1}{2} mv_0^2 \quad \dots(2.7)$$

As the electrons move forward towards B , the potential, and thus the potential energy, increases. Due to conservation property of energy, increase in potential energy leads to decrease in kinetic energy and thus decrease the velocity with which the electron travels. Thus,

$$W = \frac{1}{2} mv_0^2 = \frac{1}{2} mv^2 + qV_d \quad \dots(2.8)$$

Thus, the velocity of the electron reduces as it travels toward B , as is true since the electron is moving in a repelling field. The final speed of the electron, as it reaches the electrode B , is independent of the variations of the field distribution between the two plates and depends only upon the magnitude of the potential difference V_d . If the electron is to reach the electrode B , its initial speed must be large enough so that

$$\frac{1}{2} mv_0^2 > qV_d \quad \dots(2.9)$$

If not, Eq. (2.8) leads to the impossible result that velocity v is imaginary. Fig. 2.1 also shows the variation of the potential between the two electrodes A and B . It also gives a plot of energy with the distance. As can be seen from the figure, when an electron is released with an initial velocity such that $\frac{1}{2} mv_0^2 < qV_d$ the electron, as it travels forward, reduces its velocity and at a distance where the total energy is equal to the potential

energy, the speed of the electron becomes zero and the electron will have to halt. Which means at this distance, there is no kinetic energy and the electron is at rest. Further, the electron cannot move in the forward direction to reach the electrode *B* and will have to reverse its direction toward electrode *A*. The distance travelled by the electron between the electrodes, x_0 , depends on the total energy of the system or, in other words, on the initial kinetic energy of the electron. The higher the initial velocity, larger is the value of x_0 . If the electron were to reach the other electrode, the initial energy should be more than the potential energy at the electrode *B*. This is as shown in Fig. 2.1.

From the above discussion it can be concluded that the electron never reaches the shaded portion of the energy diagram as shown in the figure. The electron travels forward with an initial velocity toward *B* until the electron hits the potential *hill*. On hitting this hill, it reverses its direction and travels in the opposite direction but can never reach the hill. No electron can thus exist in the shaded portion of the plot since if it exists, it is supposed to have negative kinetic energy, that is, negative velocity, which is an impossible condition practically. This *potential hill* is a fictitious barrier, which obstructs the electron from entering the other side of the barrier. Physically, there is nothing like this potential hill but the electron behaves as if it is bouncing back after colliding with the potential hill. This is the *potential barrier*, which is important in understanding the behaviour of the semiconductor junction.

2.3 ENERGY-BAND THEORY

The general structure of metals and semiconductors is crystalline in nature, that is, the atoms are arranged in arrays in the form of a definite fundamental pattern. The fundamental pattern may either consist of atoms or molecules depending up on the material under consideration. The energy associated with electrons of a single atom is not applicable to these crystalline structures. The atoms are not free as in a gas, but are shared by the neighbouring atoms. So, it is not possible to consider a single atom separately and discuss about the discrete energy levels of the electrons in the atom. The energy associated with electrons in a crystal is not the same as that when the atom is singled out. This is so because the potential characterising the crystalline structure is now a periodic function in space whose value at any point is appreciably by the presence of the neighbouring atoms. The levels of the outer or valence shell are affected and the inner shell electrons are not much disturbed since the neighbouring atoms share the electrons from the outermost shell. Or, in other words, the valence shell electrons are no more an inherent property of the base atom but are shared by more than one atom. The new energy levels are determined by quantum mechanics and sharing the valence shell electrons results in an *energy-band* of closely spaced energy states instead of widely separated energy levels of the isolated atom. That is, the energy levels are no more discrete and separated by large amounts of levels as in the case of an isolated atom, but are in very closely packed energy states such that it seems to be a continuous energy-band where electrons occupy different levels in the band.

For a better understanding of the concept of energy-band theory, consider group IVA elements [carbon (C), silicon (Si), germanium (Ge) and tin (Sn)] with four valence-shell electrons. There are N atoms in a considered crystal and so, there will be $4N$ electrons in the

outer subshell of the system. Of these, $2N$ electrons are s type and remaining $2N$ are p type. Assume a situation where it is possible to vary the spacing between the neighbouring atoms without changing the basic structure of the crystal. When the interatomic distance is very large, the atoms can be considered to be isolated and the energy levels discrete, as in the case of a gas. The electrons in the inner shells are not considered since they are not affected. In the crystalline system thus formed, there are $2N$ s electrons occupying all the possible $2N$ levels. Of the possible $6N$ p states in the valence shell, only $2N$ levels are occupied and the remaining $4N$ levels of p electrons are vacant.

Now, if the interatomic spacing in the crystal is decreased, an atom will exert an electric force on its neighbours. A coupling between atoms is formed and the wave functions overlap, and the crystal becomes an *electronic system* that must follow *Pauli exclusion principle*. Pauli exclusion principle states that *in an electronic system, no two electrons can have same four quantum numbers, n , l , m_l and m_s* . Or, in other words, no two electrons can occupy the same quantum state in an electronic system. So, when an electronic system is formed by bringing the atoms close to each other in a crystal, the discrete energy levels of the electrons of single atom spread out into an *energy-band*, which is nothing but a large number of closely packed energy levels. As the interatomic spacing is decreased, since N is a very large number, and the separation between levels is small, the total spread between the minimum and maximum energy may be several electron volts. As the spacing is further decreased, the energy bands of both the s electrons and p electrons spread out as shown in Fig. 2.2. It may be noted that the s electron-band and the p electron-band are separated by an energy gap (forbidden energy gap), which decreases as the interatomic spacing is decreased. Thus, as can be seen from the figure, the $2N$ electrons occupy all the s states, while only $2N$ states of the possible $6N$ states of the p type energy-band are occupied.

As the spacing between the atoms is further reduced, the energy gap between the two energy levels decreases and tends to combine at a particular spacing value. That is, at this value of spacing, the two bands overlap and the energy gap vanishes. Now, there are $8N$ possible states in the energy-band, of which $4N$ states are occupied and $4N$ are vacant. It

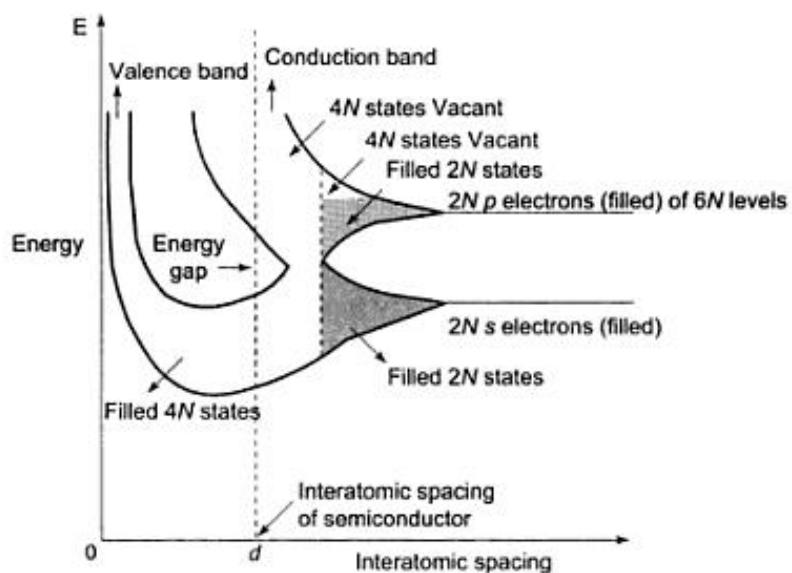


Fig. 2.2 Energy bands

may be noted at this juncture that the identity of the electron is lost—the *s* and *p* electrons are no more different and these electrons belong to the crystal as such. Simply, there are $4N$ electrons in the possible $8N$ states. Since the atom contributes four electrons to the crystal from its outermost shell, it is referred to as *tetravalent* and the energy band as *valence band*.

Reducing the spacing further is a very complex situation and it may be represented as shown in Fig. 2.2. As can be seen from the figure, the two bands, which merged with each other, will separate once again with a forbidden energy gap. Now, there are two energy bands, the lower one is referred to as *valence band* and the upper one as *conduction band*, separated by an *energy gap*. The valence band consisting of $4N$ states is totally occupied by the $4N$ electrons and the conduction band having $4N$ states is totally vacant. This is where the interatomic spacing of a tetravalent semiconductor material is found in nature. The energy gap between the energy-bands depends on the type of material and is very large for an insulator, small for a semiconductor and in case of a metal there is no energy gap and the two bands overlap.

2.4 CLASSIFICATION OF MATERIALS

A material may be classified as *metal*, *insulator* or *semiconductor* based on the energy-band structure. The conductivity of the material depends on the electrons available in the *conduction band*. The more the electrons are in this band, more is the conductivity of the material. The electrons available in this energy-band are not bound to the crystal structure but are *free* to move about randomly throughout the material. In all the discussion, the electrons referred to are these electrons, which are available in the conduction band, and the electrons in the lower energy-bands are of no use as far as conduction is concerned. The energy-band structure for all three types of materials is as shown in Fig. 2.3.

In an *insulator*, as shown in Fig. 2.3, the forbidden energy gap between the conduction band and valence band is very large, of the order of 6 eV (diamond, for example). The

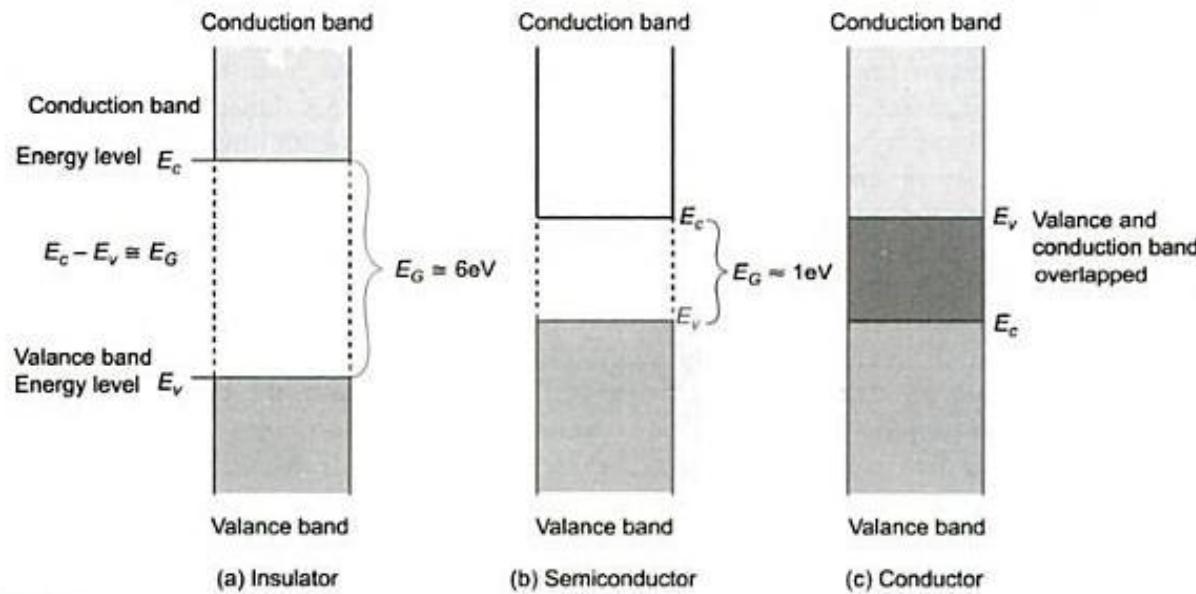


Fig. 2.3 Energy-band structure

valence band is totally filled with electrons and there are no electrons available in the conduction band. That is, all the electrons are bound to the crystalline structure and there are no electrons that can contribute to conduction. If one requires conduction in a material, the electrons from the valence band are to be shifted to conduction band. In other words, an electron that is bound in the covalent bond structure of the material is to be given a suitable energy such that the bond is broken and the excited electron reaches the conduction band level. It may be noted that the electron can only exist in the valence band or the conduction band, but if an electron in the valence band receives energy which will launch it into the forbidden energy gap, it will exist only in the valence band. Until the electron receives sufficient energy to overcome the forbidden energy gap, and thus to jump from the valence band to the conduction band, it remains in the valence band. In case of an insulator, this energy gap is so large that shifting electrons from the lower band to the conduction band is not possible and so there are no electrons in the conduction band. Thus, there is no conduction possible in these materials.

A material that has a relatively small energy gap, of the order of 1 eV, is referred to as a *semiconductor*. The energy gap E_G is 0.785 and 1.21 eV for germanium and silicon, respectively, at 0 K. At this absolute temperature (0 K), these materials are also insulators since the valence band is full and conduction band is totally empty. There is no conduction possible with such materials even at extremely small temperatures. But, as the temperature increases, the electrons in the valence band receive energy in the form of thermal energy and since E_G is small, small energy increments are sufficient to shift the electrons from the lower to upper bands. As the temperature increases, the system receives more and more energy from thermal excitations and more and more electrons are displaced from the valence band to the conduction band. Thus, the conductivity of the material improves. In other words, the covalent bond between the atoms in the crystal is broken and the electrons are released. These electrons are not bound to any structure now and are free to wander anywhere in the material. Their motion is very random, but the average number of electrons crossing a given cross-section would be the same as that of the electrons crossing from the opposite direction and so, the net movement of electrons at any given instant of time is zero. When an electron is released from the valence band into the conduction band, it leaves back an empty pocket in the valence band, which is positively charged and referred to as *hole*. A hole in a semiconductor refers to the empty energy levels in an otherwise filled valence band. This positively charged hole also contributes to conduction. As one electron shifting from the valence band to the conduction band leaves behind one hole in the valence band, the number of holes in the valence band is exactly the same as that of the electrons in the conduction band. This is true for a material that is pure. That is, in such a material, all the atoms of the crystal are of the same type and no other impurity atom is available. Then the material is said to be *intrinsic*. Introducing impurity atoms in the crystal may also enhance the conduction of the material. Such a material is referred to as *extrinsic*. The band gap energy of a crystal is a function of interatomic spacing and depends on temperature. It decreases with increase in temperature.

A *metal* is a material where there is no energy gap and the valence band and the conduction band are overlapping, as shown in Fig. 2.3. The electrons do not pertain to any definite band and so applying a small electric field to the material excites the electrons to

a higher energy level and these electrons move under the influence of the applied field to constitute conduction current. There is no possibility of a hole in a metal or a conductor since there is no differentiation of valence and conduction bands and the energy gap is absent. Electrons can exist in any level of energy in the band.

2.5 INTRINSIC AND EXTRINSIC SEMICONDUCTORS

An *intrinsic semiconductor* is the one that is pure and has no impurity atoms in its crystalline structure. An *extrinsic semiconductor* is the one in which impurities are added purposefully to increase the conductivity of the material. For example, either trivalent or pentavalent atoms are added to tetravalent atoms. Adding the impurities, the conductivity of the material increases to a great extent.

The conductivity of the material depends on the number of atoms in the conduction band of the material. For a good conductor the electron concentration n (number of electrons per unit volume) is very large ($\approx 10^{23}$ electrons per m^3); for an insulator it is very small ($\approx 10^7$) and for a semiconductor its value lies between these two values. The valence electrons in a semiconductor are not free to wander about as they are in a metal, but rather are trapped in a bond between two adjacent ions.

All the Group IVA elements (C, Si, Ge and Sn) have four electrons in the valence shell and exhibit properties of semiconductors, of which silicon and germanium are widely used in electronic devices. The crystalline structure is a three dimensional tetrahedron with one atom affixed at each vertex. The basic unit repeats in all the three directions in the structure. The structure is as shown in Fig. 2.4. The silicon or germanium material has four electrons in the valence shell and these electrons of each atom are shared by the neighbouring four atoms to form covalent bonds. Thus, an *electron pair* is formed, which is the covalent bond. Sharing four electrons from the neighbouring atoms along with the four atoms of its valence shell constitutes eight electrons in the system and thus stability is

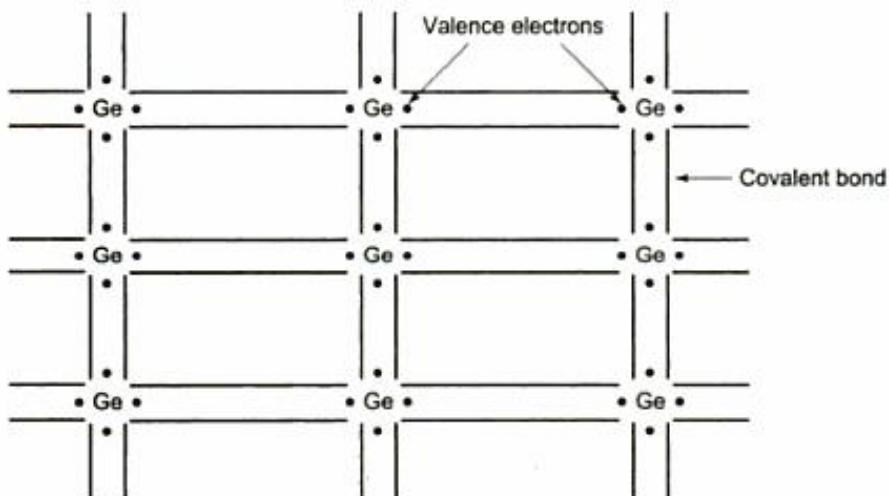


Fig. 2.4 Crystal structure of germanium at 0° K

achieved in the structure. Since four electrons are donated to the neighbouring atoms to form covalent bonds, the left-over part of the atom is an ion positively charged four times to that of the magnitude of the charge carried by each electron. There is a binding force between the adjacent atoms due to this sharing of electrons forming the covalent bonds. These valence electrons are tightly bound to the nucleus and so they are not free to wander about in the material. Even though there are four electrons available in the valence band of the atom, the crystal conductivity is very low since these electrons are bound.

The above discussion refers to the case when the material is ideal at 0° K. In this condition, the material behaves as an insulator since there are no free electrons. At room temperature, the conduction of the material increases since some of the electrons gain energy from the thermal agitation and acquire sufficient energy to get transferred from valence to conduction band. The thermal energy is sufficient to break the covalent bond and the electron that is bound previously gets released and does not belong to any particular atom. This electron is free and can go anywhere in the material. While a negatively charged electron is released to be free, it leaves behind an empty space, that is positively charged. This empty location in the valence band of the atom is referred to as hole. This positively charged hole also contributes to conduction like the free electrons in a semiconductor. Thus, breaking a covalent bond in the structure creates two carriers of current—charge carriers—one electron and one hole. The concept of electron and hole charge carriers is as shown in Fig. 2.5.

The positively charged hole contributes to conduction. The electrons in the neighbouring covalent atoms move to occupy the empty spaces in the valence band, that is, the hole. The electron moving from a bond to fill a hole leaves a hole in its initial position. Hence, the hole effectively moves in the direction opposite to that of the electron. An electron from another covalent bond may now fill this hole, in its new position, and the hole will correspondingly move one more step in the direction opposite to the motion of the electron. This conduction of the electrons from one hole to the other is equal to holes moving in the opposite direction. This mechanism of hole conduction does not involve any

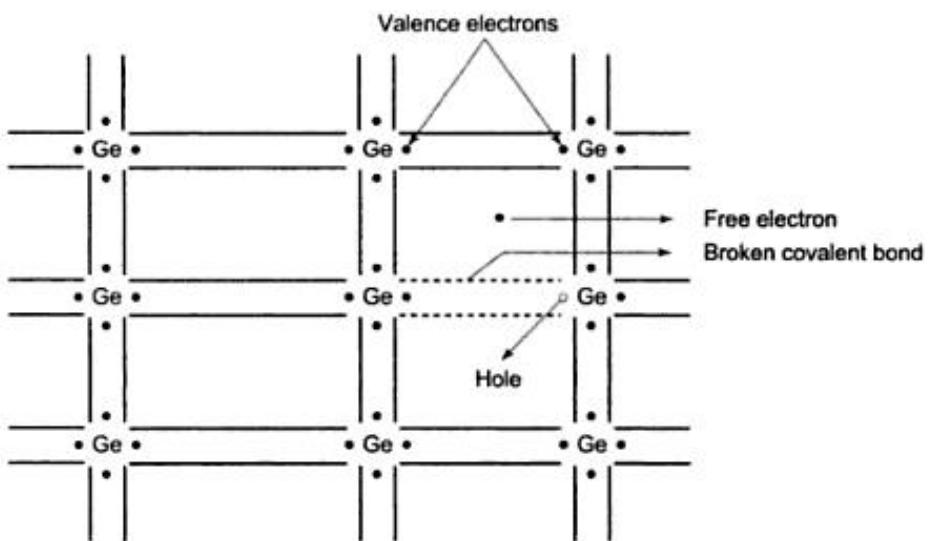


Fig. 2.5 Germanium with broken covalent bond

free electrons. So, the conduction of electricity is entirely due to holes moving in the opposite direction to that of the motion of bound electrons. This motion of positively charged holes in the forward direction is also conduction and since it does not involve free electrons, it is the conduction current or drift current due to holes in a semiconductor. Since existence of holes in a metal is not possible, such conduction current is not possible in a conductor.

The concept of hole current can be explained more elaborately with the help of Fig. 2.6. There are large numbers of filled covalent bonds in the crystalline structure of the material, as shown. They are assumed to be in straight line with a filled position at 6, as in Fig. 2.6(a). This represents a hole. Now, if the electron from position 7 leaves to occupy the vacant position 6, position 6 is occupied and an unfilled hole is available at 7. Effectively, even though the electron has moved from 7 to 6, one feels that the hole has shifted from 6 to 7. This continues and the hole can move in the forward direction when the bound electron is moving in the reverse direction. Since conventional current direction is reverse to that of the electron movement, the direction of movement of hole and the conventional current flow would be the same.

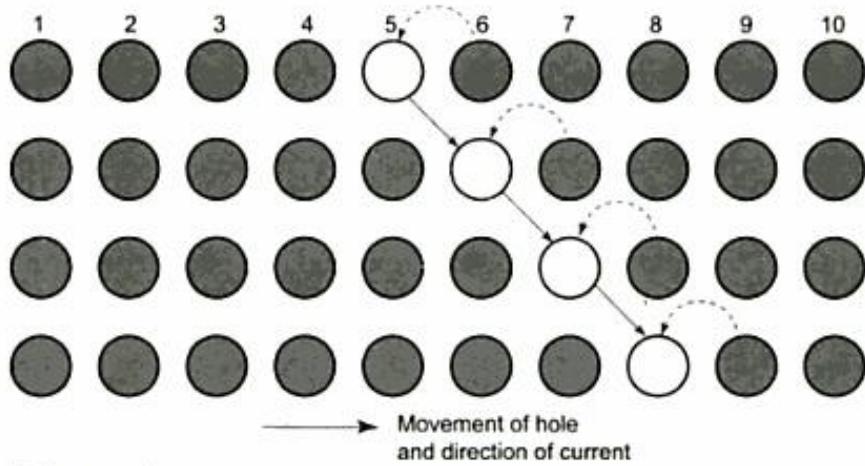


Fig. 2.6 The hole current

In a pure *intrinsic semiconductor*, the number of electrons in the conduction band is same as the number of holes in the valence band. Thus, n is the electron concentration, number of electrons per unit volume, and p is the hole concentration, number of holes per unit volume, then,

$$n = p = n_i \quad \dots(2.10)$$

where n_i is called the *intrinsic concentration* of the semiconductor material. This value of intrinsic concentration is a function of temperature, since the number of holes and electrons depends on the temperature. The higher the temperature, the greater is the value of n_i . To increase the conductivity of the material, one requires large number of charge carriers (free electrons or holes) in the material. So, when an intrinsic material is considered, its conductivity can be improved by increasing the temperature. But, increasing the temperature beyond a limit is not possible practically. Thus, increasing the charge carrier concentration by increasing the temperature is not possible. An alternative is to increase the free electrons in the conduction band or to increase the holes in the conduction band by some artificial means. This increases the conductivity of the material even at room temperature. One way out is to add impurity atoms to the crystal structure

and make the material *extrinsic* or impure by adding atoms other than the parent atoms in the structure purposefully. A small percentage of trivalent (B, Ga, In) or pentavalent (P, As, Sb) atoms is *doped* to the *intrinsic* silicon or germanium to make it extrinsic and improve conductivity.

2.6 *p*- AND *n*-TYPE SEMICONDUCTOR MATERIALS

Donor impurities: A pentavalent atom has five electrons in the valence shell. When these atoms are doped with either silicon or germanium, they displace some of the parent atoms. Four electrons of the five in the valence shell form covalent bonds with the neighbouring atoms as in the case of a parent atom and one electron is left over. This left over electron, when in the conduction band, can contribute to conduction. The amount of energy required to free the excess electron is very small, of the order of 0.01 eV for Ge or 0.05 eV for Si. Thus, there are new electrons that are free and with energy levels in the range of conduction band. These electrons are very useful for conduction. In other words, the impurity atom *donates* one electron to the material, which is a charge carrier. Thus, the pentavalent impurity is referred to as *donor impurity*. The suitable pentavalent atoms are antimony, phosphorus and arsenic. The structure of the crystal lattice of such a donor is as shown in Fig. 2.7.

When a donor impurity is added to the semiconductor, discrete energy levels are introduced in the energy gap at a very small distance below the conduction band. These levels are discrete as the doped impurity is away from the crystalline structure. The energy difference of this impurity atom's electron and the conduction band lower edge is very small, of the order of 0.01 eV for Ge or 0.05 eV for Si. Thus, at room temperature, the fifth electron is at an energy level that is in the conduction band and so is a very good carrier of current.

Such a material where donor atoms are doped to increase free electrons is known as *n-type material*. Thus, in this *n*-type material, the number of electrons is very large compared to holes. The initial concentrations of the electrons and holes are equal to the

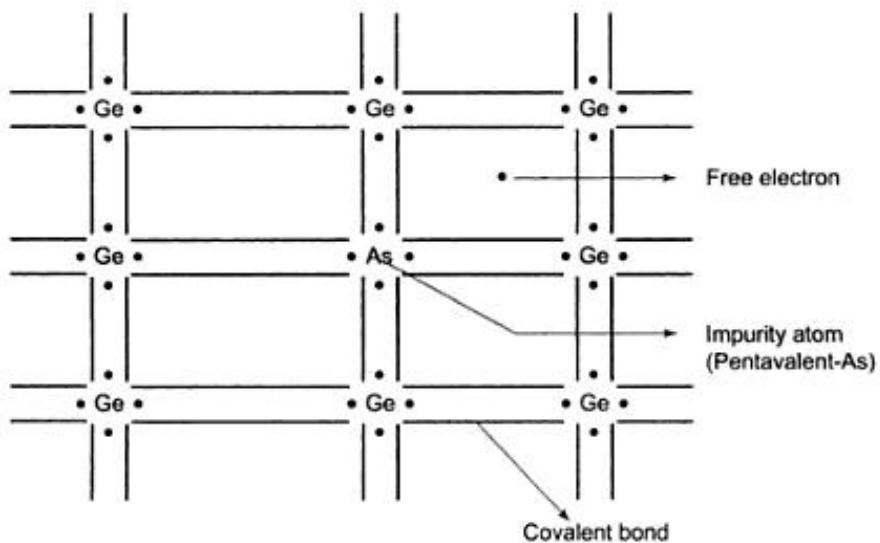


Fig. 2.7 Donor impurity

intrinsic concentration. After doping, the electron concentration increases to the extent of doping concentration, but the hole concentration would be low compared to the intrinsic concentration since the excess electrons from the impurity atoms can recombine with the holes. As a whole, the electron concentration is very large compared to hole concentration in an *n*-type material. Thus,

$$n \gg p \quad \dots(2.11)$$

Acceptor impurities: When a trivalent atom having three electrons in the outermost shell is doped with a semiconductor material, a *p*-type material is formed. The three electrons available in the valence shell are shared by the neighbouring Si or Ge atoms to form covalent bonds. The fourth bond is not formed and there is a vacancy in the bond, which leads to the creation of a hole, as shown in Fig. 2.8. These vacant spaces, holes, are positive charge carriers, which can conduct current. These holes accept electrons for conduction to take place and so, the trivalent atoms, boron, gallium and indium are known as *acceptor impurities*.

Adding acceptor impurity atoms to the semiconductor leads to insertion of discrete energy levels in the forbidden energy gap of the semiconductor. This level is nearer to the upper edge of the valence band. Since very minute energy is sufficient for the electron in the valence band to jump into this discrete energy level, large numbers of electrons contribute for the conduction through the holes created by the impurity doping. The conductivity of the material is multiplied by adding impurity atoms to the semiconductor material.

The *p*-type material thus has a large number of holes compared to that of electrons in the material. Holes are referred to as *majority carriers* in a *p*-type material whereas electrons in the *p*-type material are known as *minority carriers*. In a *p*-type material, hole concentration is very large compared to electron concentration and thus,

$$p \gg n \quad \dots(2.12)$$

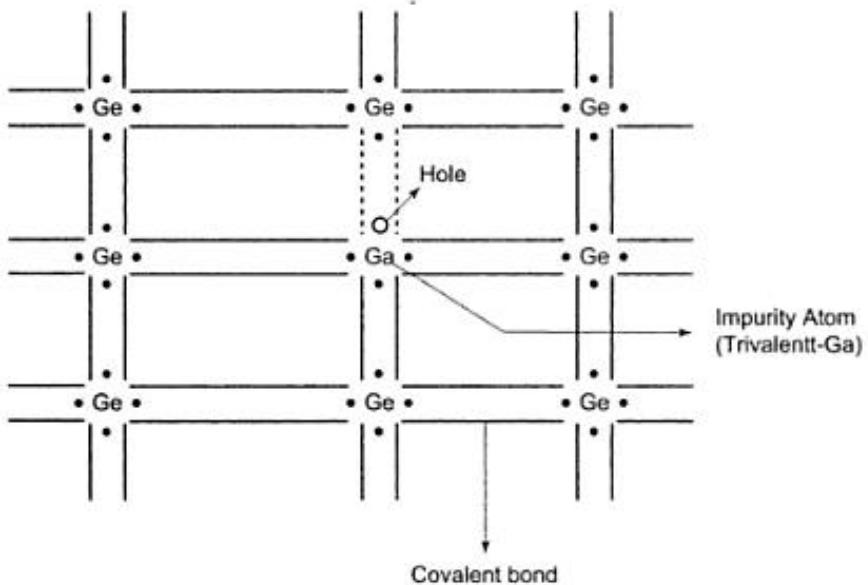


Fig. 2.8 Acceptor impurity

Mass action law: By adding acceptor atoms the hole concentration is increased and by adding donor atoms the electron concentration is increased in a semiconductor material. At thermal equilibrium, if n is electron concentration and p is the hole concentration in a given type of material, whatever may be the concentration of the impurities added, the *Mass Action Law* states that

$$np = n_i^2 \quad \dots(2.13)$$

where n_i is the intrinsic concentration and is the function of temperature.

2.7 MOBILITY AND CONDUCTIVITY

Considering a metal, there are a large number of electrons that are free and are not bound to an atom or molecule. Since there is no energy gap in metals, each atom contributes an electron or more for conduction. When an electron is removed from an atom, the remaining portion of the atom is a positively charged ion. So, one can imagine the situation as large number of electrons roaming around in the material where the positive heavy masses of ions are stationary. This is known as *electron gas theory* of a metal. So, a cloud of electrons wandering around in the material in the vicinity of fixed positive ions represents the metal.

These free electrons in the metal are not stationary but are moving randomly in the material. The electrons moving in a given direction collide with the stationary ions and change their direction and proceed further. The distance between two collisions is very random and the average value of such distances is called as *mean free path*. Since the direction is random, the number of electrons crossing a given cross-section at a given time would be same as that of the number of electrons moving in the opposite direction and hence the net current flowing would be zero.

When an electric field ϵ is now applied to a metal, the electrons would be accelerated in the direction opposite to that of the applied field and velocity would increase infinitely with time when there are no collisions with the static positive ions. However, due to the presence of these static ions, the collisions take place and the electron loses energy. When steady state is achieved, the velocity of the electrons becomes finite. This velocity, referred to as *drift velocity*, is in opposite direction to that of the applied field. The speed at time t between collision is at , where a is the acceleration and can be given as $q\epsilon/m$. Thus, the average speed is proportional to the applied field and so,

$$v = \mu\epsilon \quad \dots(2.14)$$

where μ is called the *mobility* of electrons. Thus, steady state drift speed has been superimposed upon the random thermal motion of electrons. Such a directed flow of electrons constitutes a current. To calculate the magnitude of this current, consider a metal of volume $A \times L$, where A is the cross-section area and L is the length of the material. Assume that there are N electrons in the volume considered and T is the time taken for an electron to travel a distance of L . Then the total number of electrons passing through any cross-section in unit time is N/T , or, the total charge crossing the cross-section, by definition, *current* can be given as

$$I = Nq/T = Nqv/L \quad \dots(2.15)$$

since L/T is the average drift speed v of the electrons. Current density is current per unit area of cross-section and so,

$$J = I/A \quad \dots(2.16)$$

Thus,

$$J = Nqv/(LA) \quad \dots(2.17)$$

Since N is total number of electrons in a volume LA of material considered, electron concentration n is

$$n = N/LA \quad \dots(2.18)$$

Therefore,

$$J = nqv = \rho v \quad \dots(2.19)$$

where $\rho = nq$ is the charge density and v is the drift velocity.

From Eq. (2.14),

$$J = nqv = nq\mu\epsilon = \sigma\epsilon \quad \dots(2.20)$$

where $\sigma = nq\mu$ is the *conductivity* of the metal. The above equation is nothing but Ohm's Law.

If now a semiconductor is considered, there are two types of charge carriers. The first type are free electrons, which are similar to those present in a conductor and, in addition to this, positively charged holes also contribute to current as discussed in the previous sections. So, now in a semiconductor, the total current would be superposition of the two independent components of currents due to electrons and holes. If J_n is electron current density in a semiconductor, it can be given as

$$J_n = nqv = nq\mu_n\epsilon \quad \dots(2.21)$$

where μ_n is the mobility of the electrons in the semiconductor.

Similarly, the hole current density J_p can be expressed as

$$J_p = pqv = p q \mu_p \epsilon \quad \dots(2.22)$$

where μ_p is the mobility of holes in the semiconductor material and p is the hole concentration.

Thus, the total current density can be given as

$$J = (n\mu_n + p\mu_p) q \epsilon = \sigma \epsilon \quad \dots(2.23)$$

where $\sigma = (n\mu_n + p\mu_p)q$ is the conductivity of the semiconductor.

2.8 PROPERTIES OF SEMICONDUCTOR MATERIALS

Charge densities in a semiconductor: Consider a semiconductor that is doped with donor atoms of concentration N_D and acceptor atoms of concentration N_A . n is the electron concentration after doping and p is hole concentration. Now, since N_D number of donor atoms are added per unit cubic metre of the material, it releases N_D number of free electrons per unit volume. This means that it is leaving behind N_D positive ions in the system. Now, the total positive charge available in the system would be the number of

holes p plus the number of positive ions added by doping of donor atoms, N_D , per unit volume. Similarly, if N_A acceptor atoms are added per unit volume, N_A holes and N_A negative ions per unit volume are released into the material. Thus, there are n plus N_A number of negative charges in the material per unit volume. To maintain the neutrality in the system, the number of positive charges should be the same as that of negative charges and thus,

$$N_D + p = N_A + n \quad \dots(2.24)$$

To make an n -type material, one adds only donor atoms and not acceptor atoms into the semiconductor. In that case,

$$N_D + p = n \quad \dots(2.24a)$$

In an n -type material, it is well understood that the number of electrons is very large compared to the number of holes and so, p is very small compared to n and can be neglected. Thus,

$$N_D \approx n \quad \dots(2.25)$$

That is, the *electron concentration in an n -type material is approximately equal to the added impurity donor concentration.*

On similar argument, in a p -type material,

$$N_A \approx p \quad \dots(2.26)$$

That is, the *hole concentration in a p -type material is approximately equal to the added impurity acceptor concentration.*

Applying mass action law in an n -type material,

$$n_n p_n = n_i^2 \quad \dots(2.27)$$

where n_n is the electron concentration and p_n is hole concentration in an n -type material. But since in an n -type material, $N_D = n_n$,

$$N_D p_n = n_i^2$$

Or,

$$p_n = n_i^2 / N_D \quad \dots(2.28)$$

And similarly, in a p -type material,

$$n_p p_p = n_i^2 \text{ and } n_p = n_i^2 / N_A \quad \dots(2.29)$$

Eqs. (2.28) and (2.29) give the minority carrier concentration in n -type and p -type materials, respectively.

It may be also observed that if in a material both donor and acceptor atoms are added, then the material would be intrinsic if the donor and acceptor atom concentration is same. The material can be recognised as n -type if in the material $N_D \gg N_A$ and as p -type if $N_A \gg N_D$. If one wants to convert a p -type material to n -type, one must add donor atoms in large concentration such that $N_D \gg N_A$ is satisfied.

Intrinsic concentration: As already discussed, the intrinsic concentration of the semiconductor is a function of temperature and increases with temperature. Thus, increasing the temperature increases the new electron hole pairs in the material and thus

the conductivity of the material improves. The definite relation of the intrinsic concentration with temperature is

$$n_i^2 = A_0 T^3 e^{-E_{G0}/kT} \quad \dots(2.30)$$

where E_{G0} is the energy gap at 0 K in eV, k is the Boltzmann's constant in eV/K and A_0 is a constant independent of temperature.

The constants E_{G0} , μ_n , μ_p and so on for Si and Ge materials are as listed in Table 2.1. From the table, it can be observed that only 1 atom in about 10^9 atoms contributes free

Table 2.1 Electrical Properties of Germanium and Silicon

Property	Ge	Si
Atomic number	32	14
Atomic weight	72.6	28.1
Density g/cm ³	5.32	2.33
Dielectric constant (relative)	16	12
Atoms/cm ³	4.4×10^{22}	5.0×10^{22}
E_{G0} , eV at 0 K	0.785	1.21
E_G , eV at 300 K	0.72	1.1
n_i at 300 K, cm ⁻³	2.5×10^{13}	1.5×10^{10}
P_i at 300 K, Ωcm^{-3}	45	230000
μ_n cm ² /v-s	3,800	1300
μ_p cm ² /v-s	1800	500
D_{nr} cm ² /s = $\mu_n V_t$	99	34
D_{pr} cm ² /s = $\mu_p V_t$	47	13
σ_i at 300°K ($\Omega\text{-cm}$) ⁻¹	0.0224	4.35×10^{-6}
Percentage increase in conductivity per degree rise in temperature	6	8
D_n/D_p (approximately)	2	3
Cut in Voltage V_c , V [Diodes]	0.2	0.6
Variation of I_0 with temperature per °C	11	8
Permissible Temperature of Operation (Transistors)	100°C	200°C

electrons and holes to the crystal because of broken bonds in germanium. For silicon, the ratio is further less, 1 in 10^{12} .

The energy gap: The forbidden energy gap between the valence and conduction bands is not fixed for a given semiconductor and is a function of temperature. The dependence of energy gap on temperature is as follows:

$$E_G(T) = 1.21 - 3.6 \times 10^{-4}T \quad \dots(2.31)$$

for silicon and that for germanium is

$$E_G(T) = 0.785 - 2.23 \times 10^{-4}T \quad \dots(2.32)$$

The mobility: The mobility of electrons and holes in a semiconductor depends not only on temperature but also on the applied electric field as follows:

$$\mu \propto T^{-m} \quad \dots(2.33)$$

in the temperature range of 100 – 400 K. The value of m is as follows:

$$\begin{aligned} m &= 2.5 \text{ for electrons in Si} \\ &= 2.7 \text{ for holes in Si} \\ &= 1.66 \text{ for electrons in Ge} \\ &= 2.33 \text{ for holes in Ge} \end{aligned} \quad \dots(2.34)$$

The mobility is independent of electric field ϵ when $\epsilon < 10^3$ V/cm in *n*-type silicon. When $10^3 < \epsilon < 10^4$ V/cm, μ_n varies approximately as $\epsilon^{-1/2}$. For higher fields, μ_n is inversely proportional to ϵ .

2.9 HALL EFFECT AND ITS APPLICATIONS

The type of extrinsic semiconductor and the mobility of the material can be estimated with the help of *Hall effect*. The Hall effect can be explained as follows.

Consider a material, either a semiconductor or a metal, as shown in Fig. 2.9. Assume that the specimen is carrying a current I and is subjected to a transverse magnetic field B . Then, an electric field ϵ is induced in the direction perpendicular to both B and I . This phenomenon is known as *Hall effect*. This is very useful in semiconductors to determine the type of material, carrier concentration and mobility of the material.

As shown in Fig. 2.9, if current I is assumed to be flowing in positive x direction, and the applied magnetic field B is transverse to x axis, that is, z direction, then the induced electric field will have a force in the negative y direction by the Hall effect. This induced electric field in the specimen exerts force downwards on the charge carriers flowing in the material. If the material is a metal, the charge carriers are electrons flowing in the negative

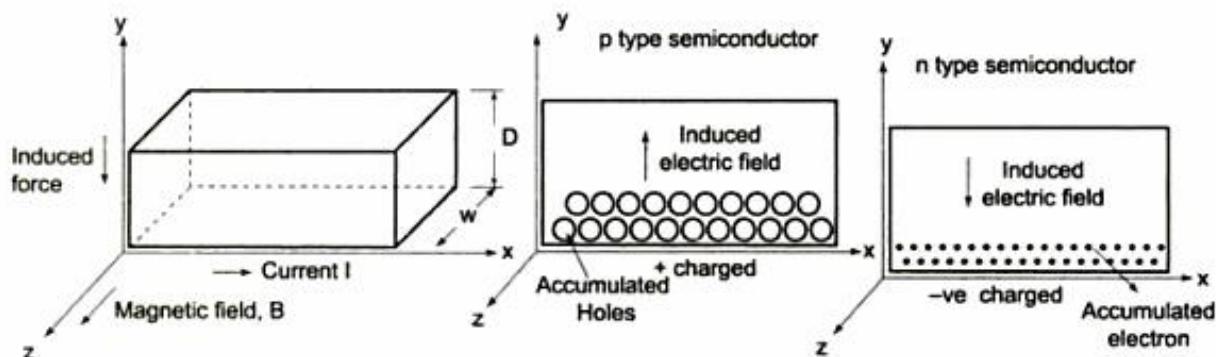


Fig. 2.9 The Hall effect

y -direction since the current is assumed to be flowing in the positive x direction. So, by the induced field these charge carriers will experience a force downwards in the negative y direction and one expect accumulation of electrons on the lower edge of the sample. Since the electrons assemble on the bottom of the specimen, equal amount of positive charge has to be deposited on top of the specimen. Thus, the electric field induced by the virtue of Hall effect will have positive field on the top whereas it will be negative at the bottom. This induces a field in the negative y direction.

When a semiconductor sample is subjected to Hall effect, the induced force due to the field will be on the charge carriers as in the case of a metal. If the semiconductor is n -type, the induced force will be exerted on both positive holes and negative electrons in the material. Since the electrons dominate the holes in an n -type semiconductor, the induced field would be same as in the case of a metal and will be in the negative y -direction. But if the specimen is a p -type semiconductor, since there are large number of positive holes, the induced field will force these holes towards the lower edge of the sample and so positive charge is accumulated on the bottom with an equal amount of negative charge on the top. This leads to the fact that the induced electric field is having a direction in the positive y -direction.

If an unknown semiconductor is subjected to the Hall effect, as explained in the earlier paragraphs, the type of material could be determined. If the induced field is in the positive direction of y axis, then the material is p type and if the induced field is in negative y -direction then the sample is n -type.

In an equilibrium state, the induced electric field ϵ due to Hall effect must exert a force on the carrier, which must balance the magnetic force. Thus,

$$q\epsilon = Bqv \quad \dots(2.35)$$

where q is the magnitude of the charge on the carrier and v is the drift velocity with which the carrier is moving.

The electric field

$$\epsilon = V_H/d \quad \dots(2.36)$$

where V_H is Hall voltage and d is the distance between the faces 1 and 2 of the specimen. The current density J can be given as

$$J = \rho v = I/wd \quad \dots(2.39)$$

Then,

$$V_H = \epsilon d = Bvd = BJd/\rho = BI/(\rho w) \quad \dots(2.40)$$

From the above equation, if V_H , B and I are measured, ρ can be determined. The Hall coefficient R_H can be defined as

$$R_H = 1/\rho \quad \dots(2.41)$$

Thus,

$$R_H = V_H w / (BI) \quad \dots(2.42)$$

The conductivity σ can be given as

$$\sigma = \rho \mu \quad \dots(2.43)$$

or,

$$\mu = \sigma R_H \quad \dots(2.44)$$

From Eq. (2.44), if R_H is determined from Hall effect and conductivity measured for a given semiconductor, the mobility can be easily determined.

2.10 THERMISTOR AND SENSISTOR

The conductivity of the semiconductor depends on the number of free electrons and holes available for conduction in a material. The number of the charge carriers depends on temperature in an intrinsic material and so the conductivity of the semiconductor depends on temperature. As the temperature increases, the electron-hole pairs increase, thus increasing the conductivity of the semiconductor. The conductivity of the material can also be improved by doping the intrinsic material with either trivalent or pentavalent atoms to form *p*-type or *n*-type semiconductor. The variation of conductivity of a material with respect to a given parameter like temperature or light intensity is known as *conductivity modulation*.

From Eq. (2.30), it is seen that the conductivity increases approximately by 6% per degree increase in temperature for germanium and the rate is 8% for silicon. In fact, such a large variation of the conductivity with temperature is a drawback in some circuits. But, this phenomenon is very useful in some applications. A semiconductor that is designed for such an application is called a *thermistor*. The thermistor is a resistor made up of semiconductor instead of conventional carbon or other materials. An ordinary resistor exhibits resistance constant value irrespective of temperature. But a thermistor, being a temperature sensitive resistor, exhibits a resistance that decreases with increase in temperature. This thermistor finds applications in thermometry, microwave power measurement, thermal relay and other thermally controlled devices. Since silicon and germanium are too sensitive to impurities, they are not used as thermistor materials, but sintered mixtures of oxides such as NiO , Mn_2O_3 and Co_2O_3 are used.

When a metal is considered, its conductivity is also not a constant value with respect to temperature. It varies with temperature. The conductivity decreases with increase in temperature in a metal. Increase of temperature in a metal results in greater thermal agitation of the ions and this results in decrease of mean free path of the free electrons. Since mean free path depends on the mobility of the material, the mobility decreases. The conductivity of the metal is directly proportional to the mobility and thus the conductivity decreases. Thus, the resistance of the metal increases with increase in temperature. This rate of increase is of the order of 0.4% per degree rise in temperature. Thus, a metal has a positive coefficient of resistance while a semiconductor has a negative coefficient of resistance.

A very heavily doped semiconductor behaves in a manner similar to that of a metal. Thus, this semiconductor also exhibits positive coefficient of resistance like that of a metal due to decrease in carrier mobility with increase in temperature. Such a device is known as *sensistor*. A sensistor is a resistor made up of a heavily doped semiconductor having

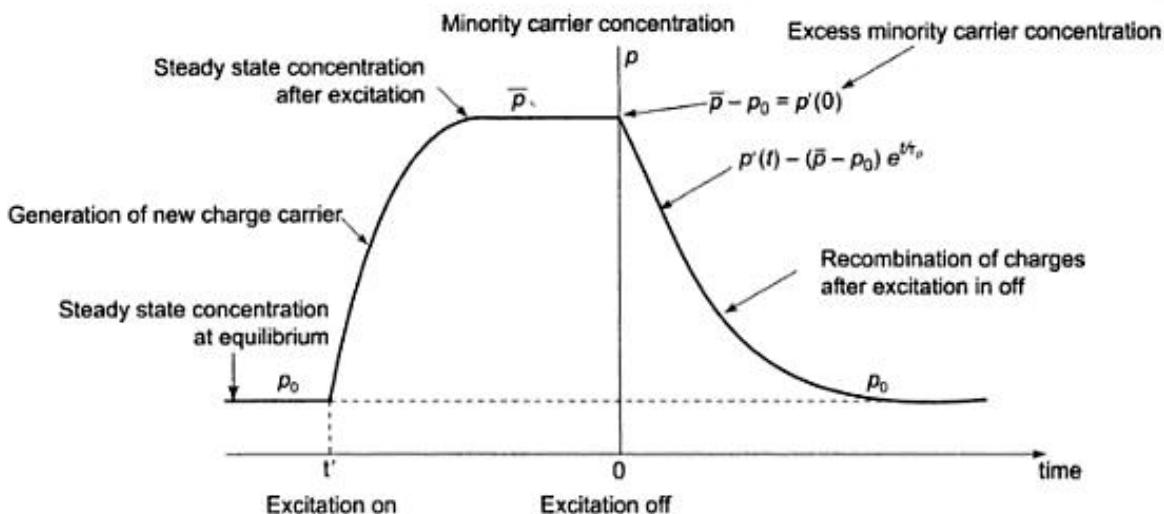
positive coefficient of resistance. This can have a temperature coefficient of resistance of the order of 0.7% per degree rise in temperature over the range of -60 to +150 °C.

The conductivity of a semiconductor can be improved by creating new electron-hole pairs in the system. Various possible schemes have been discussed in the above sections. Another scheme is to achieve *conductivity modulation* by light intensity variations. Such a material whose conductivity can be modulated by light can be referred to as a *photoconductor*. When the radiated light is exposed to the covalent bonds of the semiconductor, the photons strike the bonds to break them. Breaking one covalent bond releases two charge carriers, one electron and one hole. The number of covalent bonds broken would depend on the number of photons incident on the material. Thus, larger the intensity of the light, larger is the conductivity of the material. Such a material exhibiting photoconductivity modulation can be either referred to as a *photoconductor* or a *photoresistor*. Such a device finds large applications in the measurement of illumination (light meter), recording modulation intensity (sound track recording), on-off relay (digital control systems) and so on. The photoconducting device with the widest application is the cadmium sulfide cell.

2.11 TIME VARIATION OF EXCITED MINORITY CARRIERS

In equilibrium, at room temperature, in a semiconductor, the number of free electrons and holes remains constant. This does not mean that the given electron is always present and will contribute to conduction. The free electrons and holes are not stationary but wander throughout the material randomly due to thermal energy available at room temperature. In this process, recombination and generation of electrons take place continuously, but at any given time, the number of free electrons or holes is unaltered. To create charge carriers, one has to break a covalent bond. To break a covalent bond, energy from an external agency is expended and so, one loses energy in creating an electron-hole pair. On the other hand, when an electron recombines with a hole, one loses two charge carriers (one electron and one hole) and energy is gained by the external agency. In a system, generation and recombination take place continuously and the *lifetime* of a charge carrier is the time between generation and recombination. The term *mean lifetime* of a charge carrier is the average of the lifetimes of these carriers. τ_n and τ_p are the mean lifetimes of an electron and a hole, respectively.

Consider an *n*-type semiconductor bar. Due to thermal agitation, electron-hole pairs are generated—let the rate of generation be g . On the other hand, equal number of electron-hole pairs disappear due to recombination after thermal equilibrium is achieved. That is, the rate of generation is same as the rate of recombination at a given temperature at equilibrium. The recombination is due to electron falling into empty valence band, resulting in loss of a pair of charge carriers. Let p_0 and n_0 be the concentrations of holes and electrons at room temperature at equilibrium. At a time $t = t'$ (as shown in Fig. 2.10) the bar is subjected to illumination, which can break the covalent bonds. Thus, new electron-hole pairs are generated and in this condition the rate of generation is more than recombination and thus the electron and hole concentration increases until new equilibrium is achieved. The additional electrons and holes generated would be same in number. Let \bar{p} and \bar{n} be the new concentrations at equilibrium after excitation. Thus,

**Fig. 2.10** Minority carrier recombination

$$\bar{p} - p_0 = \bar{n} - n_0 \quad \dots(2.45)$$

Although the increase in hole concentration is same as that in electron concentration, since n -type bar is considered, there are large numbers of electrons and adding a few more electrons leads to very small rate of increase in electrons. But, when holes, the minority carriers, are considered—since they are very small in number—adding a few more leads to a large rate of change in concentration. So, the increase in the electrons can be neglected and the minority carrier behaviour is studied.

After a steady state is reached, the excitation is turned off, say, at $t = 0$. When the excitation is switched off, the rate of generation decreases and the rate of recombination would be more than that of generation, thus leading to loss of charge carriers. To understand how the rate of recombination affects the charge concentration, the following analysis is done.

Assuming that the mean lifetime τ_p is independent of hole concentration,

$$p/\tau_p = \text{decrease in hole concentration per second due to recombination}, \quad \dots(2.46)$$

$$g = \text{increase in hole concentration per second due to thermal agitation}. \quad \dots(2.47)$$

At equilibrium, since no charge can be created or destroyed, the above two rates are equal. Or, the rate of change of hole concentration would be zero,

$$dp/dt = 0. \quad \dots(2.48)$$

But after the excitation is switched off at $t = 0$, the rate of change of hole concentration would be the difference between the generation rate and recombination rate. Thus,

$$dp/dt = g - p/\tau_p \quad \dots(2.49)$$

When no radiation is falling on the sample, the generation rate would be p_0/τ_p and therefore,

$$dp/dt = (p_0 - p)/\tau_p \quad \dots(2.50)$$

If p' denotes the *excess* or *injected* carrier density, defined as increase in minority carrier concentration above equilibrium level, then, p' would be a function of time and

$$p' = p - p_0 = p'(t) \quad \dots(2.51)$$

Since p_0 is constant, substituting the above equation in Eq. (2.50),

$$\frac{dp'}{dt} = -p'/\tau_p \quad \dots(2.52)$$

The minus sign in the above equation indicates that there is a decrease in the hole concentration. Solving the above differential equation for $t \geq 0$,

$$p'(t) = p'(0)e^{-t/\tau_p} = (\bar{p} - p_0)e^{-t/\tau_p} = p - p_0 \quad \dots(2.53)$$

Thus, the *excess minority carrier concentration* after the external excitation is switched off decays towards the equilibrium value exponentially with the time constant as the mean lifetime of the carriers.

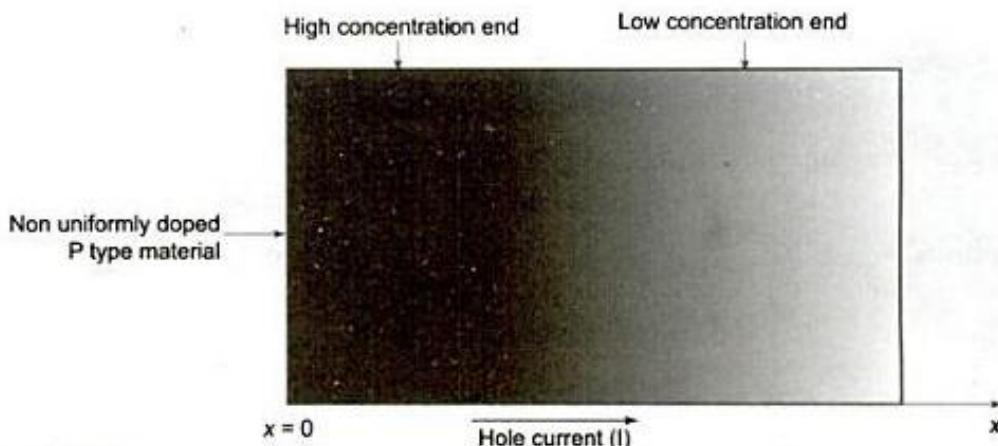
It is important to note here that all the electrons encountering a hole will not recombine. In fact, recombination results in release of energy and loss of two charge carriers. In order to recombine, when an electron collides with a hole both should have the same momentum and they must travel in the opposite directions. This is a very stringent condition and very rare. So, recombination by such direct encounters is very small.

In practice, recombination is not by direct collision as explained above, but the mechanism involves *recombination centres* or *traps*. These traps contribute electronic states in the energy gap of the semiconductor. Such a location acts effectively as a third body that can satisfy the conservation of momentum requirement. These new states are due to imperfections in the crystal. Metallic impurities in the semiconductor are capable of introducing energy states in the forbidden gap. Not only the volume imperfections, but also surface imperfection leads to the traps in the crystal. So, purposefully, gold is introduced in a controlled fashion into silicon to achieve the desired traps in the crystal.

2.12 CONCEPT OF DIFFUSION CURRENT

In a semiconductor, in addition to the conduction current due to electrons and holes, there are two more components of current due to *diffusion* of holes and electrons. This diffusion is not observed in metals. The concept of diffusion is as explained below.

Consider a *p*-type semiconductor bar where the doping is not uniform throughout the material, but is very large towards one end of the bar and the concentration decreases as one moves towards the opposite end. That is, the doping of acceptor atoms is controlled and is non-uniform. Assume that the bar is oriented in x direction with maximum doping end at $x = 0$. As seen from the figure, the concentration of the impurity in the semiconductor is a function of x and decreases with increase in x . So, there is a concentration gradient dp/dx and thus the density of carriers is also not constant. Now, consider an imaginary cross-section of the bar at some x where $x > 0$ as shown in the figure. To the left of this imaginary cross-section the concentration of the charge carriers, holes, is large compared to that to the right. This is because the concentration is maximum at $x = 0$ and decreases with increase in x . These holes are not stationary as seen previously

**Fig. 2.11** Diffusion

and are in random motion due to thermal agitation. Because of this random motion, the holes cross the imaginary cross-section in both directions. In a given time interval, there is a probability that the number of holes crossing from left to right would be more than that of holes crossing from right to left. This is a statistical phenomenon since the concentration gradient occurs in the semiconductor. Since the number of charge carriers crossing the cross-section is not the same in both the directions, there is a net transport of charge carriers in the direction of positive x direction. This leads to a current flow in the positive x direction as shown in Fig. 2.11. It should be noted that this current is not due to the repulsions of the charge carriers, but is purely a statistical phenomenon. This current is referred to as *diffusion current*.

As one expects, this diffusion current is proportional to the concentration gradient in the semiconductor. Thus, *diffusion current density is proportional to the concentration gradient*. The proportionality constant is split into components, as seen below, for convenience,

$$J_p \equiv -qD_p(dp/dx) \quad \dots(2.54)$$

where q is the charge associated with each charge carrier and D_p is the *diffusion constant* for holes measured in square metres per second. Since p decrease with increase in x , the concentration gradient dp/dx is negative. Since the hole current is in positive direction, the negative sign in the equation is inserted.

Similarly, if pentavalent atoms non-uniformly dope a semiconductor, a concentration gradient of *n*-type material can be achieved. In such a semiconductor, diffusion current due to electrons can be achieved. The constituent diffusion current density of electrons can be given as

$$J_n \equiv qD_n(dn/dx) \quad \dots(2.55)$$

where D_n is the diffusion constant of electrons. Minus sign is not required in this equation since the conventional current and the concentration gradient coincide.

Thus, in a semiconductor various components of current are possible. The electron current density due to conduction and diffusion can be given as

$$J_n = q\mu_n n\epsilon + qD_n(dn/dx) \quad \dots(2.56)$$

The hole current density due to conduction and diffusion is

$$J_p = q\mu_p p \epsilon - qD_p(dp/dx) \quad \dots(2.57)$$

Einstein relationship: Both the mobility and the diffusion are statistical phenomena. So, D and μ are not independent. The relationship between them is given by Einstein equation:

$$D_p/\mu_p = D_n/\mu_n = V_T \quad \dots(2.58)$$

where V_T is the *volt equivalent of temperature* and is defined as

$$V_T = \bar{k}T/q = T/11600 \quad \dots(2.59)$$

where \bar{k} is the Boltzmann's constant in joules per kelvin. At room temperature, $T = 300$ K and $V_T = 26$ mV.

2.13 CONTINUITY EQUATION IN SEMICONDUCTORS

As discussed in Sec. 2.11, if the semiconductor material is disturbed from equilibrium, the concentrations of holes and electrons vary with time. However, the carrier concentration in the body of a semiconductor is a function of distance, too. The *continuity equation* is a differential equation that governs the relationship of the carrier concentration both with time and distance. This equation is derived on the basis of conservation of charges property.

Consider an infinitesimal element of *p*-type semiconductor having a volume $L \times dx$. Let the average hole concentration in the volume be p . The problem is assumed to be one

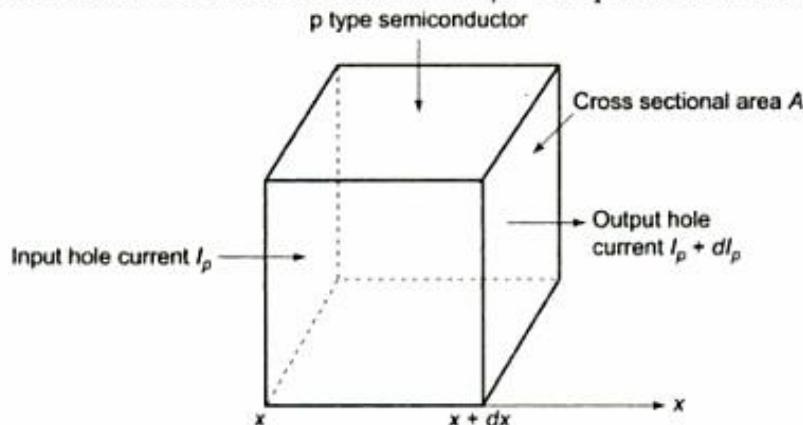


Fig. 2.12 Continuity equation

dimensional and the current I_p in the element is flowing in x direction. If I_p is the current entering into the element at x and $I_p + dI_p$ at $x + dx$ at the same time, dI_p coulombs of charge per second are leaving in addition to the input. Hence, the charge carriers in the element decrease within the volume. Since magnitude of the charges is q , dI_p/q is the decrease in the number of holes per second within the element. If the volume is Adx , then the *decrease in hole concentration per second* can be given as

$$\frac{dI_p}{qAdx} = \frac{dJ_p}{qdx} \quad \dots(2.60)$$

If $g = p_0/\tau_p$ is the increase of holes per unit volume per second due to thermal agitation, and p/τ_p is the decrease of holes per unit volume per second due to recombination, as we have seen in Sec. 2.11, the rate of hole concentration change due to thermal agitation and recombination can be given as $(p_0 - p)/\tau_p$. Thus, taking into account the conservation of charges from the above two concepts, the rate of change of hole concentration can be stated as

$$\frac{\partial p}{\partial t} = \frac{p_0 - p}{\tau_p} - \frac{1}{q} \frac{\partial J_p}{\partial x} \quad \dots(2.61)$$

The above equation is called the *continuity equation*. This can also be referred to as *law of conservation of charge*. This law can also be applied to electrons and n is substituted for p in the above equation.

2.14 INJECTED MINORITY CARRIERS

The minority carrier behaviour is seen to be exponentially decaying with time when an external excitation is removed and the time constant is the lifetime of the carrier. Now, the behaviour of the minority carrier with distance is to be considered when introduced at one end of a semiconductor. This also decays exponentially with distance, the time constant being *diffusion length* this time.

Consider a uniformly doped n -type bar of semiconductor as shown in Fig. 2.13. Let the concentration of the donor atoms be N_D and thus $n \approx N_D$ is uniform throughout the bar under consideration. Assume that at $x = 0$, radiation falls as shown in the figure. The photons of the radiation collide with the covalent bonds of the semiconductor bar on this face and break them to release new electron-hole pairs. Since the bar is n -type, the holes are minority carriers and their behaviour is to be studied now.

Consider a *low-level injection*, which means that the excess minority carriers created in the bar are very small compared to the electron concentration, that is, $p' \ll n$. The excess minority carriers are not stationary at this face but are diffused towards the other end of

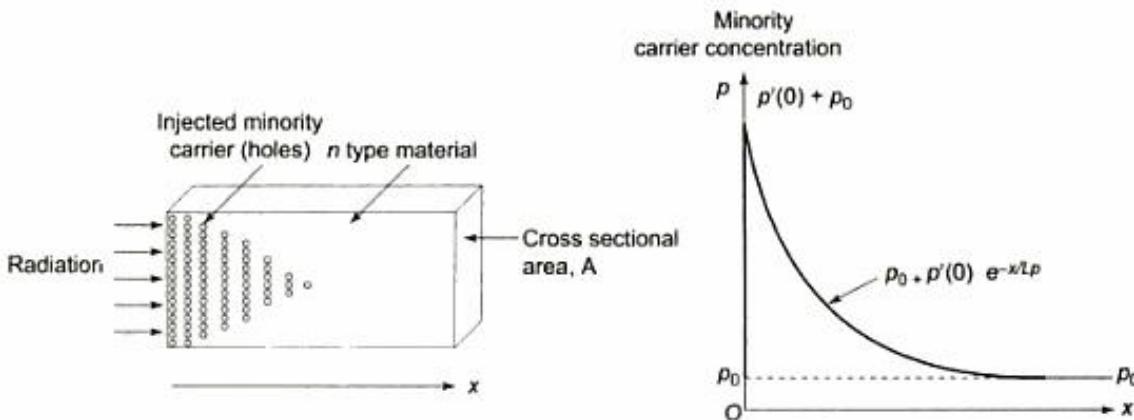


Fig. 2.13 Injected minority carriers

the bar and as they diffuse, recombination takes place with the free electrons and the minority carrier concentration decreases. Since the drift current is proportional to the charge carrier concentration, the drift current due to holes can be neglected as the amount of holes in the bar is very small compared to electron concentration, that is, $p_0 + p' \ll n$. So, the hole current is entirely due to diffusion. The other components of electron current are present in the bar. Then,

$$J_p = -qD_p(dp/dx) \quad \dots(2.62)$$

From the continuity equation (2.61), at steady state, rate of change of hole concentration is zero, $\partial p/\partial t = 0$, which leads to

$$\frac{d^2p}{dx^2} = \frac{p - p_0}{D_p \tau_p} \quad \dots(2.63)$$

Diffusion length for holes is defined as

$$L_p = (D_p \tau_p)^{1/2} \quad \dots(2.64)$$

Thus, the above differential equation can be rewritten as

$$\frac{d^2p'}{dx^2} = \frac{p'}{L_p^2} \quad \dots(2.65)$$

The general solution to such a second order differential equation can be written as

$$p'(x) = K_1 e^{-x/L_p} + K_2 e^{+x/L_p} \quad \dots(2.66)$$

where K_1 and K_2 are constants. When a very long bar is considered, as x increases, the second term increases if K_2 were to be a given value other than zero. That means as x tends to infinity, the hole concentration increases with distance, which is an impossible condition. Thus, $K_2 = 0$. If at $x = 0$, the excess concentration of holes is assumed to be $p'(0)$, then $K_1 = p'(0)$. Then,

$$p'(x) = p'(0)e^{-x/L_p} = p(x) - p_0 \quad \dots(2.67)$$

Thus, the minority carrier concentration decreases exponentially with L_p as constant. The *diffusion length* can be redefined as *the length at which the concentration falls to $1/e$ times that of the initial value* at $x = 0$. It can also be seen as the average distance that an injected hole travels before recombining with an electron.

Diffusion current: From Eq. (2.54) for current density of diffusion current due to holes and remembering $J_p = I_p/A$,

$$I_p(x) = \frac{AqD_p p'(0)}{L_p} e^{-x/L_p} = \frac{AqD_p}{L_p} [p(0) - p_0] e^{-x/L_p} \quad \dots(2.68)$$

Thus, the diffusion current falls exponentially, as is the case with hole concentration. Now, the majority carrier electron diffusion current is

$$I_n(x) = AqD_n(dn/dx) \quad \dots(2.69)$$

The excess minority and majority carriers would be the same since breaking a bond creates an electron-hole pair. Thus, $p' = n'$ or,

$$p - p_0 = n - n_0 \quad \dots(2.70)$$

Since p_0 and n_0 are independent of x ,

$$dp/dx = dn/dx \quad \dots(2.71)$$

Thus, the electron-hole current is

$$I_n(x) = AqD_n(dn/dx) = AqD_n(dp/dx) = -I_p(D_n/D_p) \quad \dots(2.72)$$

Drift current: Since the semiconductor bar is open circuited, the net current flowing in the bar, that is, the sum of drift current due to electrons and diffusion current due to holes and electrons, would be zero. Thus, if I_{nd} is the drift current due to electrons,

$$I_p + \left(I_{nd} - \frac{D_n}{D_p} I_p \right) = 0 \quad \dots(2.73)$$

or

$$I_{nd} = \left(\frac{D_n}{D_p} - 1 \right) I_p \quad \dots(2.74)$$

Thus, the electron drift current also decreases exponentially with distance.

As seen, if a drift current exists in the bar, this current would be due to a potential drop, that is, there should be some electric field existing in the bar. This can thus be calculated as

$$\epsilon = \frac{1}{Aqn\mu_n} \left(\frac{D_n}{D_p} - 1 \right) I_p \quad \dots(2.75)$$

When an electric field is present in the bar, it should also cause drift current in the bar due to holes. Hence, the drift current due to holes, I_{pd} , can be given as

$$I_{pd} = Aqp\mu_p \epsilon = \frac{p\mu_p}{n\mu_n} \left(\frac{D_n}{D_p} - 1 \right) I_p \quad \dots(2.76)$$

Since $p \ll n$ in a n -type bar, $I_{pd} \ll I_p$. Thus, the hole drift current is very small compared to the hole diffusion current, justifying the assumption made in the beginning of this discussion under low-level injection.

2.15 GRADED SEMICONDUCTOR JUNCTION

Consider a semiconductor in which the doping of the impurity atoms is non-uniform. Such a semiconductor can be referred to as *graded* semiconductor. Assume that the considered bar is doped with trivalent atoms to form the p -type semiconductor. Assume that there is

no external excitation given to the bar and the bar is at steady state. Even though the net current in the bar is zero, there is movement of the charge carriers, holes, randomly in the bar due to thermal agitation. Since p is not uniform in the bar, one can expect diffusion current due to holes to exist in the bar. In order to make the total current due to holes zero at steady state, there should be equal and opposite drift current due to holes in the bar (same is the case with electrons—total electron current should be zero). If a drift current is to be flowing in a material, there should be potential drop across the bar establishing an electric field. So, by virtue of non-uniform doping of impurities in the semiconductor, a potential drop is induced into the bar. This potential is investigated now.

Setting the total current density due to holes, J_p equal to zero, from Eq. (2.57),

$$q\mu_p p \epsilon = qD_p(dp/dx) \quad \dots(2.77)$$

Since $V_T = D_p/\mu_p$,

$$\epsilon = \frac{V_T dp}{p dx} \quad \dots(2.78)$$

The relation between the electric field and potential is $\epsilon = -dV/dx$. Thus,

$$dV = -V_T (dp/p) \quad \dots(2.79)$$

To find out the potential drop between two points 1 and 2, the above equation is to be integrated within the limits x_1 and x_2 . If p_1 is the concentration at x_1 and p_2 is the concentration of holes at x_2 ,

$$V_{21} = V_2 - V_1 = V_T \ln(p_1/p_2) \quad \dots(2.80)$$

V_{21} is the potential drop between 2 and 1 as shown in Fig. 2.14. Thus, the potential drop between the two points depends only on the concentrations of holes at the two points, but does not depend on the position of the two points under consideration. The

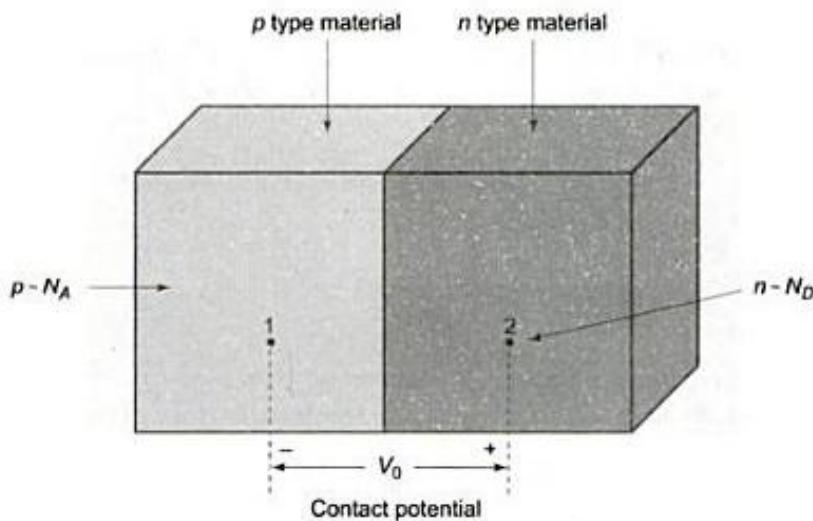


Fig. 2.14 Contact potential

potential is independent of the distance between the two points. Equation (2.80) can be recast as follows to estimate the concentration at a given point to establish the defined potential:

$$p_1 = p_2 e^{V_{21}/V_T} \quad \dots(2.81)$$

This is the Boltzmann's relationship of kinetic gas theory.

Carrying out the discussion for electrons as is done in the above for holes, where the electron current density is zero, leads to derivation of the following equation:

$$n_1 = n_2 e^{-V_{21}/V_T} \quad \dots(2.82)$$

From Eqs. (2.81) and (2.82),

$$n_1 p_1 = n_2 p_2 \quad \dots(2.83)$$

This equation states that the product np is a constant independent of x , and hence of the amount of doping, under thermal equilibrium. For an intrinsic semiconductor, $n = p = n_i$ and hence,

$$np = n_i^2 \quad \dots(2.84)$$

which is the mass action law.

Step-graded junction: Consider a junction formed between two semiconductors as shown in Fig. 2.14. The junction is formed between *p*-type and *n*-type semiconductors and the doping in the material is assumed to be uniform. Such a junction is referred to as *step-graded junction* since the concentration of impurities is suddenly changed from *p* to *n* type in a step. Let the concentration of impurities towards the left of the junction be N_A and to the right the concentration of *n*-type material be N_D . The above discussion shows that the potential developed due to concentration gradient depends on the concentration but is independent of the distance. The potential drop between any point on the left of the junction and any point to the right of the junction can be given as

$$V_0 = V_{21} = V_T \ln(p_{p0}/p_{n0}), \quad \dots(2.85)$$

where V_0 is referred to as *contact difference potential*, p_{p0} is the hole concentration in a *p*-type semiconductor at steady state and p_{n0} is the hole concentration in *n*-type semiconductor at steady state. From Eq. (2.29),

$$p_{p0} = N_A \quad \text{and} \quad p_{n0} = n_i^2/N_D \quad \dots(2.86)$$

Thus,

$$V_0 = V_T \ln \frac{N_A N_D}{n_i^2} \quad \dots(2.87)$$

The above equation gives the value of the contact difference potential developed when a step-graded junction is formed between two semiconductors. This contact potential is very important in the understanding of the behavior of the *p-n* semiconductor junction, which is the topic for the next chapter.

SUMMARY

- ◆ Energy-band theory of a crystal suggests the existence of a semiconductor whose conductivity can be increased by varying the temperature or adding impurities.
- ◆ Tetravalent atoms (Si and Ge) are basic materials used in electronic devices. Doping with trivalent or pentavalent impurities increases the conductivity.
- ◆ Trivalent atoms introduce a large number of holes, while pentavalent atoms introduce electrons. The materials are then referred to as *p* and *n* type, respectively.
- ◆ In an intrinsic pure material at a given temperature, the number of holes is same as that of electrons, while mass action law states that product of two concentrations is equal to square of intrinsic concentration in an extrinsic material.
- ◆ Holes constitute positively charged carriers and so due to drift there are two components of current in a semiconductor—current due to holes and electrons.
- ◆ Another source of current in a semiconductor is diffusion, which is not possible in a metal. This is due to concentration gradient in a semiconductor.
- ◆ The two components of current due to diffusion are due to holes and electrons. Thus, there are four different current components in a semiconductor.
- ◆ Hall effect helps one to determine the type of unknown semiconductor and it also gives its mobility.
- ◆ Thermistor is a resistor whose resistance decreases with increase in temperature, while sensistor is a resistor whose resistance increases with increase in temperature.
- ◆ Photoconductor is a device whose resistance decreases with light intensity.
- ◆ Breaking of one covalent bond requires external energy and release two charge carriers—an electron and a hole.
- ◆ Recombination of an electron and a hole in a trap in semiconductor results loss of a pair of charge carriers but it releases energy.
- ◆ Carriers are continuously being generated due to thermal creation and are simultaneously disappearing due to recombination at equilibrium.
- ◆ The newly generated minority carriers in a semiconductor due to external excitation recombine with the existing majority carriers after the excitation is removed in an exponential decay with time.
- ◆ Continuity equation governs the flow of charge carriers. It is based on the principle of charge conservation.
- ◆ The injected minority carriers decay exponentially with distance due to recombination.

- The total current in an unbiased graded semiconductor is zero. So, equal and opposite drift current should flow due to drift of charge carriers. This leads to the concept of contact potential in a graded semiconductor.
- The contact potential depends on the concentration between the two points but not on the distance between them. The higher the difference in concentrations, higher is the potential.

SOLVED PROBLEMS

2.1 Prove that the concentration n of free electrons per cubic meter of a metal is given by

$$n = \frac{dv}{AM} = \frac{A_0 dv \times 10^3}{A}, \text{ where}$$

d = density, kg/m^3

v = valence free electrons per atom

A = atomic weight

m = weight of atom of unit atomic weight, kg

A_0 = Avogadro's number, molecules/mole.

Solution The weight of an atom is considered to be equal to the atomic mass times the mass of an atom of unit atomic weight.

$$n = \left[\frac{\text{atoms}}{Am \text{ kg}} \right] \left[v \frac{\text{electrons}}{\text{atom}} \right] \left[d \frac{\text{kg}}{\text{m}^3} \right] = \frac{dv}{AM} \text{ electrons}/\text{m}^3.$$

If n = no. of atoms per molecule, then AM = Molecular weight of one mole in grams, and

$$\begin{aligned} n &= \left[\frac{1}{An} \frac{\text{mole}}{\text{g}} \right] \left[A_0 \frac{\text{molecules}}{\text{mole}} \right] \left[n \frac{\text{atoms}}{\text{molecule}} \right] \left[10^3 \frac{\text{g}}{\text{kg}} \right] \left[d \frac{\text{kg}}{\text{m}^3} \right] \left[v \frac{\text{electrons}}{\text{atom}} \right] \\ &= \frac{A_0 dv}{A} \times 10^3 \text{ electrons}/\text{m}^3. \end{aligned}$$

2.2 If a donor type impurity is added to the extent of 1 atom per 10^8 Ge atoms, calculate the value of resistivity.

Solution If there is 1 donor atom per 10^8 Ge atoms, then,

$$N_D = \frac{\text{atoms}/\text{cm}^3}{10^8} = \frac{4.4 \times 10^{22}}{10^8} = 4.4 \times 10^{14} \text{ atoms}/\text{cm}^3$$

$$\text{Hence, } n = N_D = 4.4 \times 10^{14}$$