Electronic Devices: Basic Semiconductor Theory

Atomic Theory and Structure:

- An electronic device controls the movement of electrons.
- The study of electronic devices requires a basic understanding of the relationship between electrons and the other components of an atom along with its structure.
- An atom can be thought of as consisting of a central nucleus surrounded by orbiting electrons.
- The nucleus is a largely cluster of protons and neutrons.
- The atomic structure of any stable atom has an equal number of electrons and protons. That is, atoms will have the same number of electrons in the orbit as there are protons in the nucleus.
- Each electron in an atom has a negative charge of 1.602×10^{-19} Columb, whereas each proton has a positive charge of the same magnitude.
- For all other elements except hydrogen, the nucleus also contains neutrons, which are slightly heavier than protons and have no electrical charge.
- Compared to the mass of the nucleus, electrons are relatively tiny particles of almost negligible mass. Protons and neutrons each have masses about 1800 times the mass of an electron.
- Different atoms have different number of electrons in the orbit.
- All atoms are normally electrically neutral, because, the protons and electrons are equal in number and equal but opposite in charge, so they neutralize each other electrically.
- **Positive ion:** If an atom loses an electron (somehow), it has lost some negative charge. Thus, it becomes positively charged and is referred to as a positive ion. Due to the absence of an electron, a hole is created there.
- **Negative ions:** Similarly, if an atom gains an additional electron, it becomes negatively charged and is termed as a negative ion.
- **Atomic number:** total number of protons in an atom is referred to as the atomic number of the atom.

- **Atomic weight**: It is approximately equal to the total number of protons and neutrons in the nucleus of the atom.
- **Orbital ring/ shell**:
  - Electrons can occupy only certain orbital rings or shells at fixed distances from the nucleus. An atom may have its outer shell completely filled or only partially filled.
  - Each shell can contain only a particular number of electrons. The first orbit, which is closest to the nucleus, can contain only two electrons. If an atom has three electrons, the extra electron must be placed in the next orbit.
  - The maximum number of electrons in each succeeding orbit is determined by $2n^2$ where n is the orbit number.
  - Figure below shows the atomic structure of two widely used semiconductor material- Silicon and Germanium.

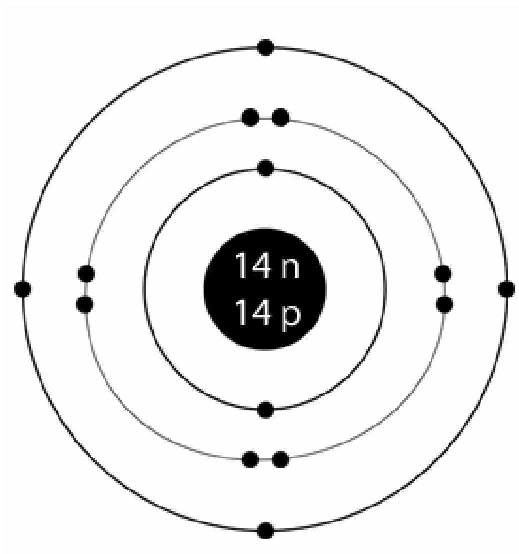


Figure: The atomic structure of Silicon

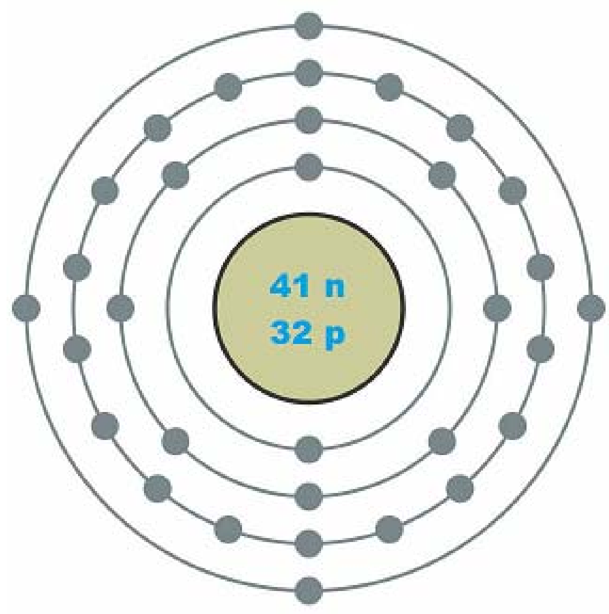
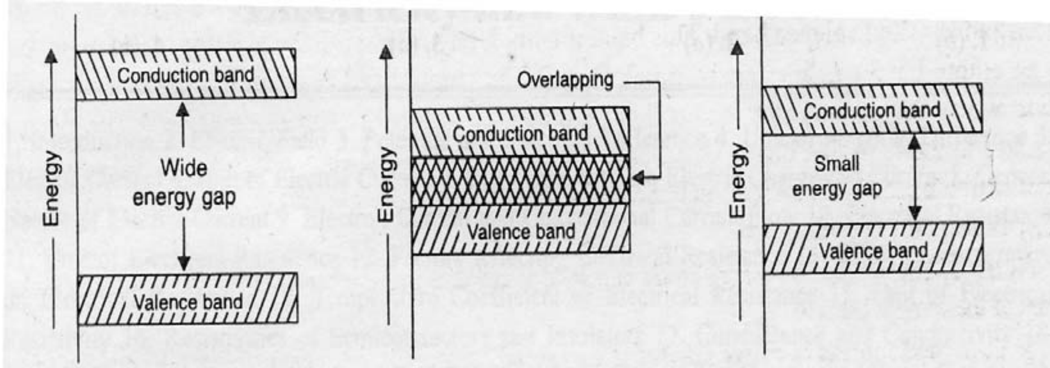


Figure: The atomic structure of Germanium

- **Valence electrons**: The electrons in the outer shell determine the electrical (and chemical) characteristics of each particular type of atom. These electrons are usually referred to as valence electrons.
- **Energy levels**:
  - The closer an electron is to the nucleus, the stronger are the forces that bind it. Each shell has an energy level associated with it that represents the amount of energy required to extract an electron from the atom. Since the electrons in the valence shell (outermost shell) are farthest from the nucleus, they require the least amount of energy to extract them.
  - Conversely, those electrons closest to the nucleus (electrons in the first orbit) require the greatest energy application to extract them from the atom.
  - The energy levels of the orbiting electrons are measured in electron volts (eV).
- **Energy bands:**
  - In an isolated atom, the electrons are acted upon only by the forces within that atom. However, when more atoms are brought closer together (as in a solid), the electrons come under the influence of

forces from other atoms. Under these circumstances, the energy levels that may be occupied by electrons merge into bands of energy levels. Therefore, the range of energies that an electron may possess in an atom is known as the energy band.

- The energy band description is extremely helpful in understanding the current flow through a semiconductor.
- Within any given material, there are two distinct energy bands in which electrons may exist: **valence band** and **conduction band**. Separating these two bands (that is, the energy band in between the condition band and the valence band) is an energy gap, termed as **forbidden gap**, in which no electrons can normally exist. For any given type of material, this gap may be large, small, or nonexistent.
- The range of energy possessed by the electrons in orbit around a nucleus is in the valence band.
- The electrons in the outermost shell of an atom, which are farthest from the nucleus, are usually referred to as valence electrons. These electrons are less tightly bound with the nucleus and they require the least amount of energy to extract them. Even applications of small electric field, some of these valence electrons are detached from the nucleus which is called free electrons. These free electrons are responsible for the conduction of current in good conductors. The range of energy possessed by free electrons is in the conduction band.
- Conduction band electrons may be easily moved by the application of relatively small amounts of energy. But much larger amounts of energy must be applied to move an electron in the valence band.
- Figure below shows the energy band for conductor, insulator and semiconductor.



(a) Insulators (b) Conductors (c) Semiconductors

- In insulator, condition and valence bands are separated by a wide energy gap (≈ 15 eV). A wide energy gap means that a large amount of energy is required, to free the electrons, by moving them from the valence band into the condition band.
- In conductors, conduction and valence bands overlap which indicates a large number of electrons available for conduction. Hence the application of a small amount of voltage results a large amount of current.
- In semiconductors, the conduction and valence bands are separated by a small energy gap (~1eV i.e. 1.1eV for Si and 0.7eV for Ge). A small energy gap means that a small amount of energy is required by the valence electrons to free them to cross over from the valence band to the conduction band. Even at room temperature, some of the valence electrons may acquire sufficient energy to enter into the conduction band and thus become free electrons. However, at this temperature, the number of free electrons available is very small. Therefore, at room temperature, a semiconductor is neither a good conductor nor an insulator.

Conduction in Solid: Electron Motion and Hole Transfer

Conduction in any given material occurs when an applied voltage causes electrons within the material to move in a desired direction. This may be due to one or both of two processes:

- Electron motion
- Hole transfer

Current Flow by Electron Motion:

- In electric motion, free electrons in the conduction band are moved under the influence of the applied electric field, thus creating an electric current.
- Since, electrons have a negative charge; they are repelled from the negative terminal of the applied voltage and are attracted toward the positive terminal.

Current Flow by Hole Transfer:

- If some of the electron positions in the valence shell of an atom are not occupied by electrons, there are holes where electrons could exist. When sufficient energy is applied, an electron may be made to jump from one atom to a hole in another atom. When it jumps, the electron leaves a hole behind it, and thus the hole has moved in a direction opposite to that of the electron.

- Under the influence of an applied electric voltage, electrons in orbit around atoms experience a force of attraction to the positive terminal of the applied voltage, and repulsion from the negative terminal. This force can cause an electron to jump from one atom to another, moving toward the positive terminal.

- Figure (a) shows an electron jumping from atom Y to atom X. When this occurs, the hole in the valence shell of atom X is filled, and a hole is left in the valence shell of atom Y (Figure B).
- If an electron now jumps from atom Z to fill the hole in Y, a hole is left in the valence shell of Z (Figure C). Thus the hole has moved from atom X to atom Y to atom Z. So a flow of current (electron motion) has occurred, and this may be said to be due to the hole movement or hole transfer.

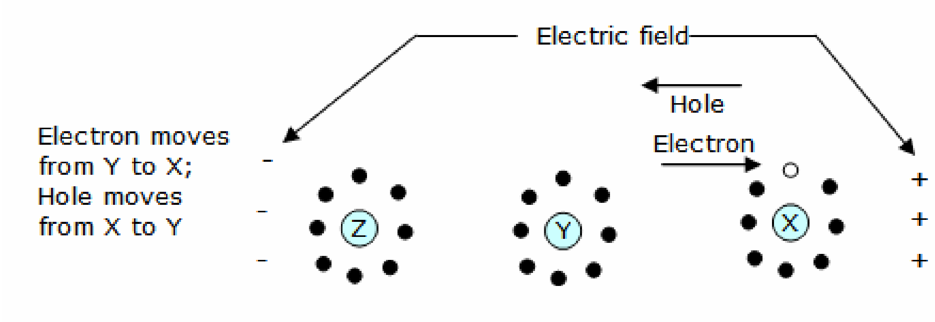


Figure A:

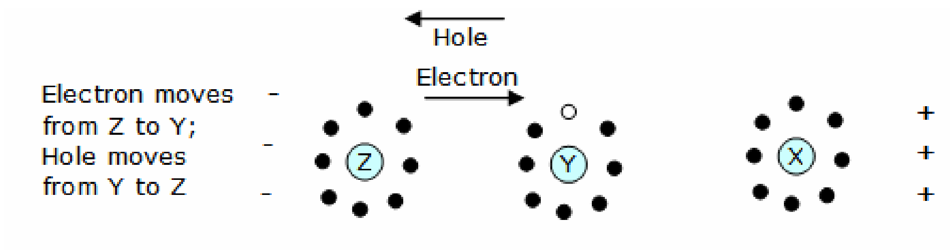


Figure B:

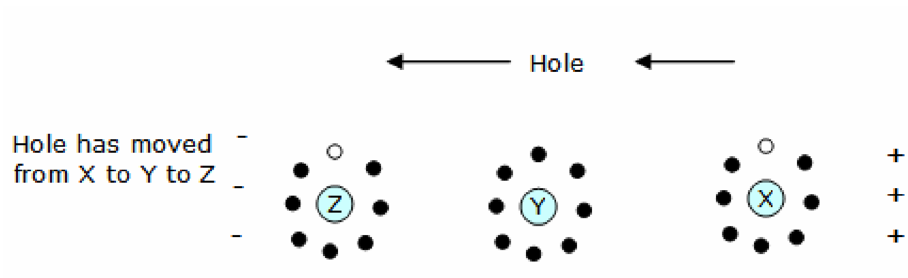


Figure C:

- Holes may be thought of as positively charged particles and they move though an electric field in a direction opposite to that of electrons.
- Since the flow of electric current is constituted by the movement of electrons and holes, electrons and holes are referred to as charge carriers.

Conductors:

- There are some materials that electricity flows through easily. These materials are called conductors.
- **Conductors** have electrons that can detach from their atoms and move around. These are called **free electrons** that can move freely.
- The loose electrons make it easy for electricity to flow through these materials, so they are known as **electrical conductors**.
- Most conductors are metals.
- Four good electrical conductors are gold, silver, aluminum and copper. This is due to the presence of a large number of free or loosely-attached electrons in their atoms.
- Elements with less than 4 Electrons in their outer rings make good conductors, because the Electrons are easily dislodged from their orbit and pushed to the atom next to them.

Insulators:

- Insulators are materials that do not let electricity flow through them.
- In insulator, the electrons are tightly bound to the atoms and do not allow free movement of electrons.
- Because the electrons don't move, these materials cannot conduct electricity very well.
- Insulator offers relatively greater difficulty or hindrance to the passage of free electrons. In other words, insulators have very high resistance.
- Some good insulators are glass, air, plastic, dry wood, mica and porcelain.
- Elements with More than 4 Electrons in their outer rings make good insulators, because the Electrons remain in the outer rings when electromotive force (Voltage) is present.

Semiconductor:

- A semiconductor is a material that is neither a conductor nor an insulator - it is somewhere in between.
- It can conduct electricity under some conditions but not others, making it a good medium for the control of electrical current.
- Semiconductor materials are the foundation of modern electronics, including radio, computers, telephones, and many other devices.
- The specific properties of a semiconductor depend on the impurities, or dopants, added to it.
- Current conduction in a semiconductor occurs via mobile or "free" electrons and holes, collectively known as charge carriers.
- Doping a semiconductor (such as silicon) with a small amount of impurity atoms (such as phosphorus or boron) greatly increases the number of free electrons or holes within the semiconductor.
- Exposing a semiconductor to light can generate electron–hole pairs, which increases the number of free carriers and its conductivity.
- Semiconductor materials typically have four electrons in the outermost valence ring.

Commonly Used Semiconductors:

- There are many semiconductors available today, but very few of them have a practical application in electronics.
- The two most frequently used semiconductors are germanium (Ge) and silicon (Si).
- It is because the energy required to break their covalent bonds (i.e. energy required to release an electron from their valence bonds) is very small. It is 0.7 eV for germanium and 1.1 eV for silicon.
- Figure below shows the atomic structure of germanium and silicon atoms.

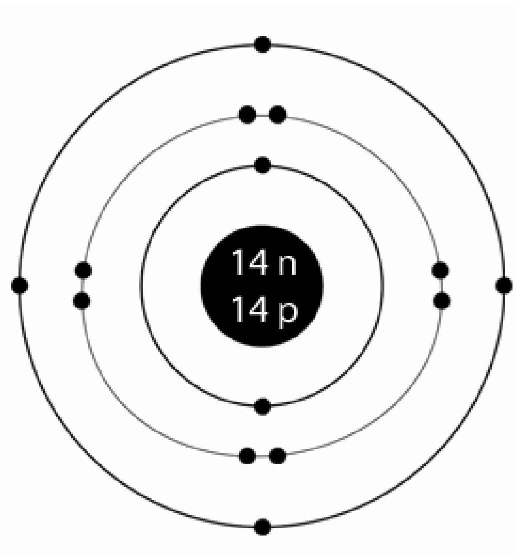


Figure: Silicon atom

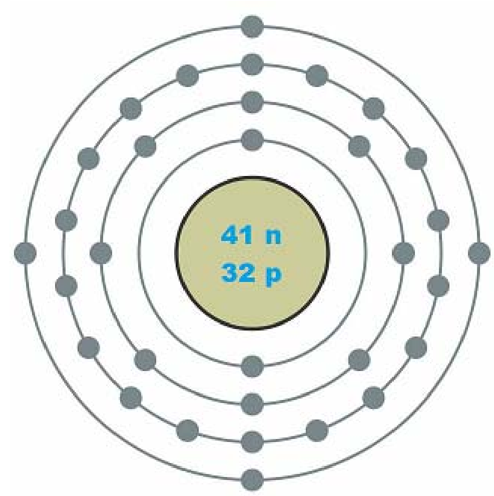
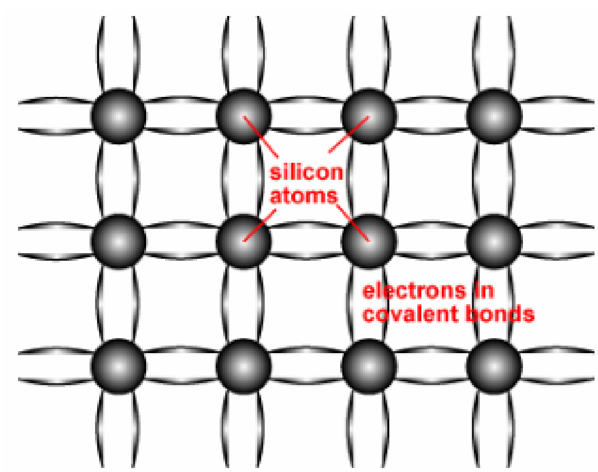


Figure: Germanium atom

- All semiconductors have crystalline structure i.e. atoms or molecules of these materials are arranged in an orderly fashion, called crystal.
- A piece of germanium is generally called germanium crystal.
- Figure below shows a schematic diagram of a crystal of pure Si, with each Si atom having four outer-shell electrons. Each Si atom is surrounded by eight outer-shell electrons—four from itself and one each from its four nearest neighbors. The crystal is neutral.



Properties of Semiconductor:

(i) A semiconductor is a substance which has almost filled valence band and nearly empty conduction band with a very small energy gap (1.1 eV for Si and 0.7eV for Ge) separating the two.

(ii) Resistivity of a semiconductor is less than an insulator but more than a conductor.

(iii) Semiconductors have negative temperature co-efficient of resistance i.e. the resistance of a semiconductor decreases with the increase in temperature and vice versa. For example, germanium is actually an insulator at low temperatures but it becomes a good conductor at high temperatures.

(iv) When a suitable metallic impurity (e.g. arsenic, gallium, boron etc) is added to a semiconductor, its current conducting properties change appreciably.

Importance of Semiconductor:

- As carbon is the building block for living things, silicon (Si), as a semiconductor, is the building block for information technology. Si-based semiconductors are the basis of most modern electronic circuits.
- Semiconductor devices can be designed to carry out switching and gate operations. That is, semiconductors can be turned into conductors when needed, and then turned back into insulators, as in turning a water faucet on and off.

Bonds in Semiconductor:

- The atoms of every element are held together by the bonding action of valence electrons.
- This bonding is due to the fact that it is the tendency of each atom to complete its last orbit by acquiring 8 electrons in it.
- However, in most of the substances, the last orbit is incomplete i.e. the last orbit does not have 8 electrons.
- This makes the atom active to enter into bargain with other atoms to acquire 8 electrons in the last orbit.

- To do so, the atom may lose, gain or share valence electrons with other atoms.
- In semiconductors, bonds are formed by sharing of valence electrons. Such bonds are called covalent bonds.
- In the formation of a covalent bond, each atom contributes equal number of valence electrons and the contributed electrons are shared by the atoms engaged in the formation of the bond.
- Figure below shows the covalent bonds among germanium atoms. Note that Ge has 32 electrons (2-8-18-4).

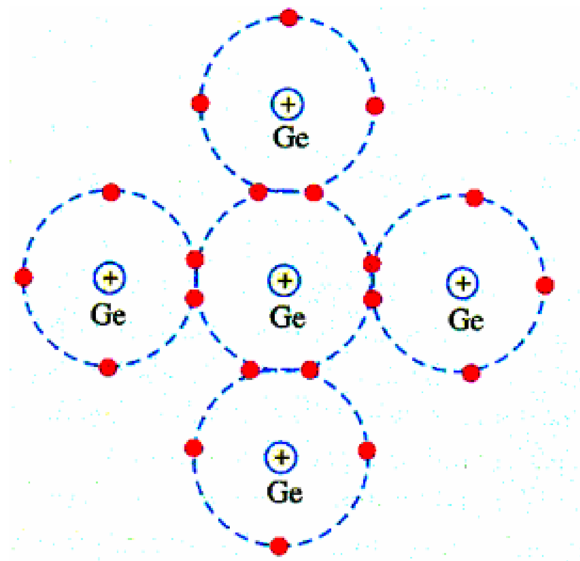


Figure: Covalent bonds among germanium atoms

Effect of Temperature on Semiconductors:

The electrical conductivity of a semiconductor changes appreciably with the variations of temperature. This is a very important point for semiconductor to keep in mind.

(i) At absolute zero temperature:

- ❖ At absolute zero temperature, all the electrons are tightly held by the semiconductor atoms. The inner orbit electrons are bound whereas the valence electrons (outer shell electrons) are engaged in covalent binding. At this temperature, the covalent bonds are very strong and there are no free electrons. Therefore, the semiconductor crystal behaves as a perfect insulator.

- ❖ In terms of energy band description, the valence band is filled and there is a large energy gap between valence and conduction bands. Therefore, no valence electron can reach the conduction band to become free electron. Due to the unavailability of free electrons, a semiconductor behaves as an insulator.

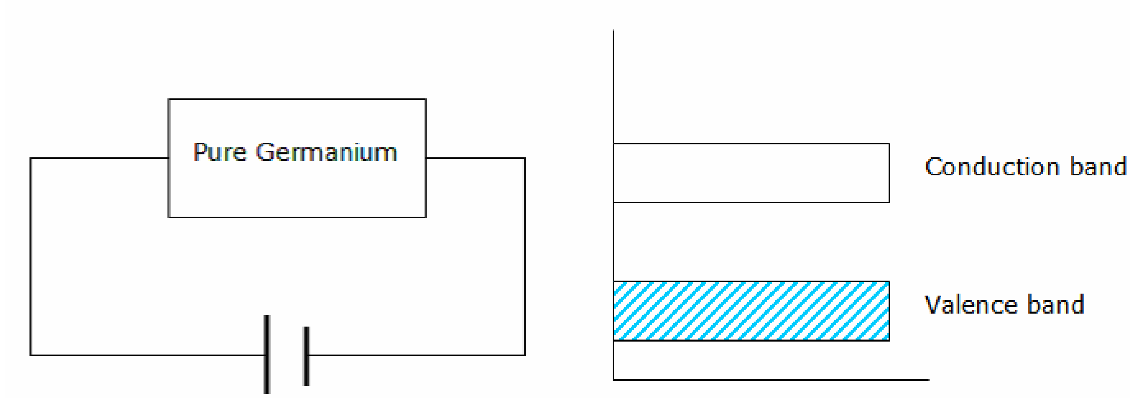


Figure: Effect of temperature on semiconductor at absolute zero

(ii) Above absolute zero temperature:

- ❖ When temperature is raised, some of the covalent bonds in the semiconductor break due to the thermal energy supplied. The breaking of bonds sets those electrons free which are engaged in the formation of these bonds. The result is that a few free electrons exist in the semiconductor. These free electrons can constitute a tiny electric current if potential difference is applied across the semiconductor crystal.
- ❖ This shows that the resistance of a semiconductor decreases with the rise in temperature i.e. it has negative temperature coefficient of resistance.
- ❖ In terms of energy band description, as the temperature is raised, some of the valence electrons acquire sufficient energy to enter into the conduction band and thus become free electrons. Under the influence of electric field, these free electrons will constitute electric current.
- ❖ It may be noted that each time a valence electron enters into

the conduction band, a hole is created in the valence band.

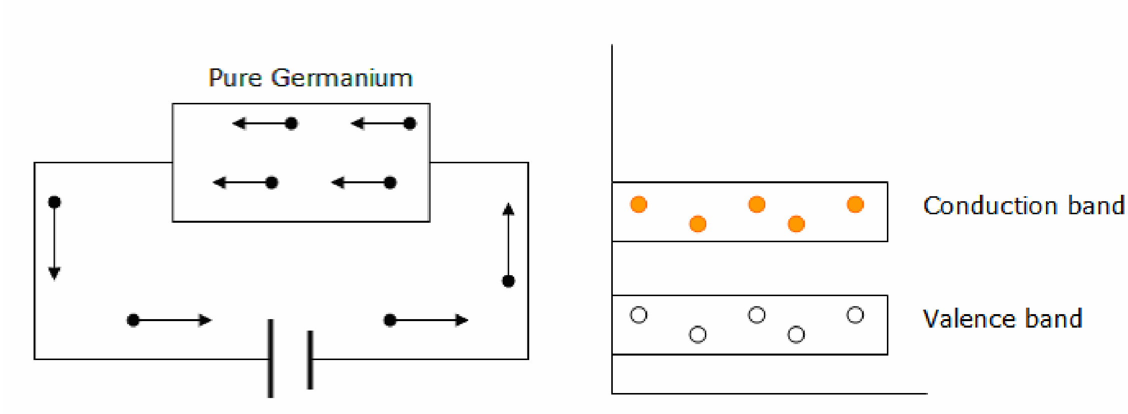


Figure: Effect of temperature on semiconductor above absolute zero

Intrinsic Vs. Extrinsic Semiconductor:

- Semiconductors fall into two broad categories- intrinsic and extrinsic.
- An intrinsic semiconductor is one, which is pure enough that impurities do not appreciably affect its electrical behavior. It is composed of only one kind of material. Silicon and germanium are two examples of this kind of semiconductor. They are also called "undoped" or "i-type" semiconductors.
- Equal numbers of electrons and holes are present in an intrinsic semiconductor.
- The concentration of carriers is strongly dependent on the temperature. At low temperatures, the valence band is completely full making the material an insulator. Increasing the temperature leads to an increase in the number of carriers and a corresponding increase in conductivity. This characteristic shown by intrinsic semiconductor is different from the behavior of most metals, which tend to become less conductive at higher temperatures.
- Both silicon and germanium are tetravalent, i.e. each has four electrons (valence electrons) in their outermost shell. Both elements crystallize with a diamond-like structure, i.e. in such a way that each atom in the crystal is inside a tetrahedron formed by the four atoms which are closest to it. Each atom shares its four valence electrons with its four immediate neighbors, so that each atom is involved in four covalent bonds.

- If we take a crystal of some pure material, such as silicon, we find that each silicon atom has four bonds (this is called the valency of the atom), and each bond links it to another silicon atom. This bonding forms a crystal lattice and occupies all of the electrons in the silicon atoms. Because there are no free electrons, this material cannot pass a current, and is an insulator.

Extrinsic Semiconductor:

- Extrinsic semiconductors are made of intrinsic semiconductors that have had other substances added to them to alter their properties.
- The electronic properties and the conductivity of a semiconductor can be changed in a controlled manner by adding very small quantities of other elements, called "dopants", to the intrinsic material.
- If we carefully add an additional element to a pure material (such as silicon), the situation changes. If we add an atom with a valency of five instead of four, we find that wherever an atom of the introduced element is found, four of its bonds will attach to nearby silicon atoms, but the fifth bond will be unattached, leaving a free electron available, which will carry a current.

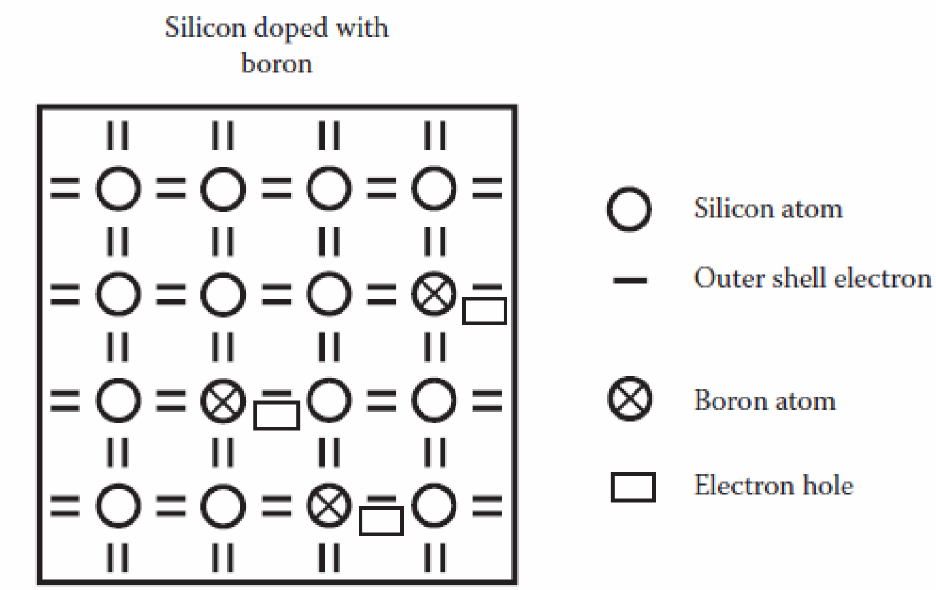
Doping and Dopant:

- The property of semiconductors that makes them most useful for constructing electronic devices is that their conductivity may easily be modified by introducing impurities into their crystal lattice. The process of adding controlled impurities to a semiconductor during the manufacturing process to increase its conductivity is known as doping. The impurities added are called dopants. Common dopants include arsenic, antimony, bismuth and phosphorous.
- The type and level of doping determines whether the semiconductor is N-type (current is conducted by excess free electrons) or P-type (current is conducted by electron vacancies).

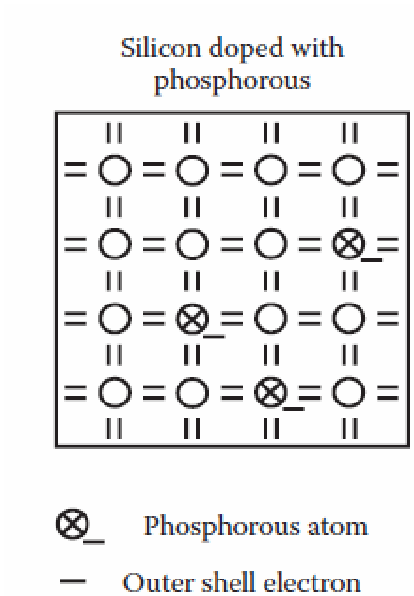
- The amount of impurity, or dopant, added to an intrinsic (pure) semiconductor varies its level of conductivity. Doped semiconductors are often referred to as extrinsic.
- By adding impurity to pure semiconductors, the electrical conductivity may be varied not only by the number of impurity atoms but also, by the type of impurity atom.

Acceptor and Donor:

- The materials chosen as suitable dopants depend on the atomic properties of both the dopant and the material to be doped.
- In general, dopants are classified as either electron acceptors or donors. A donor atom donates weakly bound valence electrons to the material, creating excess negative charge carriers. These weakly bound electrons can move about in the crystal lattice relatively freely and can facilitate conduction in the presence of an electric field.
- Conversely, an acceptor atom accepts an electron from the material to be doped and thereby produces a hole.
- Semiconductors doped with donor impurities are called n-type, while those doped with acceptor impurities are known as p-type. The n and p type designations indicate which charge carrier acts as the material's majority carrier. The opposite carrier is called the minority carrier.
- For example, the pure semiconductor silicon has four valence electrons. Boron has three valence electrons. It can be used as an acceptor when used to dope silicon. Therefore, a silicon crystal doped with boron creates a p-type semiconductor.



- On the other hand, phosphorous has five valence electrons. So it can be used as a donor when used to dope with silicon. Therefore, a silicon crystal doped with phosphorous creates an n-type semiconductor.



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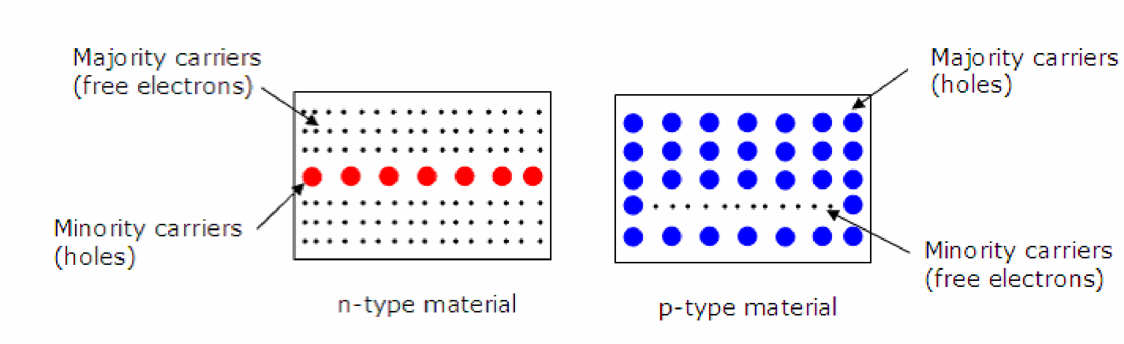
Majority and Minority Carriers:

- If we dope silicon with material having a valency of five, extra free electrons are created in the crystal. These electrons are called majority carriers- since the majority portion of current is by the flow of free electrons. Holes are the minority carriers in this case. Material doped in this way is referred to as n-type semiconductor.
- On the other hand, if we dope silicon with a material having a valency of three, holes are created in the crystal due to the absence of electrons. The holes carry a charge, equivalent to the charge on an electron, but of the opposite sign. Material doped in this way is referred to as p-type semiconductor. Holes outnumber the free electrons. Therefore, in a p-type material, holes are the majority carriers and free electrons are the minority carriers.

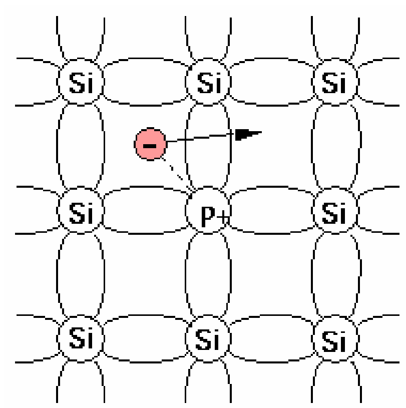


n-Type Semiconductor:

- When a small amount of pentavalent impurity is added to a pure semiconductor, it is known as n-type semiconductor.
- The addition of pentavalent impurity provides a large number of free electrons in the semiconductor crystal. Typical examples of pentavalent impurities are arsenic, antimony, phosphorous. Such impurities which produce n-type semiconductor are known as donor impurities, because they donate or provide free electrons to the semiconductor crystal.
- To explain the formation of n-type semiconductor, consider a pure silicon crystal.
    - We know that silicon atom has four valence electrons.
    - When a small amount of pentavalent impurity like phosphorous is

added to silicon crystal, a large number of free electrons become available in the crystal.

- The reason is simple. Phosphorous is pentavalent i.e. its atom has five valence electrons.
- A phosphorous atom fits in the silicon crystal in such a way that its four valence electrons form covalent bonds with four silicon atoms.
- The fifth valence electron of phosphorous atom finds no place in covalent bonds and is thus free as shown in the figure below.

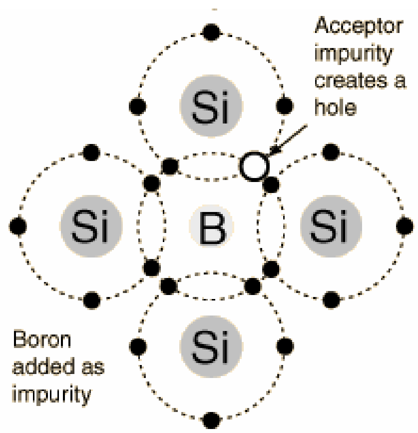


- Therefore, for each phosphorous atom added, one free electron will be available in the silicon crystal.
- Though each phosphorous atom provides one free electron, yet an extremely small amount of phosphorous impurity provides enough atoms to supply millions of free electrons.

p-Type Semiconductor:

- When a small amount of trivalent impurity is added to a pure semiconductor, it is known as p-type semiconductor.
- The addition of trivalent impurity provides a large number of holes in the semiconductor crystal. Typical examples of trivalent impurities are boron, gallium, indium etc.
- Such impurities which produce p-type semiconductor are known as acceptor impurities, because the holes created can accept the electrons.
- To explain the formation of p-type semiconductor, consider a pure silicon crystal.
    - We know that silicon atom has four valence electrons.

- When a small amount of trivalent impurity like boron is added to silicon crystal, there exist a large number of holes in the crystal.
- The reason is simple. Boron is trivalent i.e. its atom has three valence electrons.
- Each boron atom fits into the silicon crystal but now only three covalent bonds can be formed. It is because three valence electrons of boron atom can form only three single covalent bonds with three silicon atoms as shown in the figure below.



- In the fourth covalent bond, only silicon atom contributes one valence electron while boron has no valence electron to contribute as all its three valence electrons are already engaged in the covalent bonds with neighboring silicon atoms. In other words, fourth bond is incomplete; being short of one electron. This missing electron is called a hole.
- Therefore, for each boron atom added, one hole is created. A small amount of boron provides millions of holes.

■ When a doped semiconductor contains excess holes it is called "p-type", and when it contains excess free electrons it is known as "n-type", where p (positive for holes) or n (negative for electrons) is the sign of the charge of the majority mobile charge carriers.

■ An *N-type* semiconductor carries current mainly in the form of negatively-charged electron, in a manner similar to the conduction of current in a wire.

■ A P-type semiconductor carries current predominantly as electron deficiencies called holes. A hole is a place in a crystal where an electron normally would be, but is not. A hole has a positive electric charge, equal and opposite to the charge on an electron.

- In a semiconductor material, the flow of holes occurs in a direction opposite to the flow of electrons.
- The junctions which form where n-type and p-type semiconductors join together are called p-n junctions, which are the basis for all kinds of semiconductor devices.