MPC-204
Semiconductor Devices

Unit III- Optoelectronic Devices
Lecture 4

Fermi level and Effect of temperature on Intrinsic and Extrinsic Semiconductors

Recap

- The material which has electrical conductivity between that of a conductor and that of an insulator is called as semiconductor. Silicon, germanium and graphite are some examples of semiconductors.

- In semiconductors, the forbidden gap between valence band and conduction band is very small. It has a forbidden gap of about 1 electron volt (eV).

- At low temperature, the valence band is completely occupied with electrons and conduction band is empty because the electrons in the valence band does not have enough energy to move in to conduction band. Therefore, semiconductor behaves as an insulator at low temperature.

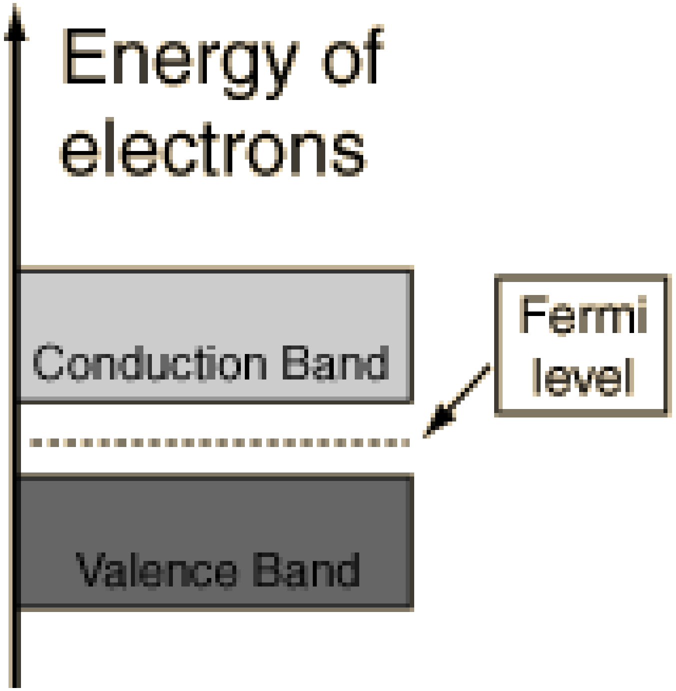
- However, at room temperature some of the electrons in valence band gains enough energy in the form of heat and moves in to conduction band. When the valence electrons moves in to conduction band they becomes free electrons. These electrons are not attached to the nucleus of a atom, So they moves freely.

Fermi Level Or Energy

- In particle physics, Fermions are those elementary particles which have Half integral spins whereas Bosons have integral spins**.**

- Since Fermi–Dirac statistics applies to particles with half-integer spin, they have come to be called fermions. It is most commonly applied to electrons, which are fermions with spin 1/2. Electrons are fermions and by the Pauli exclusion principle cannot exist in identical energy states. The Pauli exclusion principle postulates that only one Fermion can occupy a single quantum state.

Fermi Level



- Throughout nature, particles seek to occupy the lowest energy state possible. Therefore electrons in a solid will tend to fill the lowest energy states first.

- Electrons fill up the available states like water filling a bucket, from the bottom up. At T=0K, every low-energy state is occupied, right up to the Fermi level, but no states are filled at energies greater than E_F .

Fermi level" is the term used to describe the top of the collection of electron energy levels at absolute zero temperature

- At absolute zero electrons pack into the lowest available energy states and build up a "Fermi sea" of electron energy states. The Fermi level is the surface of that sea at absolute zero where no electrons will have enough energy to rise above the surface.

- At absolute zero all the electronic states of the valence band are full and those of conduction band are empty

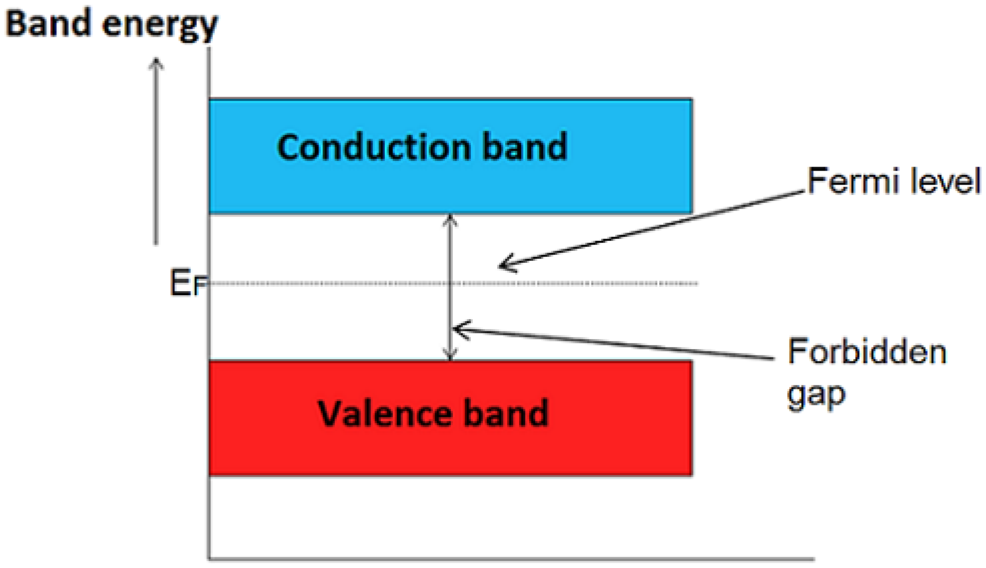
- Classically all electrons have zero energy at 0^0K (i.e., practically insulator. When temp is increased then electrons jump from VB to CB) But Quantum Mechanically all electrons are not having zero energy at 0^0K

- The maximum energy that electrons may possess at 0^0k is the Fermi energy $E_{F.}$ So Quantum mechanically electrons actually have energies extending from 0 to E_F at 0^0K

- The Fermi energy is a concept in quantum mechanics usually referring to the energy difference between the highest and lowest occupied single-particle states in a quantum system of non-interacting fermions at absolute zero temperature.

Fermi level in intrinsic semiconductor

For intrinsic semiconductors like silicon and germanium, the Fermi level is essentially halfway between the valence and conduction bands



In intrinsic or pure semiconductor, the number of holes in valence band is equal to the number of electrons in the conduction band. Hence, the probability of occupation of energy levels in conduction band and valence band are equal. Therefore, the Fermi level for the intrinsic semiconductor lies in the middle of forbidden band.

Fermi level in the middle of forbidden band indicates equal concentration of free electrons and holes.

FERMI FACTOR OR FERMI FUNCTION

- The Fermi-Dirac distribution, is a fundamental equation expressing the behaviour of mobile charges in solid materials

- Although no conduction occurs at 0 K, at higher temperatures a finite number of electrons can reach the conduction band and provide some current

- The increase in conductivity with temperature can be modelled in terms of the Fermi function, which allows one to calculate the population of the conduction band.

- Fermi factor tells us how many of the energy states in the VB and CB will be occupied at different temperatures OR we can say that the Fermi function tells us the probability that a state is occupied.

FERMI FUNCTION

The probability that the particle will have an energy *E* is

$$F(E) = \frac{1}{1 + e^{\frac{E - E_F}{KT}}}$$

Where K is Boltzman Constant : K = 1.38 x 10^{-23} J/K
T is the absolute temperature
E_f is the Fermi level or the Fermi energy

The **Fermi-Dirac distribution function**, also called **Fermi function**, provides the probability of occupancy of energy levels by Fermions. Fermions are half-integer spin particles, which obey the Pauli exclusion principle.

- Fermi factor is independent of the energy density of states, it is the probability that the states occupied at that level, irrespective of the number of states actually present i.e., the occupancy of possible states

- At absolute zero, the probability is equal to 1 for energies less than the Fermi energy and zero for energies greater than the Fermi energy.

Case-I When T=0^{0}K , then for

$$F(E) = \frac{1}{1+e^{\infty}} = 0 \qquad E > E_F$$

$$F(E) = \frac{1}{1+e^{-\infty}} = 1 \qquad E < E_F$$

Case-II When T=T^{0}K , then at E=E$_F$

$$F(E) = \frac{1}{1+e^{0}} = \frac{1}{2}$$

The Fermi level represents the energy state with a 50% probability of being filled if no forbidden band exists, .i.e., if E = E$_F$ then f(E)=1/2 for any value of temperature.

- This means that when the temperature is not 0^0K but some higher value say T=1000^0K, then some covalent bonds will be broken and some electrons will be available in CB

- This is similar to a bucket of hot water. Most of the water molecules stick around the bottom of the bucket. The Fermi level is like the water line. A fraction of water molecules are excited and drift above the water line as *vapour*, just as electrons can sometimes drift above the Fermi level.

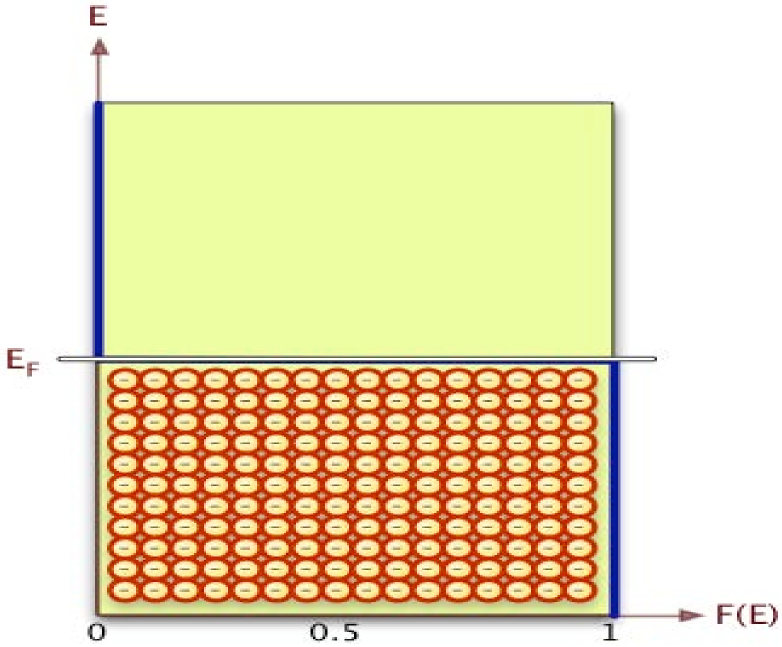


Illustration of the Fermi function for zero temperature. All electrons are stacked neatly below the Fermi level.

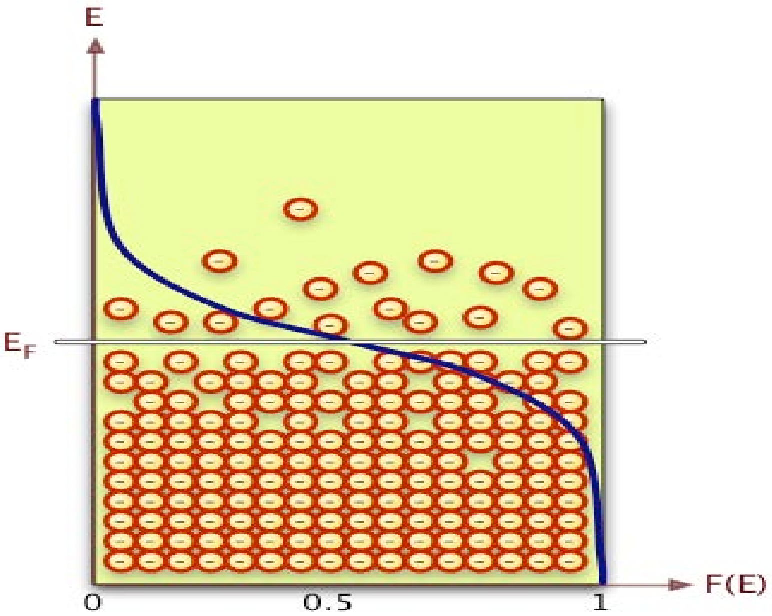
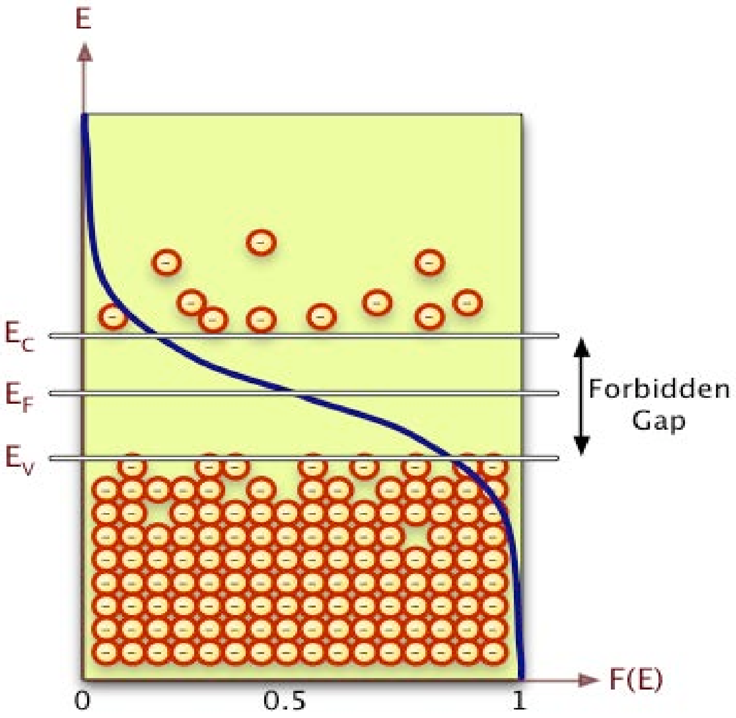
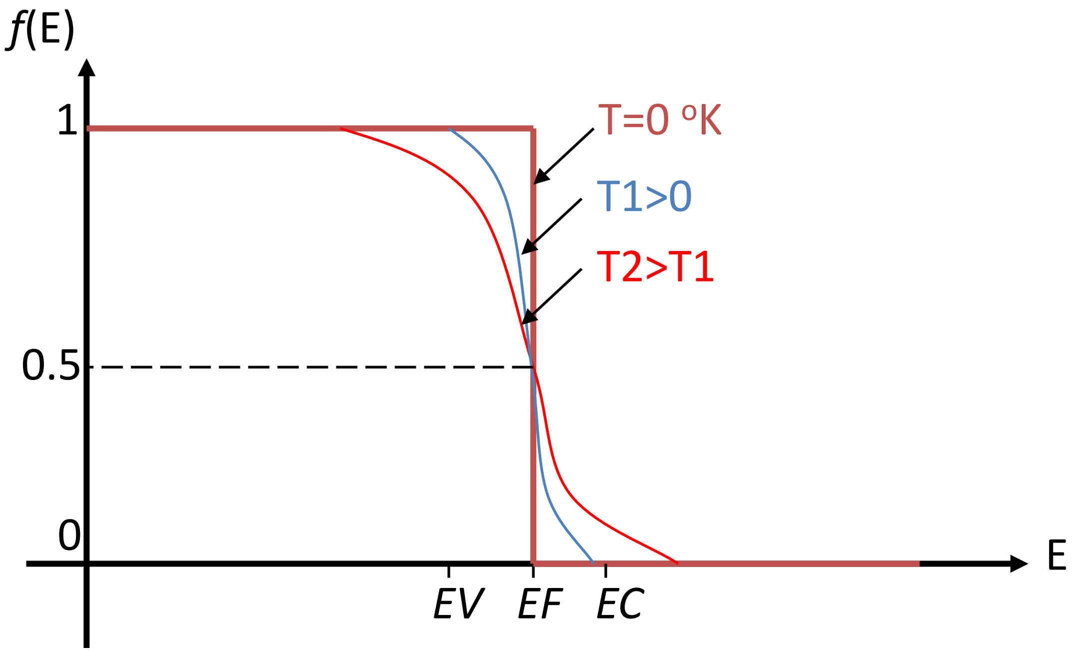


Illustration of the Fermi function for temperatures above zero. Some electrons drift above the Fermi level. Their density at higher energies is proportional to the Fermi function



In a semiconductor, not every energy level is allowed. For example, there are no allowed states within the forbidden gap

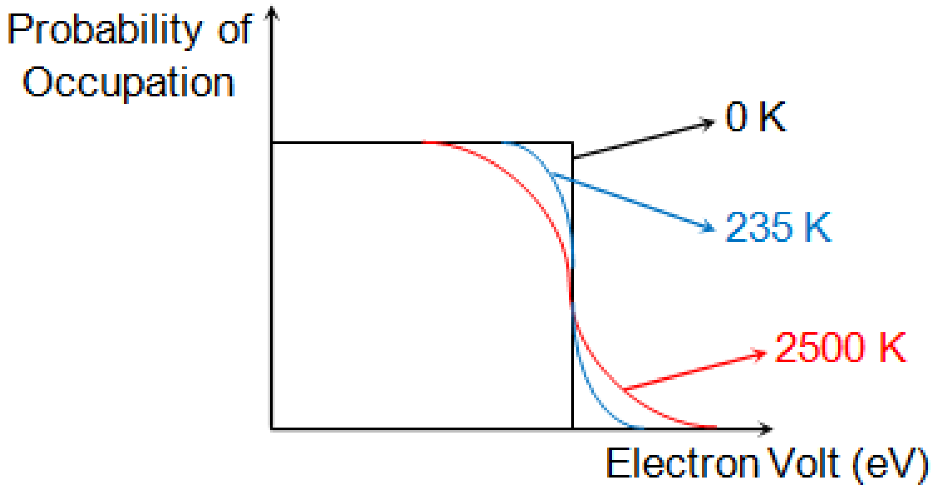
The density of electrons in a semiconductor, showing how the Fermi function is modulated by the density of allowed states (which is zero inside the forbidden gap).



- At **T = 0^{0}K**, the total number of energy levels occupied by electrons can be known by using the Fermi-Dirac Function.

- For a given energy level **E > $\mathbf{E_F}$**, the exponential term in the Fermi-Dirac function becomes 0 and Which means that the probability of finding the occupied energy level of energy greater than **$\mathbf{E_F}$** is zero.

- For a given energy level **E < $\mathbf{E_F}$** the value of which means that all the energy levels with energy are less than that of Fermi level E_F will be occupied at **T = 0^{0}K**. This indicates that the Fermi energy level is the maximum energy an electron can have at absolute zero temperature.



Fermi-Dirac Distribution Function at different Temperatures

This inturn means that no energy states which lie above the Fermi-level are occupied by electrons. Thus we have a step function defining the **Fermi-Dirac distribution function** as shown by the black curve in Figure.

However as the temperature increases, the electrons gain more and more energy due to which they can even rise to the conduction band.

POSITION OF THE FERMI LEVEL IN AN INTRINSIC SC

- Semi conductors in which impurities are not present are known as intrinsic semiconductors. The electrical conductivity of the semiconductor depends upon the total no of electrons moved to the conduction band from the valence band. Eg. silicon and germanium.

- If the temperature will be maintained at zero Kelvin, then the valence band will be full of electrons. So, at such a low temperature range it is impossible to cross the energy barrier. It will act as an insulator at zero Kelvin. The minimum energy required to the break the covalent bond in germanium crystal is 0.72 eV and for silicon its value is 1.1 eV.

- At room temperature thermal energy excite some electrons present in valence electrons to shift to the conduction band. So, the semi conductor will be able to show some electrical conductivity. As the temperature increases, the electrons movement from the valence band to the conduction band will also increase.

POSITION OF THE FERMI LEVEL IN AN INTRINSIC SC

- The density of states complements the Fermi function by telling us how many states actually exist in a particular material

- The density of available states , S(E) , is the fraction of all allowed states that lie within E and E+dE . This is a density function

- We can multiply S(E) and F(E) together, resulting in units of electrons per energy level per unit volume

$$\mathbf{S(E)\times F(E)}$$

Let the available number of states = S(E)

and Probability of their occupancy = F(E)

Suppose there are N(E) occupied states at energy E

Then the total number of occupied states N(E) by electrons in conduction band with energy between E and E+dE

$$N(E)dE = S(E)F(E)dE$$

In a solid semiconductor at thermal equilibrium, every mobile electron leaves behind a hole in the valence band. Since holes are also mobile, we need to account for the density of "hole states" that remain in the valence band. Because a hole is an unoccupied state, the probability of a mobile hole existing at energy E is 1−F(E)

$$P(E)dE = S(E)\left[1 - F(E)\right]dE$$

Energy level in C.B = E_1
Energy level in V.B = E_2

$$N(E_1)dE = S(E_1)F(E_1)dE$$

$$P(E_2)dE = S(E_2)\left[1-F(E_2)\right]dE$$

In case of intrinsic sc: $S(E_1) = S(E_2)$

$$\frac{N(E_1)dE}{P(E_2)dE} = \frac{S(E_1)F(E_1)dE}{S(E_1)\left(1-F(E_2)\right)dE}$$

$$\frac{N(E_1)}{P(E_2)} = \frac{F(E_1)}{\left(1-F(E_2)\right)}$$

At E_1 = 300^0K

$$F\left(E_1\right) = e^{\frac{-\left(E_1-E_F\right)}{KT}}$$

$$1 - F\left(E_2\right) = e^{\frac{\left(E_2 - E_F\right)}{KT}}$$

$$\frac{N(E_1)}{P(E_2)} = \frac{n_i}{p_i} = 1$$

$$E_F = \frac{E_1 + E_2}{2}$$

This equation shows that the Fermi level lies at the centre of the forbidden gap for intrinsic semiconductor and it is independent of the temperature

Fermi level of extrinsic semiconductor

➢In extrinsic semiconductor, the number of electrons in the conduction band and the number of holes in the valence band are not equal.

➢Hence, the probability of occupation of energy levels in conduction band and valence band are not equal.

➢Therefore, the Fermi level for the extrinsic semiconductor lies close to the conduction or valence band.

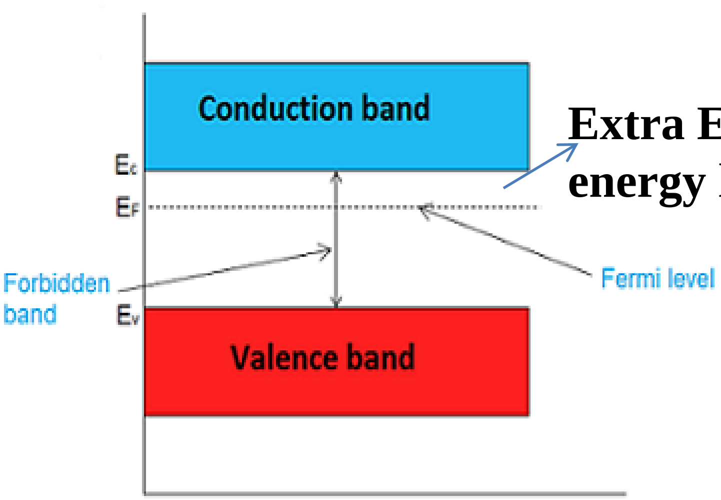
➢in n-type SC, number of electrons $n_e > n_i$ and number of holes $p_e < p_i$

➢This means $n_e > p_e$, hence the Fermi level must move upward closer to the conduction band

➢For p-type SC, $p_e > n_e$ so Fermi level must move downward from the center of the forbidden gap closer to the valence ban**d**

N-type Semiconductor

In n-type semiconductor pentavalent impurity is added. Each pentavalent impurity donates a free electron. The addition of pentavalent impurity creates large number of free electrons in the conduction band



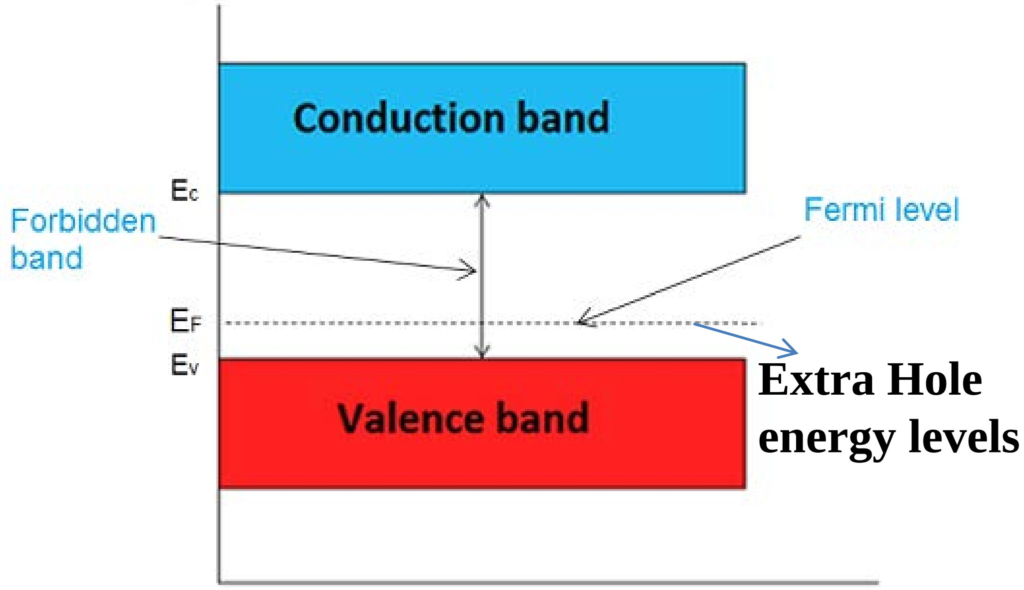
Extra Electron energy levels

- At room temperature, the number of electrons in the conduction band is greater than the number of holes in the valence band.
- Hence, the probability of occupation of energy levels by the electrons in the conduction band is greater than the probability of occupation of energy levels by the holes in the valence band.

This probability of occupation of energy levels is represented in terms of Fermi level. Therefore, the Fermi level in the n-type semiconductor lies close to the conduction band.

P-type Semiconductor

In p-type semiconductor trivalent impurity is added. Each trivalent impurity creates a hole in the valence band and ready to accept an electron. The addition of trivalent impurity creates large number of holes in the valence band.



- ➢At room temperature, the number of holes in the valence band is greater than the number of electrons in the conduction band.
- ➢Hence, the probability of occupation of energy levels by the holes in the valence band is greater than the probability of occupation of energy levels by the electrons in the conduction band.

This probability of occupation of energy levels is represented in terms of Fermi level. Therefore, the Fermi level in the p-type semiconductor lies close to the valence band.

Conduction in N and P type semiconductors

In an N type semiconductor, the current flows due to the movement of free electrons and holes. Since the free electrons being the majority carriers and holes being the minority carriers, the net current will be due to the majority carriers i.e. free electrons.

In a P type semiconductor, the current flows due to the movement of holes and free electrons. Since hole being the majority carriers and free elctrons beimg the minority carriers, the net current will be due to the majority carriers i.e. the holes.

Energy Bands of Extrinsic Semiconductors

In extrinsic semiconductors, a change in the ambient temperature leads to the production of minority charge carriers. Also, the dopant atoms produce the majority carriers. During recombination, the majority carriers destroy most of these minority carriers. This leads to a decrease in the concentration of the minority carriers.

Therefore, this affects the energy band structure of the semiconductor. In such semiconductors, additional energy states exist:

- Energy state due to donor impurity (E_D)
- Energy state due to acceptor impurity (E_A)

N-type Semiconductor

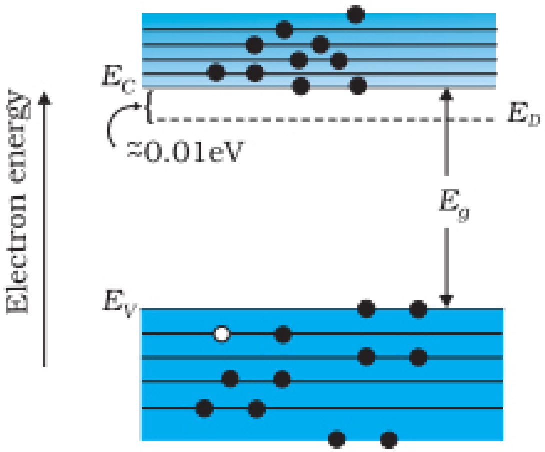
- If we consider the most common and preferred n-type dopant, phosphorus, it has the tendency to loose its fifth electron in the semiconductor onto the conduction band when it gets some external energy.

- Initially, (at 0K) the loosely held electron is still in control of the nucleus of donor atom. This is due to the bind energy of the atom, which is the energy required to bind the electron with the atom.

- Since, a donor atom can be approximated as a hydrogen atom (tendency to give only one electron), its bind energy comes out to be less than 0.1eV ! Meaning, that much energy is sufficient to ionize the donor.

- Hence, as a result, donor level adjust itself only that much far from conduction band, which is very small energy gap. The same thought can be incorporated for acceptor level.

Energy Bands of N-type Semiconductors



- The energy level of the donor (E_D) is lower than that of the conduction band (E_C).

- At 0 K all allowed energy levels in the valence band are filled by electrons.

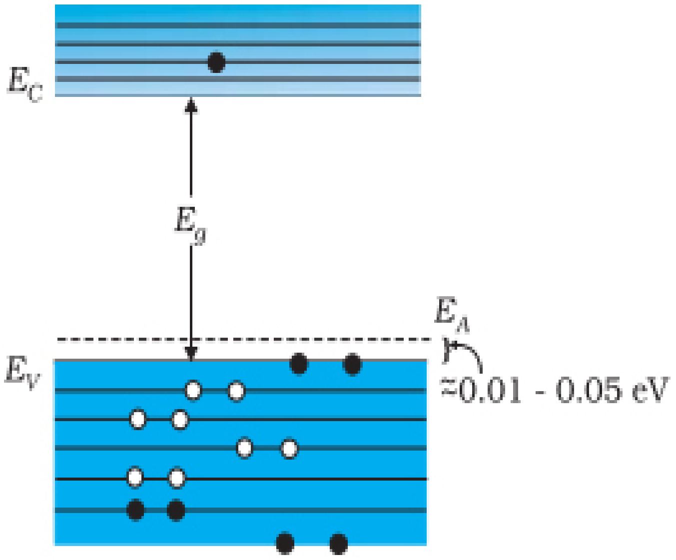
- Donor levels are filled by unbound electrons.

- Hence, electrons can move into the conduction band with minimal energy (~0.01 eV).

- Also, at room temperature, most donor atoms and very few Si atoms get ionized.

- Hence, the conduction band has most electrons from the donor impurities.

Energy Bands of P-type Semiconductors



At the room temperature, almost all acceptor atoms trap electrons and thus the number of holes available in the valence band is almost equal to the number of impurity atoms added.

- The energy level of the acceptor (E_A) is higher than that of the valence band (E_V).

- Hence, electrons can move from the valence band to the level E_A, with minimal energy. Also, at room temperature, most acceptor atoms are ionized.

- At absolute zero, all the holes are in acceptor levels, but as the temperature rises, the electrons from valence band jump into acceptor level on the absorption of energy (Ea-Ev) by each electron.

- As a result, these electrons are trapped in the acceptor levels and an equal number of holes are created in the valence band.

N-Type Semiconductor at High Temperature

➢N-type semiconductor the Fermi-level lies below the bottom of the conduction band. As temperature rises, the Fermi level goes on falling below E_C .

➢As temperature is sufficiently raised, the electrons and holes generated due to thermal agitation increase significantly and at a stage intrinsic become fully dominant over the extrinsic carriers.

➢Then the Fermi level approaches the middle of forbidden energy gap.

P-Type Semiconductor at High Temperature

- ➢Fermi level lies above the top of the valence band. The position of Fermi level depends upon the temperature and then number of impurity atoms.

- ➢As the temperature is sufficiently increased, electrons from the valence band are excited to the conduction band and finally the P-type crystal will start behaving like an intrinsic semi-conductor when the number of electrons in the conduction band will be nearly equal to the valence holes.

- ➢Thus at extremely high temperatures the Fermi level shifts towards the middle of forbidden energy gap.

Summary

- The Fermi energy level , E_F , is the energy at which the probability of occupancy is exactly 1/2 for temperatures greater than zero.

- The Fermi level lies at the centre of the forbidden gap for intrinsic semiconductor and it is independent of the temperature.

- In N-type semiconductor the Fermi-level lies below the bottom of the conduction band.

- In P-type Semiconductor the Fermi level lies above the top of the valence band.

- The position of Fermi level in both cases depends upon the temperature and then number of impurity atoms.

- At very high temperatures the Fermi level approaches the middle of forbidden energy gap, hence behave like Intrinsic semiconductor in both N and P type semiconductors.

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