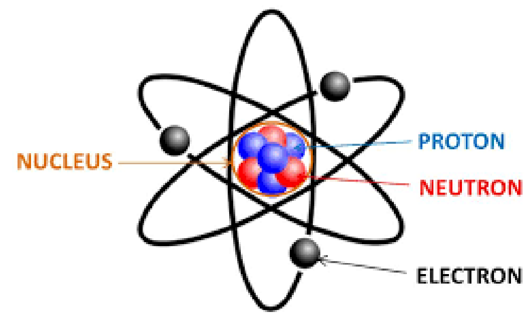
ATOM STRUCTURE

Smallest particle of an element which shows all properties of element is called atom. Some characteristics of "atoms" are as follows:

Atom takes part in chemical reactions independently.
Atom can be divided into a number of sub-atomic particles.
Fundamental particles of atom are electron, proton and neutron.



CHARACTERISTICS OF ELECTRON

# Charge	:	It is a negatively charged particle.
# Magnitude of charge	:	Charge of electron is 1.6022×10^{-19} Coulomb.
# Mass of electron	:	Mass of electron is 0.000548597 a.m.u. or 9.1×10^{-31} kg.
# Symbol of electron	:	Electron is represented by "e".
# Location in the atom	:	Electrons revolve around the nucleus of atom in different circular orbits.

CHARACTERISTICS OF PROTON

# Charge	:	Proton is a positively charged particle.
# Magnitude of charge	:	Charge of proton is 1.6022×10^{-19} coulomb.
# Mass of proton	:	Mass of proton is 1.0072766 a.m.u. or 1.6726×10^{-27} kg.
# Comparative mass	:	Proton is 1837 times heavier than an electron.
# Position in atom	:	Protons are present in the nucleus of atom.

CHARACTERISTICS OF NEUTRON

# Charge	:	It is a neutral particle because it has no charge.
# Mass of neutron	:	Mass of neutron is 1.0086654 a.m.u. or

1.6749×10^{-27} kg.

Comparative mass : Neutron is 1842 times heavier than an electron.
Location in the atom : Neutrons are present in the nucleus of an atom.

ATOMIC NUMBER

Total number of protons present in the nucleus of an atom is called "Atomic number" or "Charge number". Since the total number of protons and the total number of electrons in an atom are equal therefore atomic number may also be defined as: "Total number of electron in an atom is called Atomic number"

MASS NUMBER

Total number of protons and neutrons present in the nucleus of an atom is called "Mass number".

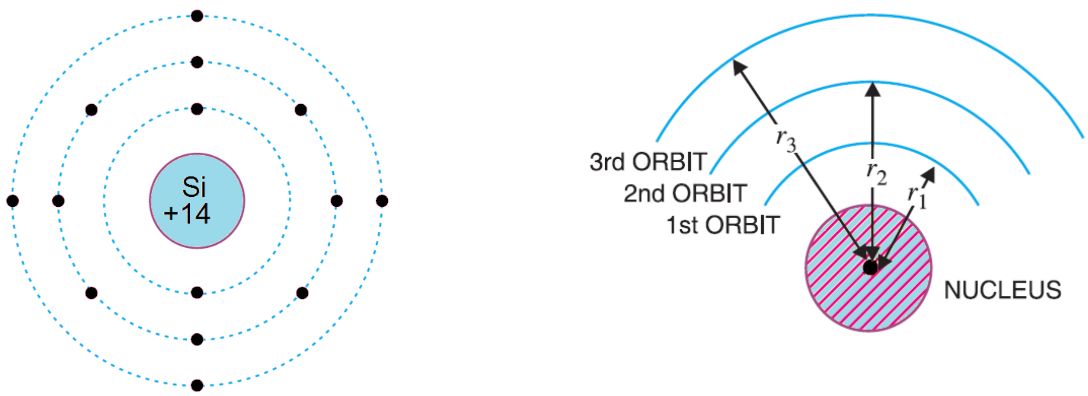
$$A = p + n$$

BOHR'S ATOMIC MODEL

The study of atomic structure is of considerable importance for electronics engineering. Various scientists have given different theories regarding the structure of atom. However, for the purpose of understanding electronics, the study of Bohr's atomic model is adequate. In 1913, Neils Bohr, Danish Physicist gave clear explanation of atomic structure. According to Bohr:

I. An atom consists of a positively charged nucleus around which negatively charged electrons revolve in different circular orbits.
II. The electrons can revolve around the nucleus only in certain permitted orbits i.e. orbits of certain radii are allowed.
III. The electrons in each permitted orbit have a certain fixed amount of energy. The larger the orbit (i.e. larger radius), the greater is the energy of electrons.
IV. If an electron is given additional energy (e.g. heat, light etc.), it is lifted to the higher orbit. The atom is said to be in a state of excitation. This state does not last long, because the electron soon falls back to the original lower orbit. As it falls, it gives back the acquired energy in the form of heat, light or other radiations.

Fig. 1 shows the structure of silicon atom. It has 14 electrons revolves only in permitted orbits (i.e. orbits of *radii r1, r2 and r3) and not in any arbitrary orbit. Thus, all radii between r1 and r2 or between r2 and r3 are forbidden. Each orbit has fixed amount of energy associated with it. If an electron in the first orbit is to be lifted to the second orbit, just the **right amount of energy should be supplied to it. When this electron jumps from the second orbit to first, it will give back the acquired energy in the form of electromagnetic radiations.



(i) (ii)

Figure 1: Atomic Structure of Silicon

ENERGY BANDS

In case of a single isolated atom, the electrons in any orbit possess definite energy. However, an atom in a solid is greatly influenced by the closely-packed neighbouring atoms. The result is that the electron in any orbit of such an atom can have a range of energies rather than a single energy. This is known as energy band.

The concept of energy band can be easily understood by referring to Fig. 2 shows the energy levels of a single isolated atom of silicon. Each orbit of an atom has a single energy. Therefore, an electron can have only single energy corresponding to the orbit in which it exists. However, when the atom is in a solid, the electron in any orbit can have a range of energies.

For instance, electrons in the first orbit have slightly different energies because no two electrons in this orbit see exactly the same charge environment. Since

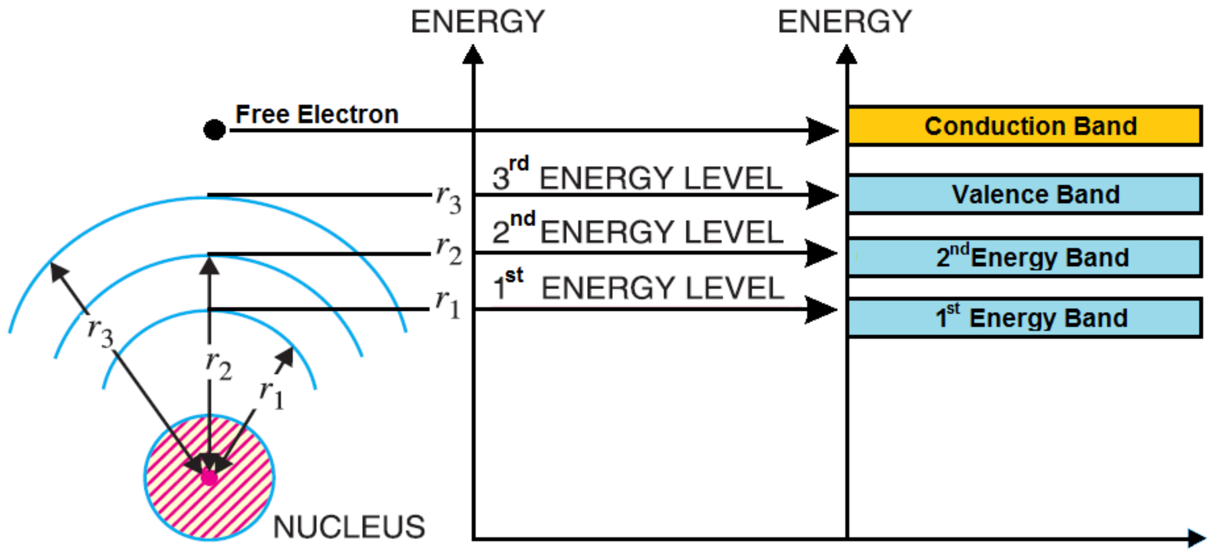


Figure 3: Concept of Energy Band Diagram

there are millions of first orbit electrons, the slightly different energy levels form a band, called 1st energy band. The electrons in the first orbit can have any energy range in this band. Similarly, second orbit electrons form second energy band and so on.

Though there are a number of energy bands in solids, the following are of particular importance

I. *Valence band*
II. *Conduction band*
III. *Forbidden energy gap*

(i) VALENCE BAND: *The range of energies (i.e. band) possessed by valence electrons is known as valence band.*

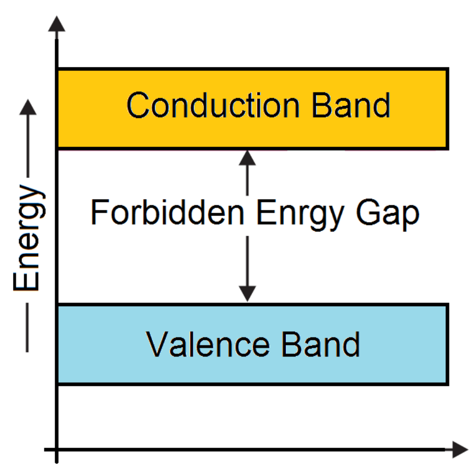


Figure 4: Energy Bands

The electrons in the outermost orbit of an atom are known as valence electrons. In a normal atom, valence band has the electrons of highest energy. This band may be completely or partially filled. For instance, in case of inert gases, the valence band is full whereas for other materials, it is only partially filled. The partially filled band can accommodate more electrons.

(ii) CONDUCTION BAND: In certain materials (e.g. metals), the valence electrons are loosely attached to the nucleus. Even at ordinary temperature, some of the valence electrons may get detached to become free electrons. In fact, it is these free electrons which are responsible for the conduction of current in a conductor. For this reason, they are called conduction electrons.

The range of energies (i.e. band) possessed by conduction band electrons is known as conduction band.

All electrons in the conduction band are free electrons. If a substance has empty conduction band, it means current conduction is not possible in that substance. Generally, insulators have empty conduction band. On the other hand, it is partially filled for conductors.

(iii) FORBIDDEN ENERGY GAP: The separation between conduction band and valence band on the energy level diagram is known as forbidden energy gap.

No electron of a solid can stay in a forbidden energy gap as there is no allowed energy state in this region. The width of the forbidden energy gap is a measure of the bondage of valence electrons to the atom. The greater the energy gap, more tightly the valence electrons are bound to the nucleus.

In order to push an electron from valence band to the conduction band (i.e. to make the valence electron free), external energy equal to the forbidden energy gap must be supplied.

CLASSIFICATION OF SOLIDS ON BASIS OF ENERGY BANDS

The difference in the behaviour of solids as regards their electrical conductivity can be beautifully explained in terms of energy bands. The electrons in the lower energy band are tightly bound to the nucleus and play no part in the conduction process. However, the valence and conduction bands are of particular importance in ascertaining the electrical behaviour of various solids.

(i) INSULATORS

Insulators (e.g. wood, glass etc.) are those substances which do not allow the passage of electric current through them. In terms of energy band, the valence band is full while the conduction band is empty. Further, the energy gap between valence and conduction bands is very large (j 15 eV) as shown in Fig. 4.5. Therefore, a very high electric field is required to push the valence electrons to the conduction band. For this reason, the electrical conductivity of such materials is extremely small and may be regarded as nil under ordinary conditions.

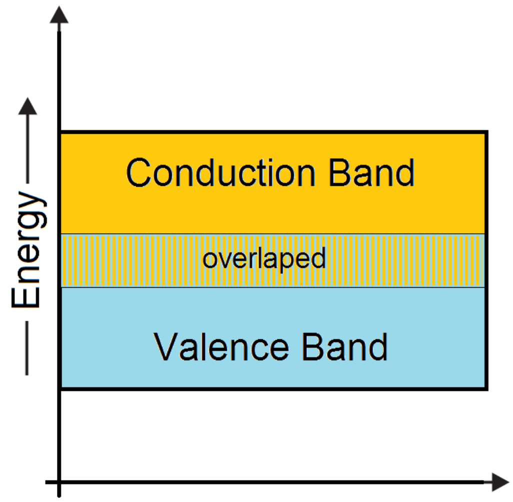


Figure 6: Energy Band Diagram of Conductor

At room temperature, the valence electrons of the insulators do not have enough energy to cross over to the conduction band. However, when the temperature is raised, some of the valence electrons may acquire enough energy to cross over to the conduction band. Hence, the resistance of an insulator decreases with the increase in temperature i.e. an insulator has negative temperature coefficient of resistance.

(ii) CONDUCTORS

Conductors (e.g. Copper, Aluminum etc.) are those substances which easily allow the passage of electric current through them. It is because there are a large number of free electrons available in a conductor. In terms of energy band, the valence and conduction bands overlap each other as shown in Fig. 4.6. Due to this overlapping, a slight potential difference across a conductor causes the free electrons to constitute electric current. Thus, the

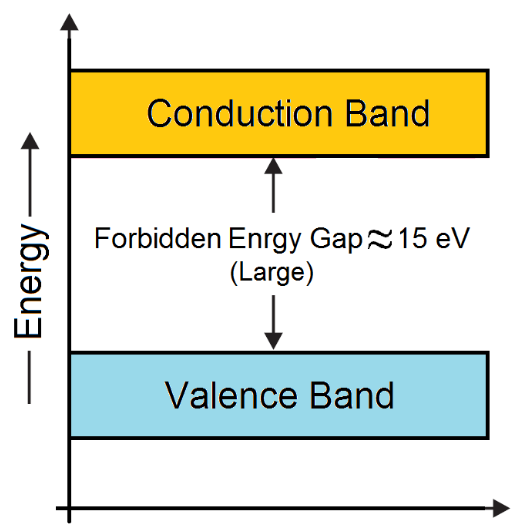


Figure 5: Energy Band Diagram of Insulator

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electrical behaviour of conductors can be satisfactorily explained by the band energy theory of materials.

(iii) SEMICONDUCTORS

Semiconductors (e.g. germanium, silicon etc.) are those substances whose electrical conductivity lies in between conductors and insulators. In terms of energy band, the valence band is almost filled and conduction band is almost empty.

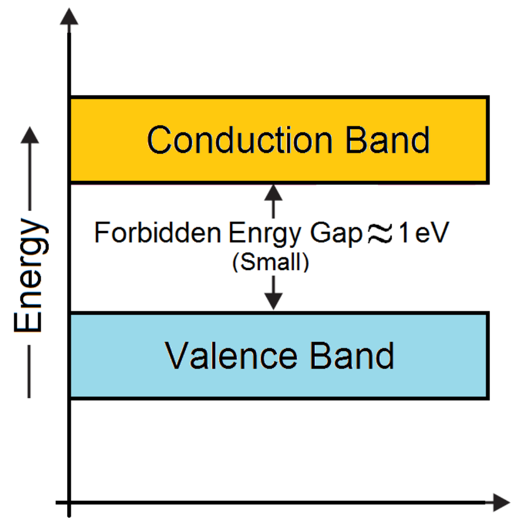


Figure 7: Energy Band Diagram of Semiconductor

Further, the energy gap between valence and conduction bands is very small as shown in Fig. 4.7. Therefore, comparatively smaller electric field (smaller than insulators but much greater than conductors) is required to push the electrons from the valence band to the conduction band.

At low temperature, the valence band is completely full and conduction band is completely empty. Therefore, a semiconductor virtually behaves as an insulator at low temperatures. However, even at room temperature, some electrons (about one electron for 1010 atoms) cross over to the conduction band, imparting little conductivity to the semiconductor. As the temperature is increased, more valence electrons cross over to the conduction band and the conductivity increases. This shows that electrical conductivity of a semiconductor increases with the rise in temperature.

Table 1: Resistivity of Materials

Sr. No.	Nature	Material	Resistivity
1	Insulator	Glass	$9X10^{11}$ Ωm
2	Conductor	Copper	$1.7X10^{-8}$ Ωm
3	Semiconductor	Germanium	0.6 Ωm

CLASSIFICATION OF SEMICONDUCTORS

There are deferent ways of classifying semiconductors depending on the property being measured. One classification that is fairly straightforward is:

I. Elemental semiconductors

II. Compound semiconductors

Out of the elemental semiconductors Si and Ge are the most common. There are different types of compound semiconductors II-VI group and III-V group are the most common and these can be understood by looking at the portion of the periodic table, shown in figure.

Elemental semiconductors (Si and Ge) belong to group IVA of the periodic table. C which is on top of the group is an insulator (diamond) with forbidden energy gap (E_g) of 5.5 eV while Sn and Pb are metals. Compound semiconductors can be formed by combining elements of groups IIIA and VA. Examples include GaAs, GaP, GaN, InSb. Similarly II-VI compound semiconductors can be formed; examples include ZnO, ZnS, CdSe, CdTe.

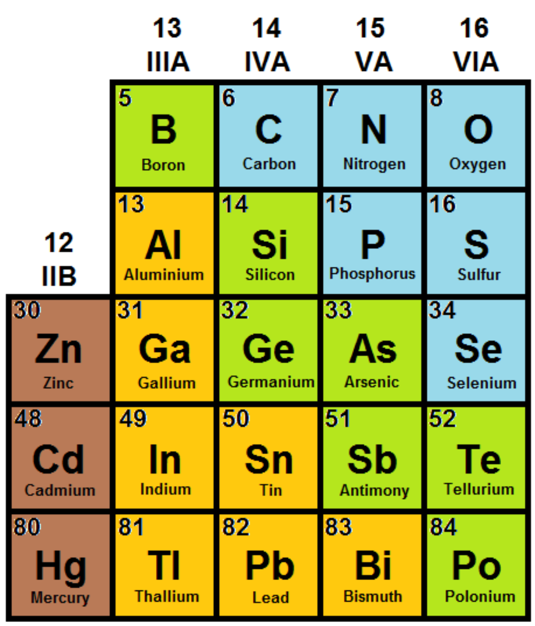


Figure: Portion of Periodic table

COMPARISON BETWEEN SILICON (Si) AND GERMANIUM (Ge)

Low cost

Silicon is relatively easy and inexpensive to obtain and process, whereas Germanium is rare material that is typically found with copper, lead or silver deposits. Because of its rarity, germanium is more expensive to work with, thus making germanium diodes more difficult to find (and sometimes more expensive) than silicon diodes.

Good temperature stability

Temperature stability of silicon is good, it can withstand in temperature range typically 140C to 180C whereas Germanium is much temperature sensitive only up to 70C.

Large forward current

Silicon is much better for high current applications as it has very high forward current in a range of tens of amperes, whereas germanium diodes have very small forward current in a range of micro amperes.

Low reverse leakage current

The reverse current in silicon flows in order of nano-amperes compared to germanium in which the reverse current is in order of micro amperes, because of this the accuracy of non-conduction of the Ge diode in reverse bias falls down. Whereas Si diode retains it property to a greater extent i.e., it allows negligible amount of current to flow.

High reverse break down voltage

The Si diode has large reverse breakdown voltage about 70-100V compared to Ge which has the reverse breakdown voltage around 50V.

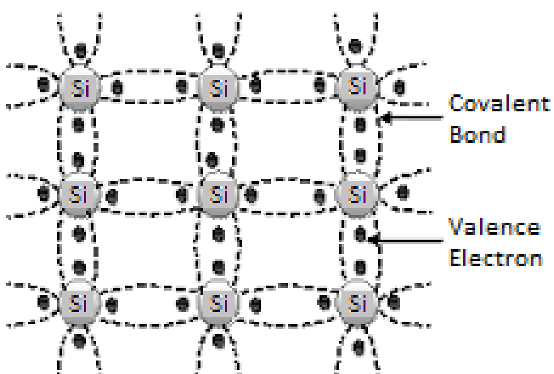
TYPES OF SEMICONDUCTORS

Semiconductors are mainly classified into two categories:

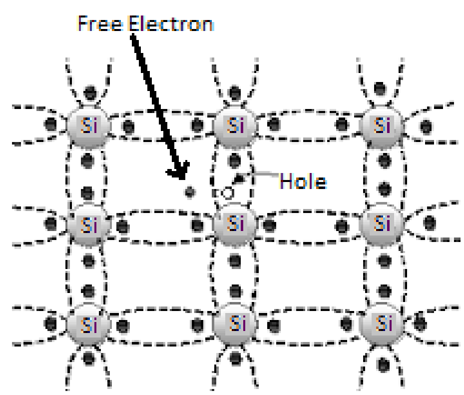
1. *Intrinsic Semiconductor*
2. *Extrinsic Semiconductor*

INTRINSIC SEMICONDUCTOR

An Intrinsic Semiconductor is one which is made of the semiconductor material in its extremely pure form. There are many semiconductors materials but Silicon (Si) and Germanium (Ge) are the two most widely used semiconductor material in electronics. The reason for this is that energy required to break their covalent bonds (i.e. the energy required to release an electron from their valence bands) is very small (0.72 for Ge and 1.12 for Si). Both the elements have the same crystal structure and characteristics. Intrinsic Semiconductor has equal numbers of negative carriers (electrons) and positive carriers (holes).



Crystal Structure of Silicon



Silicon Crystal with a broken covalent bond

For intrinsic semiconductors at temperature of absolute zero (-273.15° C) the valence band is usually full and there may be no electron in the conduction band. At absolute zero temperature, E_G for silicon and germanium are 1.21 eV and 0.72 eV respectively and it is difficult to get additional energy of this magnitude from applied electric field. Hence the conductivity of intrinsic semiconductor at absolute zero temperature is zero. However, at room temperature (300°K), the energy provided by the heat is sufficient to lift

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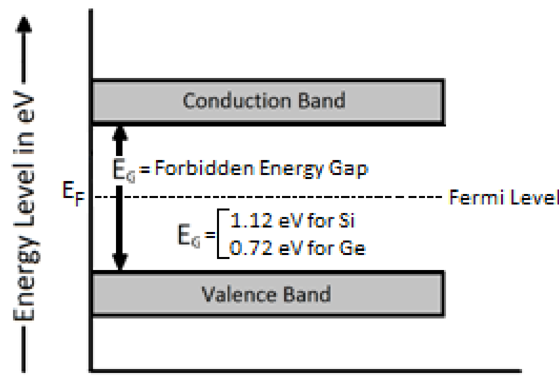
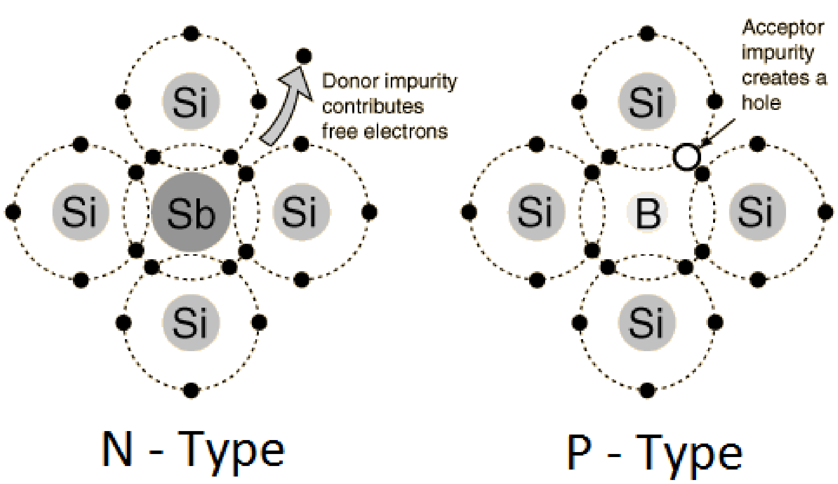
electrons from the valence band to the conduction band. So at the room temperature semiconductors are capable of conducting some electric current.



Energy Band Diagram For Intrinsic Semiconductor

EXTRINSIC SEMICONDUCTOR

Where as an extrinsic semiconductor is an improved intrinsic semiconductor with a small amount of impurities added by a process, known as doping, which alters the electrical properties of the semiconductor and improves its conductivity. Depending on whether the added impurities have "extra" electrons or "missing" electrons determines how the bonding in the crystal lattice is affected as shown in figure, and therefore how the material's electrical properties change.



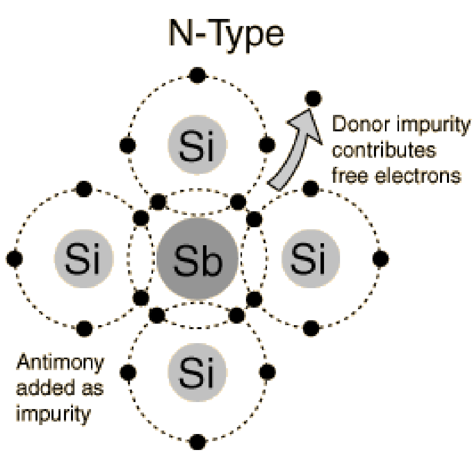
THE DOPING OF SEMICONDUCTORS

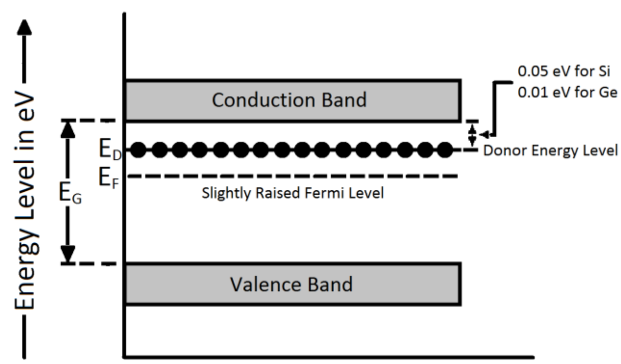
The addition of a small percentage of impurity atoms in the intrinsic semiconductor (pure silicon or pure germanium) produces dramatic changes in their electrical properties. Depending on the type of impurity added, the extrinsic semiconductors can be divided in to two classes:

1. N-type Semiconductors
2. P-type Semiconductors

N-TYPE SEMICONDUCTOR

Group V dopants are the atoms with an "extra" electron, in other words a valence shell with only one electron. When a semiconductor is doped with a Group V impurity it is called an n-type material, because the addition of these pentavalent impurities such as antimony, arsenic or phosphorous contributes free electrons, greatly increasing the conductivity of the intrinsic semiconductor. In an n-type semiconductor, the majority carrier, or the more abundant charge carrier, is the electron, and the minority carrier, or the less abundant charge carrier, is the hole.





Energy Band Diagram for N-Type Semiconductor

The effect of this doping process on the relative conductivity can be explained by energy band diagram shown in figure. When donor impurities are added to an intrinsic semiconductor, allowable energy levels are introduced at a very small gap below the conduction band, as illustrated in figure. These new allowable levels are essentially a discrete level because the added impurity atoms are far apart in

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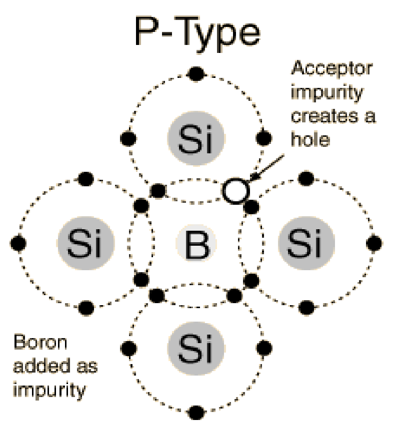
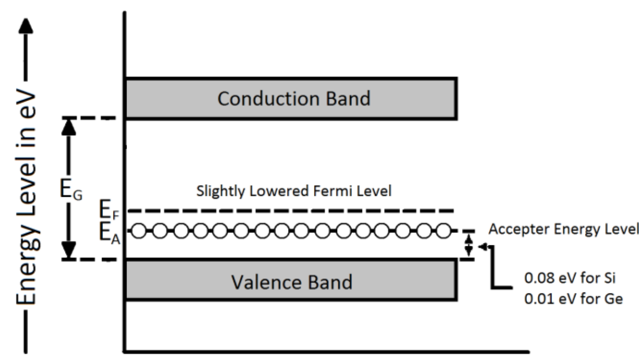
the crystal structure and hence their interaction is small. In the case of Silicon, the gap of the new discrete allowable energy level is only 0.05 eV (0.01 eV for germanium) below the conduction band, and therefore at room temperature almost all of the "fifth" electrons of the donor impurity are raised into the conduction band and the conductivity of the material increases considerable.

P-TYPE SEMICONDUCTOR

Group III dopants are the atoms with a hole in their valence shell (only "missing" one electron), When a semiconductor is doped with a Group III impurity it is called a p-type material, The addition of these trivalent impurities such as boron, aluminum or gallium to an intrinsic semiconductor creates deficiencies of valence electrons, called "holes". In a p-type semiconductor, the majority carrier, or the more abundant charge carrier, is the hole, and the minority carrier, or the less abundant charge carrier, is the electron.





Energy Band Diagram for P-Type Semiconductor

The effect of this doping process on the relative conductivity can be explained by energy band diagram shown in figure. When accepter impurities or P type impurities are added to the intrinsic semiconductor, they produce allowable discrete energy level which is just above the valance band, as shown in figure. Since a very small amount of energy (0.08 eV in case of Silicon and 0.01 eV in case of Germanium) is required for an electron to leave the valence band and occupy the accepter energy level, holes are created in the valence band by these electrons.

DIFFERENCE BETWEEN INTRINSIC AND EXTRINSIC SEMICONDUCTOR

	Intrinsic Semiconductors	**Extrinsic Semiconductors**
1	It is pure semi-conducting material and no impurity atoms are added to it.	It is prepared by doping a small quantity of impurity atoms to the pure semi-conducting material.
2	Examples: crystalline forms of pure silicon and germanium.	Examples: silicon "Si" and germanium "Ge" crystals with impurity atoms of As, Sb, P etc. or In B, Aℓ etc.
3	The number of free electrons in the conduction band and the no. of holes in valence band is exactly equal and very small indeed.	The number of free electrons and holes is never equal. There is excess of electrons in n-type semi-conductors and excess of holes in p-type semi-conductors.
4	Its electrical conductivity is low.	Its electrical conductivity is high.
5	Its electrical conductivity is a function of temperature alone.	Its electrical conductivity depends upon the temperature as well as on the quantity of impurity atoms doped the structure.

Mobility

Carrier mobility in a semiconductor is one of the most important parameters for the operation of electronic devices. Actually, the mobility measures the ability of free carriers (electrons or holes) to move in the material, when pulled by an electric field.

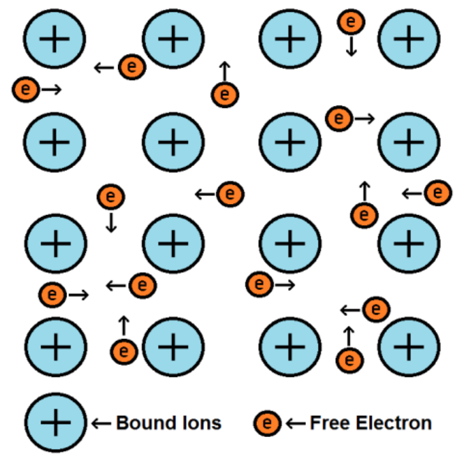


Fig. 1. Electron Gas Theory

We can better understand the mobility of an electron by ***electron gas theory***. According to electron gas theory of a metal, the electrons are in continuous motion, the direction of flight being changed by each collision with the heavy ions as shown in figure 1. The average distance between collisions is called the *mean free path*. Since the motion is random, then on average there will be as many electrons passing through unit area in the metal in any direction as in the opposite direction in the given time. Hence the average current is zero.

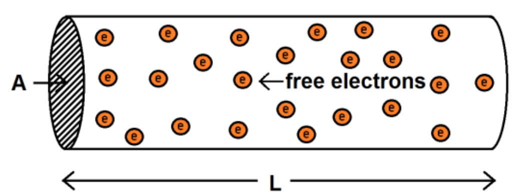


Fig. 2. Conductor

Now let us consider a conductor of length 'L' and the electric field across the conductor is ϵ (volts/meter) as shown in figure 2. As a result electrons will be accelerated and the velocity will increase with time, however at each collision, electron loses energy and steady state condition is reached where a finite value of drift speed 'V' is attained. The drift velocity is in the direction opposite to that of the electric field. The velocity at time 't' is

$$v = u + at \quad (1)$$

for $u = 0$,

$$v = at \quad (2)$$

we know that

$$F = ma \quad (3)$$

and

$$F = qE \quad (4)$$

from equation 2 and 3

$$ma = qE$$

$$a = \frac{qE}{m}$$

Acceleration 'a' is nothing but $\frac{dv}{dt}$ then,

$$\frac{dv}{dt} = \frac{qE}{m} \quad (5)$$

from equation 5 $$v \propto E$$

$$v = \mu E \quad (6)$$

Here μ is a constant known as ***mobility*** of electron. The unit of mobility is $m^2/V-S$.

Conductivity

Conductivity defines a material's ability to conduct electricity. Electric current can flow easily through a material with high conductivity. Conductivity is measured in Siemens per meter and is often represented using the Greek letter σ. Conductivity or specific conductance is the reciprocal of electrical resistivity.

If 'N' electrons are contained in a length 'L' of conductor as shown in figure 2, and if it takes an electron a time 'T' second to travel a distance of 'L' meters in the conductor. The total number of electrons passing through any cross-section of wire in unit time is N/T. The total charge per second passing through any cross-section is the **current** in amperes;

$$I = \frac{Nq}{T} \quad (1)$$

we know that $$v = \frac{L}{T}$$

we can write this $$T = \frac{L}{v} \quad (2)$$

put the value of T in equation (1) $$I = \frac{Nqv}{L} \quad (3)$$

The **current density (J)** is the current per unit area of the conducting medium.

$$J = \frac{I}{A} \quad (4)$$

where J is in *amperes/m²* and A is cross-sectional area of the conductor. By putting equation (3) in (4)

$$J = \frac{Nqv}{LA} \quad (5)$$

'LA' is the volume containing the 'N' electrons and so 'N/LA' is the electron concentration 'n' (electrons/cubic meter).

$$n = \frac{N}{LA} \quad (6)$$

now equation (5) becomes $$J = nqv \quad (7)$$

for $\rho = nq$ $$J = \rho v \quad (8)$$

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*where, ρ is the **charge density**.*

we know that $$v = \mu E \quad (9)$$

By putting equation (9) in equation (7) $$J = nq\mu E$$

for $\sigma = nq\mu$ $$J = \sigma E \quad (10)$$

*where, σ is the **conductivity** of the metal.*

Conductivity of a Semiconductor

The conductivity of the semiconductor is the combined effort of electrons and holes. Conductivity of semiconductor due to electrons in conduction band is given as

$$\sigma_e = ne\mu_e$$

where n is number of electrons per unit volume; e is electron charge; and μ_e is the electron mobility.

Similarly the conductivity σ_h of the semiconductor due to holes is given as

$$\sigma_h = pe\mu_h$$

where p is number of holes per unit volume; and μ_h is the hole mobility.

In intrinsic semiconductor conduction is by free electrons as well as by holes, so total conductivity σ is given as

$$\sigma = \sigma_e + \sigma_h$$

$$\sigma = ne\mu_e + pe\mu_h$$

$$\sigma = e(n\mu_e + p\mu_h)$$

Since in intrinsic semiconductor n=p=n_i, where n_i is the intrinsic concentration of holes or free electrons in the semiconductor. Therefore the conductivity of intrinsic semiconductor is

$$\sigma = e(n_i\mu_e + n_i\mu_h)$$

$$\sigma = n_i e(\mu_e + \mu_h)$$

current density

$$J = \sigma E$$

$$J = n_i e(\mu_e + \mu_h)E$$

where E is electric field

current

$$I = JA$$

$$I = n_i e(\mu_e + \mu_h)EA$$

$$E = \frac{V}{l}$$

$$I = n_i e(\mu_e + \mu_h)\frac{V}{l}A$$

where V is applied voltage; l is length and A is cross section area.

For N type semiconductor total number of electrons (n) is equal to the donor atom (N_D) and number of holes (p) is negligible.

$$\sigma_e = eN_D\mu_e$$

For P type semiconductor total number of holes (p) is equal to the accepter atom (N_A) and number of electrons (n) is negligible.

$$\sigma_h = eN_A\mu_h$$

Mass Action Law

When an electron breaks a covalent bond and moves away, a vacancy is created in the broken covalent bond. The vacancy so caused constitutes a hole. Whenever a free electron is generated, a hole is simultaneously created. Thus free electrons and holes are always generated in pairs. So concentration of free electrons and holes will always be equal in an intrinsic semiconductor. Such generation of free electron hole pairs is referred to as thermal 'generation'.

$$n = p = n_i$$

When N type impurity is added to an intrinsic semiconductor, the concentration of free electrons is increased and the concentration of holes is reduced due to more recombination. Similarly addition of P type impurity results in increase in hole concentration and reduction of concentration of free electrons. Theoretical analysis reveals that under thermal equilibrium the product of concentration of free electrons and concentration of holes is constant and is independent of the amount of doping. This is known as mass action law.

$$np = n_i^2$$

Charge Densities in an Extrinsic Semiconductor

If N_D is the concentration of donor atoms, there will be N_D immobile positive charges per unit volume contributed by donor ions as the donor atoms are ionized. The positive charge density will be N_D+p where p is the concentration of holes. Similarly as the accepter atoms are ionized, the total negative charge density will be N_A+n, where n is the electron concentration. Since the semiconductor is neutral, the magnitude of positive charge density will be equal to the magnitude of negative charge density.

$$N_D + p = N_A + n$$

For N type Semiconductor

$$N_A = 0 \;;\; n \gg p$$

So the free electron concentration is approximately equal to the denity of donor atoms

$$n \approx N_D$$

according to mass action law

$$np = n_i^2$$

$$p = \frac{n_i^2}{n}$$

Now the concentration of holes in N type semiconductor will be given by the expression

$$p = \frac{n_i^2}{N_D}$$

Similarly for P type semiconductor

$$n = \frac{n_i^2}{N_A}$$

Current Components in Semiconductor

- Drift Current
- Diffusion Current

Drift Current

When an electric field E volt/m is applied to a metal, the electrons move to the positive terminal of the applied voltage. In their way, they continuously collide with the atoms and rebound in a random fashion, as shown in figure. The electrons are accelerated due to the applied electric field and lose their energy at the next collision. Thus the applied electric field does not stop collision and random motion but makes the electrons to drift towards the positive terminal. Consequently, the electrons gain average drift velocity v and it is proportional to the applied electric field E.

$$v = \mu_e E$$

where μ_e is electron mobility

This steady state drift velocity is super-imposed on the random motion of free electrons caused by thermal agitation. This steady flow of electrons in one

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direction caused by the applied electric field constitutes an electric current, called drift current.

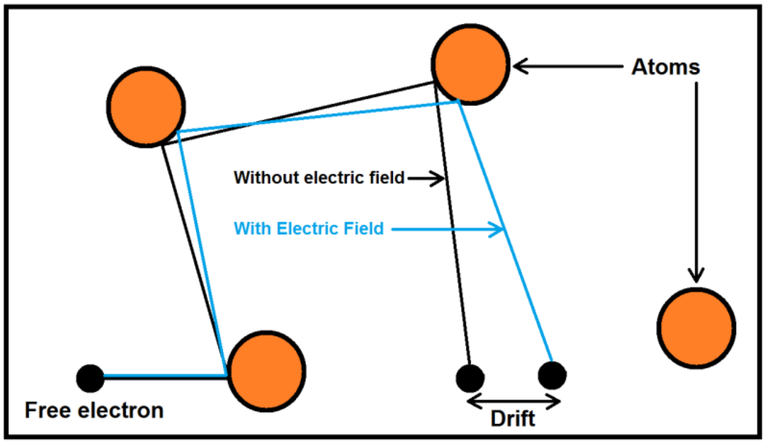

Figure: Electron path with and without electric field

Diffusion Current

If concentration of holes or electrons is greater in one region and lower in another region, the charge carriers tends to move from the region of high concentration to low concentration. The process is called the diffusion and the current due to this process is called the diffusion current.

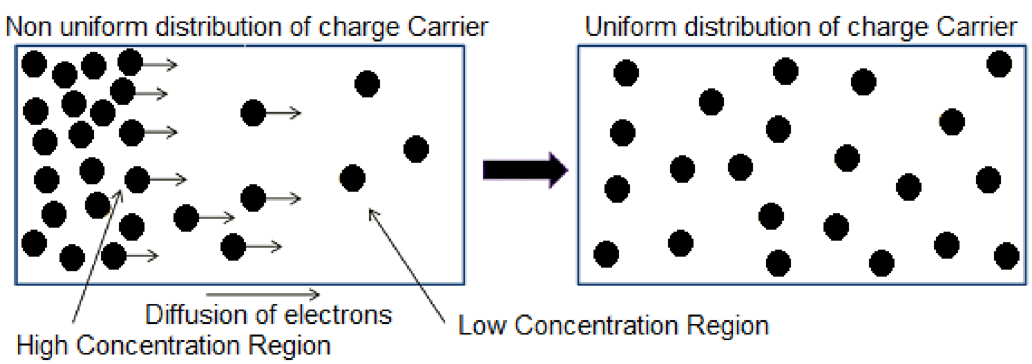

Figure: Diffusion Current