Lecture (7)

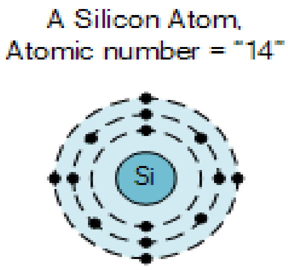
Semiconductors

A **semiconductor** is a material which has electrical conductivity between that of a conductor such as copper and that of an insulator such as glass. Semiconductors are the foundation of modern electronics, including transistors, solar cells, light-emitting diodes (LEDs), quantum dots and digital and analog integrated circuits.
In terms of energy bands, semiconductors can be defined as those materials which have almost an empty conduction band and almost filled valence band with a very narrow energy gap (of the order of 1 eV) separating the two.
Semiconductors **materials such as silicon (Si), germanium (Ge) and gallium arsenide (GaAs), have electrical properties somewhere in the middle, between those of a "conductor" and an "insulator". They are not good conductors nor good insulators (hence their name "semi"-conductors). They have very few "fee electrons" because their atoms are closely grouped together in a crystalline pattern called a "crystal lattice".**

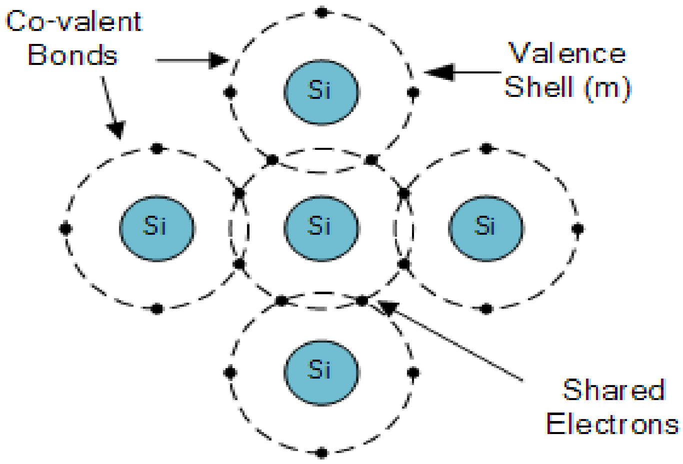
The properties of Semiconductors:

1- Resistivity range approximately ($10^{4}\,\Omega$,m to $10^{-5}\,\Omega$,m)
For Conductor ($10^{-4}\,\Omega$,m >conductor < $10^{-10}\,\Omega$,m)
For Insulator ($10^{20}\,\Omega$,m >insulator < $10^{-4}\,\Omega$,m)
2- Conductivity increase with temperature
3- Sensitive to the light .
4- The electric condition allows in a certain direction only .this property called Rectification .
5- Charge carries are pairs of (electron-hole).

The most commonly used semiconductor basics material by far is silicon. Silicon has four valence electrons in its outermost shell which it shares with its neighboring silicon atoms to form full orbital's of eight electrons. The structure of the bond between the two silicon atoms is such that each atom shares one electron with its neighbor making the bond very stable. Silicon atoms are arranged in a definite symmetrical pattern making them a crystalline solid structure. A crystal of pure silica (silicon dioxide or glass) is generally said to be an intrinsic crystal (it has no impurities) and therefore has no free electrons.



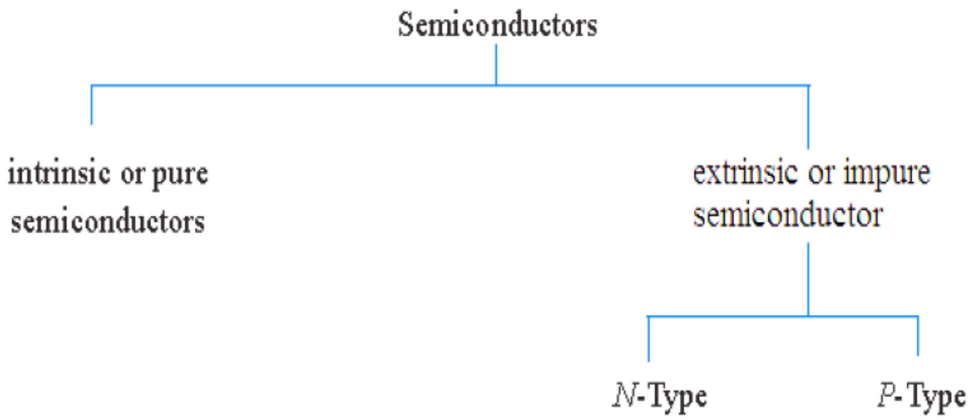
Silicon atom showing 4 electrons in its outer valence shell (m)



Silicon Crystal Lattice

Types of Semiconductors:

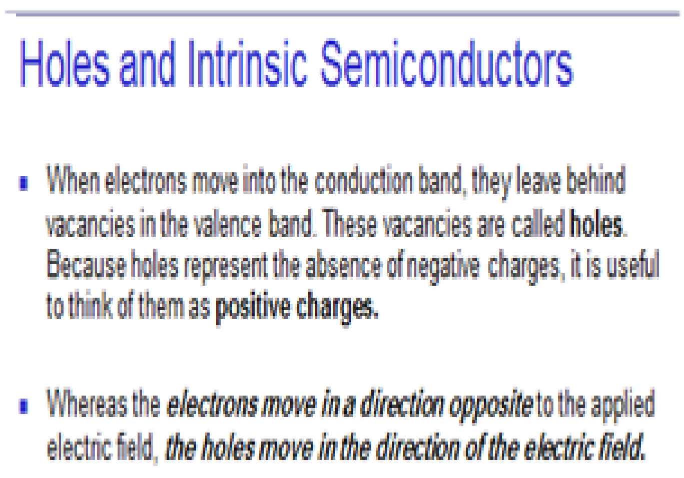
Semiconductor may be classified as under:



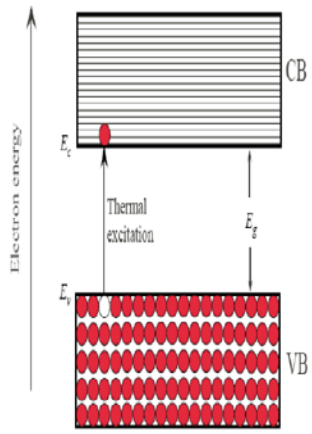
a. Intrinsic Semiconductors

An intrinsic semiconductor is one which is made of the semiconductor material in its extremely pure form. Examples of such semiconductors are: pure germanium and silicon which have forbidden energy gaps of 0.72 eV and 1.1 eV respectively. The energy gap is so small that even at ordinary room temperature; there are many electrons which possess sufficient energy to jump across the small energy gap between the valence and the conduction bands. Alternatively, an intrinsic semiconductor may be defined as one in which the number of conduction electrons is equal to the number of holes.

- When an electron jumps from the valence band to the conduction band, an empty state, or hole, is created in the valence band.
- In an intrinsic semiconductor electrons and holes are created in pairs by the thermal energy. The number of electrons in the conduction band is equal to the number of holes in the valence band.



Silicon Energy Band



Energy band diagram of a semiconductor. CB is the conduction band and VB is the valence band. AT 0 K, the VB is full with all the valence electrons.

Carrier concentration in intrinsic semiconductors

Intrinsic electron and hole concentration

- For an intrinsic semiconductor, the concentration of electrons in the conduction band is equal to the concentration of holes in the valence band
- at a constant temperature, the value of the intrinsic electron and hole concentration n_i is a constant, and independent of the Fermi energy

$$n_0 = n_i = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right]$$

$$p_0 = p_i = n_i = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right]$$

$$\boxed{n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_v)}{kT}\right] = N_c N_v \exp\left[\frac{-E_g}{kT}\right]}$$

Table 4.2 | Commonly accepted values of n_i at $T = 300$ K

Silicon	$n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$
Gallium arsenide	$n_i = 1.8 \times 10^{6}\ \text{cm}^{-3}$
Germanium	$n_i = 2.4 \times 10^{13}\ \text{cm}^{-3}$

E_{Fi} is the Fermi energy level for the intrinsic semiconductor, called the intrinsic Fermi energy

where

- n_0 is the thermal-equilibrium density of electrons per unit volume in the conduction band.
- p_0 the thermal-equilibrium density of holes in the valence band
- **Nc** is the effective density of states function in the conduction band.
- **Nv** is the effective density of states function in the valence band

Consider intrinsic Si at room temperature. Intrinsic refers to pure Si, n. Where concentration of electron and holes are given in bellow equations

$$n = N_c \exp[-\frac{(E_c - E_F)}{k_B T}]$$
$$p = N_v \exp[-\frac{(E_F - E_v)}{k_B T}]$$

For an intrinsic semiconductor n =p = n_i ,

The product of n and p: np (1 of 2)

$$np = N_c \exp\left[-\frac{(E_C - E_F)}{kT}\right] N_v \exp\left[-\frac{(E_F - E_v)}{kT}\right]$$
$$np = N_c N_v \exp\left[-\frac{(E_c - E_v)}{kT}\right]$$
$$np = N_c N_v \exp\left[-\frac{E_g}{kT}\right] \quad \text{where } E_g = E_c - E_v$$

thus the intrinsic carrier concentration (n_i) given by

$$n_i = \sqrt{N_c N_v} \exp(-\frac{E_g}{k_B T})$$

Fermi level in intrinsic semiconductors

Fermi energy can be written as (derive this eqn. in sheet)

$$\boxed{E_{Fi} = E_v + \frac{1}{2}E_g - \frac{1}{2}k_B T \ln(\frac{N_c}{N_v})}$$

Also Fermi energy can be written as a function of effective mass (derive this eqn. in sheet)

$$\boxed{E_{Fi} = E_v + \frac{1}{2}E_g - \frac{3}{4}k_B T \ln(\frac{m_e^*}{m_h^*})}$$

Where

Fermi Level and Electron-Hole Concentrations (2 of 2)

$$N_v \exp\left[-\frac{(E_{Fi}-E_v)}{kT}\right] = N_c N_v \exp\left[-\frac{E_g}{kT}\right]$$

$$E_{FI} = E_v + \frac{1}{2}E_g - \frac{1}{2}kT\ln\left(\frac{N_c}{N_v}\right)$$

$$E_{FI} = E_v + \frac{1}{2}E_g - \frac{3}{4}kT\ln\left(\frac{m_e^*}{m_h^*}\right)$$

- If $N_c=N_v$ or $m_e^*=m_h^*$; then $E_{FI} = E_v + \frac{1}{2}E_g$

$$n_0 = n_i \exp[(E_F - E_{Fi})/kT]$$

$$\boxed{E_F - E_{Fi} = kT \ln\left(\frac{n_0}{n_i}\right)}$$

$$p_0 = n_i \exp[-(E_F - E_{Fi})/kT]$$

$$\boxed{E_{Fi} - E_F - kT \ln\left(\frac{p_0}{n_i}\right)}$$

- Remember the relationship between the position of the Fermi level E_F and the density of carriers in the semiconductor (given by the Fermi-Dirac or Maxwell-Boltzman distribution functions):
- $p = N_v e^{(E_v-E_F)/kT}$ and $p_i = N_v e^{(E_v-E_i)/kT}$
  $n = N_c e^{(E_F-E_c)/kT}$ and $n_i = N_c e^{(E_i-E_c)/kT}$

with E_i the intrinsic level[1], N_c the effective density of states in the conduction band and N_v the effective density of states in the valence band. The intrinsic level E_i is an energy position within the forbidden gap that is determined by the intrinsic carrier concentration.
The conductivity of intrinsic semiconductor material is given by:

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

- With μ_n, μ_p the mobility of electrons, resp. holes. The value of the mobility is a function of the scattering processes and the effective mass of the carriers: $\mu = \frac{q\tau}{m}$, with q the charge, τ the average time between collisions (scattering), m the mass. Thus the hole and electron mobility are not necessarily the same. The mobility gives an indication into how fast a device will work (when parasitic influences are negligible). The mobility is the proportionality constant in the drift velocity-electric field relationship for small values of electric field: $v = \mu E$, with v the drift velocity and E the electric field. Electrons and holes have opposite velocities.

b. Extrinsic Semiconductors

Those intrinsic semiconductors to which some suitable impurity or doping agent or doping has been added in extremely small amounts (about 1 part in 10^8) are called extrinsic or impurity semiconductors (i.e) Semiconductors doped with donor or acceptor atoms to engineer their conductivity are called "**extrinsic**".Depending on the type of doping material used, extrinsic semiconductors can be sub-divided into two classes:

(i) N-type semiconductors(Donor) and

(ii) P-type semiconductors (Acceptor).

(i) N-type Extrinsic semiconductor: donators (group V elements: P, As, Sb)

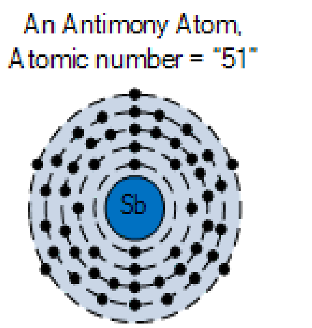
This type of semiconductor is obtained when a pentavalent material like antimonty (Sb) is added to pure germanium crystal. As shown in Fig. below, each antimony atom forms covalent bonds with the surrounding four germanium atoms with the help of four of its five electrons. The fifth electron is superfluous and is loosely bound to the antimony atom. It is seen from the above description that in N-type semiconductors, electrons are the majority carriers while holes constitute the minority carriers

In order for our silicon crystal to conduct electricity, we need to introduce an impurity atom such as Arsenic, Antimony or Phosphorus into the crystalline structure making it extrinsic (impurities are added). These atoms have five outer electrons in their outermost orbital to share with neighbouring atoms and are commonly called "Pentavalent" impurities.

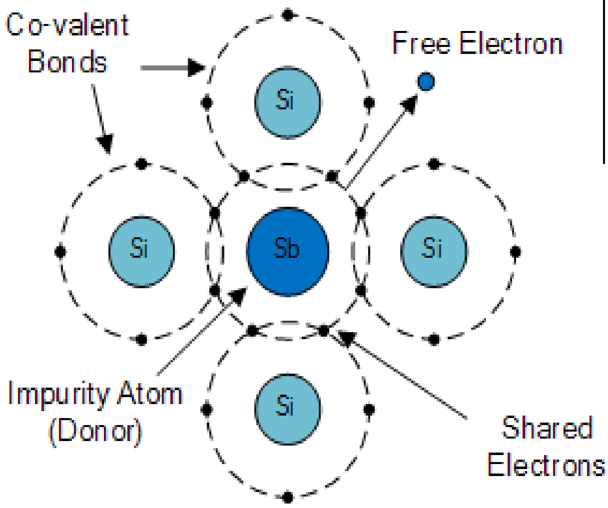
This allows four out of the five orbital electrons to bond with its neighbouring silicon atoms leaving one "free electron" to become mobile when an electrical voltage is applied (electron flow). As each impurity atom "donates" one electron, pentavalent atoms are generally known as "donors".

Antimony (symbol Sb) or Phosphorus (symbol P), are frequently used as a pentavalent additive to the silicon as they have 51 electrons arranged in five shells around their nucleus with the outermost orbital having five electrons. The resulting semiconductor basics material has an excess of current-carrying electrons, each with a negative charge, and is therefore referred to as an N-type material with the electrons called "Majority Carriers" while the resulting holes are called "Minority Carriers".

Antimony Atom and Doping



Antimony atom showing 5 electrons in its outer valence shell (o)



N-Type Semiconductor

(ii) P-type Extrinsic semiconductor: Acceptors (group III elements: B, Al, In, Ga)

This type of semiconductor is obtained when traces of a trivalent, a "Trivalent" (3-electron) impurity into the crystalline structure, such as Aluminium, Boron or Indium, which have only three valence electrons available in their outermost orbital, the fourth closed bond cannot be formed. Therefore, a complete connection is not possible, giving the semiconductor material an abundance of positively charged carriers known as holes in the structure of the crystal where electrons are effectively missing.

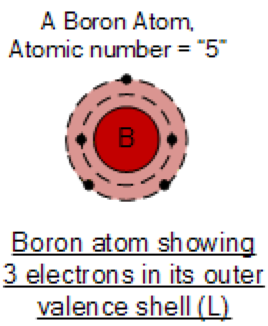
As there is now a hole in the silicon crystal, a neighbouring electron is attracted to it and will try to move into the hole to fill it. However, the electron filling the hole leaves another hole behind it as it moves. This in turn attracts another electron which in turn creates another hole behind it, and so forth giving the appearance that the holes are moving as a positive charge through the crystal structure (conventional current flow).

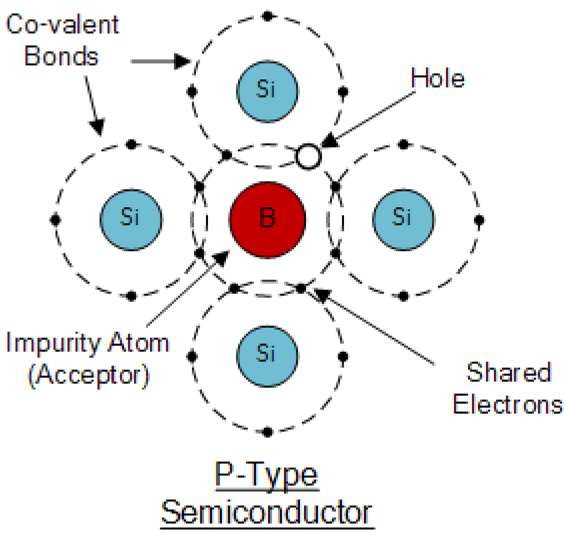
This movement of holes results in a shortage of electrons in the silicon turning the entire doped crystal into a positive pole. As each impurity atom generates a hole, trivalent impurities are generally known as "Acceptors" as they are continually "accepting" extra or free electrons.

Boron (symbol B) is commonly used as a trivalent additive as it has only five electrons arranged in three shells around its nucleus with the outermost orbital having only three electrons. The doping of Boron atoms causes conduction to consist mainly of positive charge carriers resulting in a P-type material with the positive holes being called "Majority Carriers" while the free electrons are called "Minority Carriers".

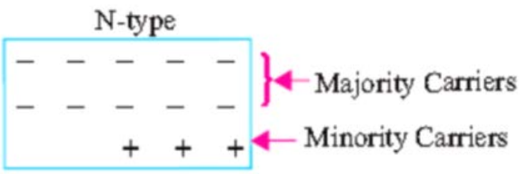
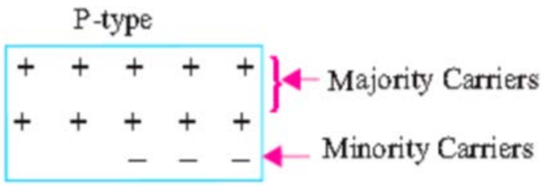
Then a semiconductor basics material is classed as P-type when its acceptor density is greater than its donor density. Therefore, a P-type semiconductor has more holes than electrons.

Boron Atom and Doping





This table shows the compares between N-type & P-type

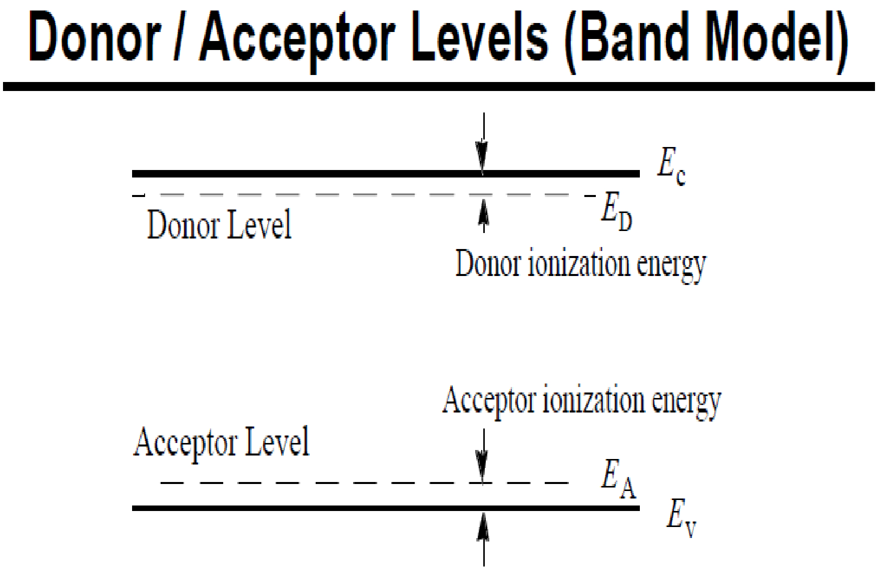
N-type(Donor)	P-type(Acceptor)
• Doped with Group V donor impuri e.g. P, As • 1. The Donors are positively charged. • 2. There are a large number of free electrons. • 3. A small number of holes in relation to the number of free electrons. • 4. Doping gives: o positively charged donors. o negatively charged free electrons. • 5. Supply of energy gives: o negatively charged free electrons. o positively charged holes.  	• Doped with Group III acceptor impurities e.g. B • 1. The Acceptors are negatively charged. • 2. There are a large number of holes. • 3. A small number of free electrons in relation to the number of holes. • 4. Doping gives: o negatively charged acceptors. o positively charged holes. • 5. Supply of energy gives: o positively charged holes. o negatively charged free electrons. 

Smplified version of energy band model, indicating

• bottom edge of the conduction band (***E*c**)

• top edge of the valence band (***E*v**)

*E*c and *E*v are separated by the **band gap energy E_g**



Charge-Carrier Concentrations

N_D: ionized donor concentration (cm^{-3})
N_A: ionized acceptor concentration (cm^{-3})

Charge neutrality condition: $N_D + p = N_A + n$

At thermal equilibrium, $np = n_i^2$ ("Law of Mass Action")

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

Note: Carrier concentrations depend on *net* dopant concentration (N_D - N_A) !

Position of Fermi Energy Level

- In an n-type semiconductor the distance between the bottom of the conduction band and the Fermi energy is a logarithmic function of the donor concentration.
- As the donor concentration increases, the Fermi level moves closer to the conduction band
- In a p-type the Fermi level moves closer to the valence band

$$n_0 = N_c \exp[-(E_c - E_F)/kT]$$

$$\boxed{E_c - E_F = kT \ln\left(\frac{N_c}{n_0}\right)}$$

$$N_d \gg n_i \qquad n_0 \approx N_d$$

$$E_c - E_F = kT \ln\left(\frac{N_c}{N_d}\right)$$

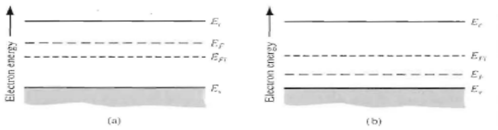
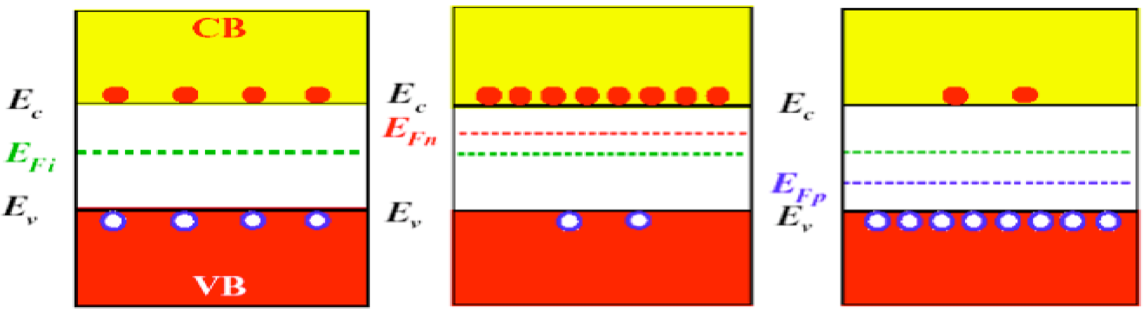


Figure 4.17 | Position of Fermi level for an (a) n-type ($N_d > N_a$) and (b) p-type ($N_a > N_d$) semiconductor.

Revisit Fermi Energies

- In an extrinsic semiconductor, the Fermi energy will move to adjust the probability of having a free electron or hole
- If n⇑ E_F⇑ toward E_c; if p⇑, E_F ⇓ toward E_v



Intrinsic Extrinsic n-type Extrinsic p-type

The effect of temperature on the conductivity of semiconductor

1- at room temperature, most of the donor atoms have given up their excess electron (most excited from E_d into the conduction band) → large increase in n_c (concentration of electrons in conduction band) → large increase in conductivity σ.

2- As T is raised, weakly bound donor electrons are promoted into the conduction band – σ rises

3. Eventually, nearly all donor electrons have been excited into conduction band. However, T still not high enough for excitation across energy gap E_g – σ levels off.

4. At higher T still, start to get excitation of electrons across E_g – intrinsic behaviour. σ rises rapidly.

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- Energies within an allowed energy band are actually at discrete levels and each contains a finite number of quantum states.
- The Fermi-Dirac probability function gives the probability of a quantum state at an energy *E* of being occupied by an electron
- The position of Fermi level changes with doping
- the Fermi energy level is a constant throughout a system
- the product of n_0 and p_0 is always a constant for a given semiconductor material, intrinsec or extrinsec, at a given temperature
- In thermal equilibrium, the semiconductor crystal is electrically neutral
- The band gap energy is the energy required to free an electron from a covalent bond.
  - E_g for Si at 300K = 1.12eV
- In a pure Si crystal, conduction electrons and holes are formed in pairs.
  - Holes can be considered as positively charged mobile particles which exist inside a semiconductor.
  - Both holes and electrons can conduct current.
- Substitutional dopants in Si:
  - Group-V elements (***donors***) contribute conduction electrons
  - Group-III elements (***acceptors***) contribute holes
  - Very low ionization energies (<50 meV)

Some definitions →

donor: impurity atom that increases n

acceptor: impurity atom that increases p

N-type material: contains more electrons than holes

P-type material: contains more holes than electrons

majority carrier: the most abundant carrier

minority carrier: the least abundant carrier

intrinsic semiconductor: $n = p = n_i$

extrinsic semiconductor: doped semiconductor