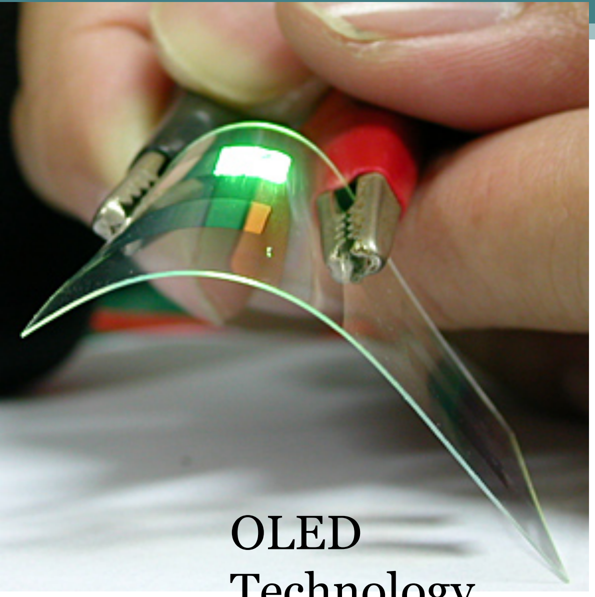
Electrical Science-2 (15B11EC211)
Unit-4
Introduction to Semiconductor
Lecture-3



OLED Technology

Solar Cells

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Outline of the module

- **Semiconductor Physics –**
  - Energy Band Model
  - Carrier Statistics
  - Intrinsic Semiconductors
  - Extrinsic Semiconductors
  - Fermi Level
  - Charge densities in a semiconductor
  - Carrier Mobility and Drift Current
  - Hall Effect
  - Recombination of charges
  - Diffusion and conductivity equation

Today we will learn

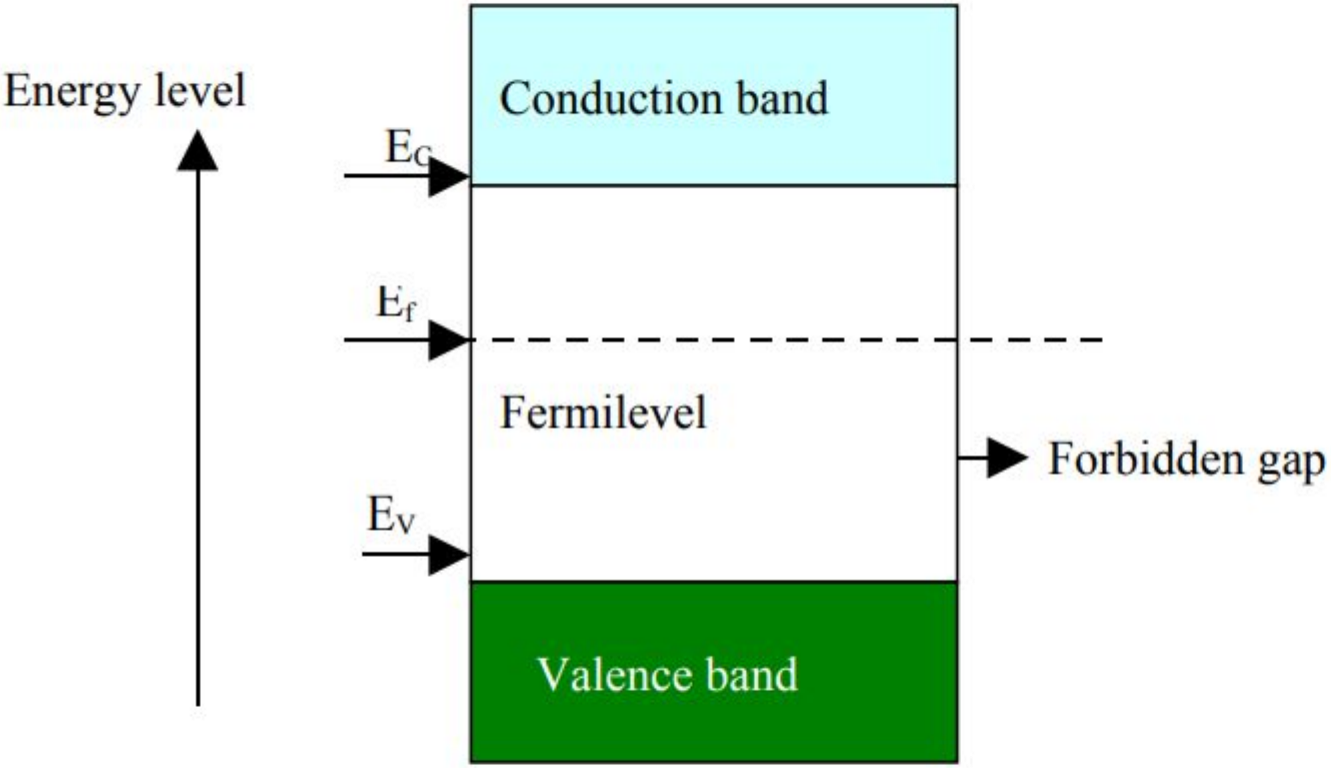
- Fermi level
- Fermi level in an intrinsic semiconductor
- Fermi level in a semiconductor having impurities (Extrinsic)
- Energy level diagram for n-type semiconductor
- Energy level diagram for p-type semiconductor
- Carrier statistics

Fermi level

- Fermi level indicates the level of energy in the forbidden gap.
- Fermi level for an Intrinsic semiconductor
    - We know that the intrinsic semiconductor acts as an insulator at absolute zero temperature because there are free electrons and holes available
    - But, as the temperature increases electron hole pairs are generated and hence number of electrons will be equal to number of holes.
    - Therefore, the possibility of obtaining an electron in the conduction band will be equal to the probability of obtaining a hole in the valence band.
    - If Ec is the lowest energy level of Conduction band and Ev is the highest energylevel of the valence band then the fermi level Ef is exactly at the center of these two levels as shown in the figure.

Ref 1, 2

Fermi level



E_C ⟶ Conduction band energy level

E_V ⟶ Valence band energy level

E_f ⟶ fermi level

Ref 1, 2

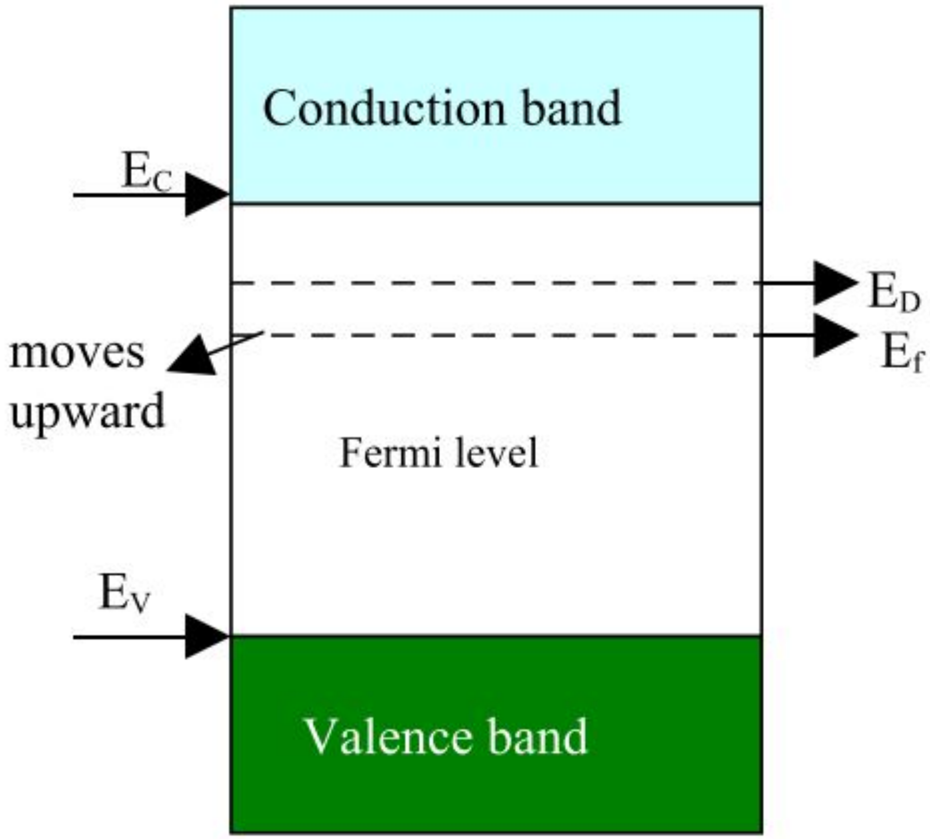
Fermi-level in a semiconductors having impurities (Extrinsic)

Fermi-level for n-type Semiconductor

- Let a donar impurity be added to an Intrinsic semiconductor
- Then, the donar energy level (E_D) shown by the dotted lines is very close to conduction band energy level (E_C).
- Therefore, the unbonded valence electrons of the impurity atoms can very easily jump into the conduction band and become free electros
- Thus, at room temperature almost all the extra electrons of pentavalent impurity will jump to the conduction band.
- The donar energy level (E_D) is just below conduction band level (E_C) as shown in figure1.
- Due to a large number of free electrons, the probability of electrons occupying the energy level towards the conduction band will be more.
- Hence, fermi level shifts towards the conduction band.

Ref 1, 2

Energy level diagram for n-type semiconductor



E_D → Energy level of donar impurity

Ref 1, 2

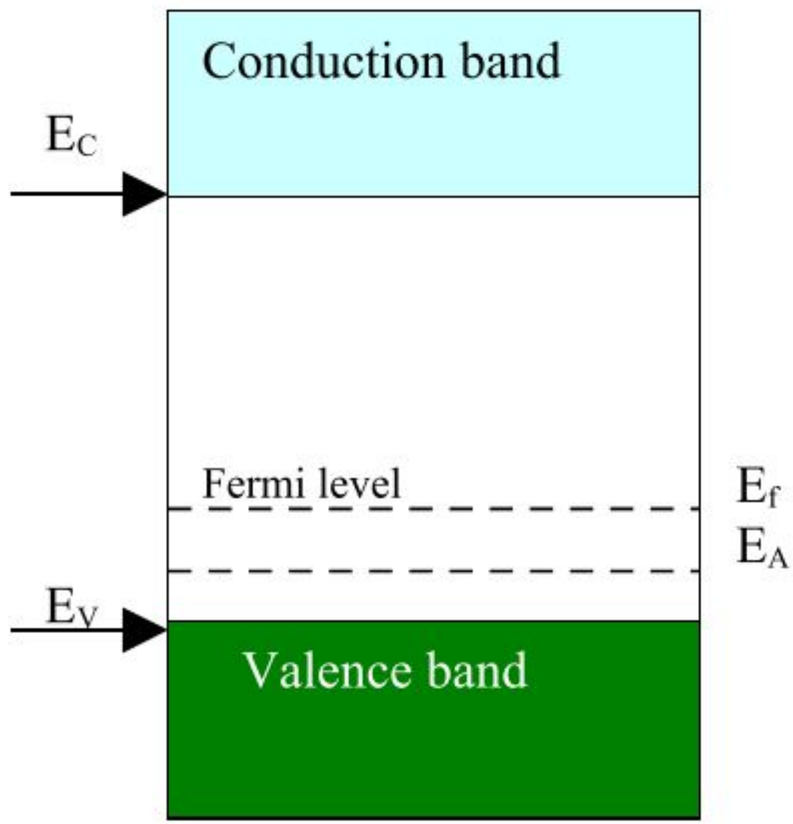
Fermi-level in a semiconductors having impurities (Extrinsic)

Fermi-level for p-type Semiconductor

- Let an acceptor impurity be added to an Intrinsic semiconductor
- Then, the acceptor energy level (E_A) shown by dotted lines is very close to the valence band shown by dotted lines is very close to the valence band energy level (E_v).
- Therefore, the valence band electrons of the impurity atom can very easily jump into the valence band thereby creating holes in the valence band.
- The acceptor energy level (E_A) is just above the valence band level as shown in figure.
- Due to large number of holes the probability of holes occupying the energy level towards the valence band will be more
- Hence, the fermi level gets shifted towards the valence band.

Ref 1, 2

Energy level diagram for p-type semiconductor



$E_A \longrightarrow$ Energy level of acceptor impurity

Ref 1, 2

The Fermi level

Electrons in solids obey Fermi - Dirac statistics:

$$f(E) = \frac{1}{1 + \exp[(E - E_F)/kT]}$$

where k is Boltzmann's constant

k=8.6210^{-5} eV/K=1.38 10^{-23} J/K.

The following consideration are used in the development of this statistics:

1. **indistinguishability of the electrons**,
2. **electron wave nature**,
3. **the Pauli exclusion principle**.

The function f**(E)** called **the *Fermi-Dirac distribution function*** gives the probability that an available energy state at ***E*** will be occupied by an electron at absolute temperature **T**.

The quantity E_F is called **the *Fermi level***, and it represents an important quantity in the analysis of semiconductor behavior. For an energy $E = E_F$ the occupation probability is

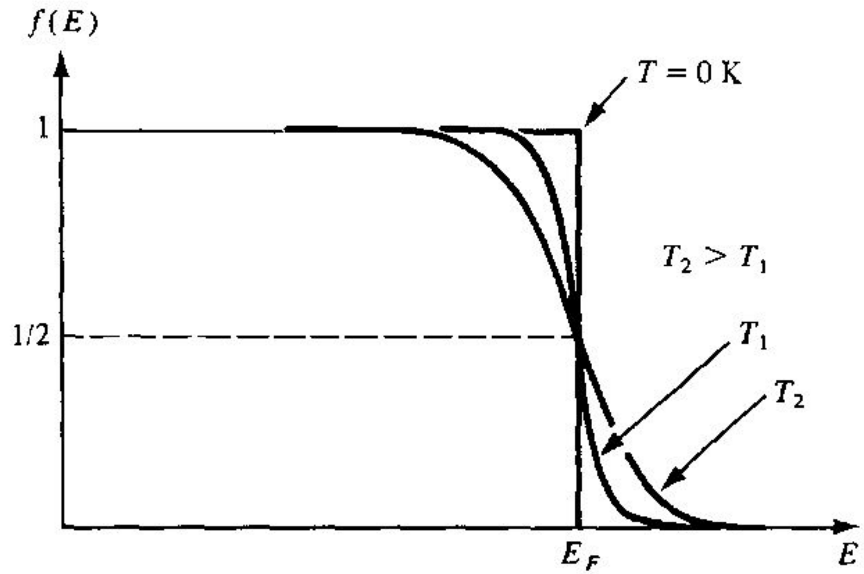
$$f(E_F) = [1 + \exp[(E_F - E_F)/kT]]^{-1} = \frac{1}{1+1} = \frac{1}{2}$$

This is the probability for electrons to occupy the Fermi level.

Ref 1, 2

The Fermi – Dirac distribution function

- At 0 K every available energy state up to E_F is filled with electrons, and all states above E_F are empty.
- At temperatures higher than 0 K, some probability **f(E)** exists for states above the Fermi level to be filled with electrons and there is a corresponding probability **[1 - f(E)]** that states below E_F are empty.
- possibility of finding an electron there.



The Fermi – Dirac distribution function for different temperatures

Ref 1, 2

The Fermi – Dirac distribution function

- The Fermi function is symmetrical about $\boldsymbol{E_F}$ for all temperatures.
- The symmetry of the distribution of empty and filled states about E_F makes the Fermi level a natural reference point in calculations of electron and hole concentrations in semiconductors.
- In applying the Fermi-Dirac distribution to semiconductors, we must recall that $f(E)$ is the probability of occupancy of an available state at E. Thus if there is no available state at E (e.g., in the band gap of a semiconductor), there is no

Ref 1, 2

Carrier Statistics

Electron and Hole Concentrations at Equilibrium

- The Fermi distribution function can be used to calculate the concentrations of electrons and holes in a semiconductor if the densities of available states in the valence and conduction bands are known.
- The concentration of electrons in the conduction band is

$$n_0 = \int_{E_c}^{\infty} f(E)N(E)dE \qquad (1)$$

where ***N(E)dE*** is the density of states (cm^{-3}) in the energy range ***dE***. The subscript 0 used for the electron and hole concentration symbols (n_0, p_0) indicates equilibrium conditions.

The conduction band electron concentration is simply the effective density of states at $\boldsymbol{E_c}$ times the probability of occupancy at $\boldsymbol{E_c}$:

$$n_0 = N_c f(E_c) \qquad (2)$$

Ref 1, 2

Carrier statistics

- The number of electrons per unit volume in the energy range ***dE*** is the product of the density of states and the probability of occupancy ***f*(E).**
- Thus the total electron concentration is the integral over the entire conduction band.
- The function ***N(E)*** can be calculated by using quantum mechanics and the Pauli exclusion principle.
- ***N(E)*** is proportional to $E^{1/2}$, so the density of states in the conduction band increases with electron energy.
- On the other hand, the Fermi function becomes extremely small for large energies. The result is that the product ***f(E)N(E)*** decreases rapidly above E_c, and very few electrons occupy energy states far above the conduction band edge.
- Similarly, the probability of finding an empty state (hole) in the valence band **[1 - *f*(E)]** decreases rapidly below E_v, and most holes occupy states near the top of the valence band.

Ref 1, 2

In this expression we assume the Fermi level $\boldsymbol{E_F}$ lies at least several $\boldsymbol{kT}$ below the conduction band. Then the exponential term is large compared with unity, and the Fermi function $\boldsymbol{f(E_c)}$ can be simplified as

$$f(E_c) = \frac{1}{1+\exp[(E_c - E_F)/kT]} \cong \exp[-(E_c - E_F)/kT] \qquad (3)$$

Since $\boldsymbol{kT}$ at room temperature is only **0.026 eV**, this is generally a good approximation. For this condition the concentration of electrons in the conduction band is

$$\boxed{n_0 = N_c \exp[-(E_c - E_F)/kT]} \qquad (4)$$

It can be shown that the effective density of states $\boldsymbol{N_c}$ is

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \qquad (5)$$

Values of $\boldsymbol{N_c}$ can be tabulated as a function of temperature. As Eq. (4) indicates, the electron concentration increases as $\boldsymbol{E_F}$ moves closer to the conduction band.

By similar arguments, the concentration of holes in the valence band is

$$p_0 = N_v[1 - f(E_v)] \qquad (6)$$

where $\boldsymbol{N_v}$ is the effective density of states in the valence band.

Ref 1, 2

The probability of finding an empty state at E_v, is

$$1-f(E_v)=1-\frac{1}{1+\exp[(E_v-E_F)/kT]}\cong\exp[-(E_F-E_v)/kT] \quad (7)$$

for E_F larger than E_v by several **kT**. From these equations, the concentration of holes in the valence band is

$$\boxed{p_0=N_v\exp[-(E_F-E_v)/kT]} \quad (8)$$

The effective density of states in the valence band reduced to the band edge is

$$N_v=2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} \quad (9)$$

Eq. (8) predicts that the hole concentration increases as E_F moves closer to the valence band.

The electron and hole concentrations predicted by Eqs. (4) and (8) are valid whether the material is intrinsic or doped, provided thermal equilibrium is maintained. Thus for intrinsic material, E_F lies at some intrinsic level E_i near the middle of the band gap, and the intrinsic electron and hole concentrations are

$$n_i=N_c\exp[-(E_c-E_i)/kT]\ ,\quad p_i=N_v\exp[-(E_i-E_v)/kT] \quad (10)$$

Ref 1, 2

Carrier statistics

The product of n_o and p_o at equilibrium is a constant for a particular material and temperature, even if the doping is varied:

$$n_0 p_0 = (N_c \exp[-(E_c - E_F)/kT])(N_v \exp[-(E_F - E_v)/kT]) = \quad (11\,(a))$$
$$= N_c N_v \exp[-(E_c - E_v)/kT] = N_c N_v \exp[-E_g/kT]$$

$$n_i p_i = (N_c \exp[-(E_c - E_i)/kT])(N_v \exp[-(E_i - E_v)/kT]) = \quad (11(b))$$
$$= N_c N_v \exp[-E_g/kT]$$

Ref 1, 2

Carrier statistics

In Eqns. (11(a)) and (11(b)) $\mathbf{E_g = E_c - E_v}$. The intrinsic electron and hole concentrations are equal (since the carriers are created in pairs), $\boldsymbol{n_i = p_i}$; thus the intrinsic concentration is

$$n_i = \sqrt{N_c N_v}\exp(-E_g / 2kT) \tag{12}$$

The constant product of electron and hole concentrations in Eq. (1) can be written conveniently as

$$\boxed{n_0 p_0 = n_i^2} \tag{13}$$

This is an important relation, and we shall use it extensively in later calculations. The intrinsic concentration for Si at room temperature is approximately $\boldsymbol{n_i} = 1.5 \text{ x } 10^{10}$ cm^{-3}.

Ref 1, 2

Another convenient way of writing Eqs. (4) and (8) is

$$\boxed{n_0 = n_i \exp\left[(E_F - E_i)/kT\right]} \tag{14}$$

$$\boxed{p_0 = n_i \exp\left[(E_i - E_F)/kT\right]} \tag{15}$$

obtained by the application of Eq. (7).

- This form of the equations indicates directly that the electron concentration is $\boldsymbol{n_i}$, when $\boldsymbol{E_F}$ is at the intrinsic level $\boldsymbol{E_i}$, and that $\boldsymbol{n_0}$ increases exponentially as the Fermi level moves away from $\boldsymbol{E_i}$ toward the conduction band.

- Similarly, the hole concentration $\boldsymbol{p_0}$ varies from $\boldsymbol{n_i}$, to larger values as $\boldsymbol{E_F}$ moves from $\boldsymbol{E_i}$ toward the valence band.

- Since these equations reveal the qualitative features of carrier concentration so directly, they are particularly convenient to remember.

Ref 1, 2

Problem 1-

A Si is doped with 9x 10^{15} cm^{-3} donors and 3x 10^{15} cm^{-3} acceptors. Find the position of the Fermi level at 40°C.

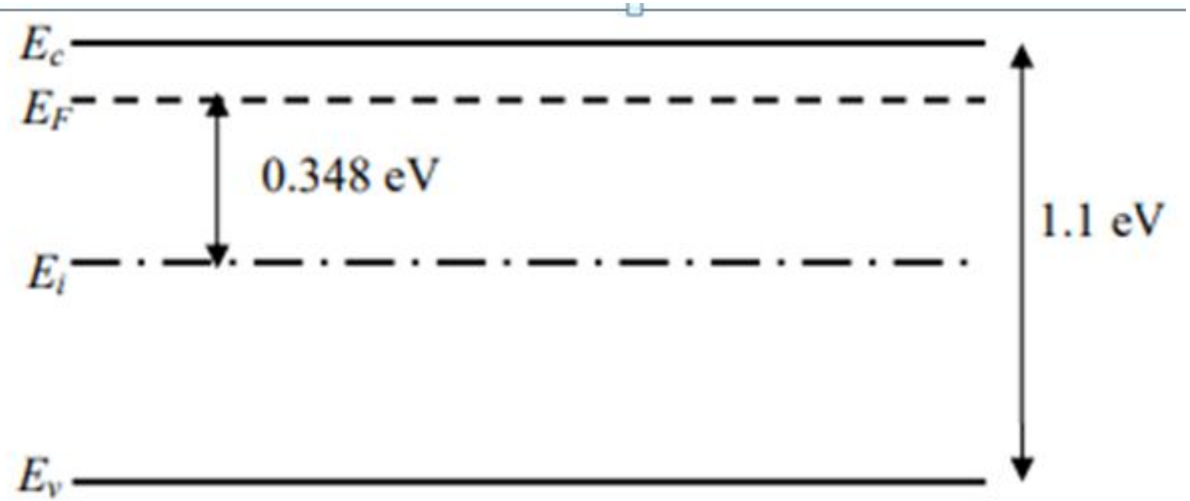
Solution:

$N_D = 9x10^{15}$ cm^{-3}; N_A=3x 10^{15} cm^{-3}; n_i=1. 5x10^{15} cm^{-3}
Since $N_D > N_A$, the Fermi level near to the donor states.

We obtain, $N_{Rd} = N_D - N_A$ =6x10^{15} cm^{-3}donor atoms;
Thus the Fermi level depends on the donor atoms N_{Rd}.
Now we consider $n_o = N_{RD}$ because $N_{RD} >> n_i$.
So we obtain, $E_F - E_i = kT$ In $[n_o/ n_i]$
= (8.62 x10^{-5}eV /K)(273+40K)ln[6x10^{15}/ 1. 5x10^{15}]
= 0.348 eV.

Solution…

The resulting band diagram is



Practice problem

An unknown semiconductor has E=1.1ev and $N_C=N_V$. It is doped with 10^{15} cm^{-3} donors where the donors level is 0.2ev below E_C. Given that E_F is 0.25ev below E_C, calculate n_i, and the concentration of electrons and holes in the semiconductor at 300K.

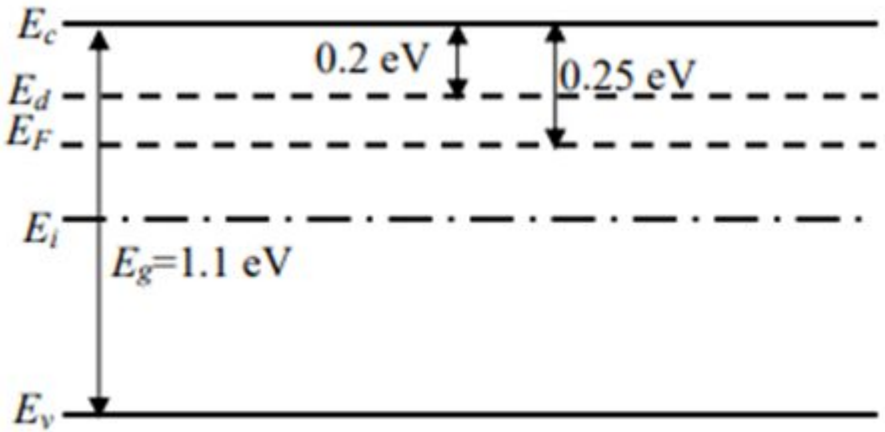
Hint-

Given E_g=1.lev; N_C= N_V; $N_d=10^{15}$ cm^{-3}: kT(300K)=0.026 ev. E_F-E_v= (1.1-0.25)-0.85 eV.

E_C-E_F = E_C-(E_F-E_v)=1.1-0.85-0.25 eV.

$$n_i = \sqrt{N_c N_v}\exp(-E_g / 2kT)$$

$$\boxed{n_0 p_0 = n_i^2}$$



References

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2. Sze and Ng," Physics of Semiconductor Devices", 3rd Ed., 2006