Semiconductor Devices

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About the Tutorial

The electronic components exploiting the electronic properties of semiconductor materials, are termed as semiconductor devices. This tutorial discusses the functional operation of semiconductor devices, explains the operation of devices in a circuit, etc.

Each topic in this tutorial is explained well using circuit diagrams for better understanding. After completing this tutorial, readers will be at a moderate level of expertise to explain the basics related to semiconductor devices.

Audience

This tutorial will be useful for all those readers who want to gain knowledge on semiconductor devices. Upon completion of this tutorial, you will able to explain the functional operation of semiconductor devices.

Prerequisites

We don’t assume any prior knowledge of Electronics is necessary to understand this tutorial. The material is meant for beginners and it should be useful for most readers.

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1. Semiconductor Devices – Introduction

It is widely seen that the distance of a nucleus from the electron of a particular atom is not equal. Normally, electrons rotate in a well-defined orbit. A particular number of electrons can only hold by outer shell or orbit. The electrical conductivity of an atom is influenced mainly by the electrons of the outer shell. These electrons have a great deal to do with the electrical conductivity.

Conductors and Insulators

Electrical conduction is the result of irregular or uncontrolled movement of electrons. These movements cause certain atoms to be good **electrical conductors**. A material with such type of atoms has many free electrons in its outer shell or orbit.

Comparatively, an **insulating material** has a relatively small number of free electrons. Consequently, the outer shell electrons of insulators tend to hold their place firmly and hardly allow any current to flow through it. Therefore, in an insulating material, very little electrical conductivity takes place.

Semiconductors

In between conductors and insulators, there is a third classification of atoms (material) known as semiconductors. Generally, the conductivity of a semiconductor lies in between the conductivities of metals and insulators. However, at absolute zero temperature, the semiconductor also acts like a perfect insulator.

Silicon and **germanium** are the most familiar semiconductor elements. Copper oxide, cadmium-sulfide, and gallium arsenide are some other semiconductor compounds that are frequently used. These kinds of material are generally classified as type IVB elements. Such atoms have four valence electrons. If they can give up four valence electrons, stability can be accomplished. It can also be achieved by accepting four electrons.

Stability of an Atom

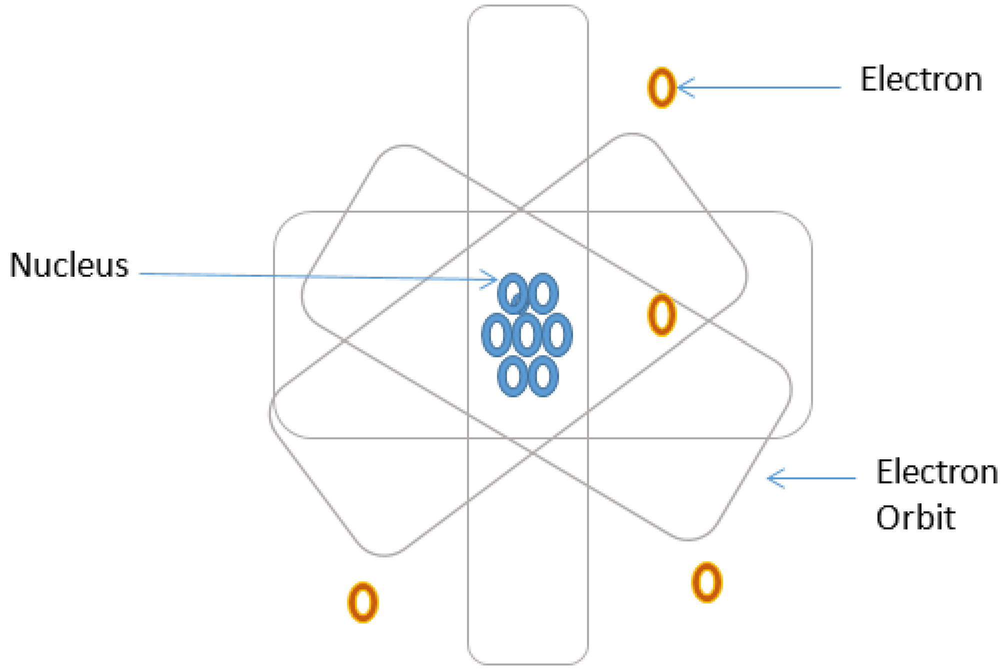
The concept of stability of an atom is an important factor in the status of semiconductor materials. The maximum number of electrons in the valence band is 8. When there are exactly 8 electrons in the valence band, it can be said that the atom is stable. In a **stable atom**, the bonding of valence electrons is very rigid. These types of atoms are excellent insulators. In such atoms, free electrons are not available for electrical conductivity.

Examples of stabilized elements are gases such as Argon, Xenon, Neon, and Krypton. Due to their property, these gases cannot be mixed with other material and are generally known as **inert gases**.

If the number of valence electrons in the outer shell is less than 8, then the atom is said to be unstable i.e., the atoms having fewer than 8 valence electrons are unstable. They always try to borrow or donate electrons from the neighboring atoms to become stable. Atoms in the outer shell with 5, 6, or 7 valence electrons tend to borrow electrons from other atoms to seek stability, while atoms with one, two, or three valence electrons tend to release these electrons to other nearby atoms.

2. Semiconductor Devices – Atomic Combinations

Anything that has weight is matter. As per the theory of atom, all matter, whether it is solid, liquid, or gas is composed of atoms. An atom contains a central part called nucleus, which holds the neutrons and the protons. Normally, protons are positively charged particles and neutrons are neutrally charged particles. Electrons which are negatively charged particles are arranged in orbits around the nucleus in a way similar to the array of planets around the Sun. The following figure shows the composition of an atom.



Atoms of different elements are found to have different number of protons, neutrons, and electrons. To distinguish one atom from another or to classify the various atoms, a number which indicates the number of protons in the nucleus of a given atom, is assigned to the atoms of each identified element. This number is known as the **atomic number** of the element. The atomic numbers for some of the elements which are associated with the study of semiconductors are given in the following table.

Element	Symbol	Atomic Number
Silicon	Si	14
Germanium	Ge	32
Arsenic	As	33
Antimony	Sb	51
Indium	In	49
Gallium	Ga	31
Boron	B	5

Normally, an atom has an equal number of protons and planetary electrons to maintain its net charge at zero. Atoms frequently combine to form stabilized molecules or compounds through their available valence electrons.

The process of combining of free valence electrons is generally called **bonding**. Following are the different kinds of bonding that takes place in atom combinations.

- Ionic bonding
- Covalent bonding
- Metallic bonding

Let us now discuss in detail about these atomic bondings.

Ionic Bonding

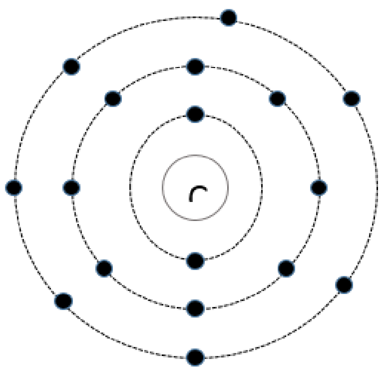
Each atom is seeking stability when the atoms bond together to form molecules. When the valence band contains 8 electrons, it is said to be a **stabilized condition**. When the valence electrons of one atom combine with those of another atom to become stable, it is called **ionic bonding**.

- If an atom has more than 4 valence electrons in the outer shell it is seeking additional electrons. Such atom is often called an **acceptor**.

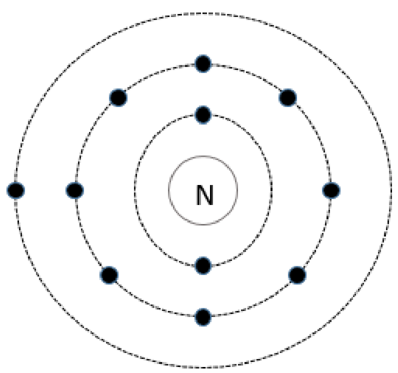
- If any atom holds less than 4 valence electrons in the outer shell, they try to move out from these electrons. These atoms are known as **donors**.

In ionic bonding, donor and acceptor atoms frequently combine together and the combination becomes stabilized. Common salt is a common example of ionic bonding.

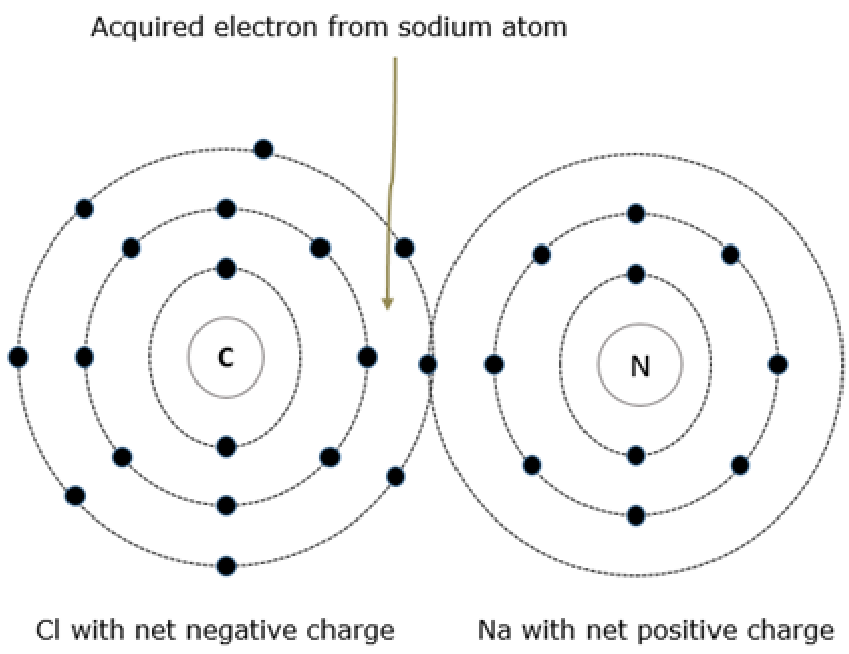
The following figures illustrate an example of independent atoms and ionic bonding.



Normal Chloride atom with 2-8-7 electrons



Normal Sodium atom with 2-8-1 electrons



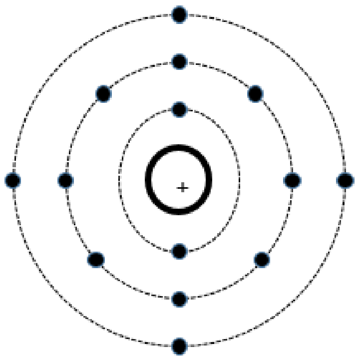
Ionic bonding of sodium chloride atom

It can be seen in the above figure that the sodium (Na) atom donates its 1 valence electron to the chloride (Cl) atom which has 7 valence electrons. The chloride atom immediately becomes overbalanced negatively when it obtains the extra electron and this causes the atom to become a negative ion. While on the other hand, the sodium atom loses its valence electron and the sodium atom then becomes a positive ion. As we know unlike charges attract, the sodium and chloride atoms are bound together by an electrostatic force.

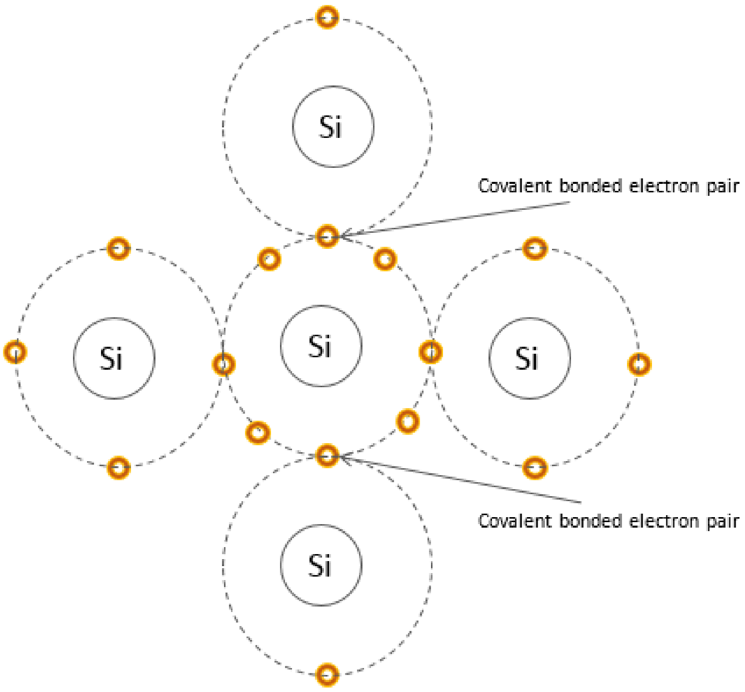
Covalent Bonding

When the valence electrons of neighboring atoms are shared with other atoms, covalent bonding takes place. In covalent bonding, ions are not formed. This is a unique dissimilarity in covalent bonding and ionic bonding.

When an atom contains four valence electrons in the outer shell, it can share one electron with four neighboring atoms. A covalent force is established between the two linking electrons. These electrons alternately shift orbits between the atoms. This covalent force bonds the individual atoms together. An illustration of covalent bonding is shown in the following figures.



A single silicon atom



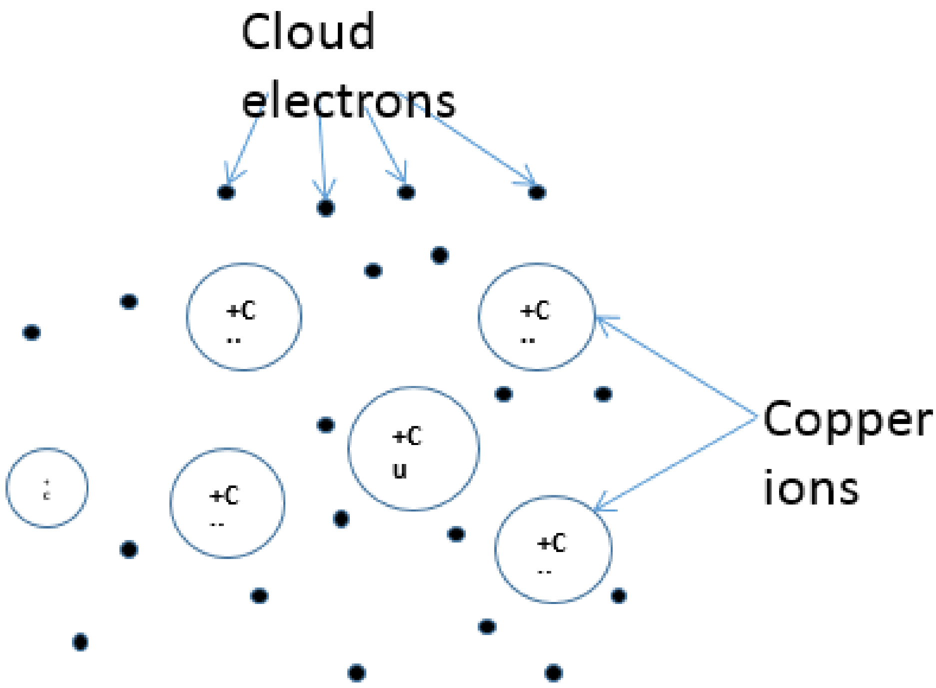
A silicon atom in covalent bonding

In this arrangement, only the nucleus and valence electrons of each atom are shown. Electron pair are created due to individual atoms are bonded together. In this case, five atoms are needed to complete the bonding action. The bonding process widens out in all directions. Each atom is now linked together in a lattice network and a crystal structure is formed by this lattice network.

Metallic Bonding

The third type of bonding generally occurs in good electrical conductors and it is called as metallic bonding. In metallic bonding, an electrostatic force exists between the positive ions and electrons. For example, the valence band of copper has one electron in its outer shell. This electron has a tendency to roam around the material between different atoms.

When this electron leaves one atom, it instantly enters the orbit of another atom. The process is repetitive on a nonstop basis. An atom becomes a positive ion when an electron leaves it. This is a **random process**. It means that one electron is always linked with an atom. It does not mean that the electron is associated with one particular orbit. It is always roaming in different orbits. As a consequence, all atoms are likely to share all the valence electrons.

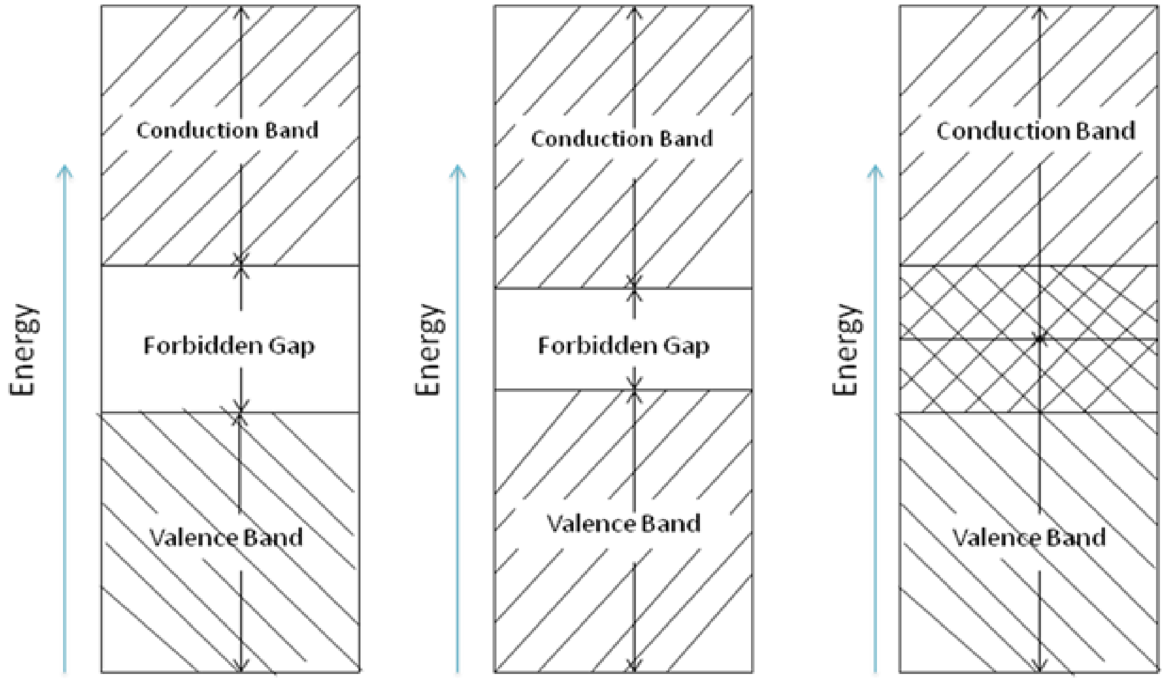


Electrons hang around in a cloud that covers the positive ions. This hovering cloud bonds the electrons randomly to the ions. The following figure shows an example of the metallic bonding of copper.

3. Semiconductor Devices – Conduction in Solid Materials

The number of electrons in the outer ring of an atom is still the reason for the difference between conductors and insulators. As we know, solid materials are primarily used in electrical devices to accomplish electron conduction. These materials can be separated into conductors, semiconductors, and insulators.

However, conductors, semiconductors, and insulators are differentiated by energy-level diagrams. The amount of energy needed to cause an electron to leave its valence band and go into conduction will be accounted here. The diagram is a composite of all atoms within the material. Energy-level diagrams of insulators, semiconductors, and conductors are shown in the following figure.



Valence Band

The bottom portion is the **valence band**. It represents the energy levels closest to the nucleus of the atom and the energy levels in the valance band hold the correct number of electron necessary to balance the positive charge of the nucleus. Thus, this band is called the **filled band**.

In the valence band, electrons are tightly bound to the nucleus. Moving upward in the energy level, the electrons are more lightly bound in each succeeding level toward the nucleus. It is not easy to disturb the electrons in the energy levels closer to the nucleus, as their movement requires larger energies and each electron orbit has a distinct energy level.

Conduction Band

The top or outermost band in the diagram is called the **conduction band**. If an electron has an energy level, which lies within this band, and is comparatively free to move around in the crystal, then it conducts electric current.

In semiconductor electronics, we are concerned mostly in the valence and conduction bands. Following are some basic information about it:

- The valence band of each atom shows the energy levels of the valence electrons in the outer shell.

- A definite amount of energy must be added to the valence electrons to cause them to go into the conduction band.

Forbidden Gap

The valence and conduction bands are separated by a gap, wherever exists, called forbidden gap. To cross the forbidden gap a definite amount of energy is needed. If it is insufficient, electrons are not released for conduction. Electrons will remain in the valence band till they receive additional energy to cross the forbidden gap.

The conduction status of a particular material can be indicated by the width of the forbidden gap. In atomic theory, the width of the gap is expressed in electron volts (eV). An electron volt is defined as the amount of energy gained or lost when an electron is subjected to a potential difference of 1 V. The atoms of each element have a dissimilar energy-level value that allows conduction.

Note that the **forbidden region** of an insulator is relatively wide. To cause an insulator to go into conduction will require a very large amount of energy. For example, Thyrite.

If insulators are operated at high temperatures, the increased heat energy causes the electrons of the valence band to move into the conduction band.

As it is clear from the energy band diagram, the forbidden gap of a semiconductor is much smaller than that of an insulator. For example, silicon needs to gain 0.7 eV of energy to go into the conduction band. At room temperature, the addition of heat energy may be sufficient to cause conduction in a semiconductor. This particular characteristic is of great importance in solid-state electronic devices.

In case of a conductor, the conduction band and the valence band partly overlaps one another. In a sense, there is no forbidden gap. Therefore, the electrons of valence band are able to release to become free electrons. Normally at normal room temperature little electrical conduction takes place within the conductor.

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