SEMICONDUCTOR PHYSICS

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Contents

- Introduction to semiconductor physics
- Fermi Dirac statistics
- Fermi level in intrinsic and extrinsic semiconductors
- Fermi level and energy band diagram in P and N type of semiconductors
- Hall effect and its applications
- PN junction diode on the basis of energy band diagram
- NPN Transistor
- Solar cell

Lecture Plan

Introduction, **importance of semiconductor physics in engineering and technology, b**and theory of solids**,** energy bands in metals, insulators and semiconductors, How energy bands are formed? (with examples of Li, Be),
Semiconductors and their useful properties, Fermi Dirac statistics, Fermi Dirac formula, concept of Fermi level and its physical significance
Discussion of intrinsic and extrinsic semiconductors on the basis of Fermi level, Fermi level in intrinsic semiconductors at T = 0 K and T > 0 K (mathematical and graphical description)
Fermi level and energy band diagram in P and N type of semiconductors at T = 0 K and T > 0 K, effect of impurity concentration (doping level)
Quantitative description of semiconductors (I, J, V, E, R, ρ, σ, v_d, μ etc). **without derivation**
Hall effect and its applications
PN junction diode on the basis of energy band diagram
NPN Transistor (basics and energy band diagram) and **solar cell (to be taught in lab)**

The properties and applications of any solid are governed by it's two characteristics,

its atom and the inter-atomic interaction

Property ⇒ Material ⇓	Type	Density of charge carriers n (m^{-3})	Resistivity ρ Ω-m	Temperature coefficient of resistivity (K^{-1})
Copper	Metal (conductor)	9×10^{28}	2×10^{-8}	$+4\times10^{-3}$
Silicon	Semiconductor	1×10^{16}	3×10^{-3}	-70×10^{-3}
Diamond	Insulator		10^{16}	

Significant difference in the electrical properties of conductors, semiconductors and insulators

A quantum mechanical theory called as band theory of solids which explains reason for this variation

This theory explains the behavior of electronic devices such as diodes, BJT, FET, LED, Photodiodes, solar cells, etc

Transistor invented in 1947

Transforming old vacuum tube electronics to solid state electronics.

PN junction diode, NPN or PNP transistor, FET, photodiode, LED, solar cells etc.

Several advantages
compact size, fast action, requirement of less power etc.

BAND THEORY OF SOLIDS

- The energy levels of atoms become energy bands when a solid is formed
- Explained on two approaches
  - Felix Bloch : Restrictions on the allowed energy levels of the electrons due to the periodicity of the crystal
  - Walter Heitler and Fritz London: Splitting of the energy levels of the electrons due to their interaction

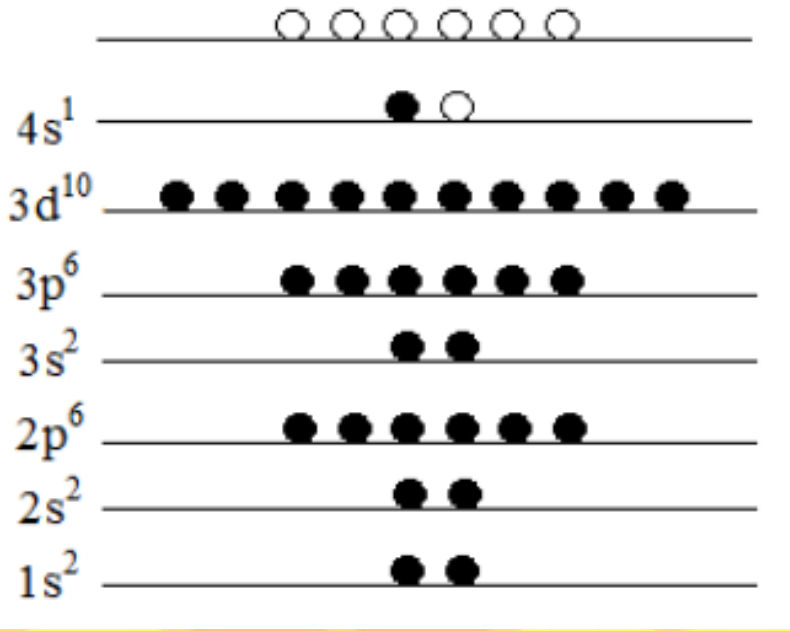
- Ex: **Copper – 29 Electrons**

  According to **Pauli's exclusion principle**, these electrons are distributed in to 29 exclusively different quantum states characterized by a group of four quantum numbers (n, l, m_l, m_s)

  Electronic configuration of copper

  $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^1$

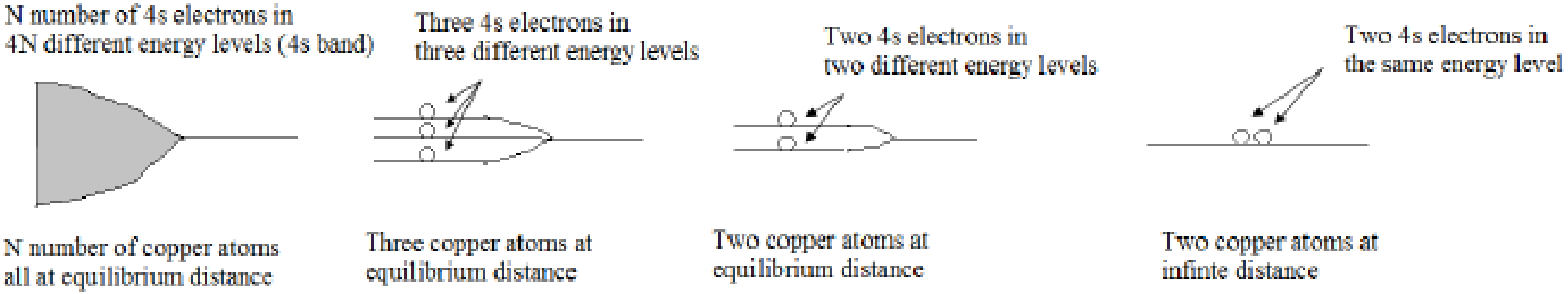
- Discrete energy levels



N copper atoms at infinite distance, then such atoms do not interact with each other

At equilibrium, the **inter-atomic distance** of the copper atoms in the solid form is **2.6Å**.

If the atoms come close to each other at such distance, the valance electrons will start strongly **interacting with each other**.
In such case the electrons cannot be accommodated in the same energy levels.
For ex. the two 4s electrons cannot be accommodated in the same 4s level.
The 4s level splits in to two closely spaced 4s sublevels.



The electrons undergo a strong electrostatic interaction hence their energies change

According to **Quantum Mechanics, the electrons behave like waves**. Thus when electrons come in the proximity, their **wavefunctions overlap**. As a result, **symmetric and anti-symmetric wavefunctions, which correspond to two distinct energy levels, are formed**.

when an **Avagadro number of atoms come close and form bonds** becomes a single system and thus **Pauli's exclusion principle** applies to the pair.

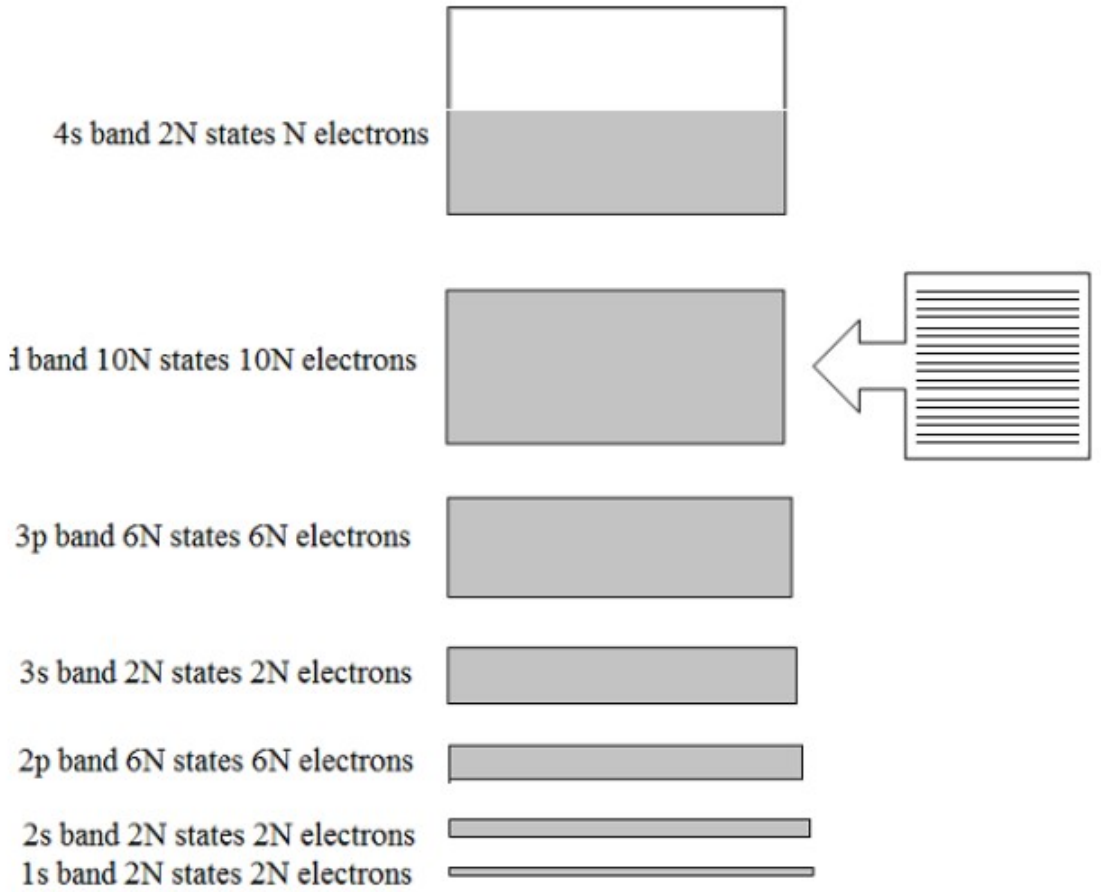
Accordingly, **there have to be N different quantum states with different energies for the N 4s electrons**.

Thus when **N atoms come together, there will be N number of energy levels, all belonging to 4s category**.

The **wavefunctions of these electrons also overlap and the levels split and form bands**

The number of quantum states in the band is the product of occupancy of the corresponding level and the number of atoms.

s band consists of 2N states, p band contains 6N states, d band contains 10N states



Inbetween any two allowed energy bands, there are **forbidden bands,** which consist of forbidden energy levels

The **energy band diagram** is **characterized** by the **total number of bands** which it involves, their **occupancy**, **size** and the **forbidden gap** between them

4s band has an occupancy of 2N states, however, it contains only N number of electrons occupying the lower levels. 4s band is thus partially (half) filled

the **higher band have greater width as compared to the lower bands**

the upper bands are due to **stronger interaction of valance electrons**. As we move down, the **lower level electrons interact weakly due to greater distance and screening effect** of the upper level electrons.

Due to larger distance, the **wavefunctions of these electrons overlap to a lesser extent**.

As a result the splitting effect is weak and therefore the bands are narrower

Valance band, conduction band and forbidden gap

The electrons in the outermost orbit of any element are called as **valance electrons**

The group of energy levels of the valance electrons constitutes a valance band

topmost or highest occupied band

All the bands above the valance bands are empty

In the group of unoccupied bands, the **lowest unoccupied band** is called as **conduction band**

When the electrons in the valance band are bound to their parent atoms, but when these electrons are excited to conduction band, they become free and thus take part in conduction

Between the valance band & conduction band, there is a group of forbidden energy levels.

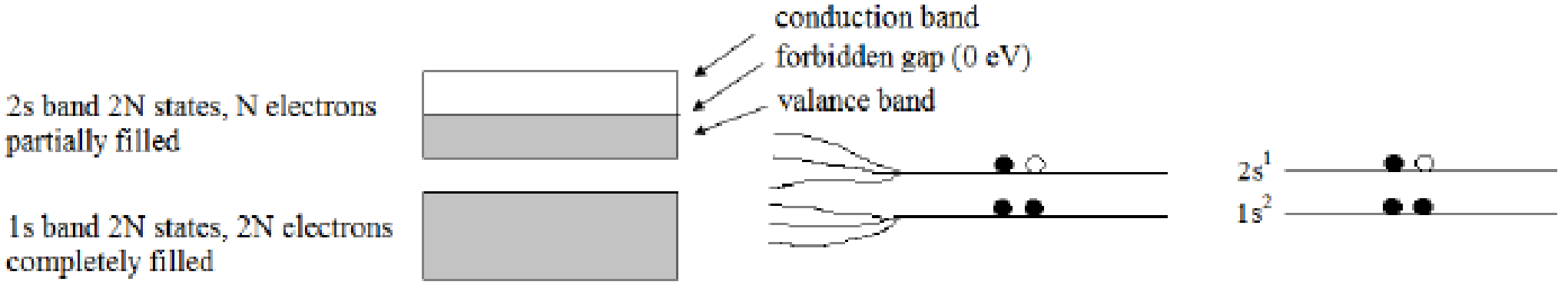
Quantum mechanically these levels are not allowed to the electrons.

This group is called as a **forbidden gap or the band gap**

Lithium (Z =3)

$1s^2$ $2s^1$

Energy level diagram consists of **1s level having two electrons** and **2s level having 1 electron**. Lithium atoms come together and form bonds, the energy levels split and form energy bands



There are two bands, namely 1s band and 2s band.
1s band has 2N states filled by 2N electrons. Thus **1s band is completely filled**.

2s band has 2N available states, but as the 2s level for lithium atom contains only 1 electron, the 2s band contains only N number of electrons

According to **auf-bau rule**, **these electrons fill up the states in the increasing order of energy**. Thus the lower N states are filled with N electrons and upper N states remain unoccupied.

Thus **2s band of lithium is partially (half) filled**.

The lower filled part itself is the highest occupied band that it valance band, while in the same 2s band, the upper unfilled band is the lowest unoccupied band that is conduction band

the **gap between these two bands is almost 0 eV** (actually 10^{-28} eV)
According to kinetic theory, the thermal energy of the electrons is given by **(3/2)kT**.
At 0K, there is no energy available for the electrons to rise in the conduction band,

at 300 K, the thermal energy is **0.038 eV**, which is sufficient for the electrons to go in the conduction band.
It may be noted that there are no forbidden levels in between the valance and the conduction band.

The allowed but empty energy levels in the conduction band are in the vicinity of the filled level in the valance band.
When the electrons are excited to the conduction band, they become free.

As the valance electrons can be made free very easily, lithium, at room temperature, has plenty of electrons in conduction band, and consequently, **lithium behaves as conductor**.

Lithium belongs to **group I in the periodic table**.

The other elements in group I, such as sodium (Z= 11), potassium etc. also have partially filled valance bands and thus are conductors.

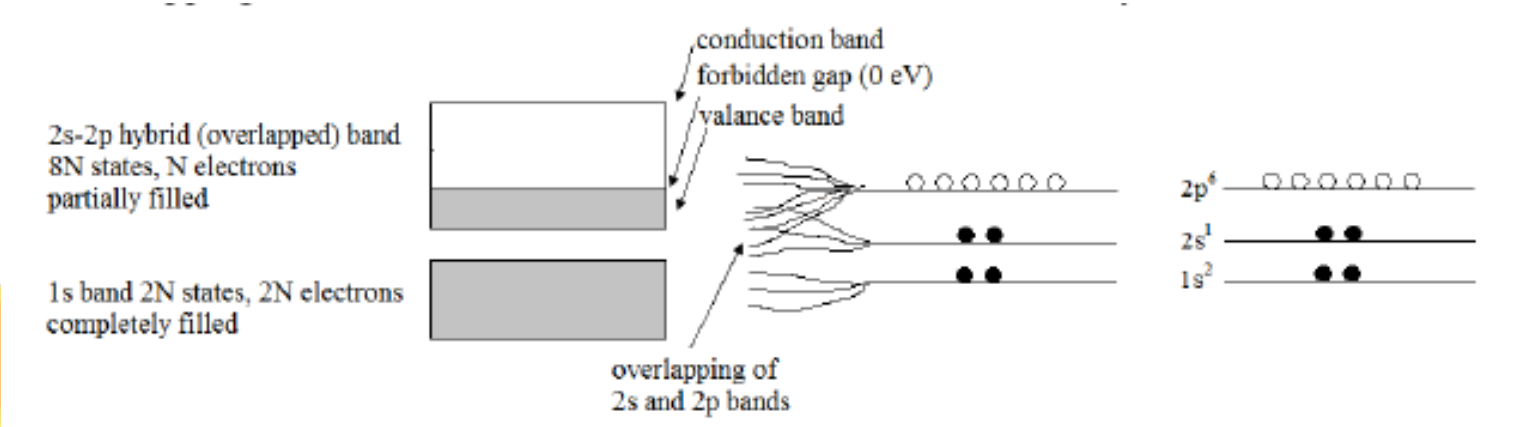
The other examples of the elements with partially filled valance band are, aluminium (Z =13), copper(Z = 29), silver (Z = 47) and gold (Z = 79). As we know, all these elements are good conductors of electricity.

Any element having partially filled valance band should behave like a conductor

Beryllium (Z = 4)

$1s^2\ 2s^2\ 2p^{\cdots}$

we expect that the 2s band of the beryllium should be completely filled and should behave like the valance band.
The next band should be 2p, it should be empty and should behave like a conduction band.
We expect that because of the existence of a finite gap (containing forbidden levels) between the valance and conduction band, beryllium **should behave like an insulator**.
But **behaves like a conductor**.
Beryllium atoms come close, the 2s and 2p bands split.
As the distance approaches equilibrium separation, the 2s and 2p band expand and **at certain stage they merge (overlap) in to each other**.
Thus instead of separate 2s and 2p bands, we get **2s-2p hybrid band having 2N + 6N = 8N** available states. Out of these 8N states only lower 2N states are filled while the upper 6N states are unfilled.
Thus 2s-2p hybrid band is partially filled and thus beryllium behaves as a conductor.
Beryllium belongs to group II elements in the periodic table.



Insulators

ex: Diamond, band gap of **5.7 eV**.

The thermal energy of the valance electrons at 300 K is approximately **0.038 eV**

This is quite insufficient for the valance electrons to cross the band gap and enter in the conduction band

The electron cannot be excited to any energy level within the band gap, as these energy levels are forbidden.

Thus the concentration of the free electrons in diamond is extremely poor
it is an insulator

Imparted any energy is immediately lost by the electron during it's collisions with the crystal imperfections

The band gap of diamond is 5.7 eV
The energies of the photons in the visible range is 1 to 3 eV.
Thus light cannot be absorbed in diamond
Therefore it is transparent to the light

Conductors

Due to either **partially filled valance band** or **overlapping of valance and conduction bands**, there is **no forbidden gap** in the conductors

At **absolute zero, the energy of electrons is not sufficient to enter the conduction band**

At room temperature, **due to thermal energy, the electrons just below the Fermi level can be easily excited to the conduction band**.

When electric field is applied, the electrons start moving an constitute the current.

The resistivity of the conductors (metals)

$$\rho = \frac{m}{ne^2\tau}$$

n - Number density of the electrons in the conduction band
τ - The relaxation time, that is the average time between the successive collisions.

Zero band gap, all valance electrons are set free at room temperature
When the **temperature is raised** further, this sea of electrons is thermally agitated offers resistance to the flow of conduction electron and increases with the temperature
Conductors thus have **Positive temperature coefficient** of resistance

Semiconductors

Band gap of silicon --- 1.12 eV
Band gap of germanium --- 0.72 eV
Band gap of insulator > Band gap of Semiconductor > Band gap of of conductor

At room temperature, the thermal energy raises a small number of electrons in to conduction band

free electron density
silicon **10^{16} /m^3** < copper (10^{28} /m^3)

semiconductors exhibit a small conductivity better than insulators

the concentration of the charge carriers in the semiconductors can be increased significantly by adding impurities

Semiconductors have two kinds of charge carriers

When an electron is excited to the conduction band, it leaves a vacancy in the valance band. This vacancy is called **hole** (positive charge carrier).
Thus semiconductors have bipolar conduction (electrons and holes).

Thermistors: (Temperature dependent resistors)
When heat is applied, the electrons are thermally excited to the conduction band. Thus resistance of the semiconductors decreases with temperature.
Semiconductors are thus said to have N**egative temperature coefficient of resistance**

Semiconductors can convert light in to electricity and vice versa

Name of the semiconductor	Symbol	Band gap (eV)	Wavelength corresponding to the band gap (A°)	Description
Silicon	Si	1.12	11099	Solar cells and other electronic components
Germanium	Ge	0.67	18553	Electronic devices
Silicon carbide	SiC	2.3	5404	Yellow LEDs
Gallium Nitride	GaN	3.44	3613	Electronics and spintronics, blue LEDs
Gallium Phosphide	GaP	2.26	5500	Red orange and green LEDs (after doping)
Gallium Arsenide	GaAs	1.43	8693	Next to silicon, IR LEDs, solar cells (after doping)
Cadmium sulphide	CdS	2.42	5136	Photoresistor, solar cells, quantum dots, lasers
Zinc Oxide	ZnO	3.37	3689	Laser diodes and conductive coatings

FERMI DIRAC STATISTICS

It is the statistical description of an electrons in semiconductors
It gives the **probabilityof an electron to have an energy E**
It is a quantum statistics, which is **applicable to all particles having odd half integral spin** i.e. 1/2,3/2, 5/2..
Ex: Electron

In this statistics electrons are treated as wave, **which obeys Pauli's exclusion principle**-- **Fermions**

Fermions are **identicle but indistinguishable**, whose wave functions overlap considerably

The **wave functions of Fermions change the sign when electrons in any pair are exchanged** and thus are called as **antisymmetric wave functions**

The probability P(E) that fermion occupies a quantum state of energy E, at Temparature T is given by

$$P(E) = \frac{1}{1 + e^{\frac{(E - E_F)}{kT}}}$$

k- Boltzman Constant
E_F- Fermi energy

Probability of occupancy of higher energy levels increases with temperature

Fermi energy

The energy of the top most filled level in the ground state of the N-electron system

$$\mathbf{E_F = (\hbar^2/2m)\,(N\pi/2L)^2 = (\hbar^2/2m)\,(n_F\pi/L)^2}$$

$N=2n_F$

n_F --- Uppermost filled Level

An electron of mass **m** confined to a length **L**

Fermi energy plays important role in determining properties of semiconductors

Fermi Level

The highest occupied energy level of the electrons in the valance band at 0^o K

At 0^oK all energy states upto E_F are occupied and all states above E_F are unoccupied (empty)

Probability P(E) that fermions occupies a quantum state of energy E, at Temparature T is given by

$$P(E) = \frac{1}{1 + e^{\frac{(E-E_F)}{kT}}}$$

k- Boltzman Constant
E_F- Fermi energy

At T=0K, there are two possibilities

$E>E_F$ or $E<E_F$
At T=0K and $E>E_F$ we have $(E-E_F) >0$ Positive, Thus

$$P(E) = \frac{1}{1 + e^{\frac{(E-E_F)}{0}}} = \frac{1}{1 + e^{+\infty}} = 0$$

Thus at T = 0 K, **the probability of occupancy of all the levels above the Fermi level is zero**.
Thus at T = 0 K, **all the energy levels above the Fermi level are certainly unoccupied**

At T=0K and E<E_F we have (E-E_F) <0 Negative, Thus

$$P(E) = \frac{1}{1 + e^{\frac{(E-E_F)}{0}}} = \frac{1}{1 + e^{-\infty}} = 1$$

Thus at T = 0 K, the **probability of occupancy of all the energy levels below the Fermi level is one**.
Thus at T = 0 K, **all the energy levels below the Fermi level are certainly occupied**.

At **T=0K and E=E_F** we get

$$P(E) = \frac{1}{1 + e^{\frac{0}{0}}} = indeterminate$$

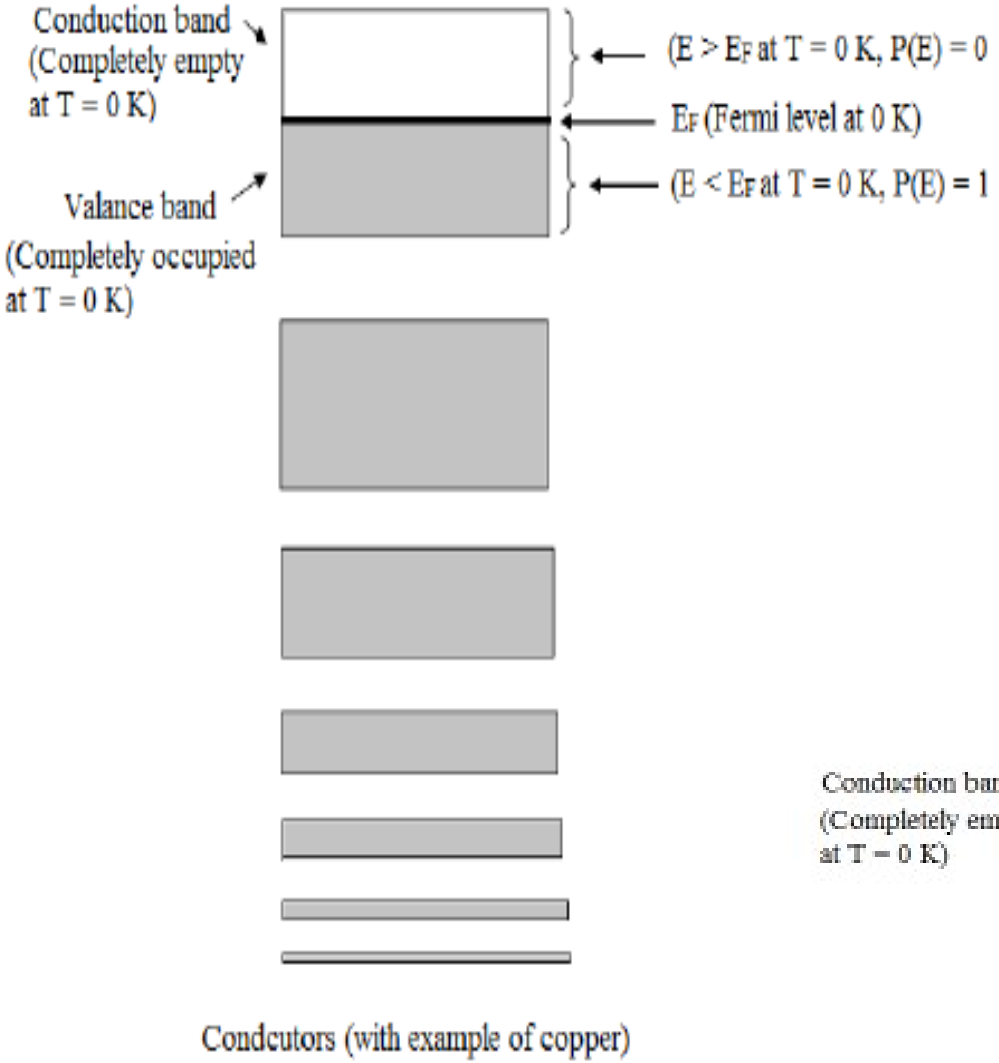
This not possible

At **T>0K and E=E_F** we get

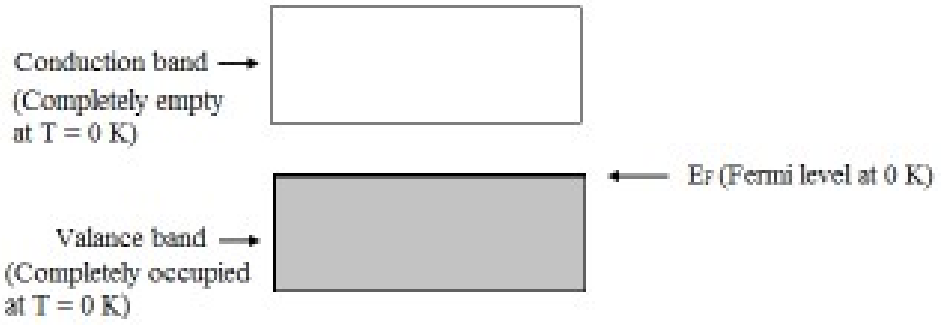
$$P(E) = P(E_F) = \frac{1}{1 + e^{\frac{0}{T}}} = \frac{1}{1 + e^{0}} = \frac{1}{1 + 1} = \frac{1}{2} = 0.5 = 50\%$$

Thus the **probability of the occupancy of the Fermi level at any finite (nonzero) temperature is Always 50%**.
This is applicable to **metals, semiconductors as well as insulators**

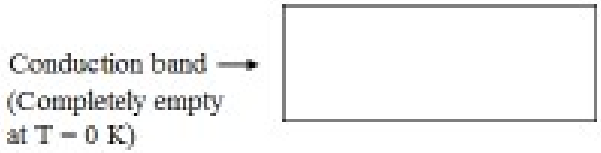
Physical significance of Fermi level Depending on temperatures



Condcutors (with example of copper)

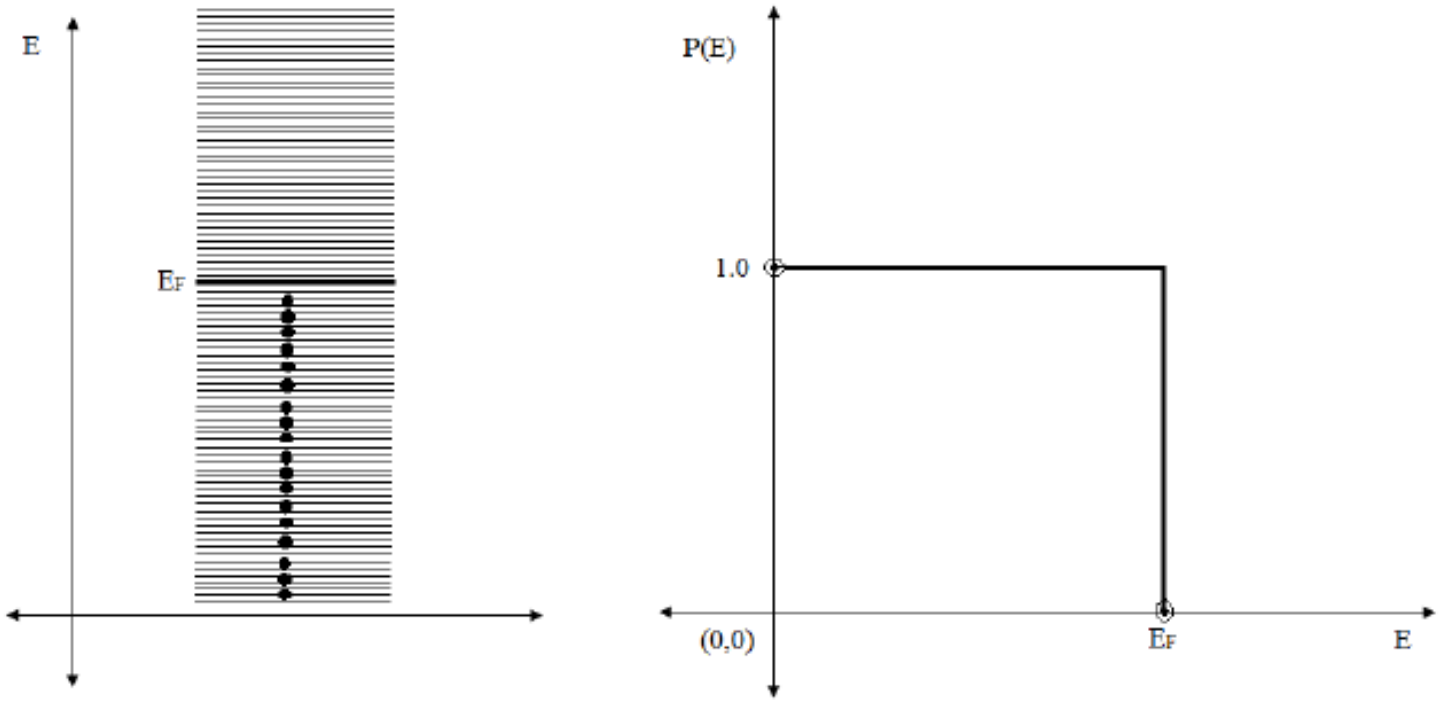


Semiconductors

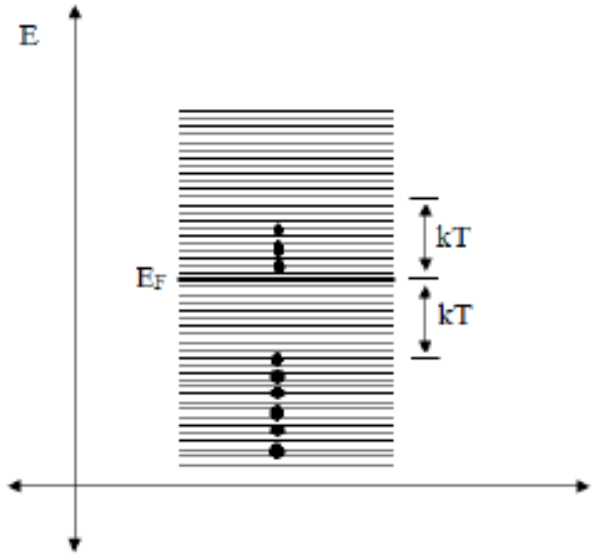


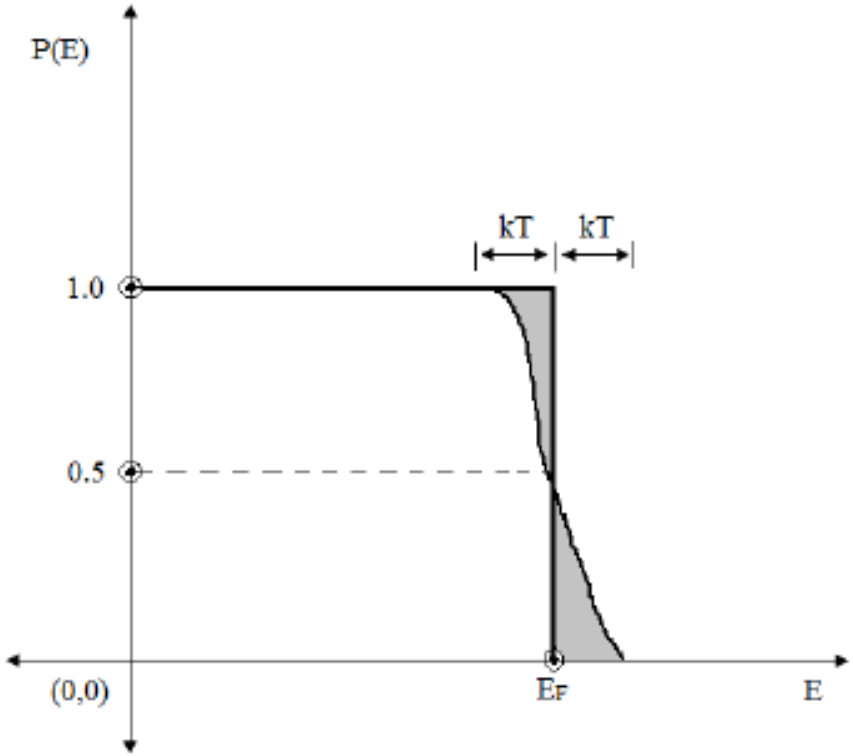
Insulators

The significance of Fermi level in conductors (metals) at T = 0 K

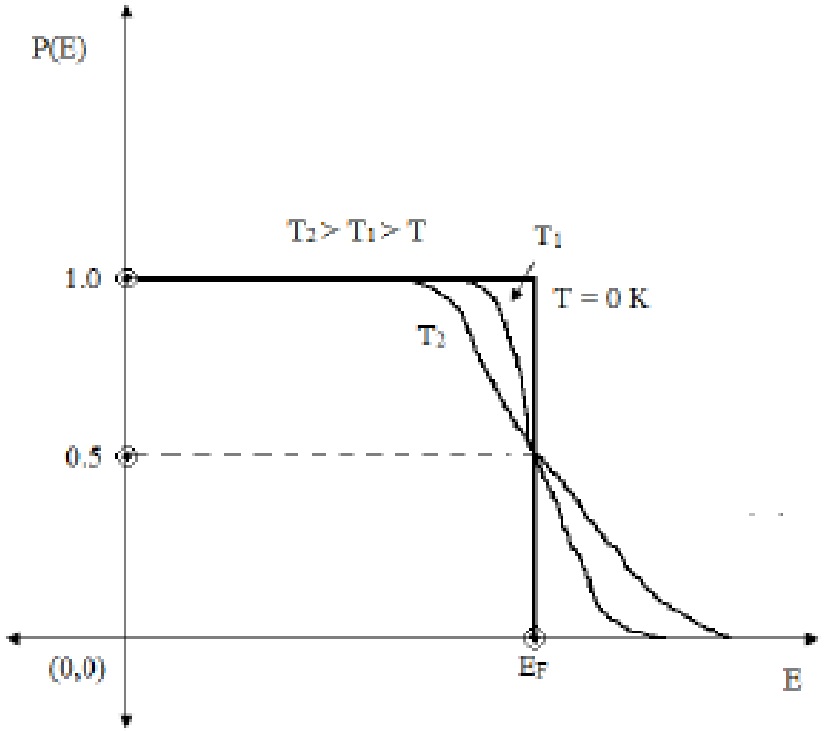


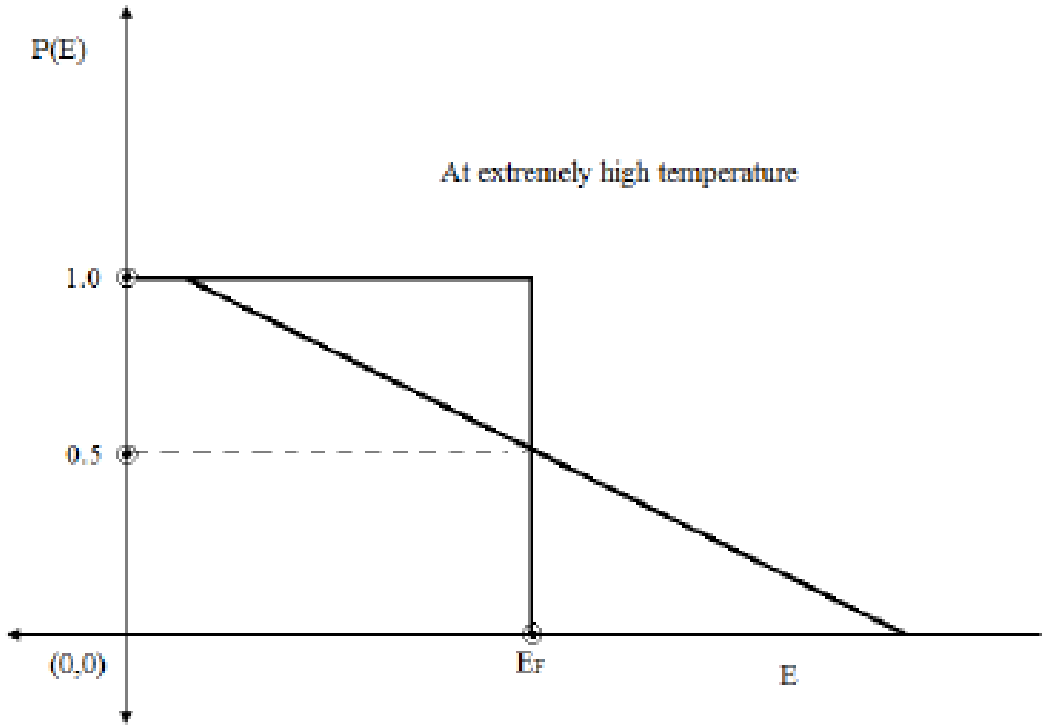
The significance of Fermi level in conductors (metals) at T > 0 K



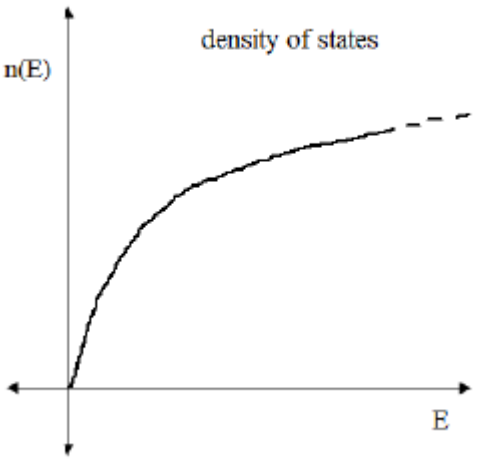


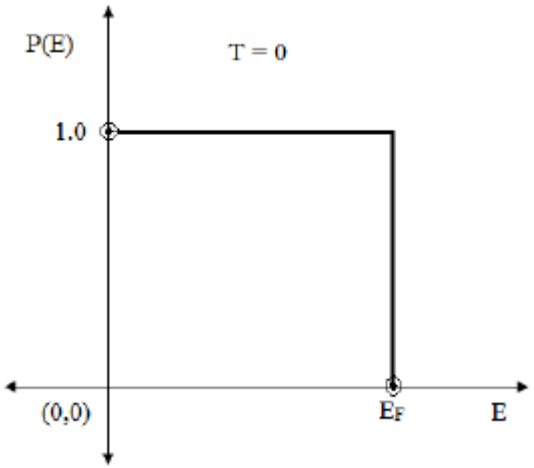
Graphical representation of Fermi Dirac statistics. Physical significance of the Fermi level

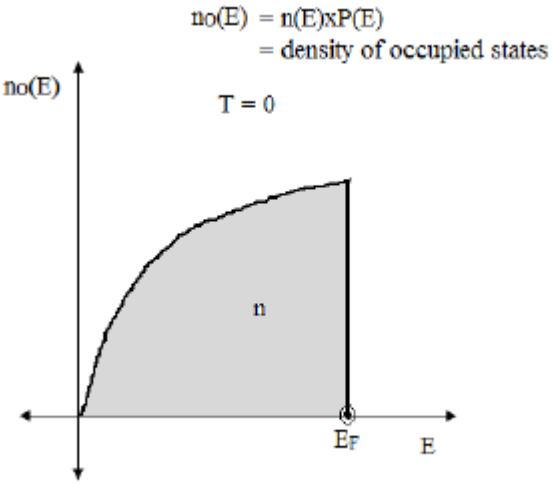




Density of states at T = 0 K



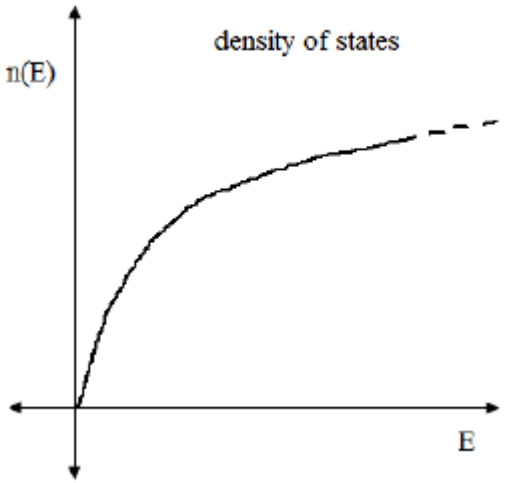


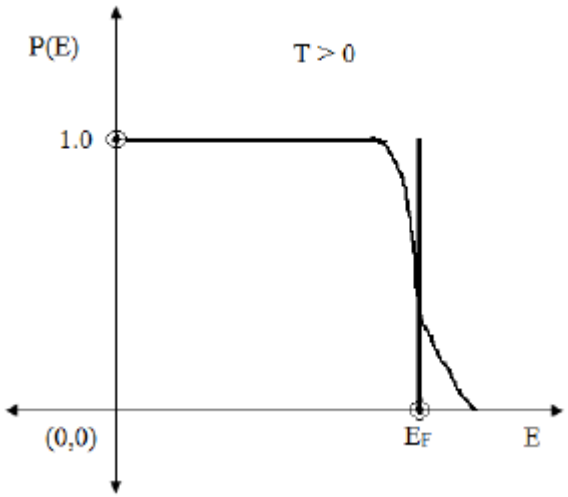


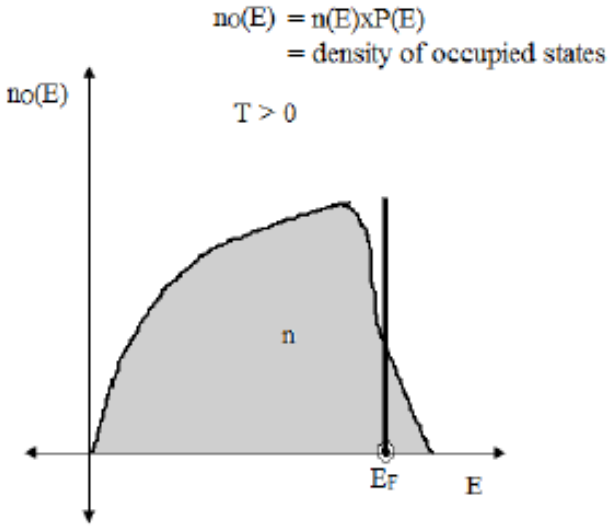
$$n(E) = \frac{8\sqrt{2}\pi m^{\frac{3}{2}}}{h^3} E^{\frac{1}{2}}$$

Density of states = number of quantum states n(E), per unit energy interval

Density of states at T > 0 K





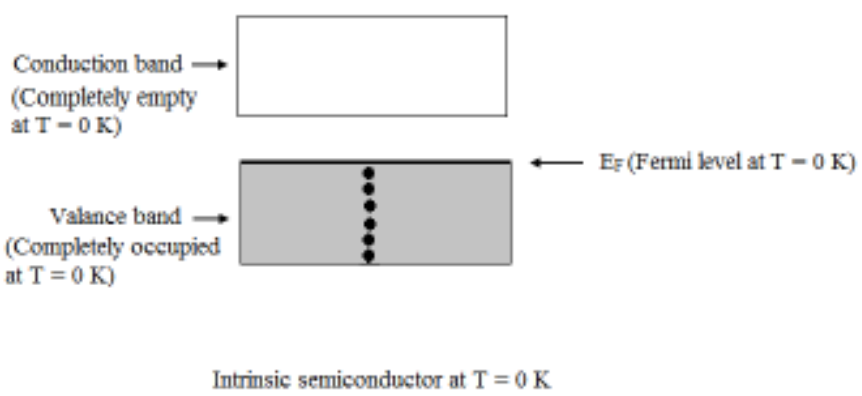


The probability of the occupancy of the levels above the fermi level increases at the cost of energy levels below E_F.

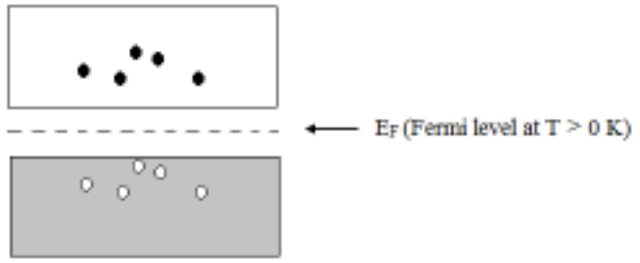
Thus density of the occupied states above E_F increases at the cost of density of occupied states below E_F

The graphs at T>0K are almost similar to the graphs of T=0K indicates that **even at higher** temperatures, **modifications take place only in the closet vicinity of Fermi level**.

Fermi Level in Intrinsic Semiconductors



Intrinsic semiconductor at T = 0 K



Intrinsic semiconductor at T > 0 K

At 0^oK highest occupied level is fermi level

At any non-zero temperature, Fermi level is an average level whose probability of occupancy is 50%

$$E_F = \frac{E_V + E_C}{2}$$

E_V and E_C are the average energies of the electrons in valance and conduction bands

Intrinsic semiconductors, the Fermi level is situated in the middle of the band gap

Fermi Level in N-Type Semiconductors

There are donor energy levels just below the conduction band.

At 0°K, these levels are occupied by unshared electrons of pentavalent impurity.

Majority of the electrons in the conduction band come from these donor levels.

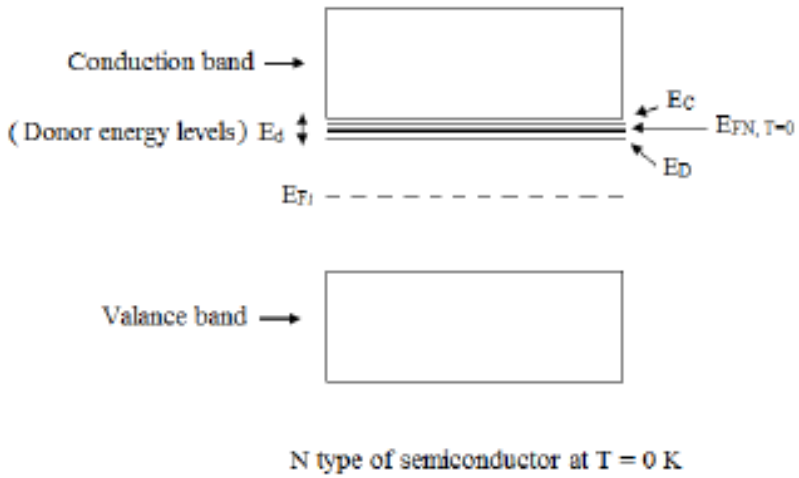
At 0 K, all these electrons exist in donor levels only. Therefore the Fermi level of N type of semiconductor at 0 K is situated in the middle of the donor levels

$\mathbf{E_C \geq E_{FNT=0K} \geq E_D}$

$$E_{FN\,T=0K} = \frac{E_C + E_D}{2}$$

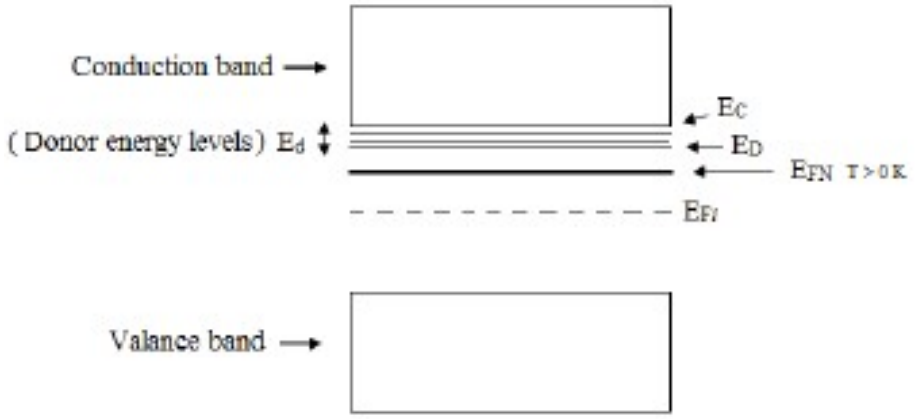
E_C --- lowest energy level in the conduction band

E_D --- lowest energy level amongst the donor levels



N type of semiconductor at T = 0 K

As every phosphorous atom ‘donates’ one free electron, it is called as‘donor impurity’. Unlike the 4 shared electrons, the energy levels of unshared electrons cannot be represented in the valance band, as it would mean that their energy gap is 1.1 eV. The negligible energy required to detach the unshared electrons indicates that the energy levels ofthese electrons be shown just below the conduction band. These energy levels are called **donor levels**

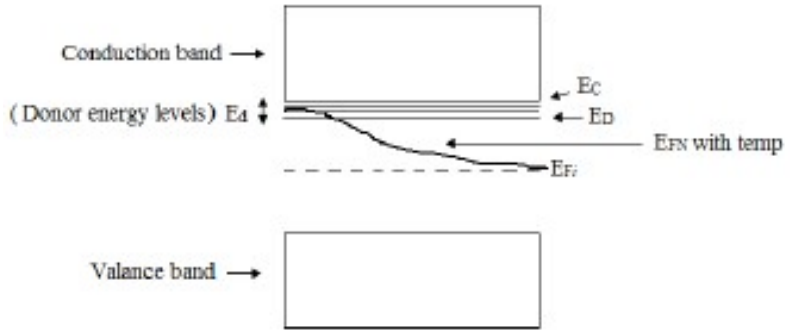


N type of semiconductor at T > 0 K

$$E_D \geq E_{FN\ T>0K} \geq E_{Fi}$$

Temperature is raised, the electrons in the donor levels start gaining thermal energy and they move to conduction band.
Thus the **donor levels are gradually depleted**.
As a result, the **Fermi level starts moving down**.

Temperature is **further raised**, the **electrons in the valance band also start going in to the conduction band.**
This results in generation of holes in valance band.
To account for this, the Fermi level further shifts down.
At moderate temperatures, the Fermi level can never reach the intrinsic Fermi level,
in between the lowest donor level and intrinsic Fermi level



N type of semiconductor
Variation of Fermi level with temperature

At extremely higher temperature, almost **all electrons in the valance band are excited to the conduction band**.
These electrons are extremely large in number as compared to the electron donated by the donor levels.
Thus **at very high temperatures, the concentration of the electrons in conduction band and holes in the valance band is almost equa**l.

This indicates that at very high temperatures, **N type semiconductor is converted to intrinsic semiconductor**.

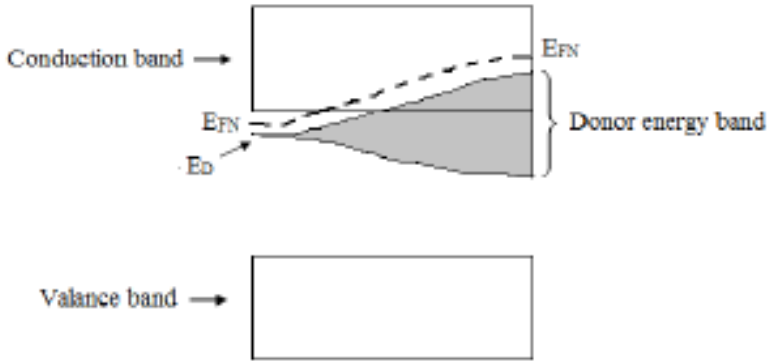
In this situation the Fermi level of the N type of semiconductor coincides with the intrinsic Fermi level.

Effect of dopant concentration on Fermi level of N type semiconductor

At moderate concentration, the distance between the donor atoms is large enough.
Interaction between the donor atoms is also weak.
Therefore **the donor levels do not split and they remain discrete**.
If the **concentration is further increased the distance between the donor atoms decreases and they start interacting**.

----> **the donor levels interact and they become a donor band**.
If the **concentration is still increased, donor levels split to a greater extent and the donor band expands and invades in the conduction band**.

As a result the **Fermi level also enters in the conduction band**



N type of semiconductor
Effect of increasing doping concentration

Fermi Level in P-Type Semiconductors

E_F in P-type is opposite to N-Type semiconductor

There are acceptor levels near the valance band.

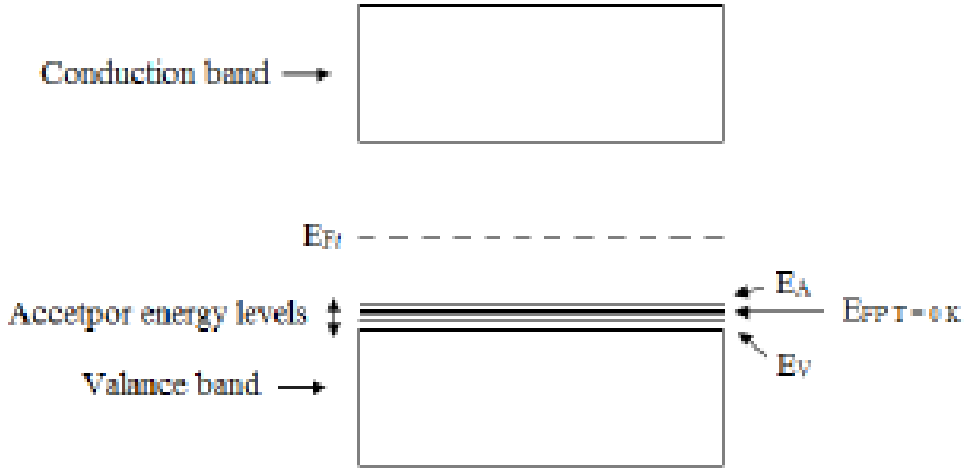
The holes in P type semiconductor are only due to transitions of electrons from valance band to the acceptor levels.

As the **valance band is the source of electrons and acceptor levels are recipients of them**, the **Fermi level is situated in the middle of the group of acceptor levels**

$$E_A \geq E_{FPT=0K} \geq E_V$$

E_A is the highest acceptor level

E_V is the highest level in the valance band



P type of semiconductor at T = 0 K

Temperature is raised, the electrons in the valance band **gain thermal energy to raise in the acceptor levels.**

As a result, **concentration of electrons in the acceptor levels increases and the Fermi level moves upward.**

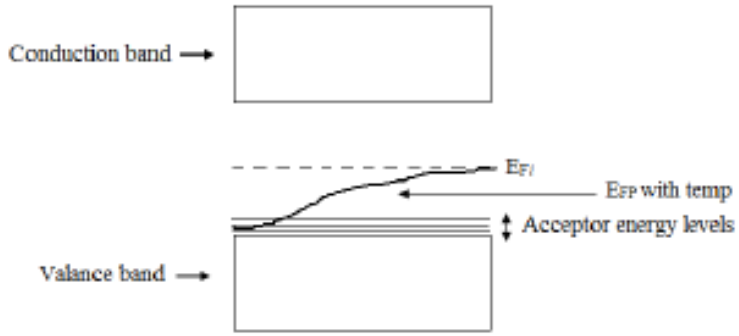
As the temperature is further increased, at moderate temperatures, the electrons in the valance band are thermally excited to the conduction band.
Thus, concentration of the electrons in the conduction band increases.
As a result, the Fermi level further shifts up

$$E_{Fi} \geq E_{FP\ T > 0K} \geq E_A$$

at moderate temperatures, it cannot touch the intrinsic Fermi level
if the temperature is extremely high, then the almost all the electrons in the valance band are excited to the conduction band.

concentration of intrinsic charge carriers overcomes the concentration of holes due to acceptor impurity.

concentration of electrons in the conduction band and holes in the valance band becomes almost equal.



P type of semiconductor
Variation of Fermi level with temperature

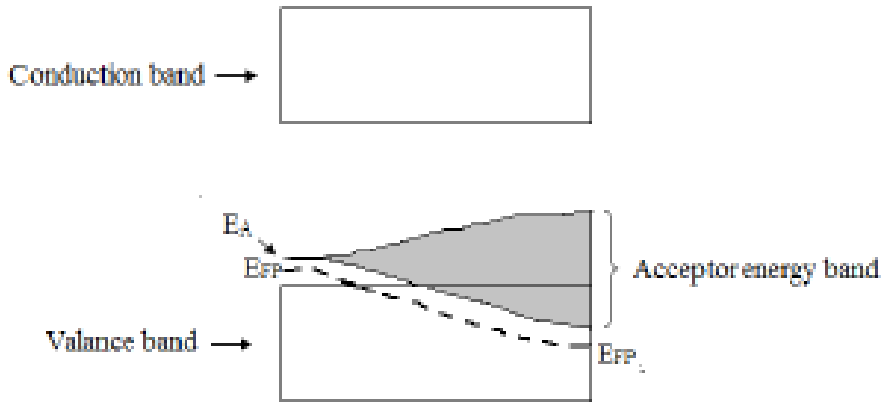
Thus at extremely high temperatures, the P type semiconductor is converted in to intrinsic

Effect of dopant concentration on Fermi level of P type semiconductor

At very low doping level, the distance between the acceptor impurity atoms is comparatively large.
Interaction between the acceptor impurity atoms is weak
acceptor levels are discrete.

Doping level is increased, the atom-to-atom distance of the acceptor impurity decreases. They interact and thus the acceptor levels split.

Doping level is further increased, the acceptor levels become acceptor band and then it penetrates in the valance band



P type of semiconductor
Effect of increasing doping concentration

The current which occurs due to a gradual drift of electrons towards the positive terminal (or holes towards the negative terminal) is called as drift current, The corresponding velocity is called as drift velocity (v_d)

$$v_d = \frac{\Delta l}{\Delta t}$$

Mobility $\mu = \frac{v_d}{E}$

Current= **$I = nqv_d A$**

n-- carrier concentration/charge particle density/number of charge carriers per unit volume
J - current density

$J = \frac{I}{A}$ and $\mu = \frac{v_d}{E}$, we have

$$J = \frac{I}{A} = nq v_d$$

$$J = \frac{I}{A} = nq\mu E$$

Conductivity = $\boldsymbol{\sigma = nq\mu}$

semiconductors contain two kinds of charge carriers; electrons and holes

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