Course: Basic Electronics (EC21101)

Course Instructor: Prof. Kapil Debnath

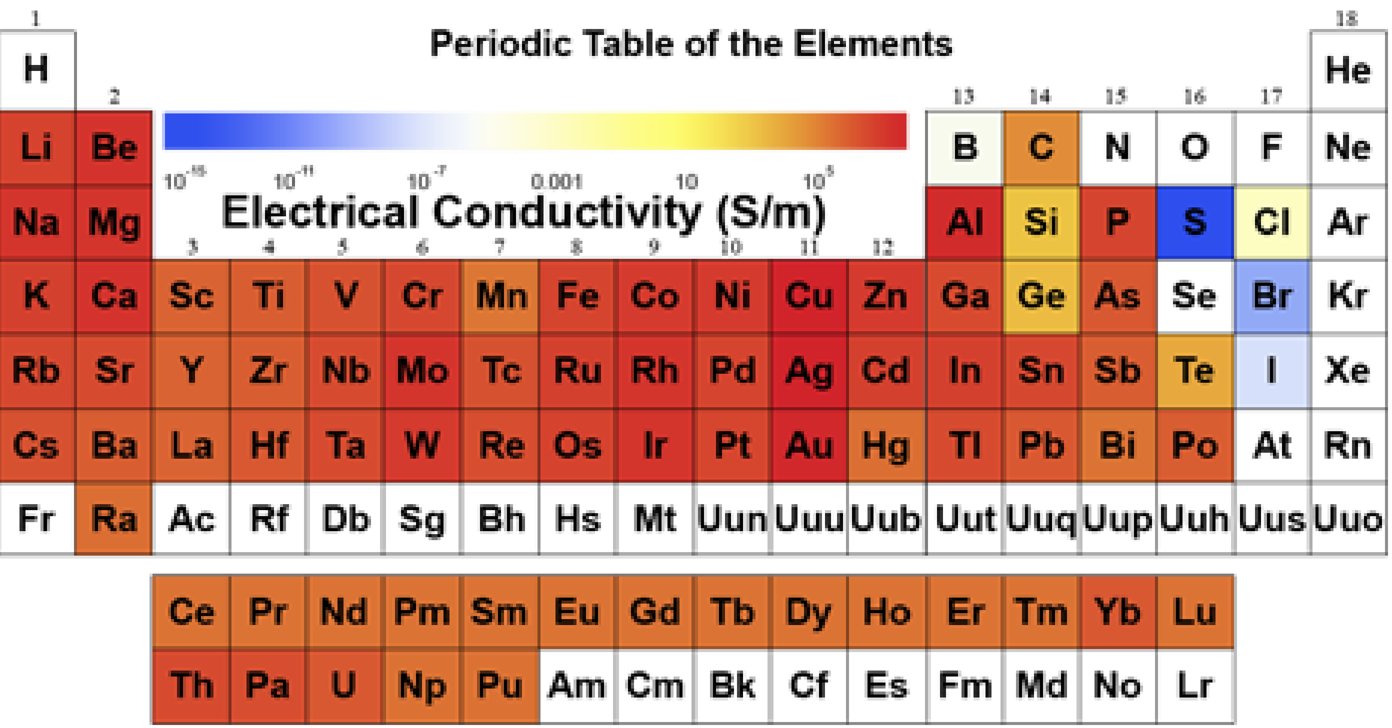
Lecture 2: Semiconductor

- **Contact Email:** k.debnath@ece.iitkgp.ac.in
- **website:** https://kdebnath8.wixsite.com/nanophotonics
- **Office: R314, ECE Dept, Discussion time: Friday 5pm**

Semiconductor materials

Today's electronic components are based on semiconductors. Hence a basic understanding is needed to fully appreciate the working of such devices.

Semiconductor*, any of a class of crystalline solids intermediate in electrical conductivity between a conductor and an insulator.*



Li 1.1×10^{7} S/m

Na 2.1×10^{7} S/m

Si 1000 S/m

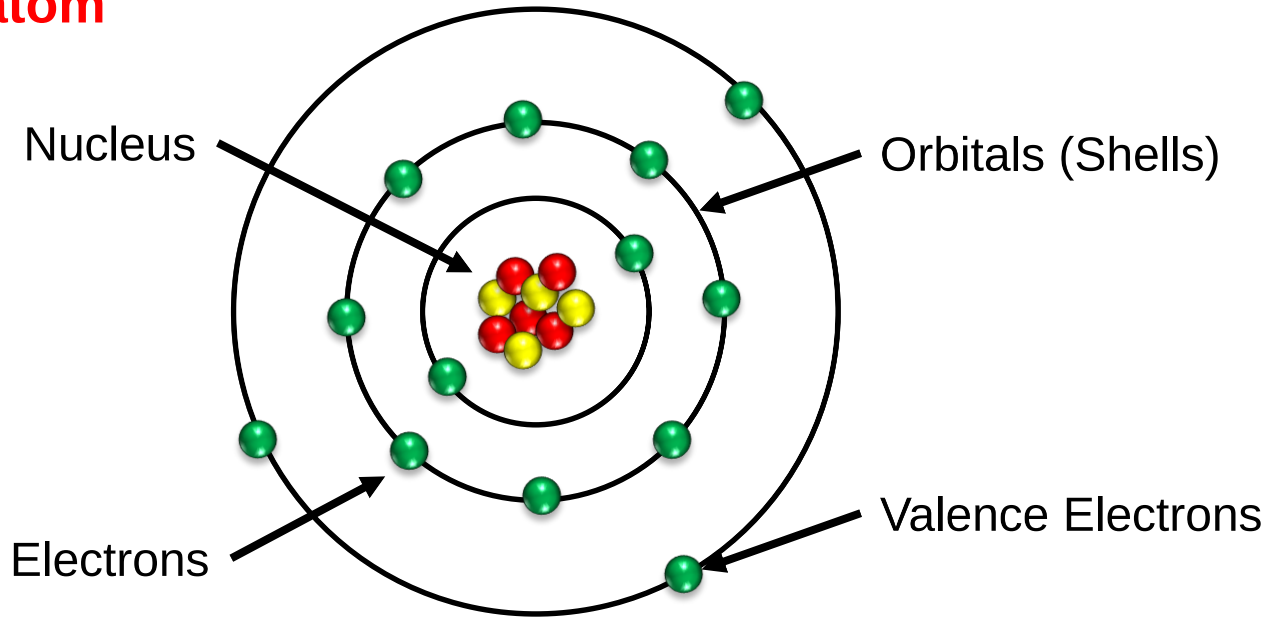
Ge 2000 S/m

Cl 0.01 S/m

S 2.1×10^{-15} S/m

Semiconductor materials

The conductivity of a material depends on the electron distribution in its atom



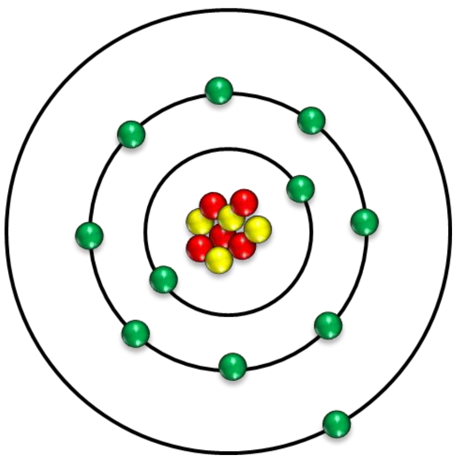
Simple (but not accurate) model of atoms (Rutherford model)

The number of valence electrons are primarily responsible for chemical activity or electric conductivity of a material. Lesser the number of valence electrons more reactive the material is.

Semiconductor materials

Sodium (11)

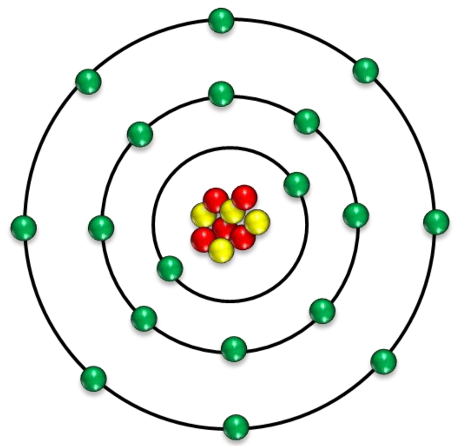
$1s^2 2s^2 2p^6 3s^1$



Only one electron in the valence shell. High tendency to interact

Argon (18)

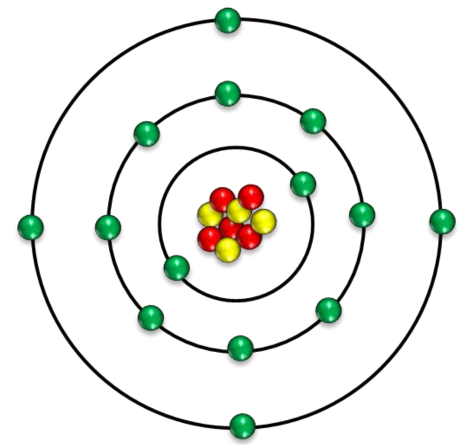
$1s^2 2s^2 2p^6 3s^2 3p^6$



8 electrons in the valence shell, i.e. the shell is complete and hence no tendency to interact.

Silicon (14)

$1s^2 2s^2 2p^6 3s^2 3p^2$



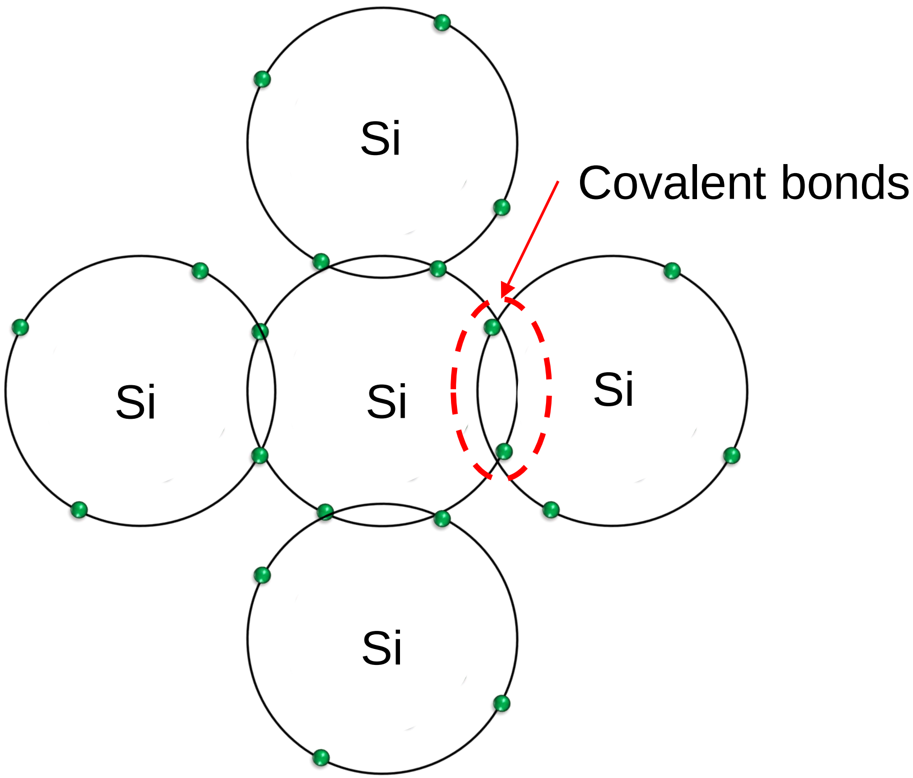
The valence shell is partially filled by 4 electrons. Not as reactive as Sodium also not as inert as Argon.

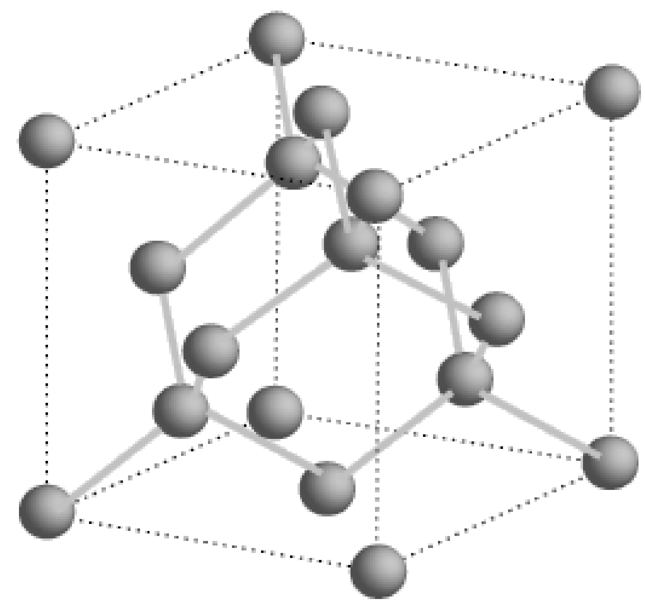
Semiconductor materials

Silicon crystal

When individual silicon atoms come close to each other the valence electrons interact with each other, thus forming covalence bonds between neighbouring atoms

Now all the silicon atoms have 8 electrons at their valence shells and becomes inert



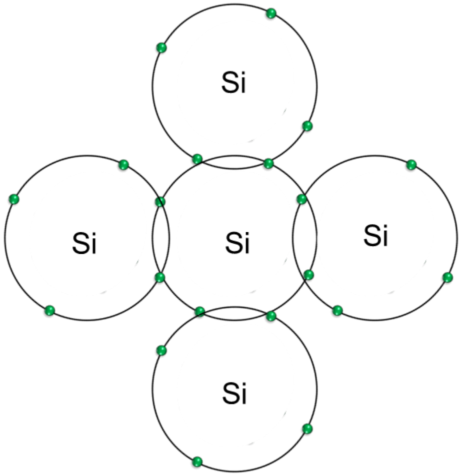


Arrangement of silicon atoms in a 3D crystal (tetrahedral)

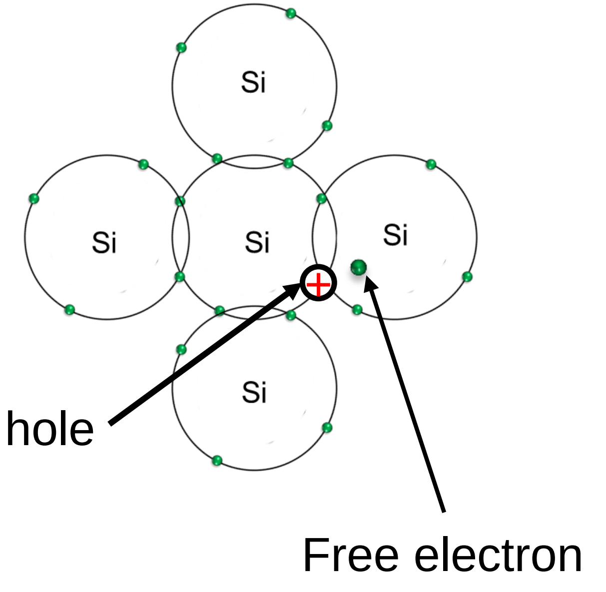
Semiconductor materials

Silicon crystal

At 0K silicon crystal acts as insulator, since there is no free electrons available for current flow.



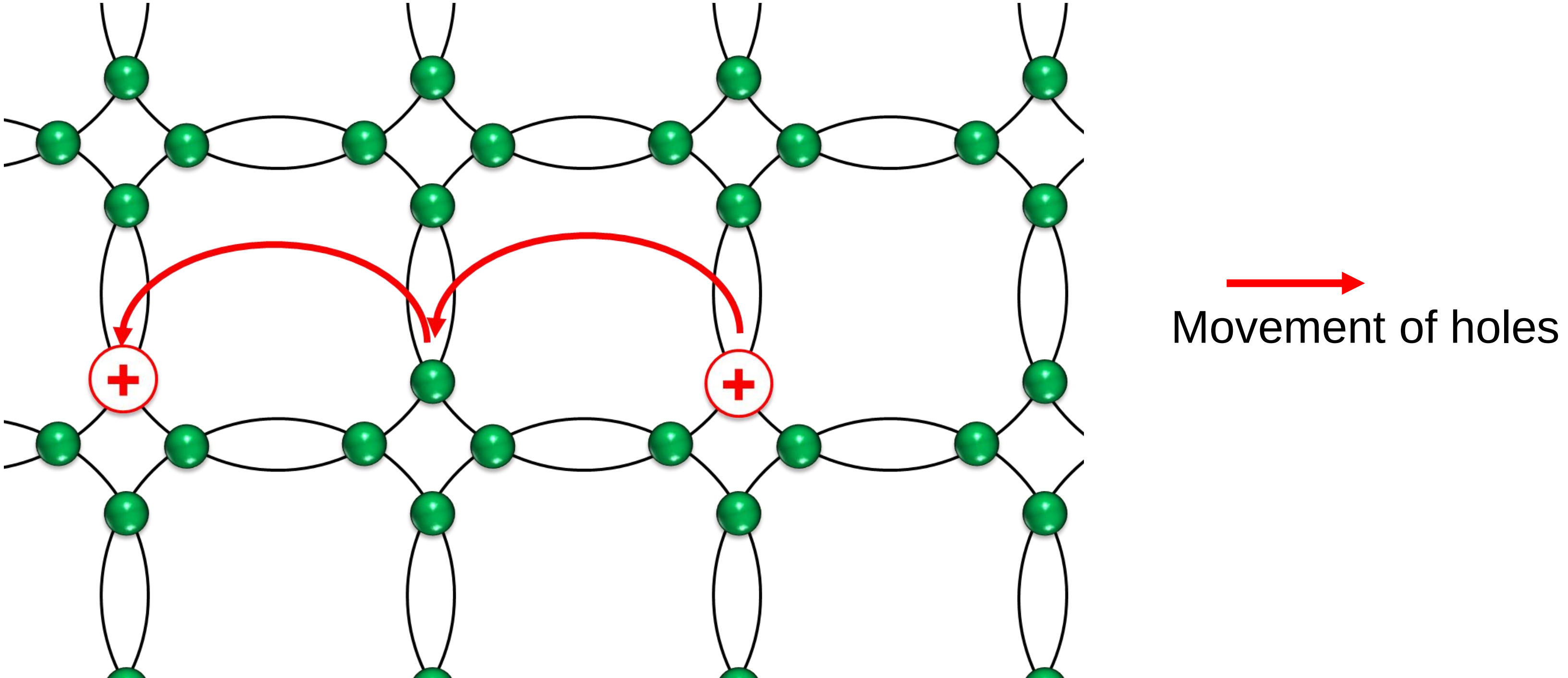
When the temperature rises above 0K, the valence electrons may gain thermal energy. Any such electron may gain enough thermal energy to break the covalent bond and move away from its original position. Thus these electrons become free electron and contribute to current flow. This process also leaves behind a positively charged empty state known as "hole", which also contributes to the flow of current. This is quite different from metals, where the only charge carriers are electrons.



Semiconductor materials

Holes

Concept of 'hole' very unique to semiconductors. Since, the net charge of the material remains neutral, if a negatively charged electron breaks the covalent bond and moves away from its original position, a positively charged empty state, i.e. 'hole' is created at that position. A valence band electron adjacent to that empty state may now move into that position, making it appear as if a positive charge is moving through the semiconductor. Therefore, in semiconductors, two types of charged particles contribute to the current: negatively charged free electrons and positively charged holes. Movement of holes is relatively a slower process as it requires two processes : release of an electron and subsequent trapping of the same electron.

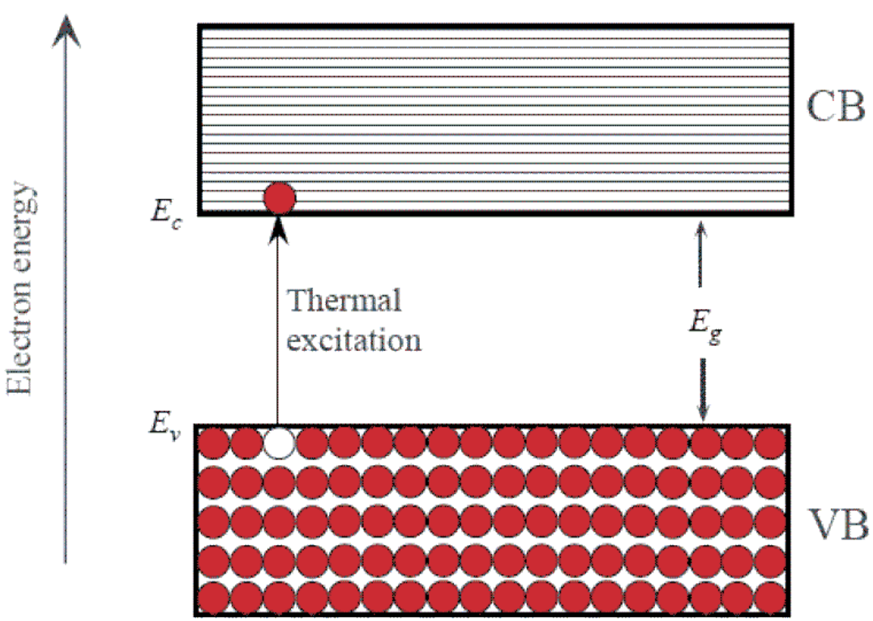


Semiconductor materials

Energy Bands

In an isolated atom, the electrons occupy discrete energy states. In other words, the electrons can have only discrete energy values. However, in a crystal, due to interactions between the atoms, electron starts to have a range of energy values, known as energy bands. At 0K, all the valence electrons occupy the valence energy band. at T>0K, in order to break the covalent bond, the valence electrons must gain a minimum energy, E_g, called ***bandgap energy****. The electrons which gain this minimum energy now exists in another energy band called conduction band and considered as free electrons.*

SILICON ENERGY BAND

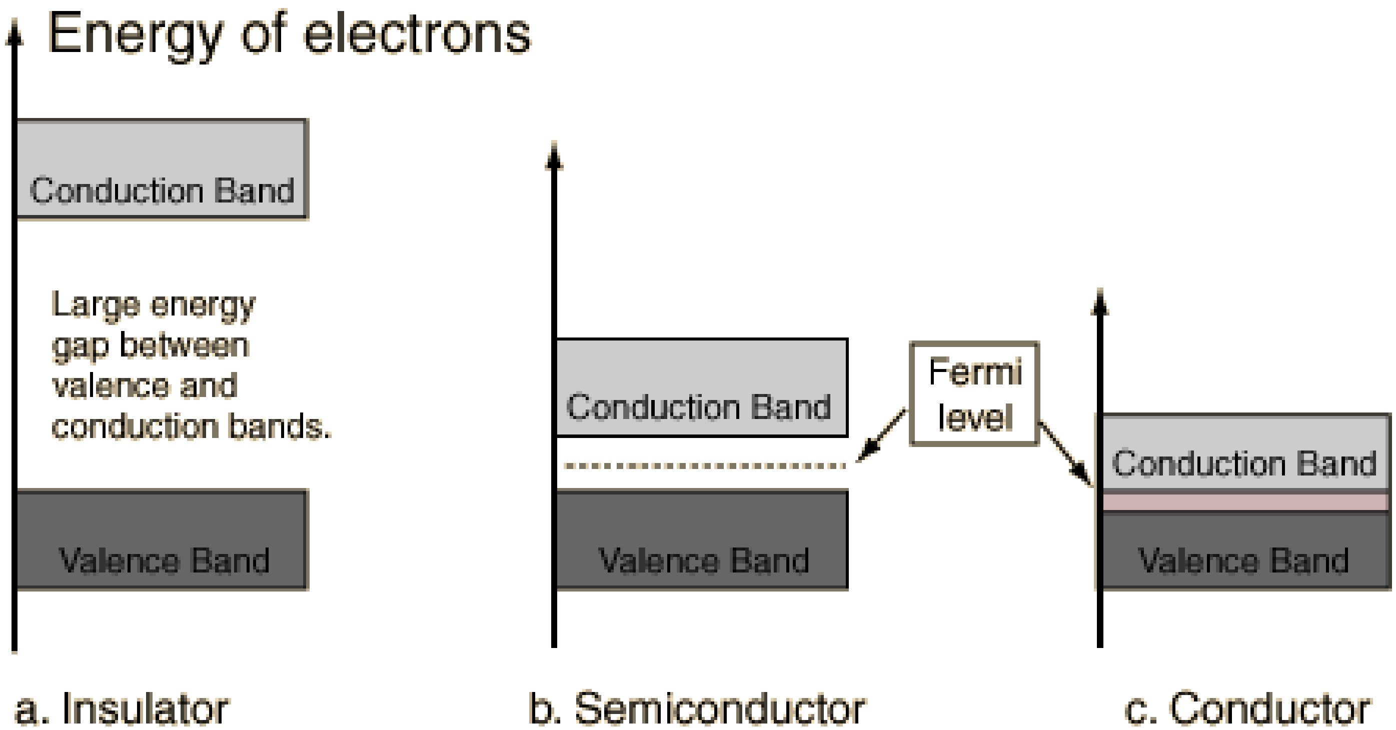


E_v is the maximum energy of the valence energy band

E_c is the minimum energy of the conduction energy band

The region between E_c and E_c is called forbidden energy band, where no charge carrier is allowed.

Semiconductor materials



Insulators have very large energy band gap, hence even at room temperature hardly any electron occupy conduction band

Semiconductors have non-zero energy band gap. At room temperature, some valence electrons can move to conduction band.

In metals or conductors, because of the abundance of free electrons the valence band and conduction band overlap with each other.

Diamond 5.5eV

Aluminium nitride 6eV

Silicon 1.14eV

Germanium 0.66eV

$$\boxed{1\text{eV} = 1.60 \times 10^{-19}\text{J}}$$

Semiconductor materials

Carrier density in pure semiconductor:

The concentration of free electrons (also holes) is given by $\boxed{n_i = BT^{3/2} e^{\left(-E_g/_{2kT}\right)}}$

Where, E_g is the bandgap energy in eV, T is the temperature, k is the Boltzmann's constant (86×10^{-6}*eV/K), B is a proportionality constant which depends on the semiconductor material. For Silicon, Eg is 1.14eV and B is* 5.23×10^{15}*cm^{-3}K$^{-3/2}$.*

At room temperature (T=300K), concentration of free electrons in silicon is approximately $n_i = 1.5 \times 10^{10}$cm^{-3}

Whereas, the concentration of silicon atoms is approximately 5×10^{22}*cm^{-3}*
We will here denote electron density as n and density of holes as p, so we have

$$np = n_i^2$$

We will discuss the significance of this equation later.

For a good conductor, the electron concentration is much higher, for example, in aluminium the free electron concentration is about 6.0×10^{22}*cm^{-3}.*

Comparison of conductivity

Si 1000 S/m

Al 10^6 S/m

Unlike metal, for semiconductors, the resistivity decreases with temperature

Semiconductor materials

Classification of semiconductor materials:

An ***intrinsic semiconductor*** *is a single-crystal semiconductor material with no other types of atoms within the crystal. In an intrinsic semiconductor, the densities of electrons and holes are equal, since each thermally generated electron in conduction band leaves behind a hole in the valence band.*

An ***elemental semiconductor*** *is composed of a single element, such as Si, Ge.*

A ***compound semiconductor*** *is composed of two or more elements, such as gallium arsenide (GaAs), Gallium nitride (GaAs), Indium Phosphide (InP) etc.*

An ***extrinsic semiconductor*** *is realized by doping an intrinsic semiconductor by a specific impurity which is able to deeply modify its electrical properties.*

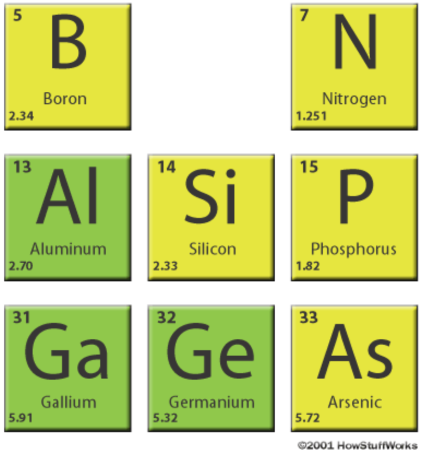
Semiconductor materials

Doping

As we have seen in the previous slide that the conductivity of intrinsic semiconductors are much lower than metals. Hence, from an application point of view, intrinsic semiconductors are of less use to us. But the beauty of semiconductor technology is that by introducing impurities in an otherwise perfect crystal of a semiconductor material, we can tune the conductivity of the same semiconductor material. i.e. we can significantly modify the charge carrier concentration (i.e. electrons and holes) within the material. The process of introducing defects in semiconductor material is known as doping.
To understand the process of doping and which impurities we should use, we will pay a close look at a small section of the periodic table.

What if we introduce group III or group IV atoms as impurities in an otherwise perfect semiconductor crystal, say within a silicon crystal?

III IV V



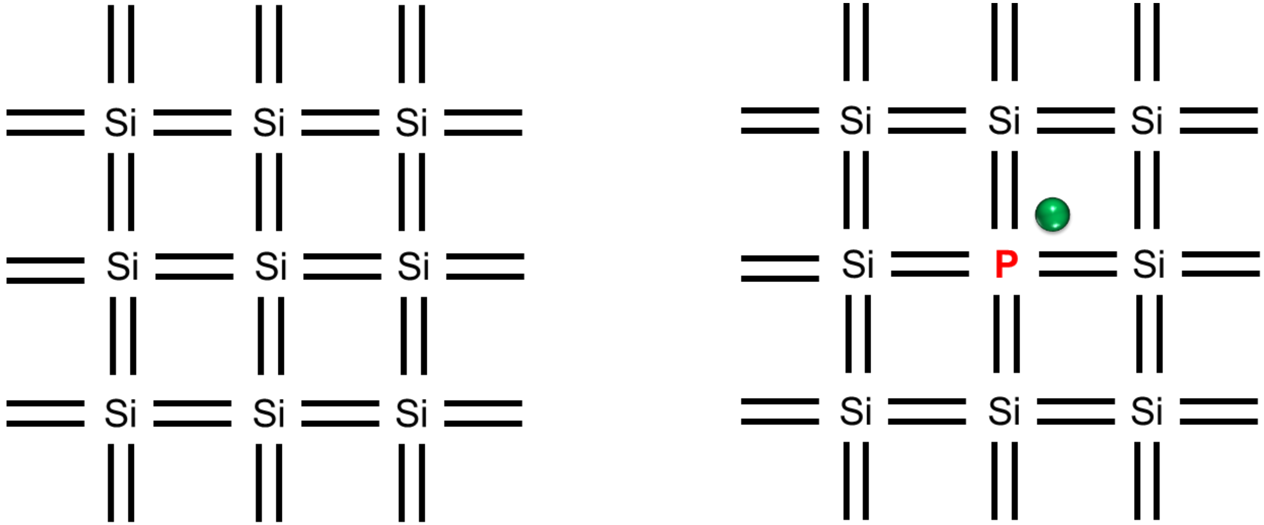
Number of electrons in the outer shell 3 4 5

Semiconductor materials

Doping

Lets assume, we replace one silicon atom with a phosphorous atom. Now we have a phosphorous atom within the crystal which has 5 electrons in its outer shell instead of 4, so when the covalent bonds are getting formed between the silicon atoms and the phosphorous atom, we have an extra electron in the outer shell of the phosphorous atom which can not be shared with the silicon atoms. This extra electron is now loosely bound to the phosphorous atom and can easily participate in current conduction. Depending on how many phosphorous atom we introduce to the silicon crystal, we can increase the number of these loosely bound electrons. Thereby, we can increase the conductivity of the overall device.

There are mainly two ways we can dope a intrinsic semiconductor, such as spin-on-doping, ion-implantation. Doped semiconductors are known as extrinsic semiconductor.



Pure silicon crystal **Silicon crystal with donor impurity**

Semiconductor materials

Extrinsic semiconductor

As we have seen, doping a pure silicon with phosphorous atom introduces an extra electron to the crystal, thus this type of impurity is known as donor atoms, as it donates an electron which is free to move.

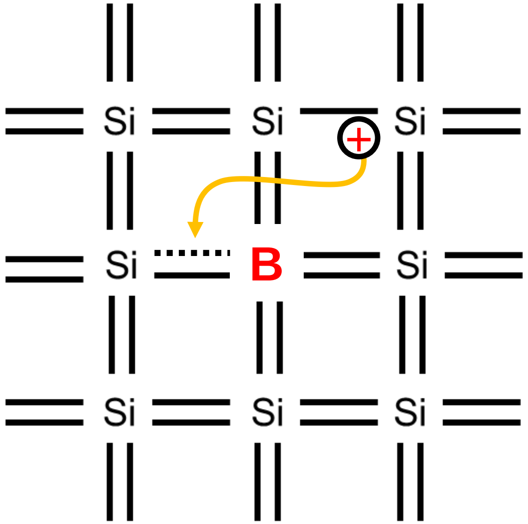
This type of extrinsic semiconductor is known as n-type semiconductor. Because this material has now more "free" electrons than a pure semiconductor.

Commonly used donor atoms are phosphorous (P), arsenic (As), antimony (Sb), bismuth (Bi).

Instead of a group V impurity, if we introduce a group III impurity into the silicon crystal, say boron (B), the three valence electrons of boron will be used to satisfy the covalent bond requirements for three out of four silicon atoms. This leaves one bond position open for the fourth silicon atom. And at room temperature, adjacent silicon electrons have sufficient thermal energy to move into this position, thereby creating a hole. In this process, since the boron atom has accepted a valence electron, this type of impurity is known as acceptor atoms.

This type of extrinsic semiconductor is known as p-type semiconductor. Because this material has now more holes than a pure semiconductor.

Commonly used Acceptor atoms are boron (B), aluminium (Al).



Silicon crystal with acceptor impurity

Semiconductor materials

Extrinsic semiconductor

Typical doping concentration is in the range of 10^{15}-10^{17} atoms/cm^3. i.e. 1 impurity atom per 10^5-10^7 silicon atoms. So, due to doping we are now getting 10^{15}-10^{17} free electrons/cm^3 in comparison to 10^{10} free electrons/cm^3 in a pure silicon.

So we can say that

the density of free electrons (holes) = the density of donor atoms (acceptor atoms)

We represent donor impurity as N_d and acceptor impurity as N_a.

$$n \approx N_d$$
$$p \approx N_a$$

Previously we have seen for a pure semiconductor, $n = p = n_i$, i.e. $np = n_i^2$. This was obvious, given the fact that in a pure semiconductor, a free electron can only be generated by leaving behind a hole in the valence band.

However, it is interesting to note that even for extrinsic semiconductor, under thermal equilibrium,

$$n_o p_o = n_i^2$$

Where n_o (p_o) is the thermal equilibrium concentration of free electrons (holes).

i.e. under thermal equilibrium, the product of two charge carrier concentrations is always equal to the square of the intrinsic carrier concentration.

Semiconductor materials

Extrinsic semiconductor

In a n-type semiconductor,

$$p_o = \frac{{n_i}^2}{N_d}$$

In a p-type semiconductor,

$$n_o = \frac{{n_i}^2}{N_a}$$

Example: If a pure silicon substrate is doped with phosphorous with impurity concentration of $10^{15}/cm^3$, then at room temperature (300K)

$$n_o \approx N_d \approx 10^{15} cm^{-3}$$
$$p_o = \frac{{n_i}^2}{N_d} \approx \frac{10^{20}}{10^{15}} = 10^5 cm^{-3}$$

In this n-type semiconductor, electron concentration is $10^{15} cm^{-3}$, whereas hole concentration is only $10^5 cm^{-3}$. Hence the majority of charge carriers are electrons. Hence, in this case electrons are called majority carrier and holes are called minority carriers.

For a p-type semiconductor, holes are majority carriers and electrons are minority carriers.

Semiconductor materials

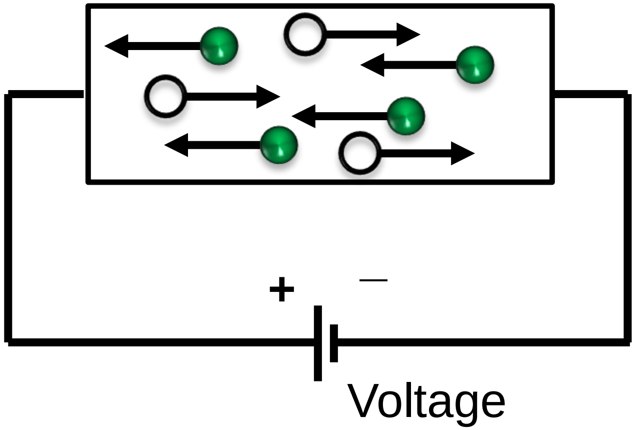
Charge transport in semiconductors

As we discussed there are two types of charge carriers present in semiconductors: electrons and holes. If these charges move in a certain direction, a current is generated. There are two basic mechanisms which cause electrons and holes to move in a semiconductor:

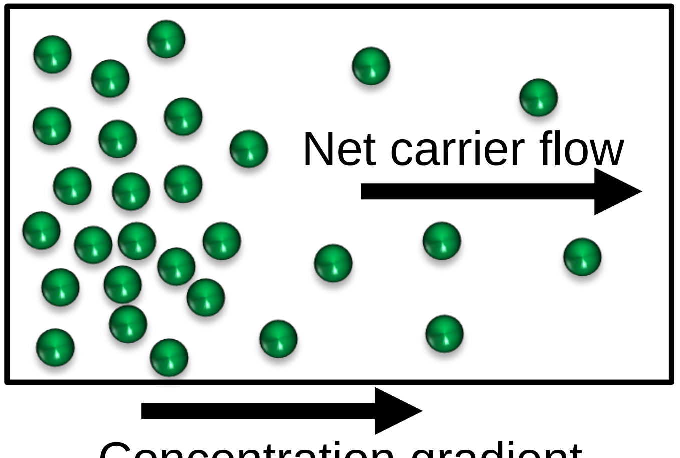
a) *Drift: movement of charge carriers caused by an electric field (applied voltage). This is similar to charge carrier movement in metals.*

b) *Diffusion: movement of charge carriers caused by the variation in charge carrier concentration, i.e. concentration gradient. Such concentration gradient can be caused by nonhomogeneous doping distribution or by injection of electrons or holes into a region of the semiconductor. This process of charge movement is unique to semiconductors.*

Drift process



Diffusion process



Semiconductor materials

Drift velocity and mobility

When an electric field is applied to a semiconductor, this field produces a force that acts upon electrons and holes. As a result these charge carriers experiences a net acceleration (according to Newton’s second law of motion), hence their velocity increases. However, as the charge carriers move through the material, they often collide with the ions of the crystal. Due to these inelastic collision with ions, charge carriers losses their energy. Eventually a steady state condition is reached when the charge carriers moves at a net velocity, known as drift velocity, v_d. For electrons the drift velocity is opposite to the direction of applied electric field and for holes its in the same direction. (Same discussion is true for electrons in metals).

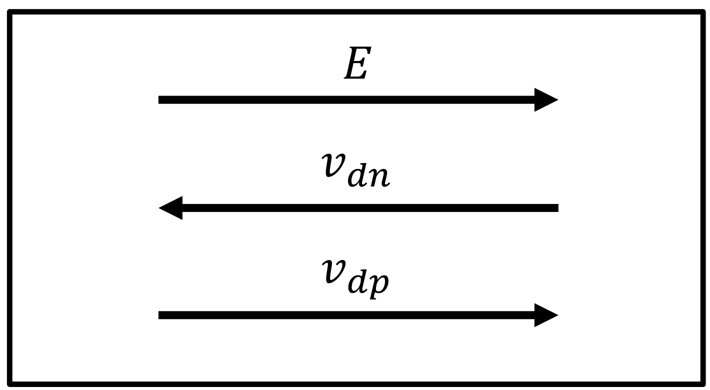
The drift velocity is proportional to the applied electric field and the proportionality constant is known as mobility.

For electrons:

$$v_{dn} = -\mu_n E$$

For holes:

$$v_{dp} = \mu_p E$$



Units

E: V/cm

v_d: cm/s

μ: $cm^2/V.s$

Mobility can be thought as a parameter indicating how well an electron or hole can move in a semiconductor.

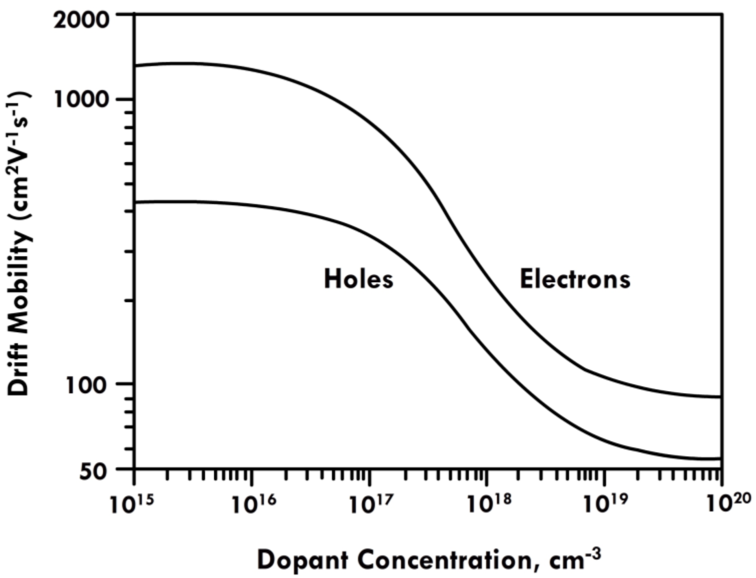
Semiconductor materials

Drift velocity and mobility

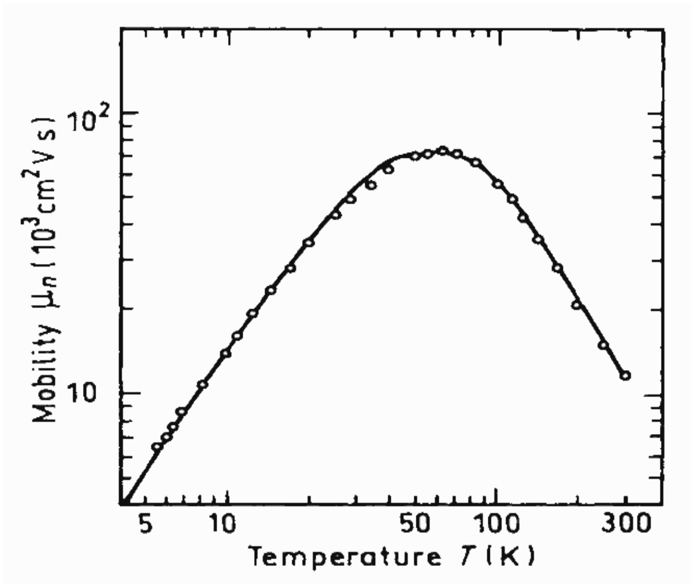
Electron and hole mobilities for intrinsic semiconductors @ 300K

	Si	Ge	GaAs
$\mu_n(cm^2/V.s)$	1400	3900	8500
$\mu_p(cm^2/V.s)$	470	1900	400

As you can see the electron mobility is always higher than hole mobility. Also carrier mobility strongly depends on the temperature and doping concentration.



Mobility as a function of doping



Mobility as a function of temperature

Semiconductor materials

Drift current density

Consider a voltage V is applied to a n-type semiconductor of length L and cross section of A.
Then the electric filed is given by $E = V/L$

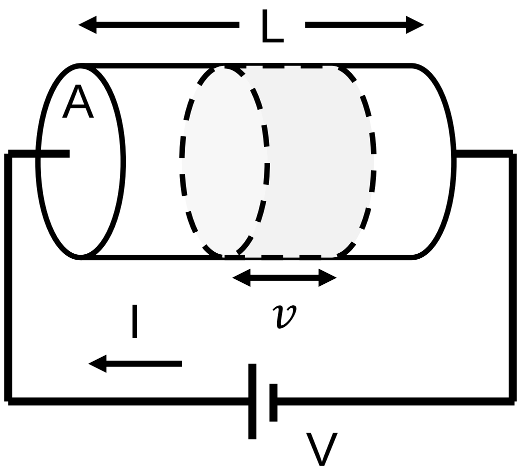
The total amount of charge crossing through a cross-section per unit time is $vAne$*. Where e is the magnitude of electronic charge. This is nothing but the current flowing through the system.*
i.e. $I = vAne$
For electrons v *and I has different signs and for holes* v *and I has the same sign.*

$$I = \mu_n \frac{V}{L} Ane$$

By rearranging this equation we get

$$R = \frac{V}{I} = \frac{L}{\mu_n Ane} = \frac{1}{\mu_n ne}\frac{L}{A}$$

$\frac{1}{\mu_n ne}$ *is nothing but the resistivity of the material*



Here we are ignoring the signs of different quantities and mainly focusing on the magnitudes

Semiconductor materials

Drift current density

Current density is defined as the number of charge carriers passing through a unit cross section per unit time and has unit of A/m².

The drift current density for electrons, $J_n = \mu_n E n e$

The drift current density for electrons, $J_p = \mu_p E p e$

Total drift current density, $J = \left(\mu_n n e + \mu_p p e\right) E$

This equation can help us to calculate current through a semiconductor when an electric field is applied

$$J = \left(\mu_n n e + \mu_p p e\right) E$$
$$\Rightarrow J = \sigma E = \frac{1}{\rho} E$$

σ *is the conductivity of the semiconductor (unit* $(\Omega . cm)^{-1}$*) and* ρ *is the resistivity of the semiconductor in* $\Omega . cm$.

Observe the similarity of this equation with well known "Ohm's Law" $I = \frac{1}{R} V$

Semiconductor materials

Diffusion current

Diffusion is defined as the movement of charge carriers from a region of high concentration to a region of low concentration.

If charge carriers (say electrons) are injected to one side of a silicon slab, which otherwise have constant electron concentration, a concentration gradient is developed. Now electrons will move from high concentration region to low concentration region, giving rise to electric current. This is called diffusion current.

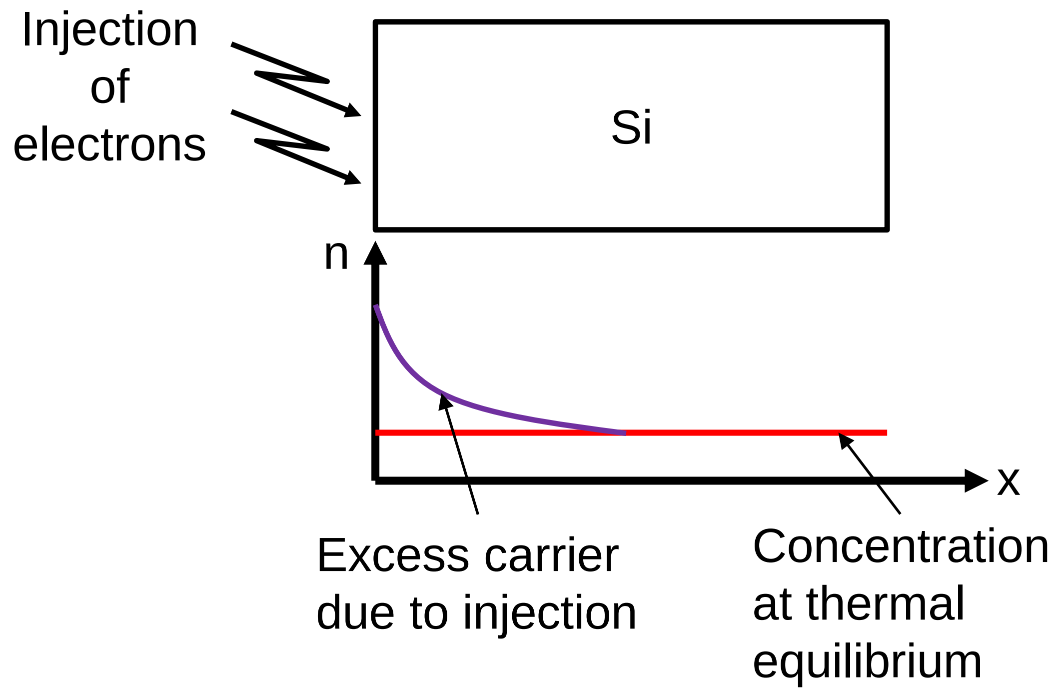
Diffusion current is quite different from drift current, because for diffusion to happen no external electric field is required.

Diffusion current density is proportional to the concentration gradient. If the concentration is uniform no diffusion takes place. So we can write:

$$J \propto \frac{dn}{dx}$$

$$\Rightarrow J = D_n \frac{dn}{dx} e$$

Where D_n is known as electron diffusion coefficient. This parameter depends on the material property.



Semiconductor materials

Example of diffusion

Process of diffusion when a drop of ink is dropped into a glass of water

Semiconductor materials

Diffusion current

For holes,

$$J = -D_p \frac{dp}{dx} e$$

Where D_p is the hole diffusion coefficient.

Unit for D is cm^2/s.

Total diffusion current density can be expressed by:

$$J = \left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx} \right) e$$

For silicon, $D_n = 34\ cm^2/s$ and $D_p = 12\ cm^2/s$

Einstein Relationship

The mobility and diffusion coefficients of charge carriers are not independent and related by the following equations.

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$

V_T is known as “volt-equivalent of temperature” and expressed as:

$$V_T = \frac{kT}{e}$$

Which has unit of V and at room temperature, V_T=0.026V

Semiconductor materials

Generation and recombination of charge carriers

Under thermal equilibrium, as we know, the number of charge carriers will remain constant in a semiconductor. However, when we increase the temperature of the material, electron-hole pairs are generated. i.e. more and more electrons are now found in the conduction band leaving behind more and more holes in the valence band. This process of creating electron-hole pairs is called generation. At the same time, free electrons also fall into empty covalent bonds (i.e.), resulting in the loss of electron-hole pairs. This process is know as recombination. The time between generation and recombination of an electron-hole pair is called mean lifetime.

The carriers that are generated due to increase in temperature are called excess carriers. Excess carriers can also be injected through external current or shining light onto the material.

Under non thermal equilibrium condition, the charge carrier densities are expressed as

$$n = n_o + \delta n$$

$$p = p_o + \delta p$$

Where n_o and p_o are the thermal equilibrium concentrations of electrons and holes and δn and δp are the excess electron and hole concentrations.