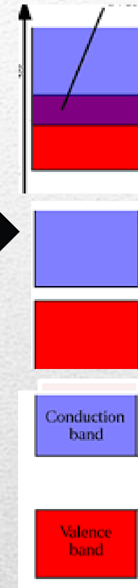
SEMICONDUCTORS

STATES OF MATTER

Solids

Liquids

Gas



Conductors

Semiconductors

Insulators

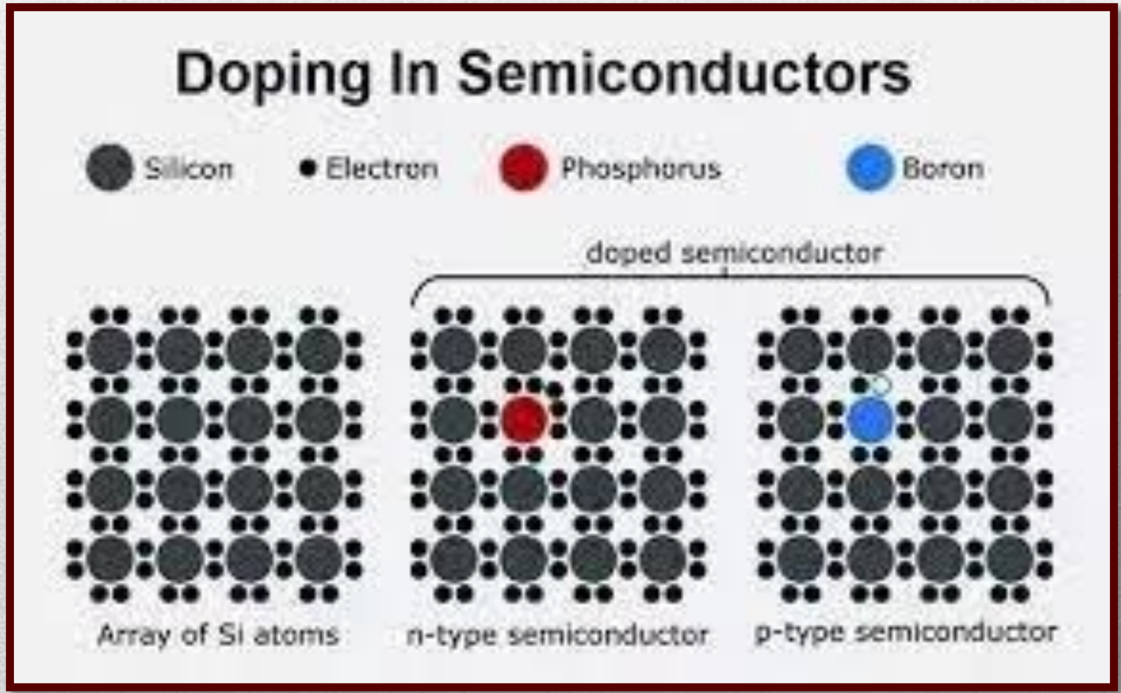
Band Gap values
Conductors: VB and CB overlaps
Semiconductors: ~1-3 eV
Insulators: > 5eV

DOPING IN SEMICONDUCTORS

- **Semiconducting materials are very sensitive to impurities in the crystal lattice.**
- **The controlled addition of these impurities is known as doping.**
- **Allows the tuning of the electronic properties: technological applications.**
- **Pure semiconductor are called ‘intrinsic’.**
- **Introduction of dopants →’extrinsic semiconductors’.**
- **Introduction of dopants → (i) new intra-band, energy levels**

  (ii) Generation of positive or negative charge carriers.

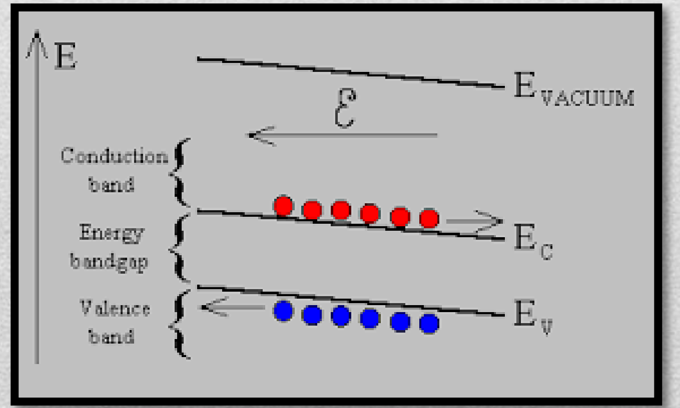
- **Extrinsic Semiconductors-**
- **(i) n-type: Pentavalent impurity- electrons as majority charge carriers (Donor Atoms)**
- **(ii) p-type: Trivalent impurity- holes as majority charge carriers (Acceptor atoms)**

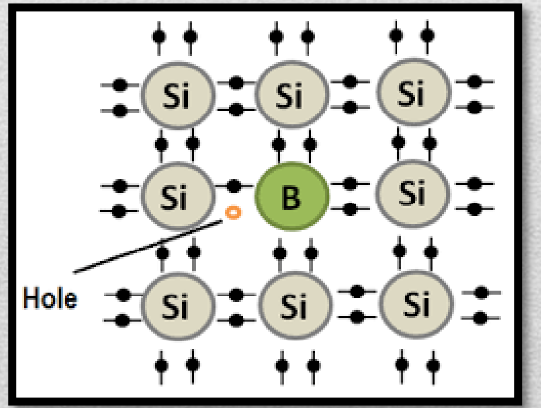


https://www.quora.com/Why-is-doping-required-in-a-semiconductor

CONCEPT OF HOLES

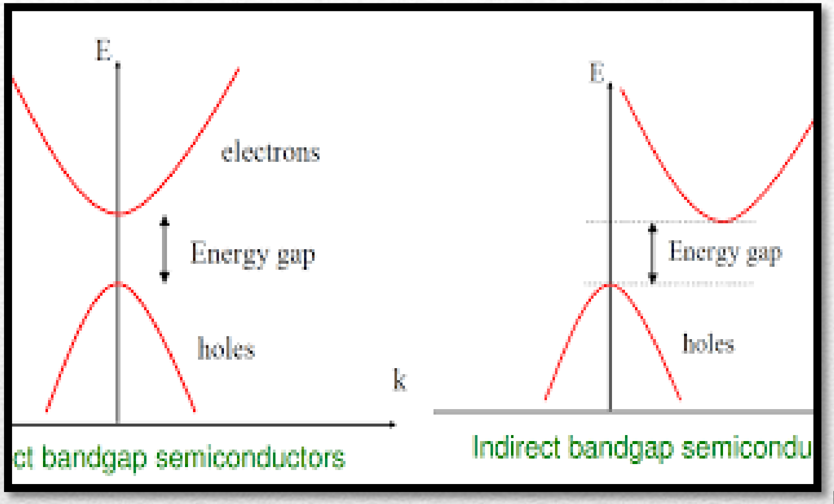
- **A hole can be seen as the "opposite" of an electron.**
- **Holes have a positive charge.**
- **They are the *absence* of an electron in an atom (not physical particles).**
- **They are formed when electrons in atoms move out of the valence band to the conduction band.**
- **Holes can move from atom to atom in semiconducting materials as electrons leave their positions.**





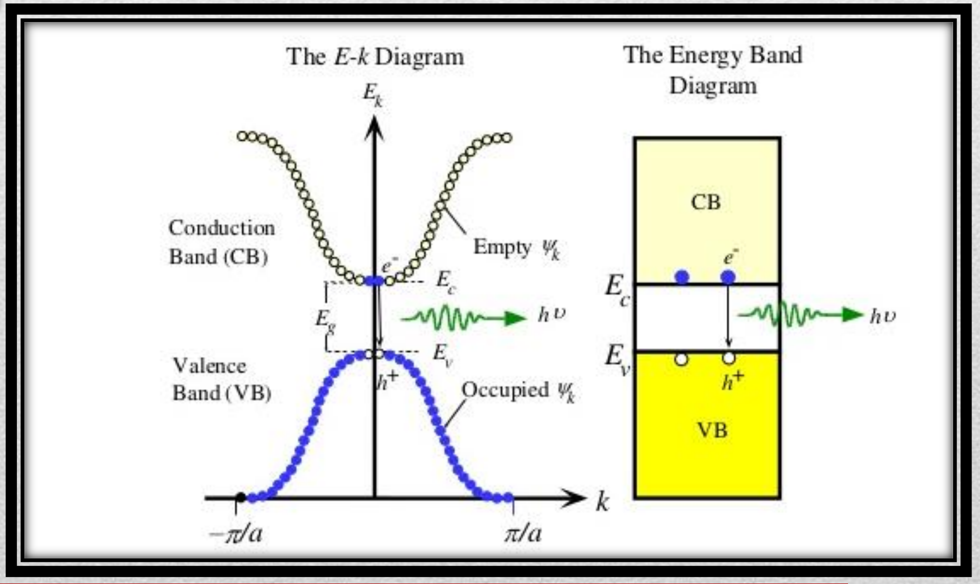
https://ecee.colorado.edu/~bart/book/eband4.htm

BAND GAP IN SEMICONDUCTORS



Direct gap is important in optoelectronics as direct band gap materials have efficient radiative absorption and emission, which is what makes LEDs and laser diodes work

- An E-k diagram shows characteristics of a particular semiconductor material.
- It shows the relationship between the energy and momentum of available quantum mechanical states for electrons in the material.

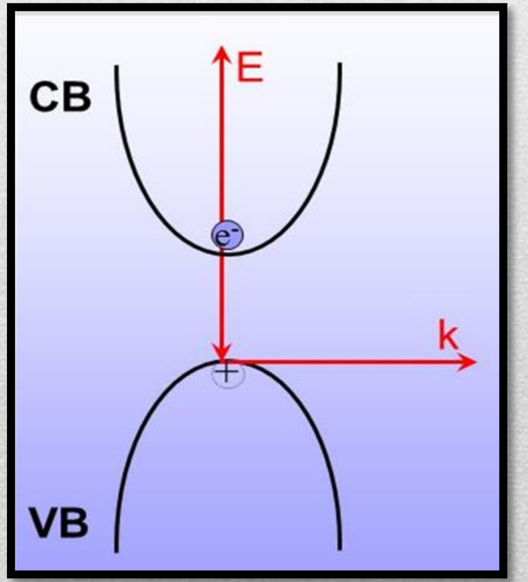


http://edetec106.blogspot.com/2016/01/differentiate-between-direct-and.html
https://www.slideshare.net/chinkitkit/chapter-4a-36657201

EFFECTIVE MASS

- **The effective mass represents the effect of all the internal forces on the motion of the electron in the conduction band.**
- **Assumption: Mass of electron in solid is same as the mass of a free electron.**
- **Experimentally: In some solids, electron mass is more while for some it is less than the free electron mass.**
- **Effective mass: Experimentally determined electron mass.**
- **Reason: Interaction between the drifting electrons and the atoms in the solids.**
- **Sign of effective mass: determined from the sign of curvature of the E-k curve.**

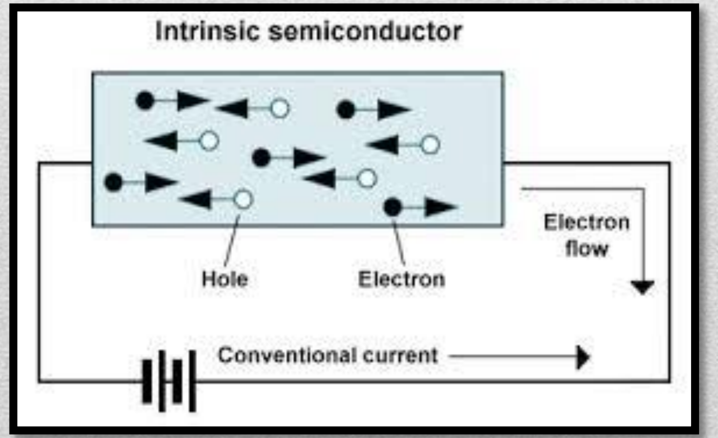
- **The curvature of a graph at a minimum point is a positive quantity and while the curvature at a maximum point is a negative quantity.**
- **Particles (electrons) : near the minimum has a positive effective mass.**
- **Particles (holes) : near the valence band maximum has a negative effective mass.**
- $m^* = \frac{\hbar^2}{d^2E/dk^2}$



For Derivation refer class notes

MOBILITY

- When an electric field is applied across a solid, it accelerates the electrons in the direction of applied field.
- The moving electrons undergo repeated collisions with the atoms and hence moves with a steady velocity known as Drift velocity represented as υ_d .
- $\vartheta_d \propto E \rightarrow \vartheta_d = \mu E$ *where μ is the mobility of electrons*.
- Mobility: measure of how quickly an electron can move through a metal or semiconductor in presence of electrical field.
- Semiconductor mobility depends
  (i) defect concentration (ii) temperature.
- μ_e (metals) = 10^{-3} m^2/Vs
- μ_e (semiconductors) = 10^{-1} m^2/Vs.



CARRIER CONCENTRATION

- **The density of electrons in a semiconductor → the density of available states and the probability that each of these states is occupied.**
- **The density of occupied states per unit volume *is given as***

$$n(E) = g_c(E)f(E)$$

- **Holes correspond to empty states in the valence band → the probability of having a hole equals the probability that a particular state is not filled.**
- **Hole density per unit energy, $p(E)$ is given as**

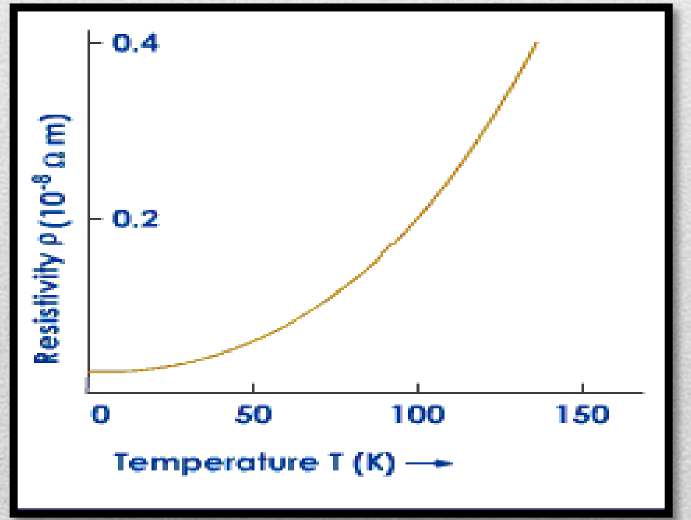
$$p(E) = g_v(\mathrm{E})\ [1 - f(E)]$$

where $g_v(E)$ is the density of states in the valence band.

- **The density of carriers is then obtained by integrating the density of carriers per unit energy over all possible energies within a band.**

CONDUCTIVITY IN METALS

- **Conductivity is attributed to *free-charge carriers in metals.***
- **Increase in temperature → increases the vibrations of the metal ions.**
- **Increased vibrations → causes frequent collisions between the electrons → drains out energy of the free electrons → restricts the movement of the delocalized electrons → drift velocity decreases → resistivity of the metal increases → current decreases → conductivity of the material decreases.**



- **$J = \sigma E$ (Ohm's law)**
  $\rho = 1/\sigma$

The temperature dependence is given as

$\rho_t = \rho_0 [\, 1 + \alpha\,(T - T_0)$

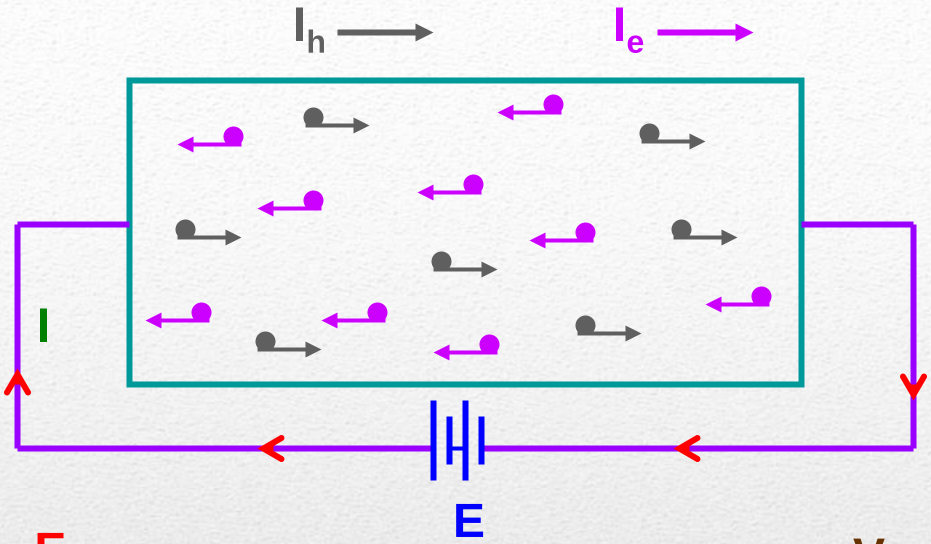
https://www.askiitians.com/iit-jee-electric-current/temperature-dependence-of-resistivity/

Electrical Conductivity of Semiconductors:

$I = I_e + I_h$

$I_e = neAv_e \qquad I_h = peAv_h$

So, $I = neAv_e + peAv_h$



If the applied electric field is small, then semiconductor obeys Ohm's law.

$$\therefore \frac{V}{R} = neAv_e + peAv_h$$

$$= eA\,(nv_e + pv_h)$$

Or $$\frac{V\,A}{\rho l} = eA\,(nv_e + pv_h)$$

since $R = \dfrac{\rho l}{A}$

$$\frac{E}{\rho} = e\,(nv_e + pv_h)$$

since $E = \dfrac{V}{l}$

Mobility (μ) is defined as the drift velocity per unit electric field.

$$\therefore \frac{1}{\rho} = e\,(n\mu_e + p\mu_h)$$

Or $\boxed{\sigma = e\,(n\mu_e + p\mu_h)}$

Note:

1. The electron mobility is higher than the hole mobility.
2. The resistivity / conductivity depends not only on the electron and hole densities but also on their mobilities.
3. The mobility depends relatively weakly on temperature.

CONDUCTIVITY IN INTRINSIC SC

- **For Intrinsic semiconductors, the conductivity is given by**

$$\sigma = e(n\mu_e + p\mu_h) = n_i e(\mu_e + \mu_h)$$

μ_n and μ_p refer to the mobilities of the electrons and holes

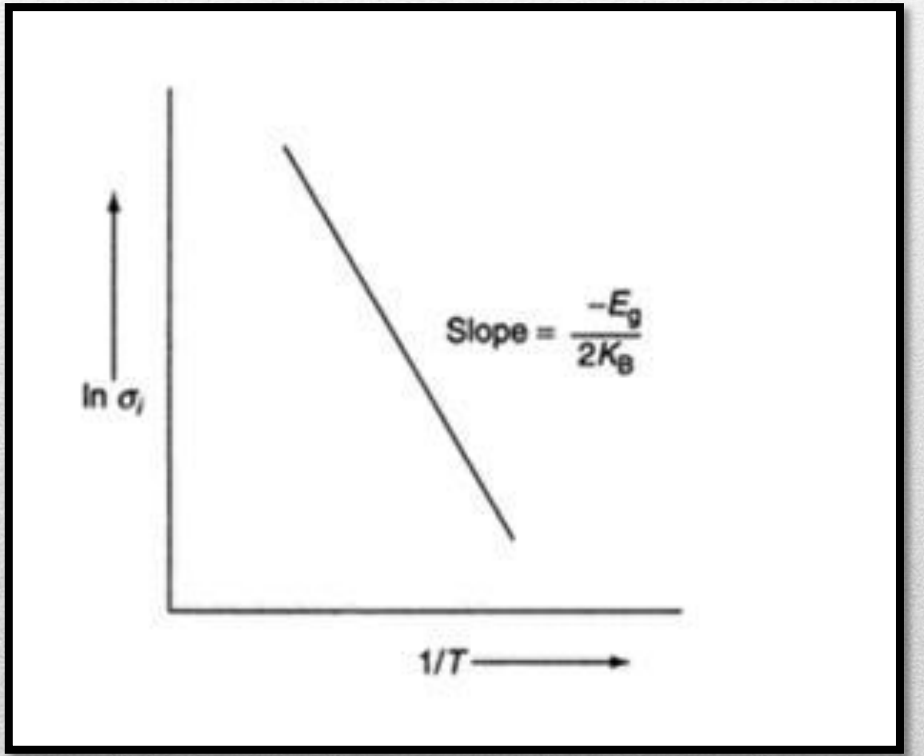
***n* and *p* refer to the density (concentration) of electrons and holes**

n_i is the intrinsic charge carrier density

- **The electrons in the valance band gains energy → moves to higher energy levels in the conduction band → becomes charge carriers**

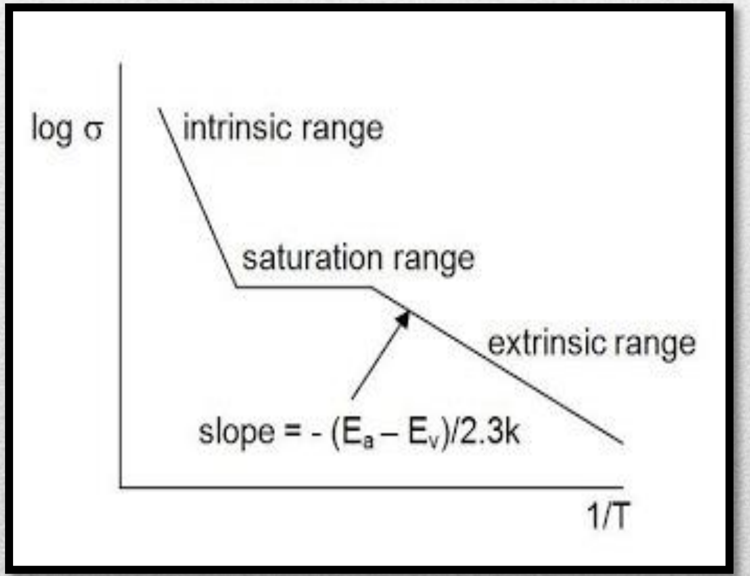
- **Carrier concentration depends exponentially on the band gap and is given as $n_i = \sqrt{N_c N_v}\exp\left(-\frac{E_g}{2k_B T}\right)$**

- **In Intrinsic semiconductors→ Conductivity increases with increasing temperature.**
- $\boldsymbol{log_e \sigma = \frac{-E_g}{2kT} + log_e B}$



CONDUCTIVITY IN EXTRINSIC SC

- **Low temperature → frozen charge carriers → resistivity is extremely high.**
- **Moderate increase in temperature → Rapid decrease in resistivity with the increase of ionized charges.**
- **At sufficiently high temperature → dopants are completely ionized → conductivity decreases and the resistivity increases again.**
- **At still higher temperature → resistivity decreases sharply due to appreciable excitation of all carriers and crossing the energy gap.**



- In doped semiconductor (Extrinsic), majority carriers greatly outnumbers the minority carriers, so that the equation can be reduced to a single term involving the majority carrier.

- For n-type semiconductor

$$\sigma_n = ne\mu_e$$

- For p-type semiconductor

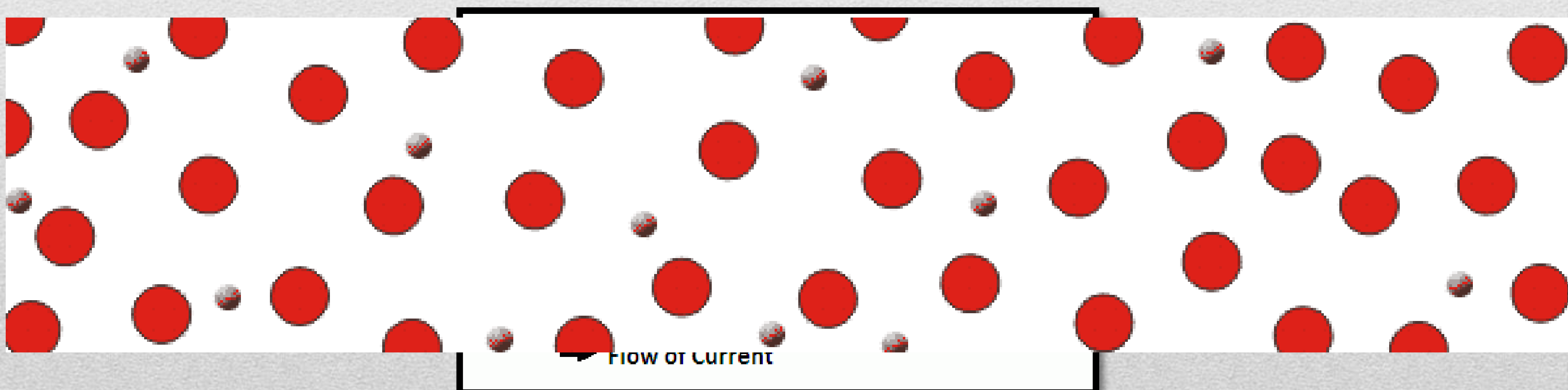
$$\sigma_p = pe\mu_h$$

- Conductivity of a material is determined by two factors:
  (i) concentration of free carriers available to conduct current
  (ii) their mobility (or freedom to move).

In a semiconductor, both mobility and carrier concentration are temperature dependent.

DRIFT CURRENT

- Absence of field: free electrons move in a conductor with random velocities and random directions.
- Presence of field: the randomly moving electrons experience an electrical force in the direction of the field.
- Electrons shift towards higher potential with their random motion.
- The electrons will drift towards higher potential along with their random motions.



https://web2.ph.utexas.edu/~coker2/index.files/current.htm

- **Electrons have a net velocity towards the higher potential end of the conductor known as the drift velocity of electrons.**
- **The drift movement of electrons inside an electrically stressed conductor, is known as drift current.**
- **The drift current density for hole and electrons are given by**

$$J_{(drift)el} = -nev_e$$

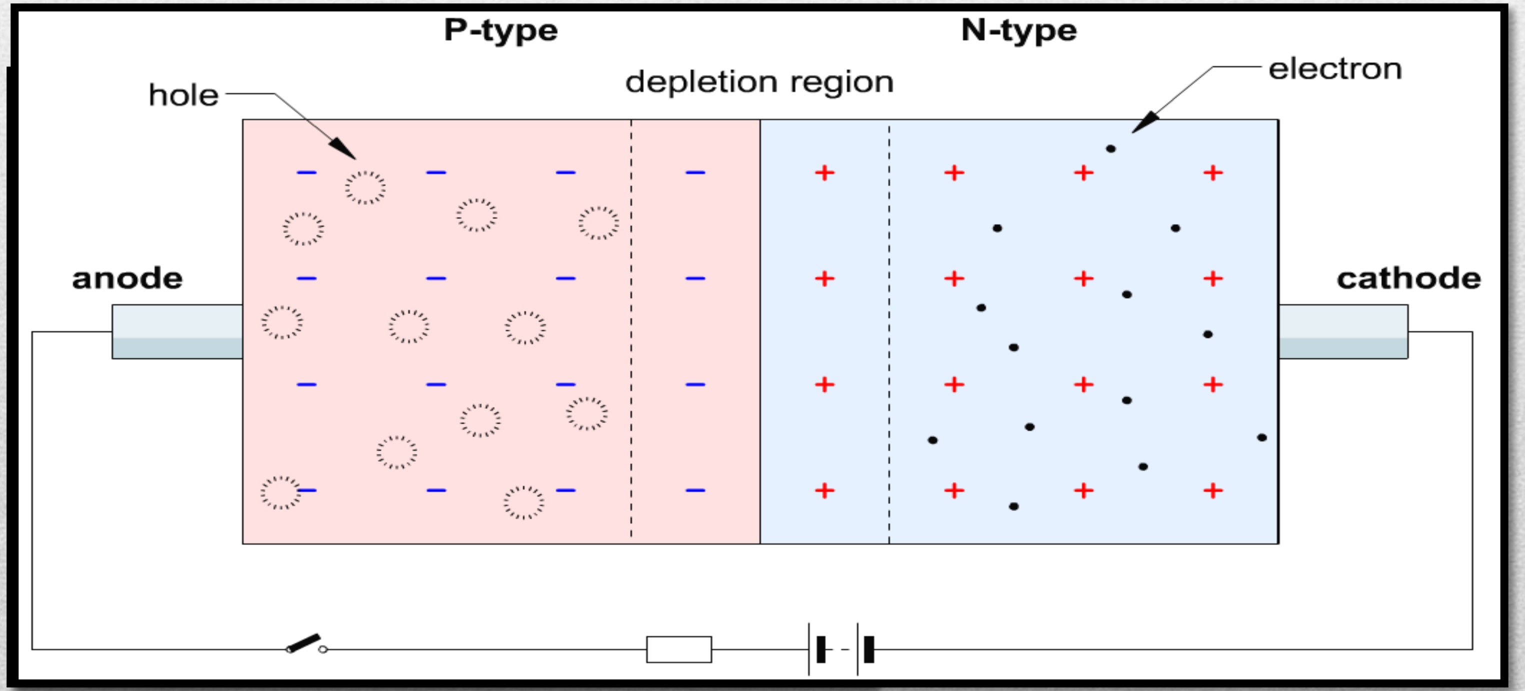
$$J_{(drift)hole} = pev_h$$

- **where *n*, *p* are the electron and hole densities, v_h and v_e are the drift velocities of holes and electrons respectively.**
- **Negative sign indicates that the electrons having -ve charge move in direction opposite to the applied field.**
- **Total drift current density**

$$J_{(drift)Total} = J_{(drift)hole} + J_{(drift)el} = pev_h + nev_e$$

DIFFUSION CURRENT

- In semiconducting material → Dopants are introduced to some region → even distribution of carriers takes place to maintain the uniformity → known as diffusion process
- Movement of the mobile charge carriers are responsible for the flow of diffusion current from one region to the other.
- No source of energy is required diffusion current.



http://semesters.in/v-i-characteristics-of-p-n-junction-diode-notes-for-electronics-engineering

DIFFUSION CURRENT

- **Non-uniformity of charge carriers (electrons/holes) → gives the diffusion current (is independent of the electric field) → depends on the concentration gradient.**
- **Concentration of electrons (*n*) and holes(*p*) varies with the distance *x*.**
- **Diffusion current density for electrons is $J_{(diff)el} = eD_n \frac{dn}{dx}$, where D_n is the diffusion coefficient for electrons and dn/dx is the concentration gradient of electrons.**
- **Diffusion current density for holes is $J_{(diff)ho} = -pD_p \frac{dp}{dx}$, where D_p is the diffusion coefficient for holes and dp/dx is the concentration gradient of holes.**
- **Resultant diffusion current density for both holes and electrons is given as $J_{(diff)Total} = eD_n \frac{dn}{dx} - pD_p \frac{dp}{dx}$**

TOTAL CURRENT DENSITY

Total current density in semiconductor is the sum of drift current and diffusion current is given by

$$J_{Total}=J_{drift}+J_{diffusion}$$

$$J_{Total}=J_{(drift)hole}+J_{(drift)el}+J_{(diffusion)el}+J_{(diffusion)hole}$$

$$J_{Total}=pev_h+nev_e+eD_n\frac{dn}{dx}-pD_p\frac{dp}{dx}$$

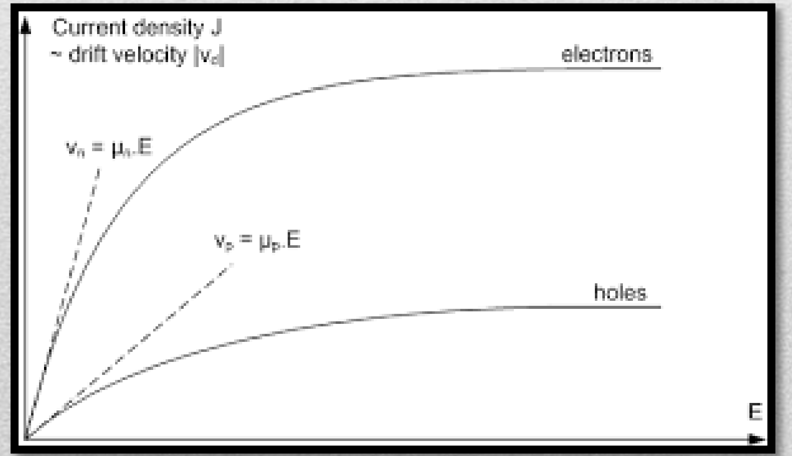


Figure shows the plot for the current density J_{drift} and the absolute value of the drift velocity, over the electric field E. The mobility of holes and electrons can be evaluated using the tangential of the drift velocity.

http://lamp.tu-graz.ac.at/~hadley/psd/problems/diffusioncurrent2/s.pdf

FERMI DIRAC DISTRIBUTION FUNCTION

- **The probability density functions describes the probability that particles occupy the available energy levels in a given system.**

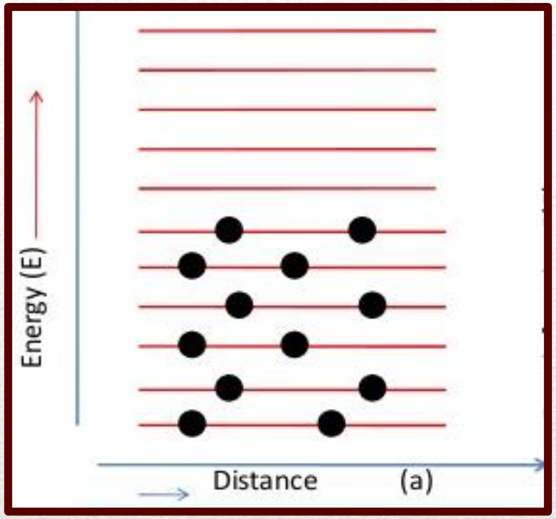
- **Fermions : half-integer spin particles- Electrons are Fermions- obeys Pauli exclusion principle → one Fermion occupies a single quantum state → fills the available states in an energy band.**

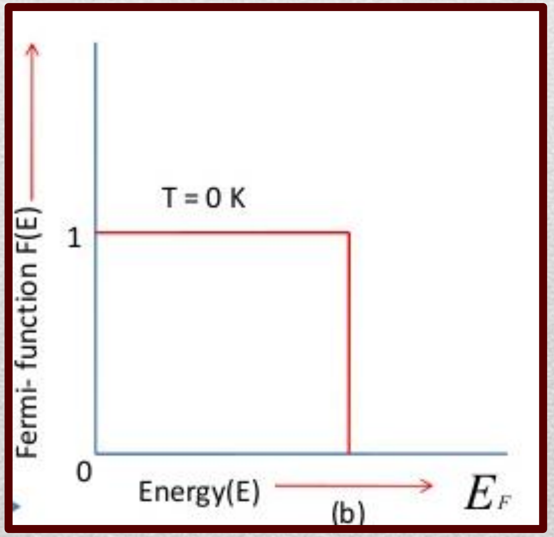
- **Fermi function : The probability that an energy level at energy, *E*, in thermal equilibrium with a large system, is occupied by an electron.**

- **Fermi Dirac distribution function is given as:**

- $f(E) = \frac{1}{1+exp^{(E-E_F)/kT}}$
- **E_F : Fermi energy; k : Boltzmann constant; T: Temperature**

FERMI LEVEL IN A CONDUCTOR





Fermi function is $f(E) = \frac{1}{1+exp^{(E-E_F)/kT}}$

Case 1: At T= 0 K; E< E_F => (E-E_F) is negative

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

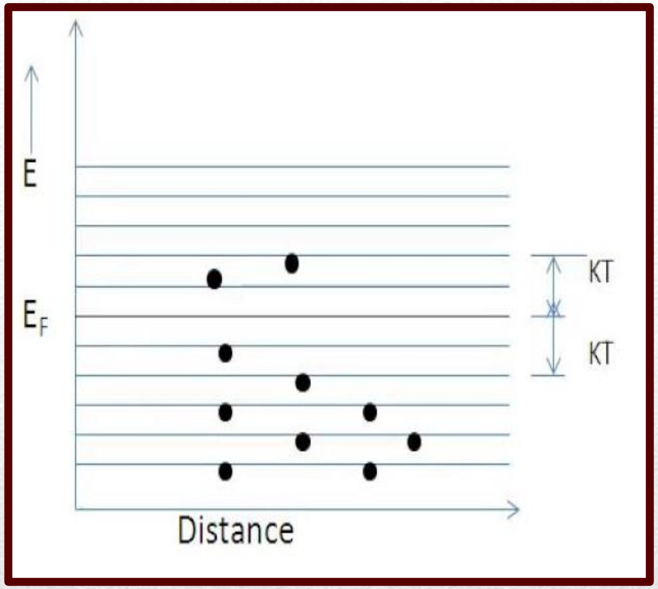
All *levels lying below E_F* are occupied.

Case 2: At T= 0 K; E> E_F => (E-E_F) is positive

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

***All energy levels lying above E_F* are vacant**

What happens to the fermi level at high temperature ?

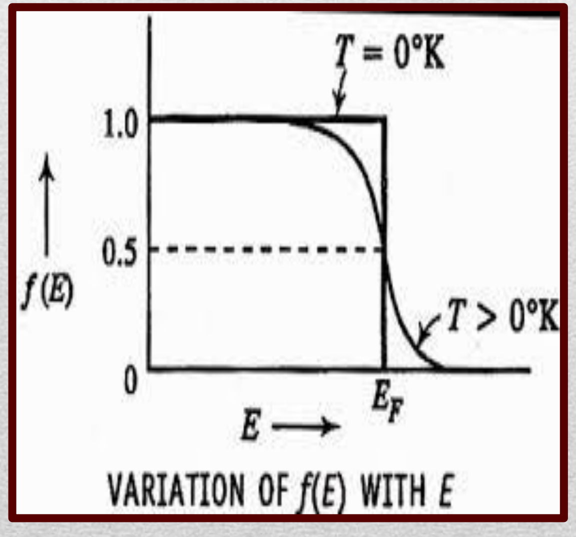


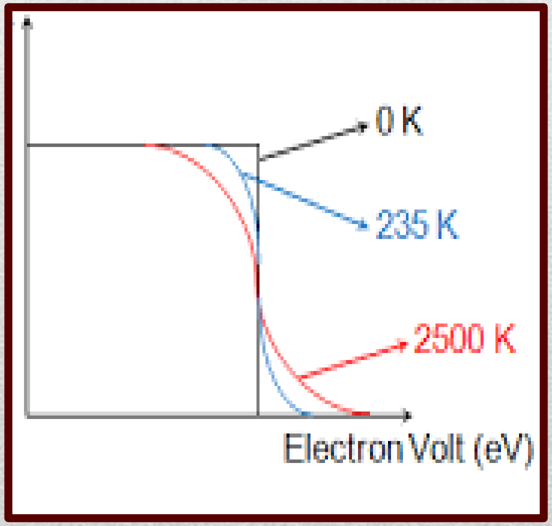
Case 3: At T > 0 K; $E=E_F$

$$\therefore f(E) = \frac{1}{1+e^{\left(\frac{0}{kT}\right)}} = \frac{1}{1+e^{0}} = \frac{1}{1+1} = \frac{1}{2}$$

The probability of occupancy at any temperature T > 0 K is 50 %.

Fermi energy: Average energy possessed by electrons participating in conduction at temperature above 0K.





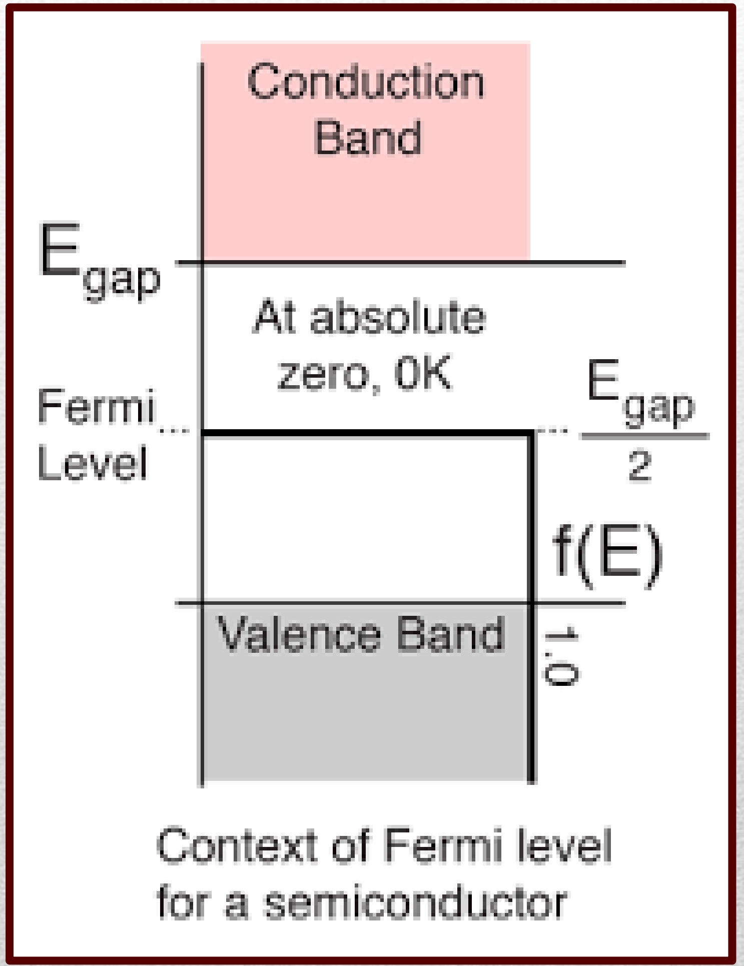
***Fermi velocity*: v_F: It is the velocity of the electrons in the highest occupied states in metals at zero temperature.**

$$v_F = \sqrt{2E_F/m}$$

https://www.electrical4u.com/fermi-dirac-distribution-function/

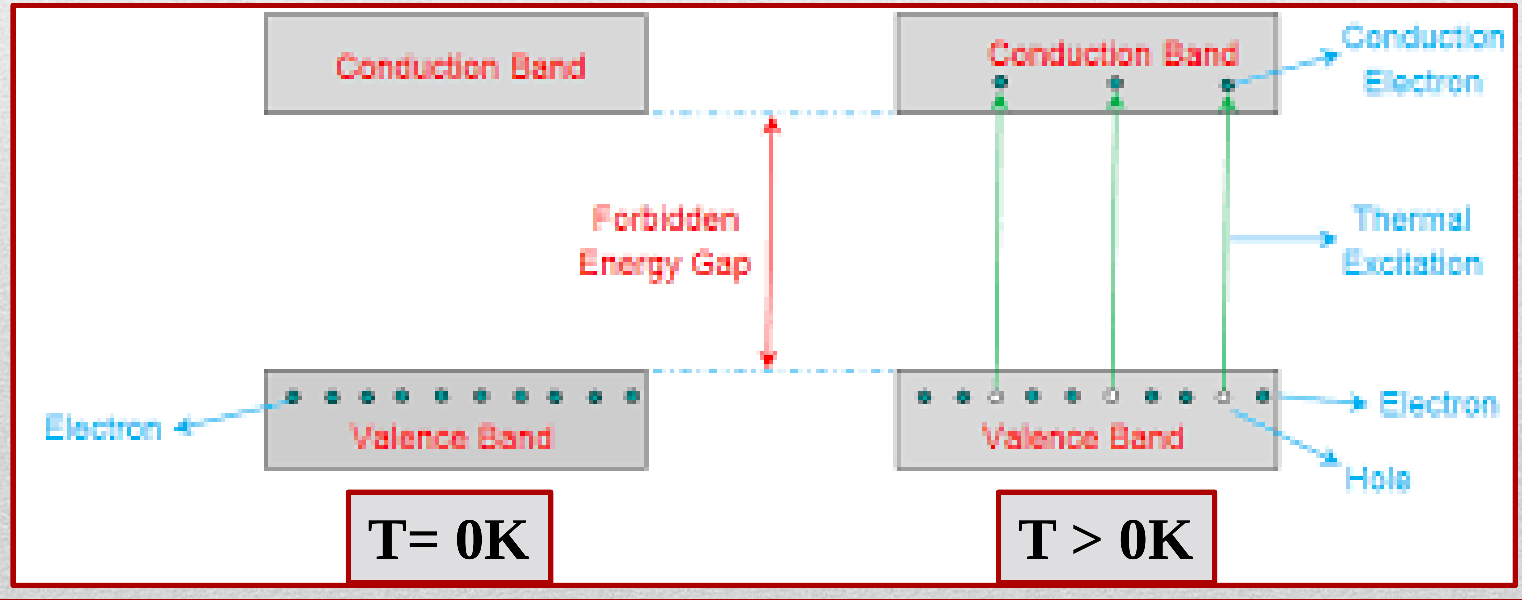
WHAT IS FERMI LEVEL

- **The highest energy level that an electron occupies at the absolute zero temperature is known as the Fermi Level.**
- **The Fermi level lies between the valence band and conduction band. At T=0 K, the electrons are all in the lowest energy state → Fermi level can be considered as the sea of fermions (or electrons) above which no electrons exist.**
- **The Fermi level changes as the temperature increases or electrons are added to or withdrawn from the solids.**



FERMI LEVEL IN INTRINSIC SC

- At T=0 K, the valence band will be full of electrons → impossible to cross the energy barrier → acts as an insulator.
- At T > 0 K → the electron movement from the valence band to the conduction band increases → create holes in the valence band in place of electrons.
- The electron concentration '*n*' is equal to hole concentration '*p*'.



POSITION OF FERMI LEVEL IN INTRINSIC SC

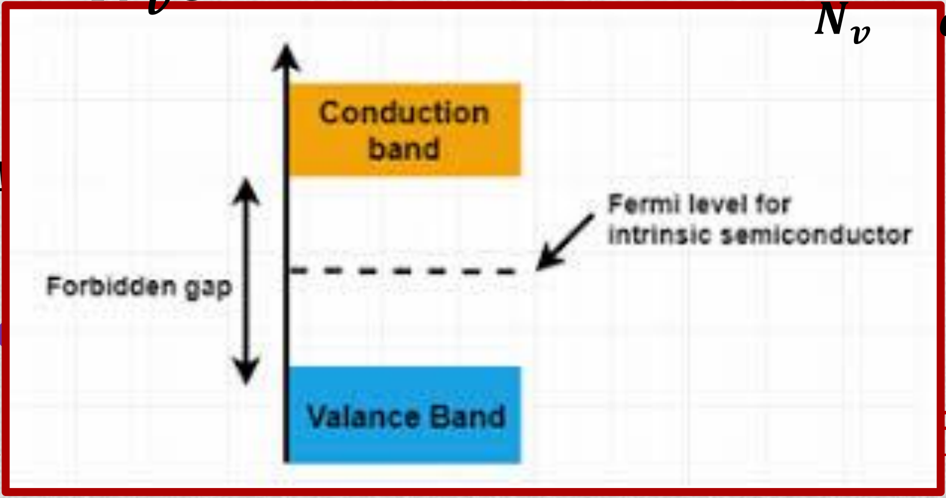
Let, n be the number of electrons in the semiconductor band.
p be the number of holes in the valence band.
At temperature T > 0 K

n= $N_c e^{-(E_c-E_F)/kT}$ p= $N_v e^{-(E_F-E_V)/kT}$

N_c is the effective density of states in the conduction band and N_v is the effective density of states in the valence band. For an intrinsic semiconductor, $n_e = n_v$

$N_c e^{-(E_c-E_F)/kT}$=$N_v e^{-(E_F-E_v)/kT}$ ➡ $\frac{N_C}{N_v} = \frac{e^{-(E_F-E_V)/kT}}{e^{-(E_c-E_F)/kT}}$

➡ $e^{\frac{-(2E_F-E_V}{kT}}$



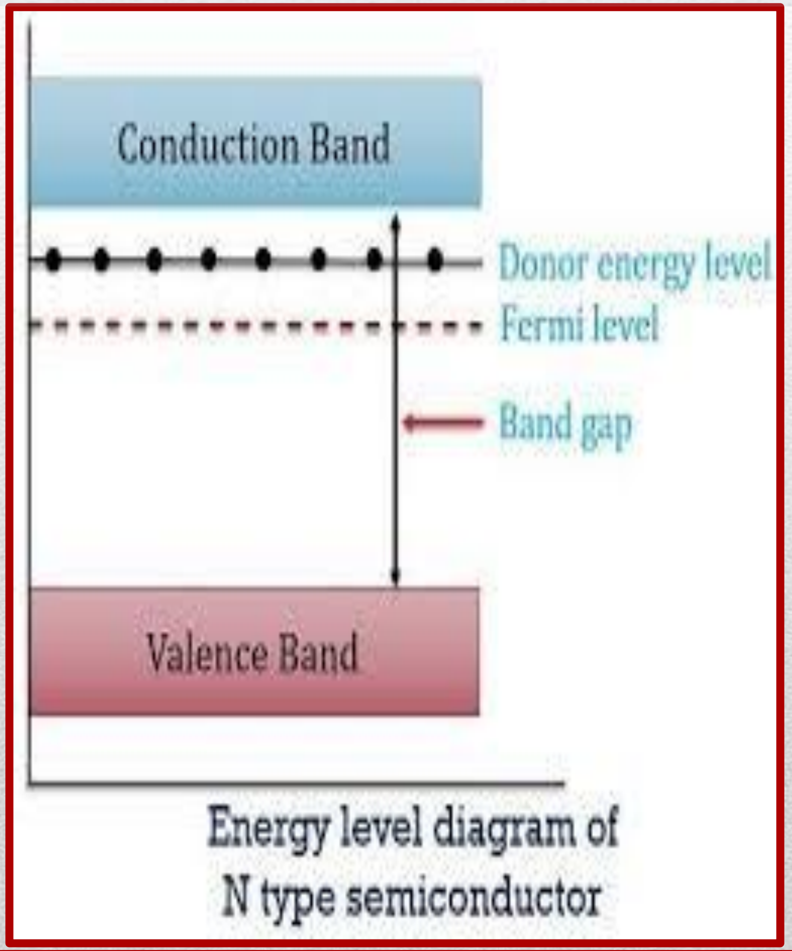
Taking log on b

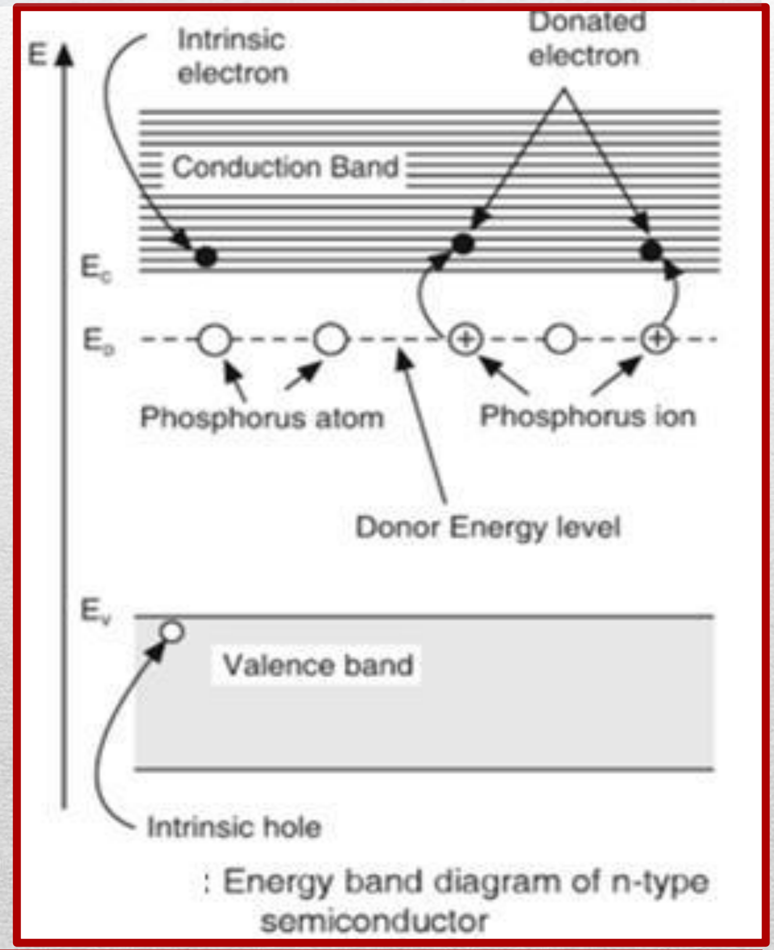
$E_F = \frac{E_C+E_V}{2}$

∴ Fermi level i f the band gap.

FERMI LEVEL IN EXTRINSIC SC

N-type SC- pentavalent impurity : electrons as majority charge carriers: donor impurities

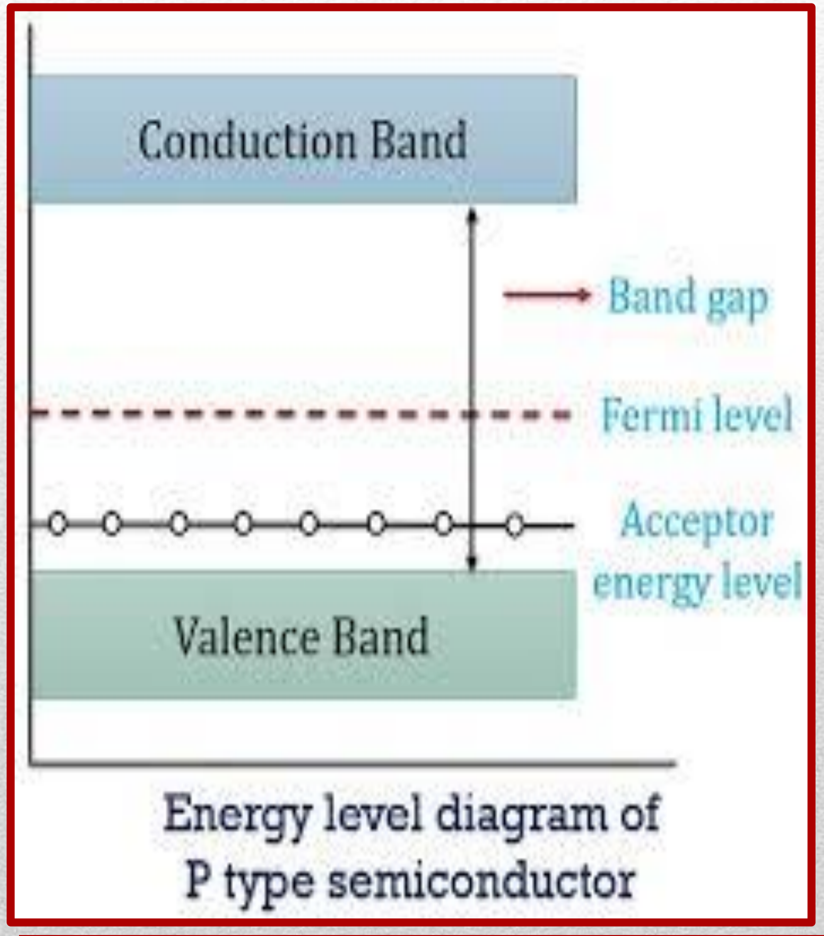


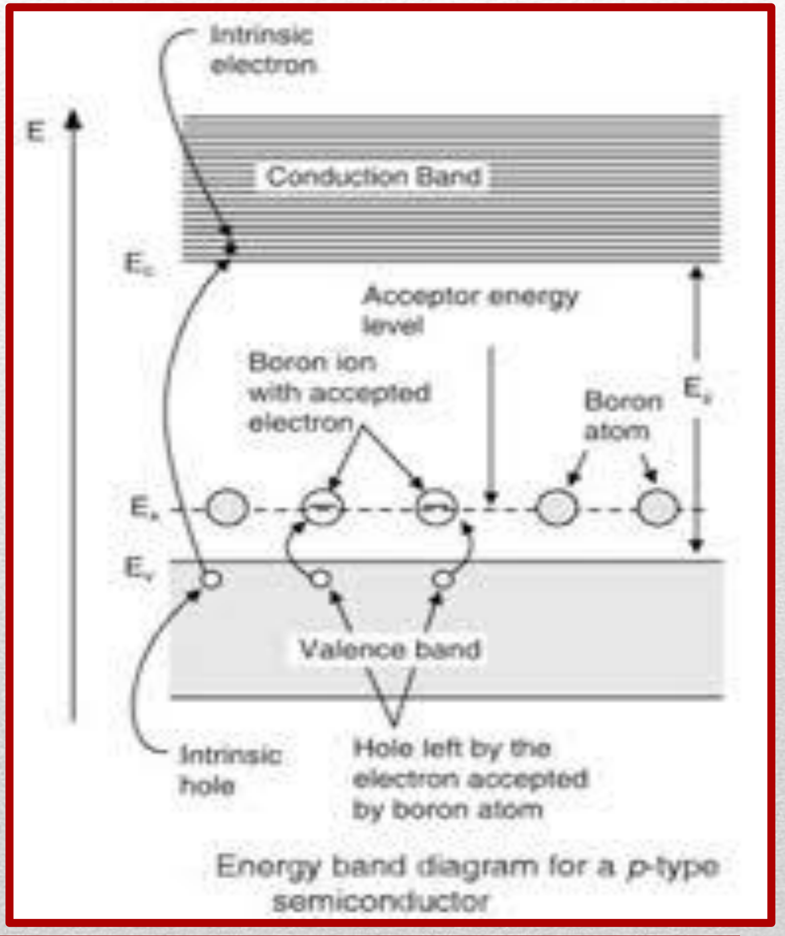


https://sites.google.com/site/puenggphysics/home/unit-5/fermi-level-of-extrinsic-semiconductor

FERMI LEVEL IN EXTRINSIC SC

P-type SC- trivalent impurity : holes as majority charge carriers: acceptor impurities

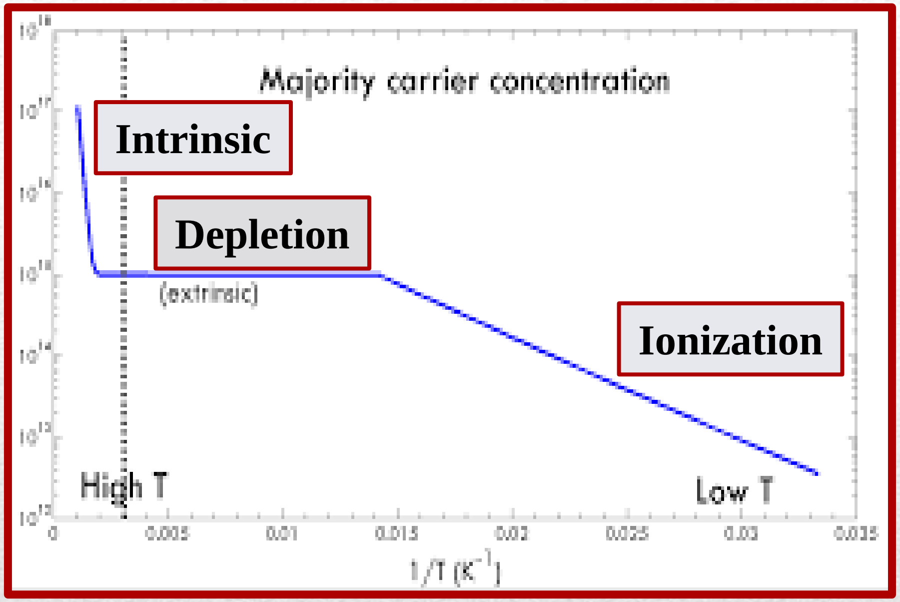


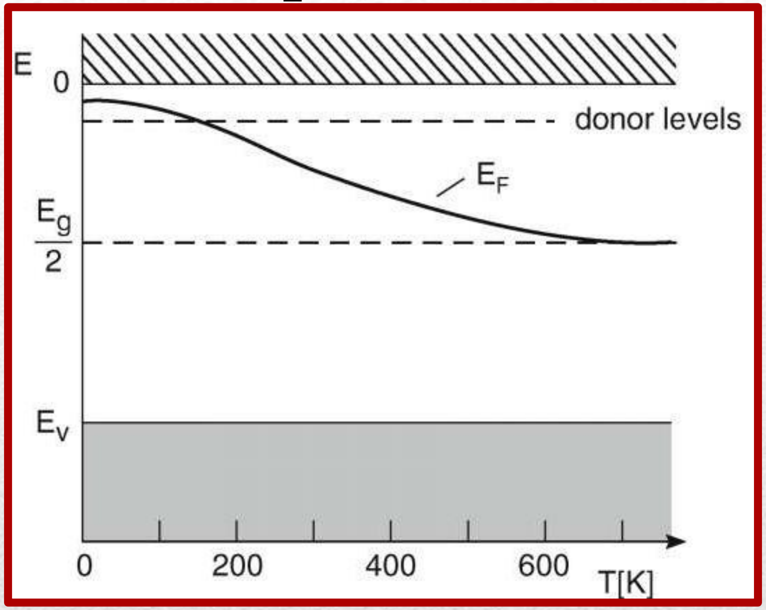


https://sites.google.com/site/puenggphysics/home/unit-5/fermi-level-of-extrinsic-semiconductor

EFFECT OF TEMPERATURE ON THE FERMI LEVEL OF N-TYPE SEMICONDUCTOR

EFFECT OF TEMPERATURE ON E_F OF N- TYPE SC





Region I: Ionization region: $E_{F_n} = \frac{E_c+E_D}{2}$

Region II: Depletion Region: $E_{F_n} = E_D$

Region III: Intrinsic Region: $E_{F_n} = E_{F_i} = \frac{E_g}{2}$

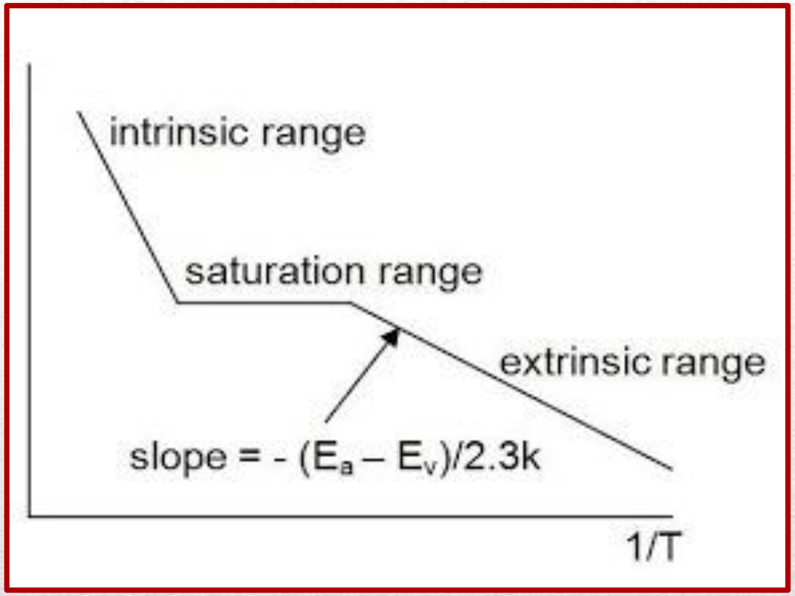
Fermi level position in n type semiconductor with respect to intrinsic Fermi level is given as

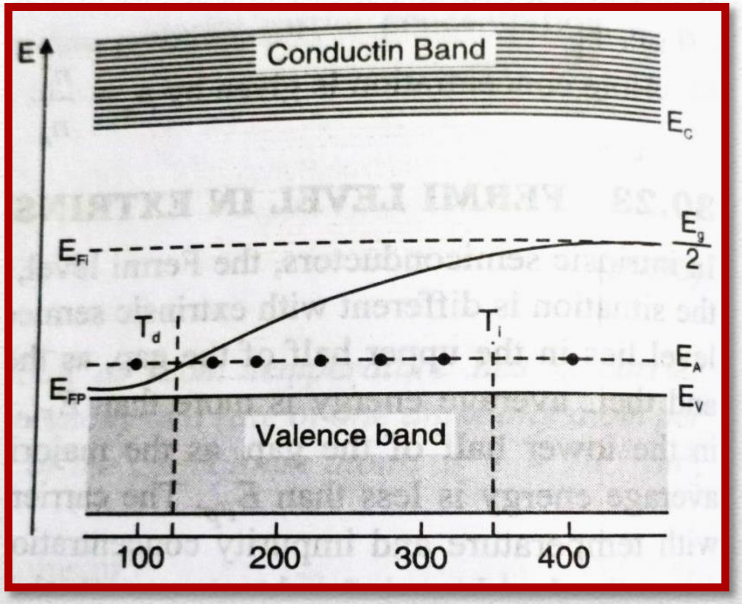
$$E_{F_n} - E_{F_i} = k_B T \ln \frac{n}{n_i}$$

https://nptel.ac.in/content/storage2/courses/113106062/Lec7.pdf

EFFECT OF TEMPERATURE ON THE FERMI LEVEL OF P-TYPE SEMICONDUCTOR

EFFECT OF TEMPERATURE ON E_F OF P- TYPE SC





Region 1: Ionization region: $E_{F_p} = \frac{E_V + E_A}{2}$

Region 2: Depletion Region: $E_{F_p} = E_A$

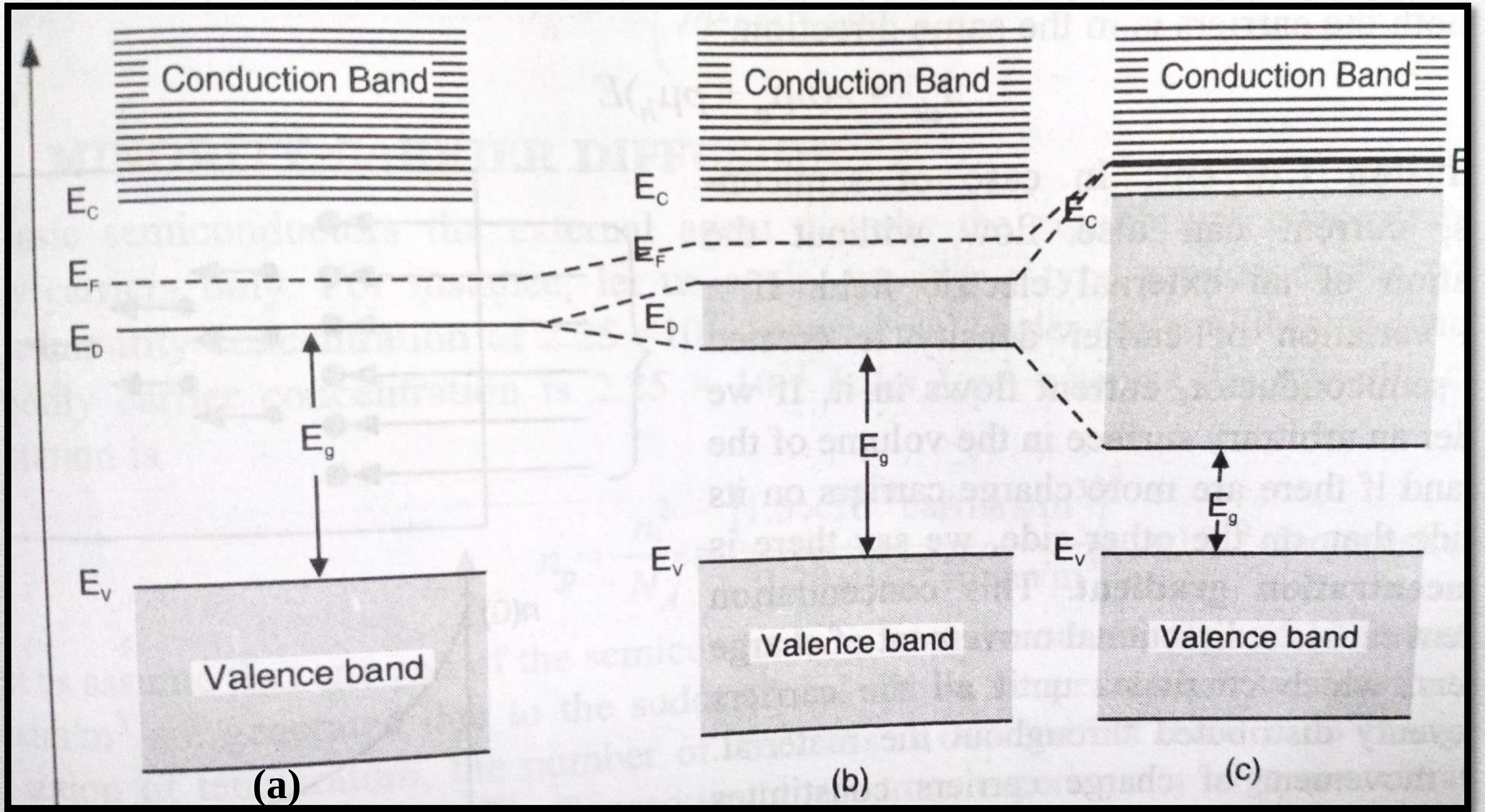
Region 3: Intrinsic Region : $E_{F_p} = E_{F_i} = \frac{E_g}{2}$

Fermi level position in p type semiconductor with respect to intrinsic Fermi level is given as

$$E_{F_P} - E_{F_i} = -k_B T \ln \frac{p}{n_i}$$

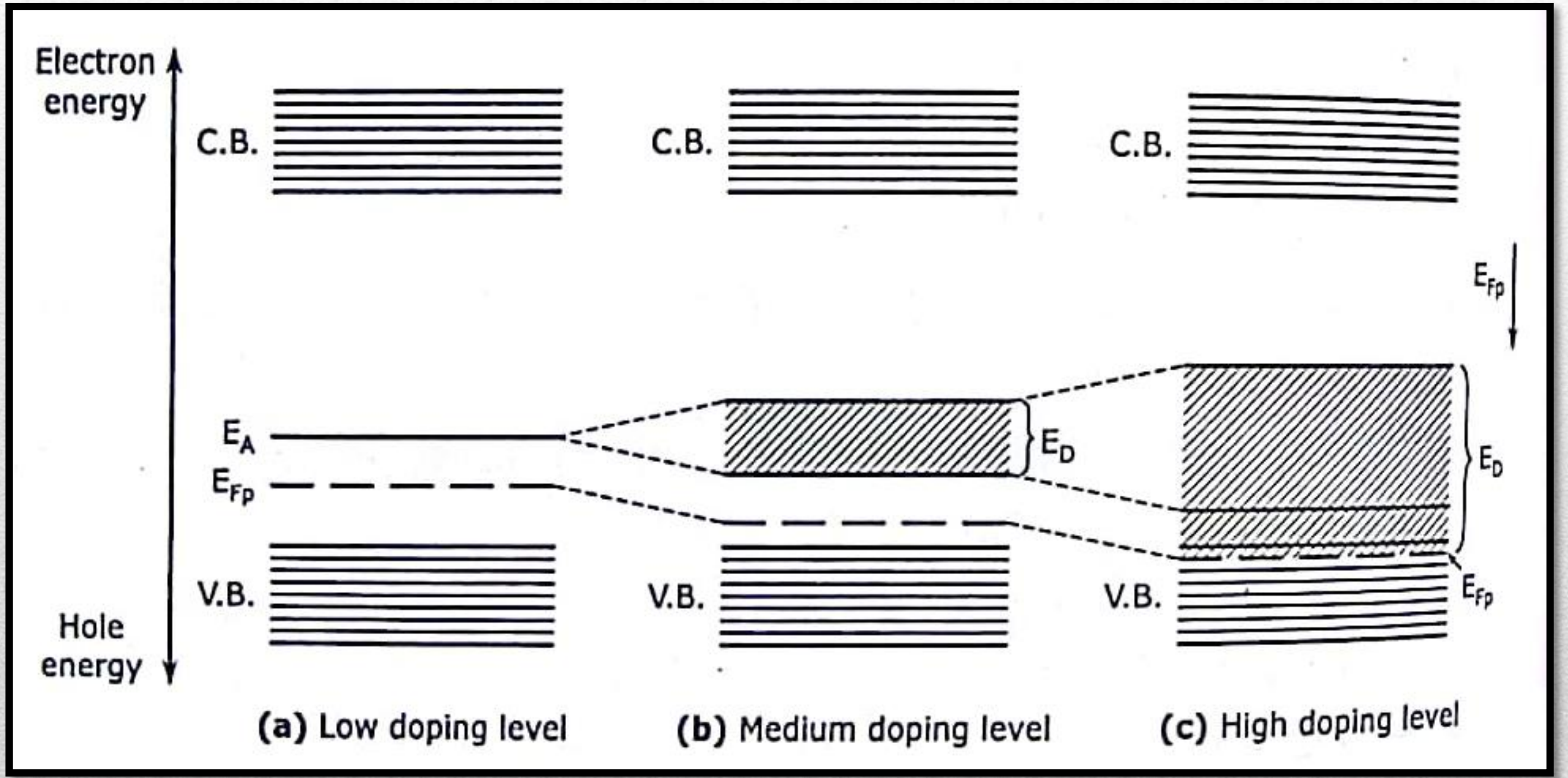
https://nptel.ac.in/content/storage2/courses/113106062/Lec7.pdf

EFFECT OF IMPURITY CONCENTRATION ON E_F OF N- TYPE SC



A book of Engineering Physics by Avadhanulu and Kshirsagar

EFFECT OF IMPURITY CONCENTRATION ON E_F OF P- TYPE SC



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