Electronics

Electric Conductivity (σ)

$\sigma = \frac{1}{\rho}$

σ – Electric Conductivity

ρ- Resistivity

Electric conductivity is equal to inverse value of resistivity at a given temperature.

$\rho = \Omega m$

So, $\rho = \Omega^{-1} m^{-1}$

$\Omega^{-1} = S$ (Siemens (unit))

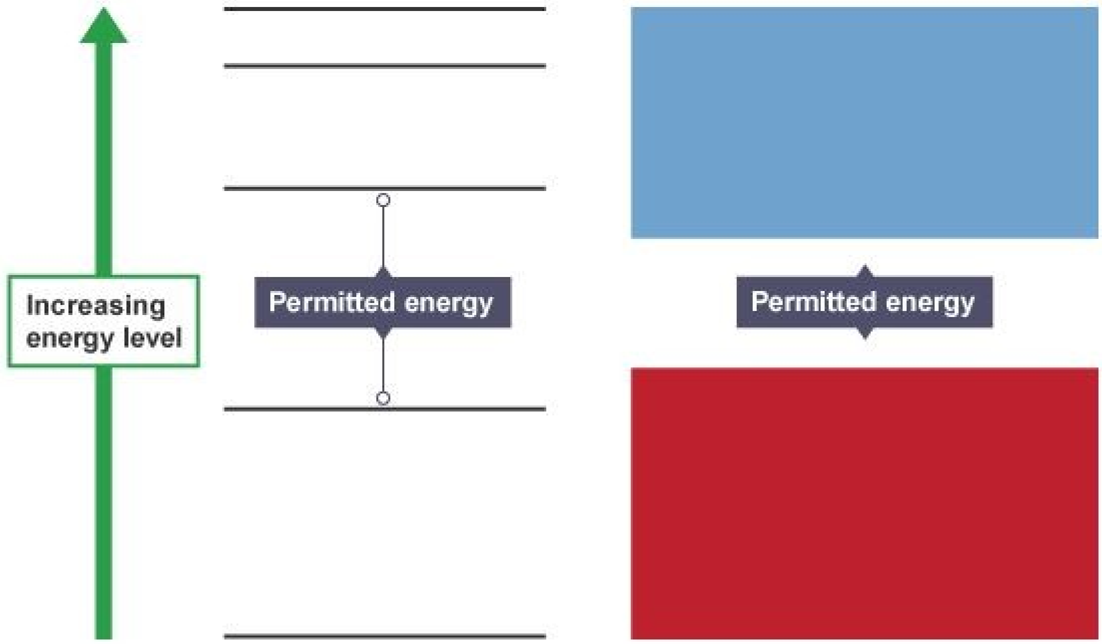
In respect of electric conductivity matters can be divided in to three categories

1. Conductors
2. Semiconductors
3. Insulators

Band theory of conduction

Electrons orbit the positive nucleus of an individual atom in permitted energy levels, as shown on the left of the diagram below.

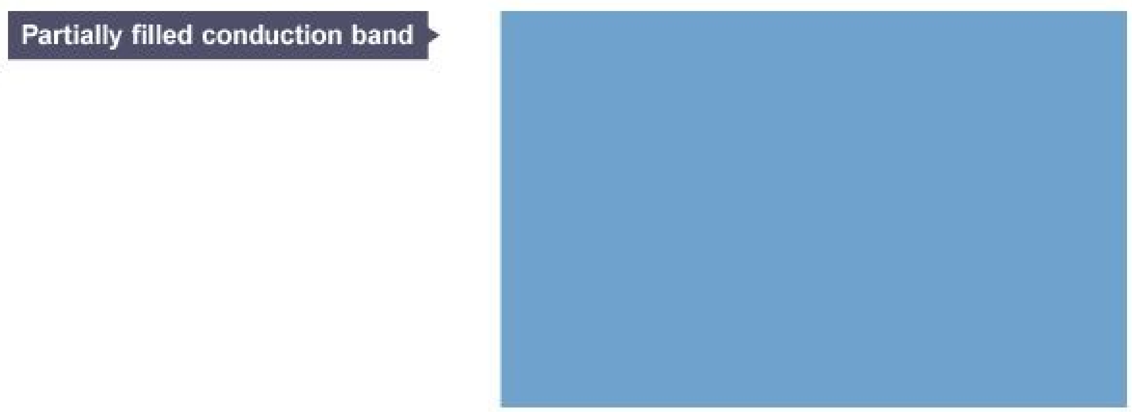
In a large collection of atoms such as a metal wire or a semiconductor crystal the energy levels become reorganized into two bands as shown on the right of the diagram.



Electrons can’t exist in the energy 'gap' between bands.

Conductors

In a conductor there are no band gaps and electrons can move easily using a continuous, partially filled conduction band.

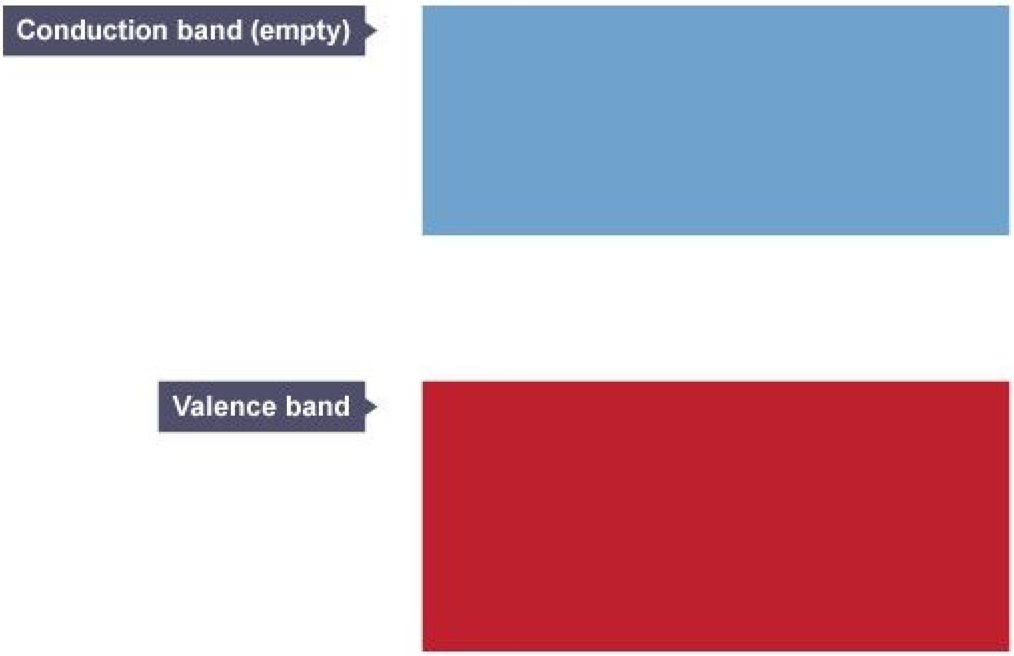


Insulators

An insulator has a large gap between the lower energy levels (the valence band) and the upper conduction band.

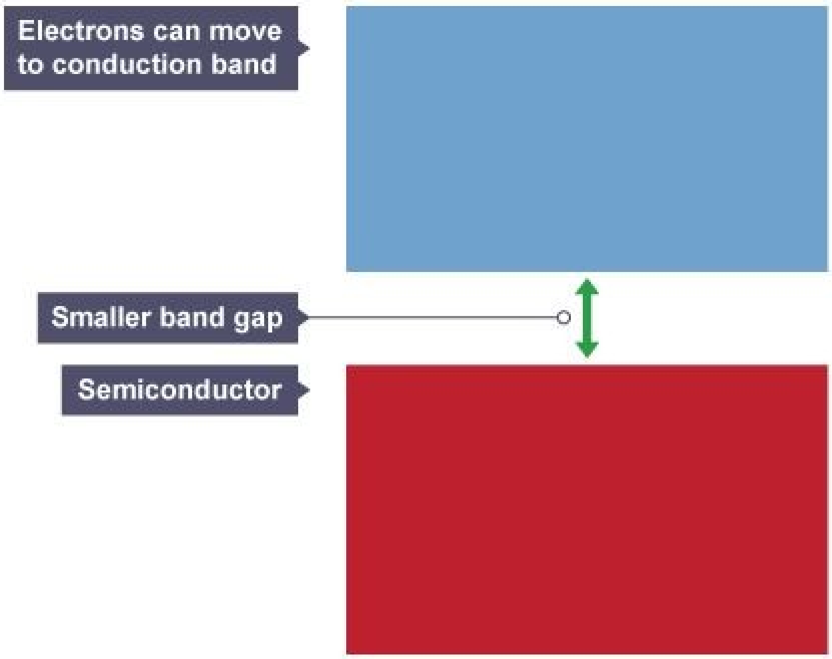
The valence band is full as no electrons can move up the conduction band which is empty as a result.

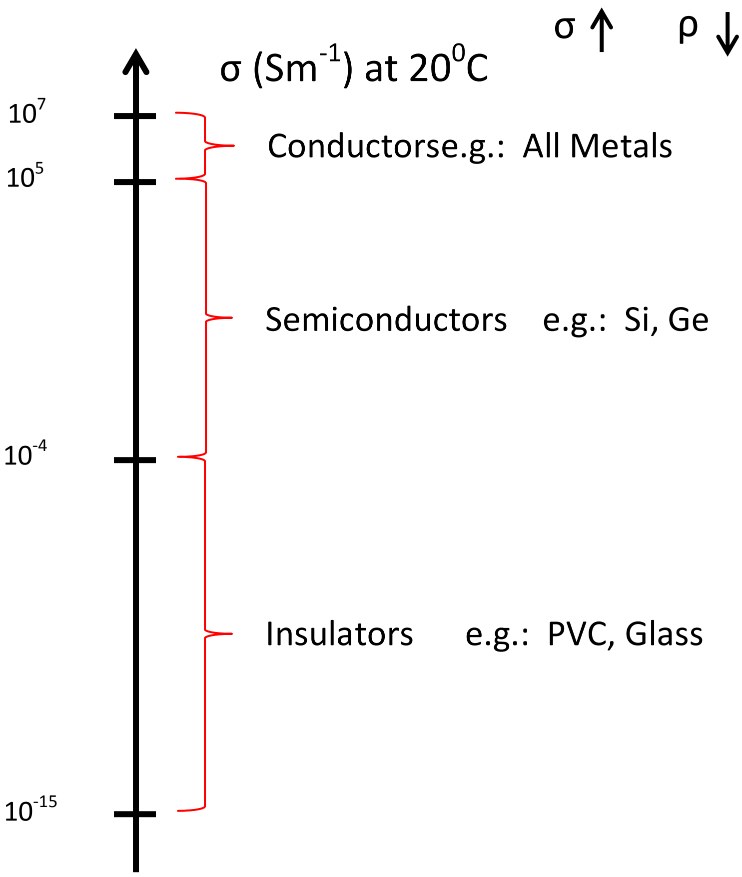
The material can't conduct as only the electrons in a conduction band can move easily.



Semiconductors

In a semiconductor, the gap between the valence band and conduction band is smaller and at room temperature there is sufficient energy available to move some electrons from the valence band into the conduction band allowing some conduction to take place.An increase in temperature increases the conductivity of a semiconductor.





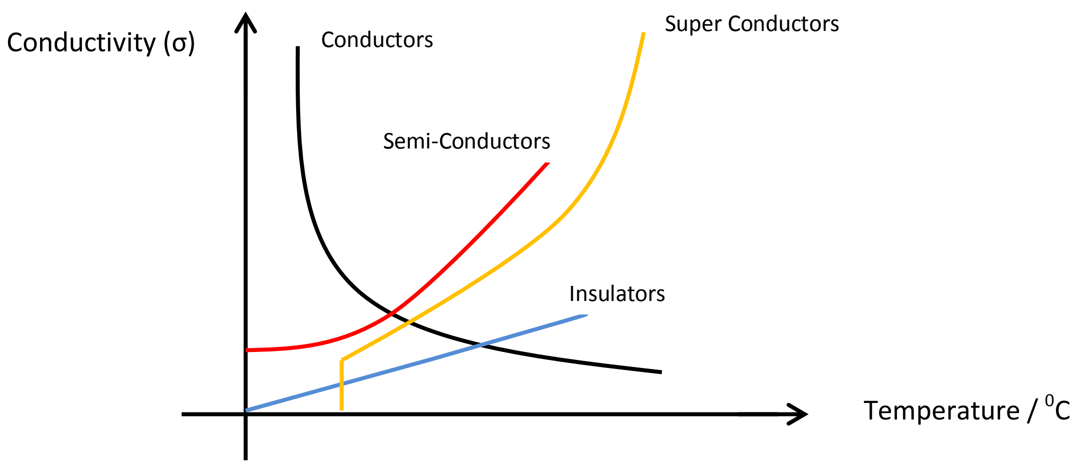
Factors Affecting Conductivity

1. Mobility of carriers

(e.g. – Mobility of free electrons are approximately two times of holes)

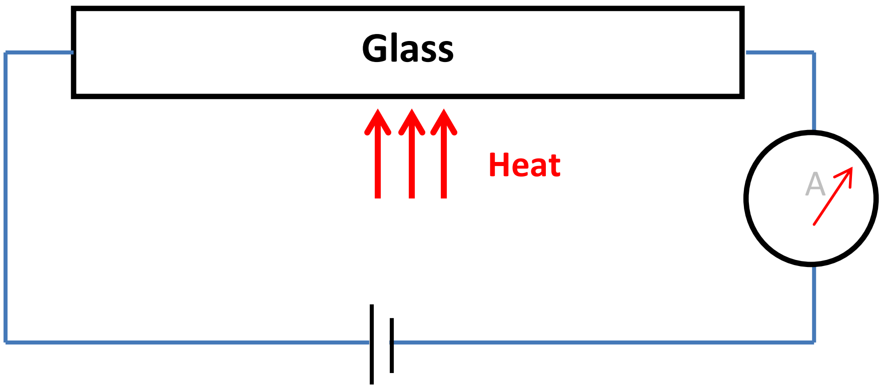
2. Concentration of carriers / Number Density
3. Charge of carriers
4. Temperature

What happens to the conductivity of the conductors, semiconductor and Insulators when temperature is increased?



1. For metals, the thermal conductivity is mainly a function of the motion of free electrons. As the temperature increases, the molecular vibrations increase (in turn decreasing the mean free path of molecules). So, they obstruct the flow of free electrons, thus reducing the conductivity.

2. In room Temperature there is no free electron in Insulators. But when temperature increases due to break down of bonds small amount of free elections can move up the conduction band from valence band.



If a glass is warmed, some of the weaker chemical bonds break. Thus, the glass begins to soften slightly. As the temperature is increased further, the next weakest bonds break, and the glass becomes softer still. At some point, the structure has collapsed to an extent that the positively charged cations can break free and become mobile. This means that they can move through the softened glass. The motion of the charged species constitutes electrical conduction and redox reactions can then occur at the electrodes that are imposing the electric field. As the glass becomes hotter, it becomes more fluid and the ions can move more readily. Thus, in contrast to metallic conductors, the conductivity of the softened glass increases with temperature, instead of decreasing.

3. Semi-conductors act as non-metals at low temperatures - the electrons are trapped within the atom. As the temperature of the semi-conductor is increased, the electrons in the valence band gain sufficient energy to escape from the confines of their atoms. A hole is the absence of an electron in a particular place in an atom. Although it is not a physical particle in the same sense as an electron, a hole can be passed from atom to atom in a semiconductor material. As a result, in higher temperatures, a semi-conductor's Conductivity increases, resistivity decreases.

   Remark:

   - In physics, a hole is an electric charge carrier with a positive charge (+e), equal in magnitude but opposite in polarity to the charge on the electron. Holes and electrons are the two types of charge carriers responsible for current in semiconductor materials.
   - So heat can increase conductivity by emitting electrons and make holes. Other than heat light can emit elections as well from some semi-conductor materials. This phenomena is called photoconductivity
   - Photoconductivity is an optical and electrical phenomenon in which a material becomes more electrically conductive due to the absorption of electromagnetic radiation such as visible light, ultraviolet light, infrared light, or gamma radiation.[1]

   - When light is absorbed by a material such as a semiconductor, the number of free electrons and electron holes increases and raises its electrical conductivity. To cause excitation, the light that strikes the semiconductor must have enough energy to raise electrons across the band gap, or to excite the impurities within the band gap. When a bias voltage and a load resistor are used in series with the semiconductor, a voltage drop across the load resistors can be measured when the change in electrical conductivity of the material varies the current through the circuit.

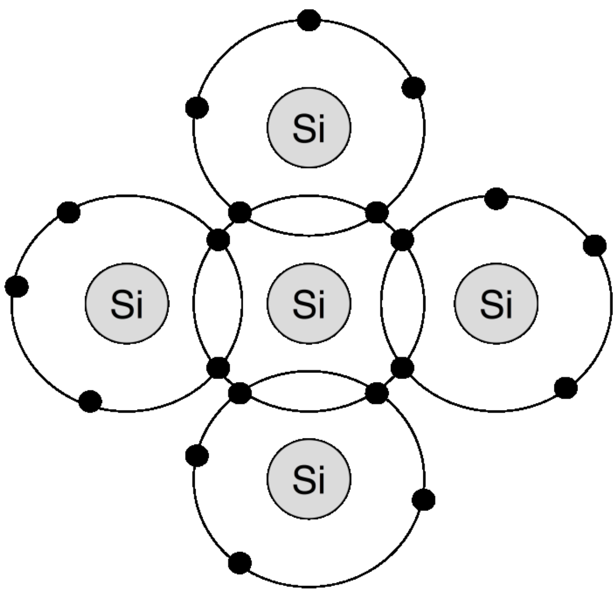
     e.g.: selenium(Se), employed in early television and photocopying (xerography)

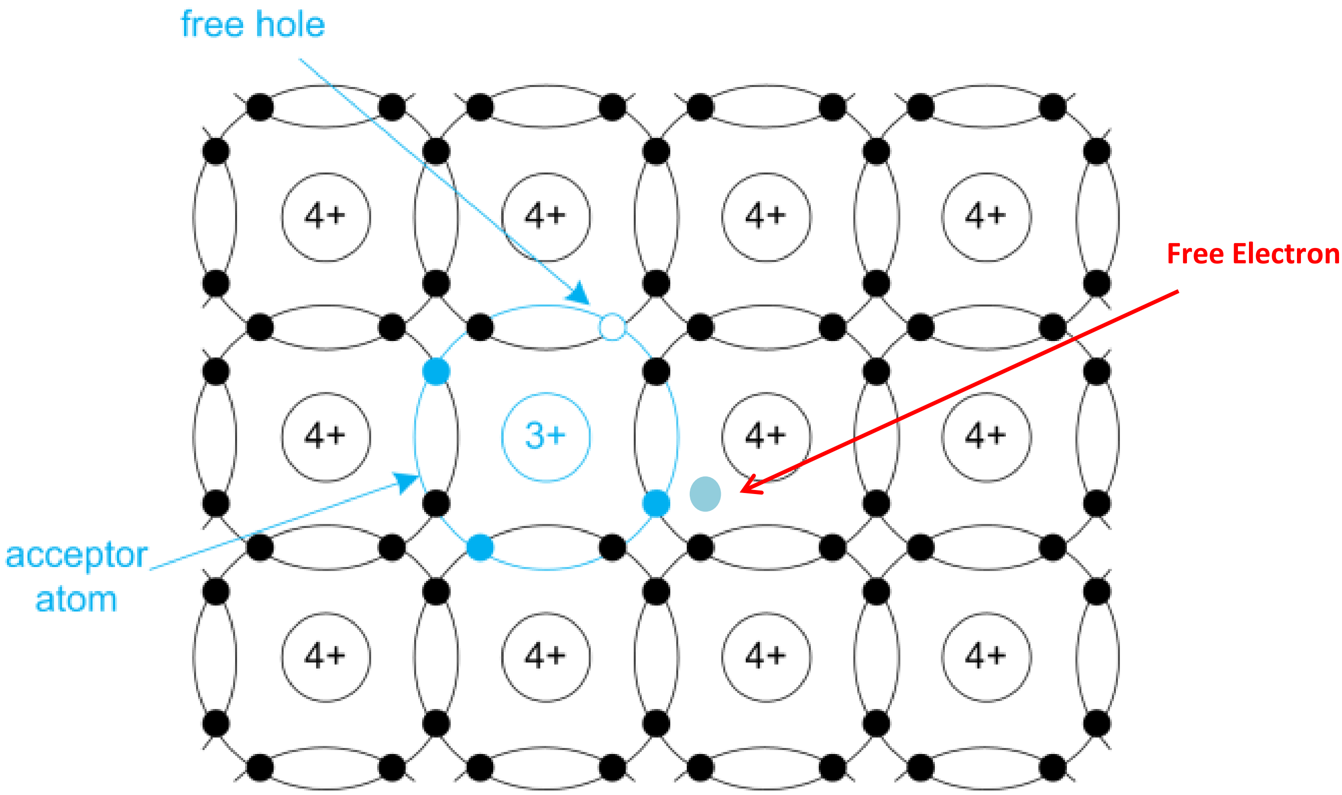
An intrinsic semiconductor, also called an undoped semiconductor or i-type semiconductor, is a pure semiconductor without any significant dopant species present. The number of charge carriers is therefore determined by the properties of the material itself instead of the amount of impurities. In intrinsic semiconductors the number of excited electrons and the number of holes are equal: n = p.

the key concept is "n = p". If the semiconductor is doped by both donor and acceptor equally, then "n = p "still holds, then it is still intrinsic. However, it is not "undoped semiconductor".

The electrical conductivity of intrinsic semiconductors can be due to crystallographic defects or electron excitation. In an intrinsic semiconductor the number of electrons in the conduction band is equal to the number of holes in the valence band.
Examples include silicon and germanium.
A silicon crystal is different from an insulator because at any temperature above absolute zero, there is a finite probability that an electron in the lattice will be knocked loose from its position, leaving behind an electron deficiency called a "hole". If a voltage is applied, then both the electron and the hole can contribute to a small current flow.

The conductivity of a semiconductor can be modeled in terms of the band theory of solids. The band model of a semiconductor suggests that at ordinary temperatures there is a finite possibility that electrons can reach the conduction band and contribute to electrical conduction.





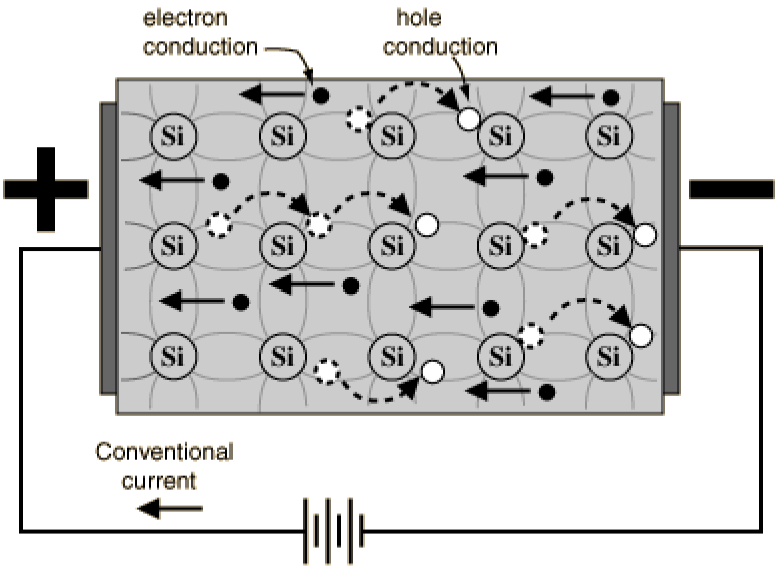
Recombinations

Because hole-electron pairs are continually created by thermal agitation of a semiconductor lattice,it might seem that the number of holes and free electrons would continually increase with time. Thisdoes not happen because free electrons are continually recombining with holes. At any temperature,a stable state is reached when the creation rate of hole-electron pairs is equal to the recombinationrate. The mean lifetime τn (s) of a free electron is the average time that the electron exists in thefree state before recombination. The mean lifetime τ p (s) for the hole is defined similarly. In theintrinsic semiconductor, τn is equal to τ p because the number of free electrons must be equal tothe number of holes. However, the addition of an impurity to the semiconductor lattice can causethe mean lifetimes to be unequal.

The mean life time of the free electron is approximately 1nS - 1μS.

Semiconductor Current

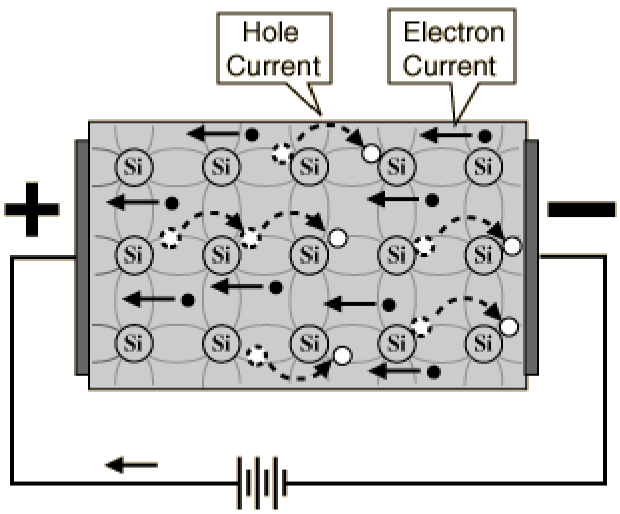
Both electrons and holes contribute to current flow in an intrinsic semiconductor.



Semiconductor Current

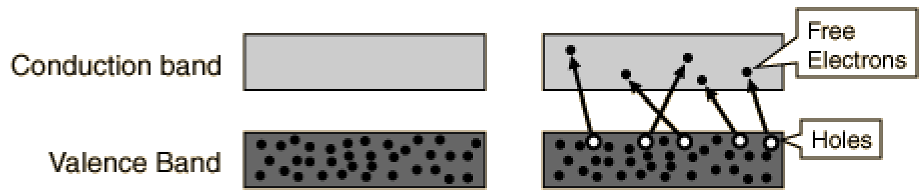
The current which will flow in an intrinsic semiconductor consists of both electron and hole current. That is, the electrons which have been freed from their lattice positions into the conduction band can move through the material.

In addition, other electrons can hop between lattice positions to fill the vacancies left by the freed electrons. This additional mechanism is called hole conduction because it is as if the holes are migrating across the material in the direction opposite to the free electron movement.

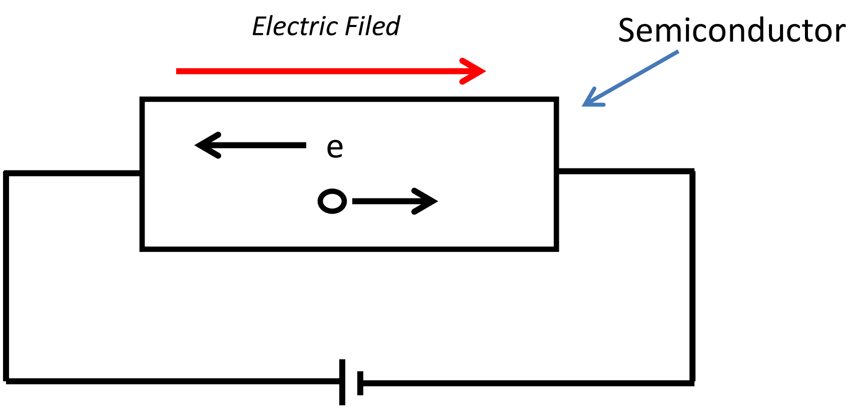


The current flow in an intrinsic semiconductor is influenced by the density of energy states which in turn influences the electron density in the conduction band. This current is highly temperature dependent.

Electrons and Holes



In an intrinsic semiconductor like silicon at temperatures above absolute zero, there will be some electrons which are excited across the band gap into the conduction band and which can produce current. When the electron in pure silicon crosses the gap, it leaves behind an electron vacancy or "hole" in the regular silicon lattice. Under the influence of an external voltage, both the electron and the hole can move across the material. In an n-type semiconductor, the dopant contributes extra electrons, dramatically increasing the conductivity. In a p-type semiconductor, the dopant produces extra vacancies or holes, which likewise increase the conductivity. It is however the behavior of the p-n junction which is the key to the enormous variety of solid-state electronic devices.



$$I = I_e + I_n$$

Where ;

I = Total Current

I_e= Electron Current

I_n = Hole Current

For an intrinsic semiconductor, the concentration of electrons in the conduction band is equal to the concentration of holes in the valence band.

We may denote,

N_e: intrinsic electron concentration

N_e : intrinsic hole concentration

N_i:Intrinsic Carrier Concentration

So,

$N_e = N_h = N_i$

The total current which will flow in an intrinsic semiconductor;

$I = I_e + I_n$

However;

$I = VANQ$

Where;

V-velocity of carrier particles; A- cross sectional area; N - Number density

Q-Charge of the carrier particles

$I_e = V_h A N_h e$

$I_n = V_e A N_e e$

$I = V_h A N_h e + V_e A N_e e$

$N_i = N_e = N_h$

$I = V_h A N_i e + V_e A N_i e$

$$\boxed{I = (V_h + V_e) A N_i e}$$

e.g.:

- Current flows through a copper wire. The cross sectional area of the copper wire is $3.0x10^{-10}m^2$. Calculate velocity and mobility of elections.

Molecular weight of Copper: 68.5 $gmol^{-1}$
Conductivity of Copper: 8950 Ωm
Density of Copper: 8950 kgm^{-3}
N_A= 6.022 x $10^{23}mol^{-1}$
Charge of the election: -1.6 x 10^{-19} C

Molecular Volume V;

$$V=\frac{m}{d}$$

$$V = \frac{63.5 \, X \, 10^{-3}}{8950} = 7.0X10^{-6}m^3$$

Assumption: Every Cu atom releases an election to valence band.

$$N = \frac{6.02 \, X \, 10^{23}}{7.0 \, X \, 10^{-6}} = 8.49X10^{23}m^{-3}$$

I =VANe

$10 = V \text{ x } 3 \text{ x } 10^{-10} \text{ x } 8.49 \text{ x } 10^{23} \text{ x } 1.6 \text{ x } 10^{-19}$
$10 = V \text{ x } 3 \text{ x } 8.49 \text{ x } 1.6 \text{ x } 10^{-6}$
$\underline{V = 0.25 \text{ mmS}^{-1}}$

$\sigma = \mu Ne$

$$\sigma = \frac{1}{\rho}$$

$$\mu = \frac{1}{\rho Ne}$$

$\mu = S^{-1}V^{-1}m^2$