Lecture 2:
Semiconductor Physics

II. Extrinsic Semiconductor

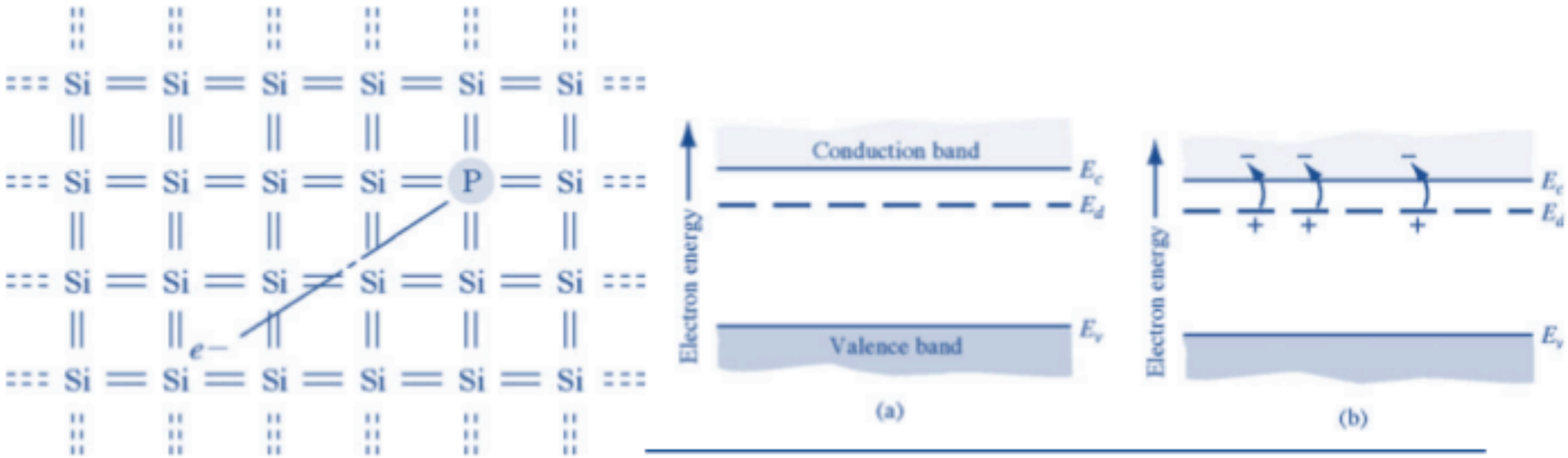
Dopant atoms and energy levels

The intrinsic semiconductor may be an interesting material, but the real power of semiconductor is extrinsic semiconductor, realized by adding small, controlled amounts of specific dopant, or impurity atom.

n-type semiconductor

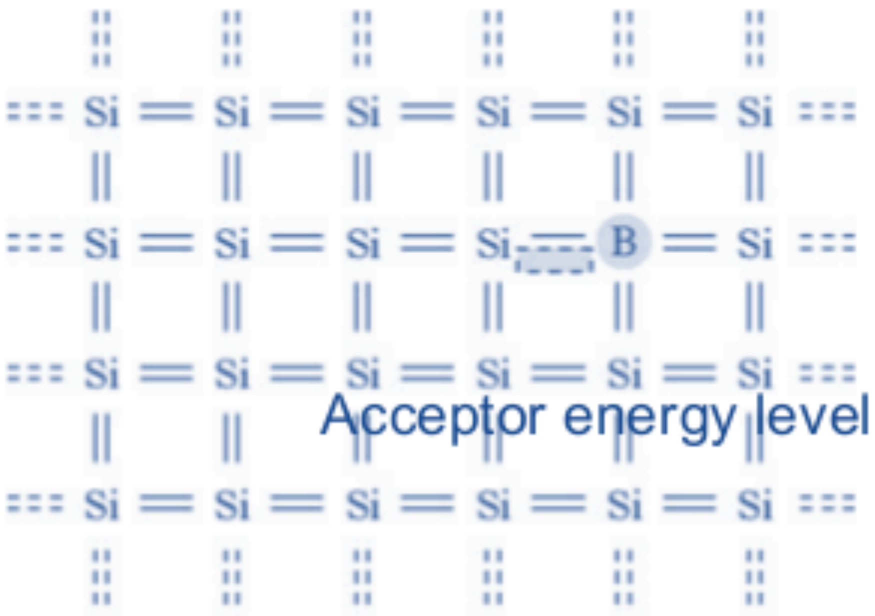
- A group V element, such as P atom is added into Si. 5 valence electrons, 4 of them contribute to the covalent bonding, leaving the 5th electron loosely bound to P atom, referred as a **donor electron**

- The energy level Ed is the energy state of donor impurity
- If a small amount of energy, such as thermal energy, is added to the donor electron, it can be elevated into CB, leaving behind a positively charged P ion.
- This type of impurity donates an electron to CB and so is called **donor impurity atoms**, which add electrons to contribute the CB current, without creating holes in VB

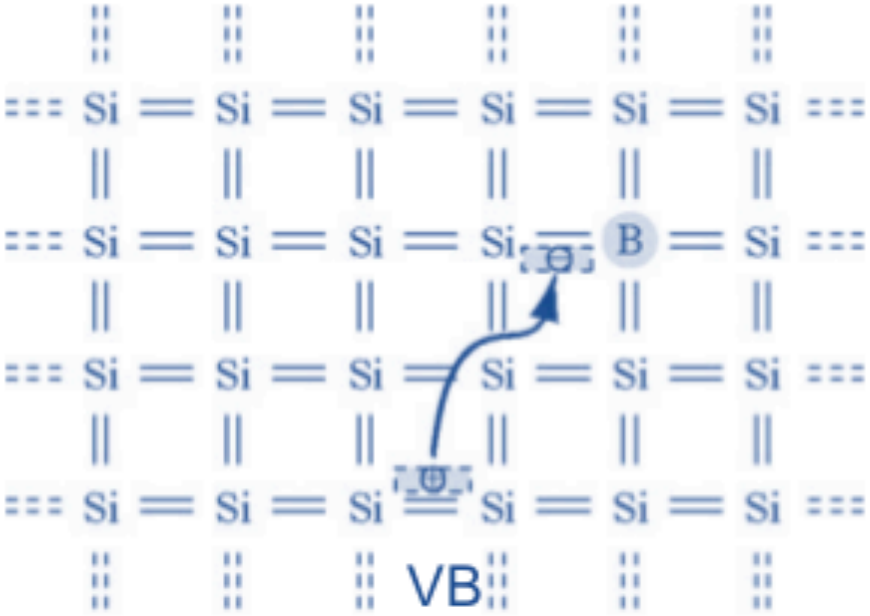


p-type semiconductor

- For silicon, a group III element, such as B atom is added. 3 valence electrons are all taken up in covalent bonding, one covalent bonding position appears to be empty. (Fig. a)
- The valence electrons in the VB (Fig. b) may gain a small amount of thermal energy and move to the empty state of group III element, forming empty state in VB
- The energy level E_a is the energy state of group III element in Si..

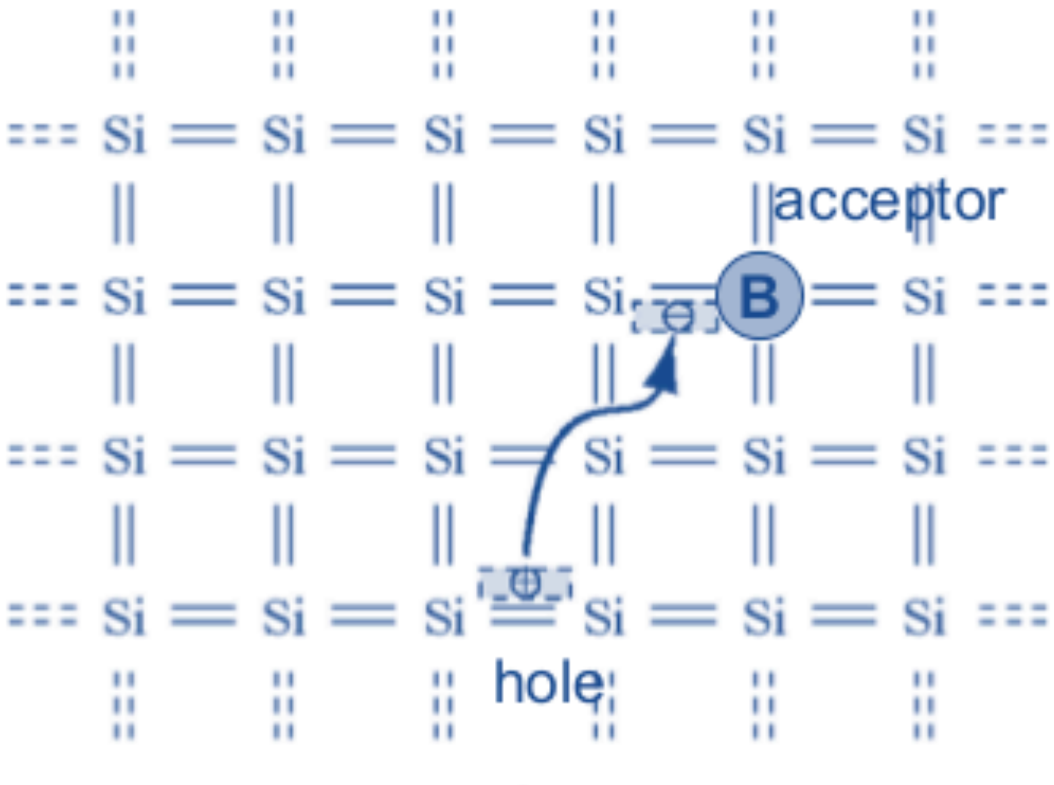


(a)

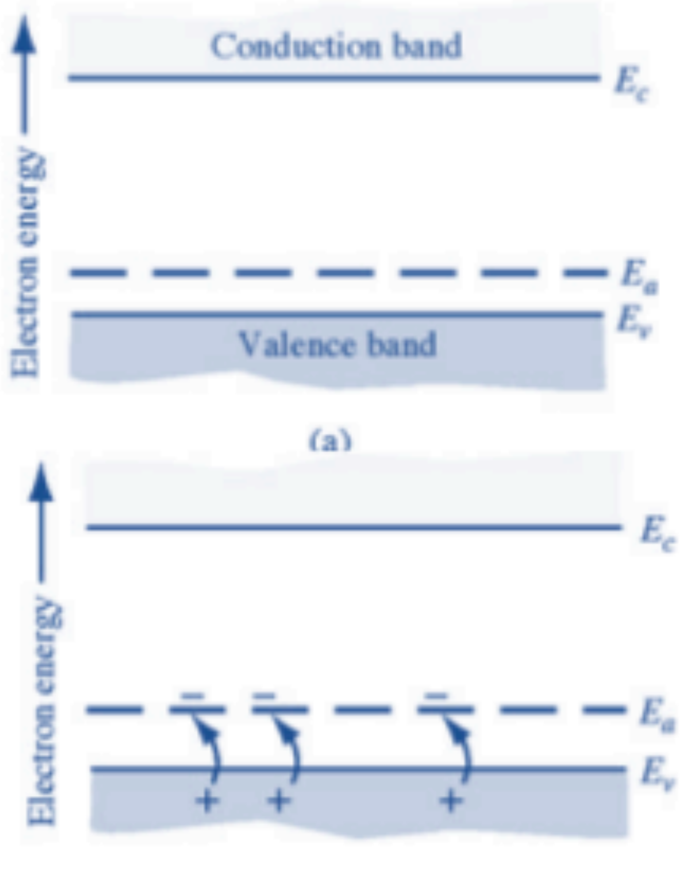


(b)

- The empty positions in the VB are thought of as **holes**.
- The group III atom accepts an electron from the VB and so is referred to as an **acceptor**
- The holes in the VB, formed due to the adding of acceptor impurity atoms without creating electrons in the CB, can move through the crystal generating a current

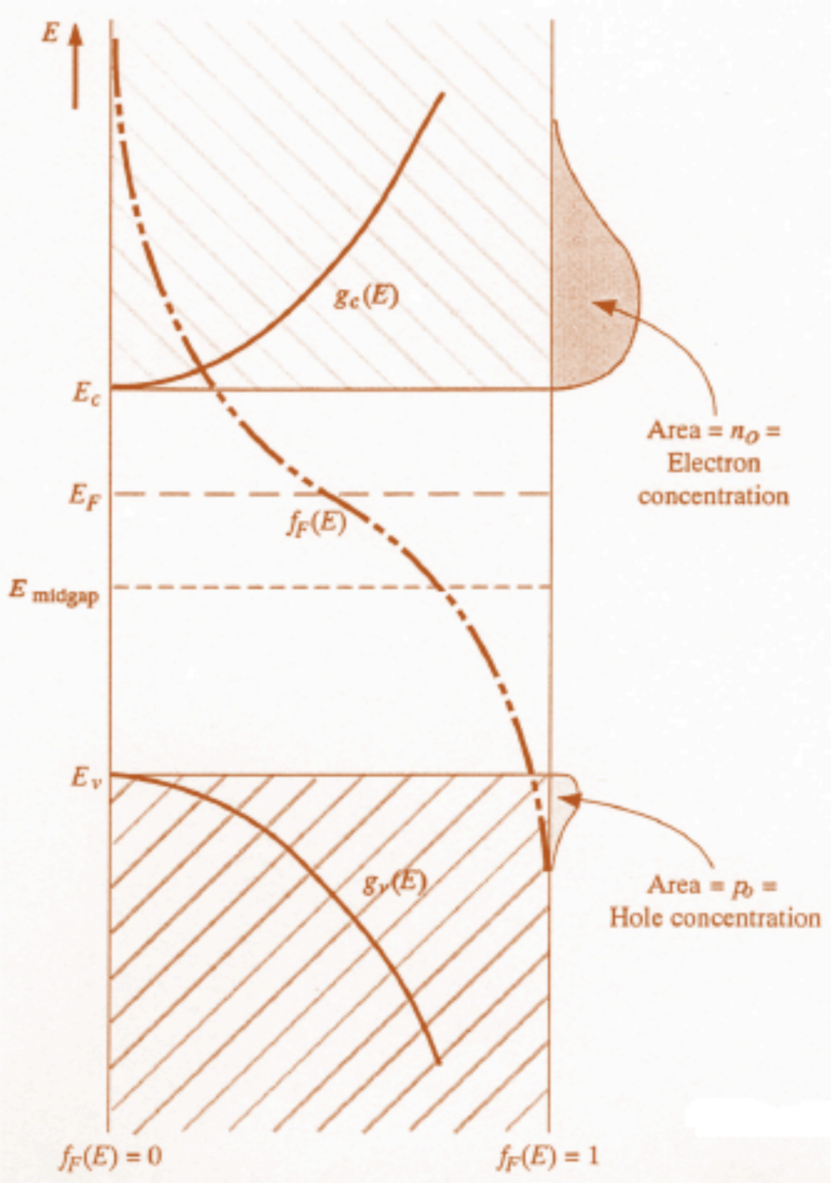


(b)



(a)
(b)

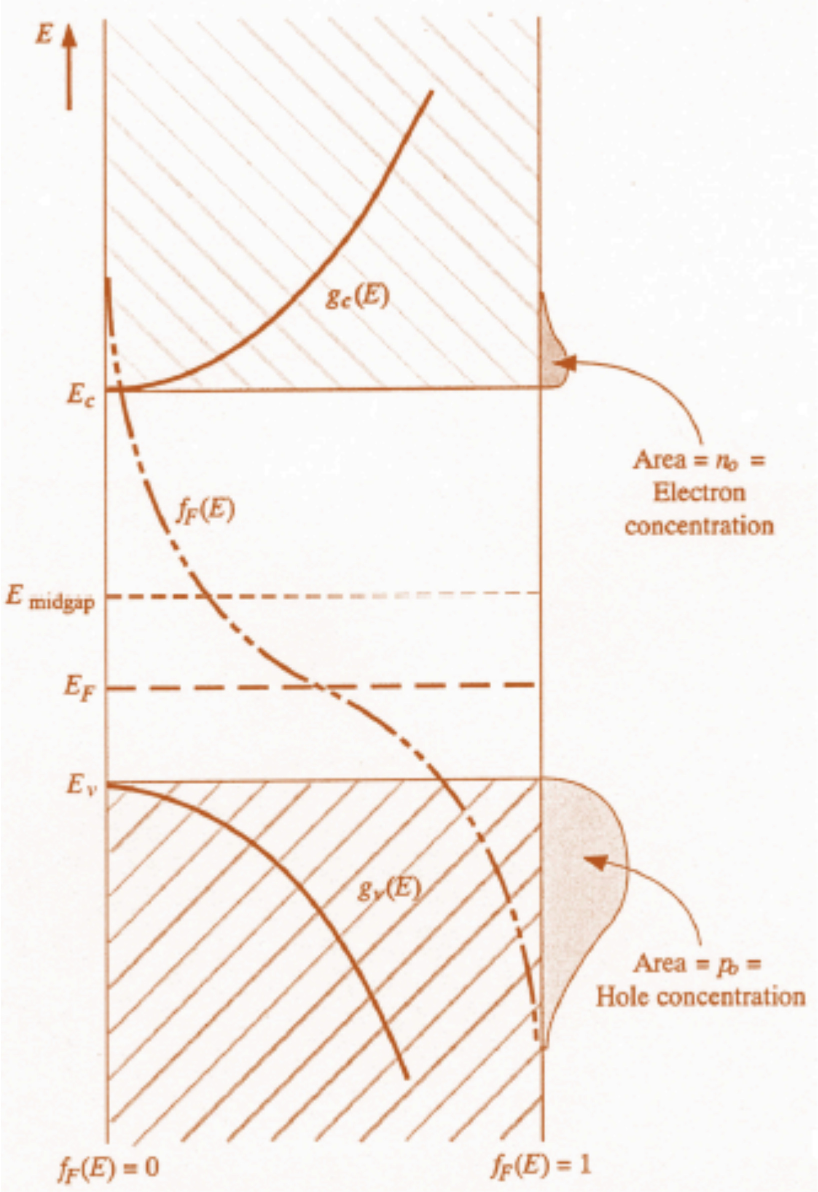
Equilibrium Distribution of Electrons and Holes in Extrinsic Semiconductors



Adding donor or acceptor impurity atoms to a semiconductor will change the distribution of electrons and holes in the material. Since the Fermi energy is related to the distribution function, the Fermi energy will change as dopant atoms are added.

In general, when $E_F > E_{\text{midgap}}$, the density of electrons is larger than that of holes, and the semiconductor is **n-type**.

Equilibrium Distribution of Electrons and Holes in the Extrinsic Semiconductor



In general, when $E_F < E_{midgap}$, the density of electrons is smaller than that of holes, and the semiconductor is **p-type**.

$$\boxed{\begin{aligned} n_0 &= N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] \\ p_0 &= N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right] \end{aligned}}$$

The above are **general equations for n_0 and p_0 in terms of the Fermi energy**. The values of n_0 and p_0 will change with the Fermi energy, E_F.

We can derive another form of the equations for the thermal-equilibrium concentrations of electrons and holes:

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

Concentration in intrinsic

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

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

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

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

$$\boxed{p_0 = n_i \exp\left[\frac{E_{Fi} - E_F}{kT}\right] = n_i \exp\left[\frac{-(E_F - E_{Fi})}{kT}\right]}$$

The $n_0 p_0$ Product

$$n_0 p_0 = N_c N_v \exp\left[\frac{-(E_c - E_F)}{kT}\right] \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

$$\boxed{n_0 p_0 = N_c N_v \exp\left[\frac{-E_g}{kT}\right] = n_i^2}$$

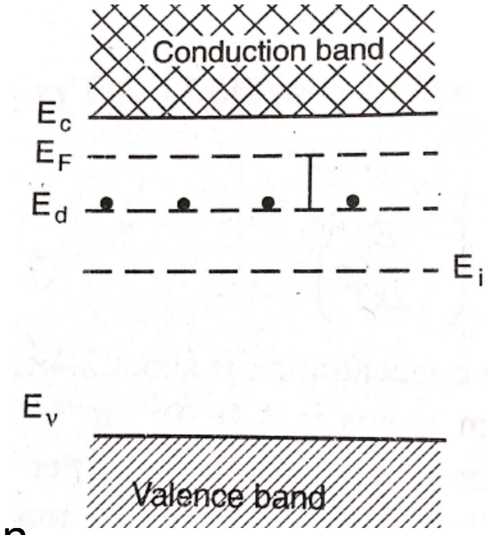
The product of n_0 and p_0 is always a constant for a given semiconductor material at a given temperature. **It is one of the fundamental principles of semiconductors in thermal equilibrium**.

It is important to keep in mind that the above equation is derived using the Boltzmann approximation.

We can think of the intrinsic concentration n_i simply as a parameter of the semiconductor material.

Carrier Concentration and Fermi level in n-type Semiconductor

At 0K, all donors are in un-ionized state i.e. all donor states are occupied by electrons. But, as temperature increases, some donors get ionized and contribute electrons to the conduction.



N_d = concentration of donor atoms in the donor level ; N_d^+ = concentration of ionized donor atoms ; N_d^0 = concentration of un-ionized donor atoms

The electron concentration in conduction band is $n = N_C e^{-\frac{(E_C - E_F)}{kT}}$ (1)

1) In equilibrium, crystal must be electrically neutral, *i.e.* $\boldsymbol{N_d^+ + p = n}$. The no. of electrons in conduction band (n) must be the sum of the concentration of ionized donors in the donor levels and the concentration of thermally generated holes in the valence band.

2) If a sufficient number of donors are present to produce electrons in CB, the concentration of thermally generated holes gets suppressed as $np = n_i^2$. Thus p may be neglected.

$$N_d^+ \approx n \text{ or } p = n_i^2 / N_d^+ \quad (2).$$

The probability of finding unionized donor atoms at energy level E_d is given as

$$\frac{N_d^0}{N_d} = f(E_d) \Rightarrow N_d^+ = N_d[1 - f(E_d)] \text{ as } N_d^+ + N_d^0 = N_d$$

$$N_d^+ = N_d\left[1 - \frac{1}{1 + \exp\left(\frac{E_d - E_F}{kT}\right)}\right] \approx N_d \exp\left(\frac{E_d - E_F}{kT}\right)$$

with the assumption $E_F - E_d << kT$

Hence, from $N_d^+ \approx n$ we can write $N_C e^{-\frac{(E_C - E_F)}{kT}} = N_d e^{\frac{E_d - E_F}{kT}}$

On solving, $$\boxed{E_F = \frac{E_d + E_C}{2} + \frac{kT}{2}\ln\left[\frac{N_d}{N_C}\right]}$$

but $N_C = 2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}$ So, we get $E_F = \frac{E_d + E_C}{2} + \frac{kT}{2}\ln\left[\frac{N_d h^3}{2\left(2\pi m_e^* kT\right)^{3/2}}\right]$

This gives position of Fermi level at **moderate temperature in n-type** semiconductor.
This equation is not valid at T = 0K as E_F becomes indeterminate .

Also this is not valid for T = ∞ as in this range extrinsic semiconductor behaves like an intrinsic semiconductor.

Thus free electron concentration in the conduction band would be $n = N_C e^{-\frac{(E_C - E_F)}{kT}}$

Substituting $$E_F = \frac{E_d + E_C}{2} + \frac{kT}{2} \ln\left[\frac{N_d}{N_C}\right]$$

we get, $$n = N_C \exp\left\{\frac{E_d - E_C}{2kT} + \frac{1}{2}\ln\left[\frac{N_d}{N_C}\right]\right\}$$

$$\boxed{\Rightarrow n = \sqrt{N_C N_D}\, e^{-\frac{\Delta E}{2kT}}}$$

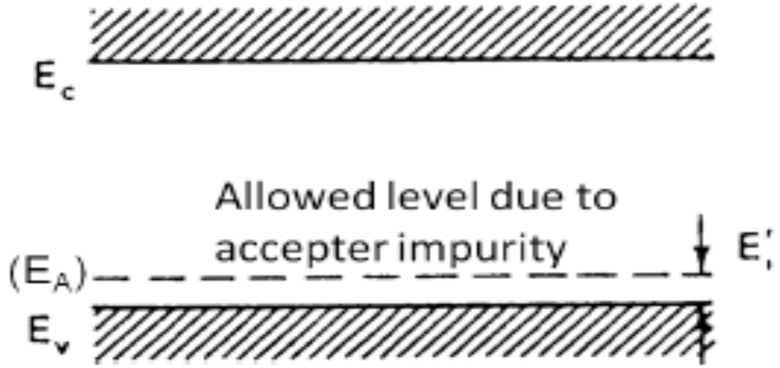
where $\Delta E = E_C - E_d$

Ionization energy of donors atoms

Carrier Concentration and Fermi level in p-type Semiconductor

At 0K, all acceptors are in un-ionized acceptor state. But, as temperature increases, some acceptors get ionized by acquiring electrons from the valence band, thus creating holes in the valence band.

Suppose there are N_A acceptors per unit volume occupying the donor level, the hole concentration in valence band at a temperature T



$$p = N_V e^{\frac{E_V - E_F}{kT}}$$

Also

$$p = N_A^- + n$$

However, if acceptors are sufficiently ionized,

$$N_A^- \approx N_A$$

$$\Rightarrow p \approx N_A$$

But, $np = n_i^2$

$$\Rightarrow n = \frac{n_i^2}{p} = \frac{n_i^2}{N_A}$$

Fermi Level and conductivity in p-type Semiconductor

If all acceptors are ionized

$$p \approx N_A = N_V e^{\frac{(E_V - E_F)}{kT}}$$

$$\Rightarrow (E_V - E_F) = kT \ln \frac{N_A}{N_V}$$

$$\Rightarrow \frac{(E_V - E_F)}{kT} = \ln \frac{N_A}{N_V}$$

$$\boxed{\Rightarrow E_F = E_V - kT \ln \frac{N_A}{N_V}}$$

If N_A^- acceptors are ionized

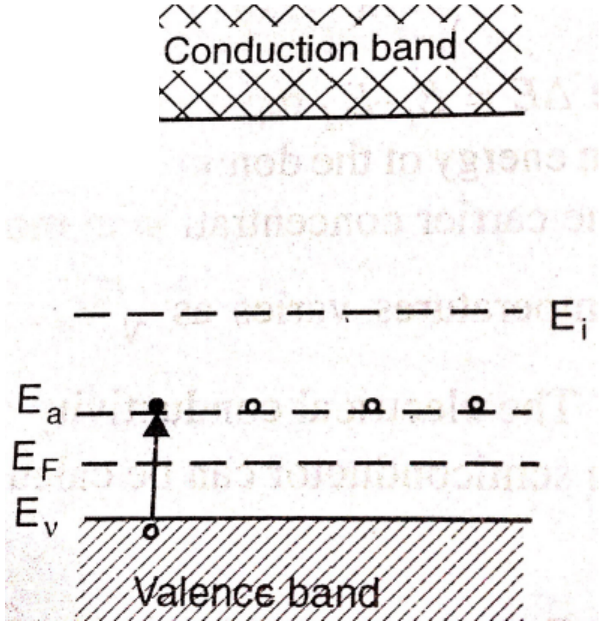
$$p \approx N_A^- = N_A f(E_A)$$

$$= N_A \left[\frac{1}{1 + e^{(\frac{E_A - E_F}{kT})}} \right]$$

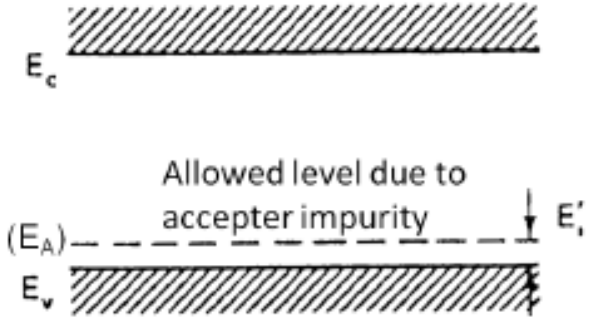
$$= N_A e^{(\frac{E_F - E_A}{kT})}$$

Assuming $E_A - E_F \gg kT$

$$\Rightarrow p = N_A^- = N_A e^{(\frac{E_F - E_A}{kT})}$$



$$\Rightarrow p = N_A^- = N_A e^{(\frac{E_F - E_A}{kT})}$$

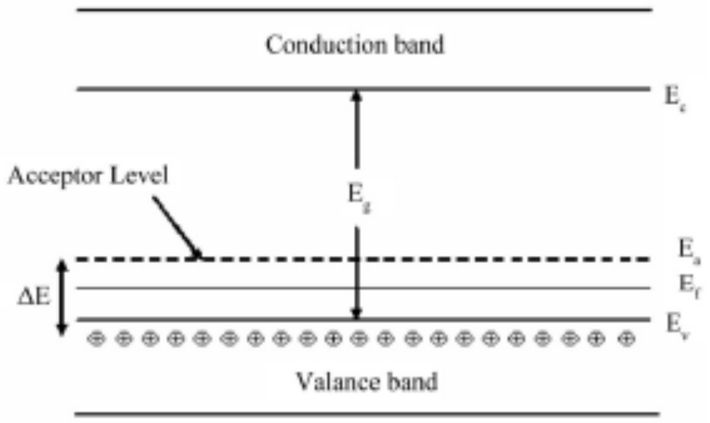


$$\Rightarrow N_A e^{(\frac{E_F - E_A}{kT})} = N_V e^{\frac{(E_V - E_F)}{kT}}$$

$$\Rightarrow \ln N_A + \frac{E_F - E_A}{kT} = \ln N_V + \frac{E_V - E_F}{kT}$$

$$\Rightarrow \ln N_A - \ln N_V = \frac{E_V - E_F}{kT} - \frac{E_F - E_A}{kT} = -\frac{2E_F}{kT} + \frac{E_V + E_A}{kT}$$

$$\Rightarrow \frac{2E_F}{kT} = \frac{E_A + E_V}{kT} - \ln \frac{N_A}{N_V}$$



$$\Rightarrow E_F = \frac{E_A + E_V}{2} - \frac{KT}{2} \ln \frac{N_A}{N_V}$$

Since,

$$N_V = 2\frac{(2\pi m_h^* kT)^{\frac{3}{2}}}{h^3} \qquad \Rightarrow E_F = \frac{E_A + E_V}{2} - \frac{KT}{2} \ln \frac{N_A h^3}{2(2\pi m_h^* kT)^{\frac{3}{2}}}$$

$$E_F = \frac{E_A + E_V}{2} - \frac{KT}{2}\ln\frac{N_A h^3}{2(2\pi m_h^* kT)^{\frac{3}{2}}}$$

This gives position of Fermi level at **moderate temperature** in p-type semiconductor. This equation is not valid at T = 0K as second term becomes indeterminate quantity at 0K. Also this is not valid for T = ∞ as in this range extrinsic semiconductor behaves like an intrinsic semiconductor.

Thus free electron concentration in the conduction band would be

$$p = N_V \exp\left(\frac{E_V - E_F}{kT}\right)$$

Substituting $E_F = \frac{E_A + E_V}{2} - \frac{KT}{2}\ln\frac{N_A}{N_V}$

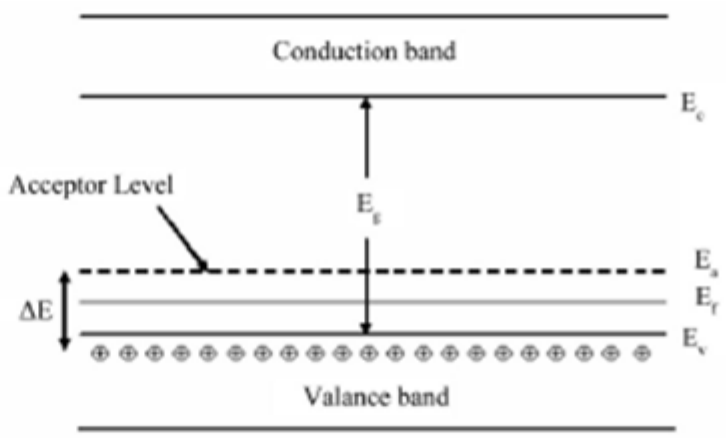
$$\Rightarrow p = N_V \exp\left(\frac{E_V}{kT} - \frac{E_F}{kT}\right) = N_V \exp\left(\frac{E_V}{kT} - \frac{E_A + E_V}{2kT} + \frac{\cancel{KT}}{2\cancel{kT}}\ln\frac{N_A}{N_V}\right)$$

$$\Rightarrow p = N_V \exp\left(\frac{E_V - E_A}{2kT} + \frac{1}{2}\ln\frac{N_A}{N_V}\right)$$

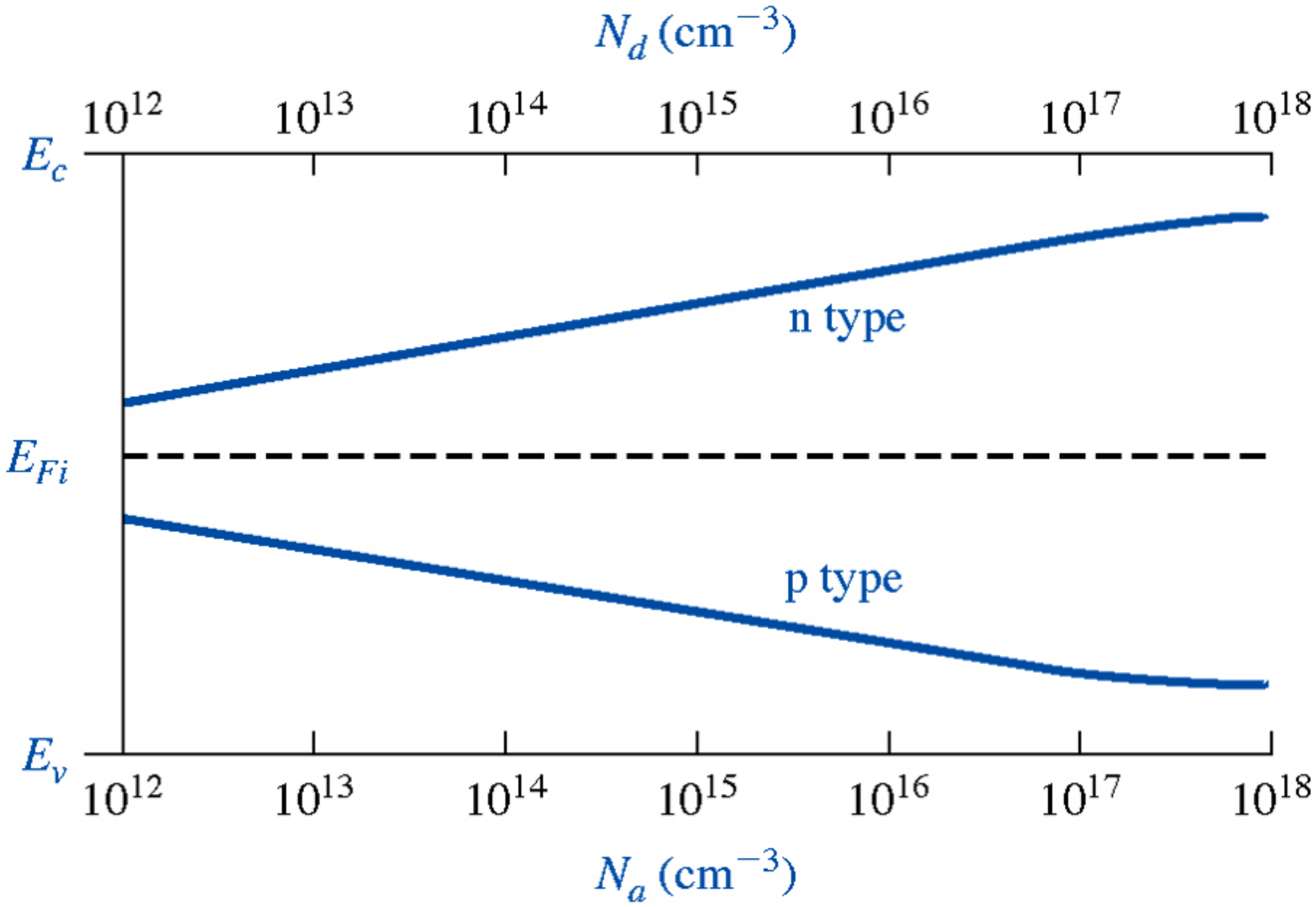
$$p = N_V \exp\left(\frac{E_V - E_A}{2kT} + \frac{1}{2}\ln\frac{N_A}{N_V}\right) \quad = N_V\left(\frac{N_A}{N_V}\right)^{\frac{1}{2}} \exp\left(\frac{E_V - E_A}{2kT}\right)$$

$$\Rightarrow p = (N_A N_V)^{\frac{1}{2}} \exp\left(\frac{\Delta E}{2kT}\right)$$

Ionization energy of acceptors



Variation of Fermi-Energy with Doping Concentration



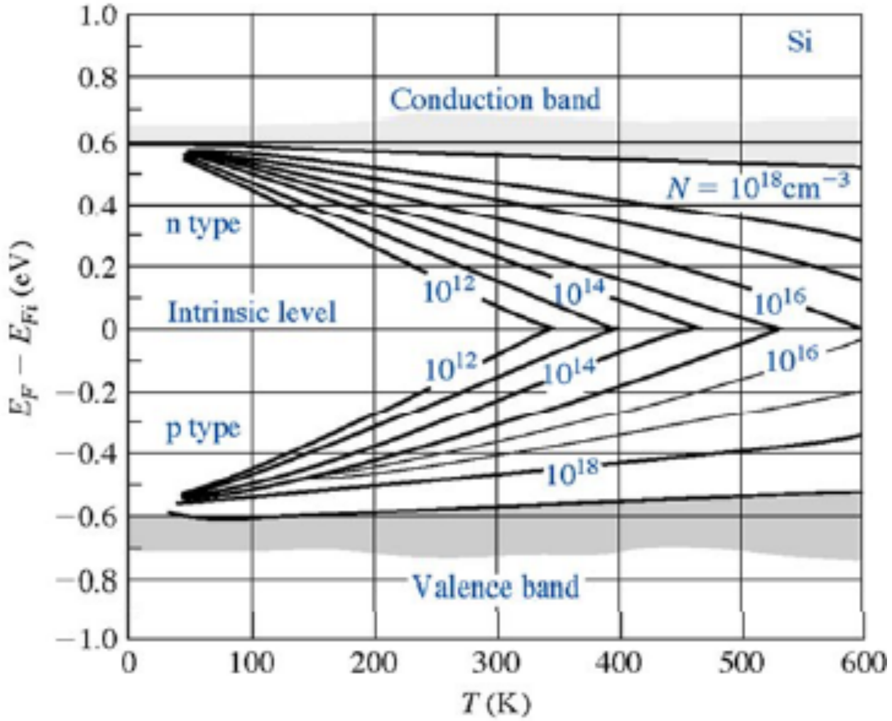
Variation of Fermi level with temperature and concentration of charge carriers (impurity concentration) in extrinsic semiconductor

Fermi level in n-type semiconductor:

$$E_F = \frac{E_D + E_C}{2} + \frac{KT}{2} \ln \frac{N_D h^3}{2(2\pi m_e^* kT)^{\frac{3}{2}}}$$

Fermi level in p-type semiconductor:

$$E_F = \frac{E_A + E_V}{2} - \frac{KT}{2} \ln \frac{N_A h^3}{2(2\pi m_h^* kT)^{\frac{3}{2}}}$$



As the temperature is increased, the Fermi level moves closer to the intrinsic Fermi level. At the low temperature where freeze-out occurs, the Fermi level goes above E_d for n-type semiconductors and below E_a for p-type semiconductors.

Example → Fermi energy

$\text{n - type Si semiconductor, T} = 300\text{K}$

$N_a = 10^{16}\text{cm}^{-3}$ and $n_i = 1.5\times10^{10}\text{cm}^{-3}$

Fermi energy is 0.20 eV below the conduction band edge

Solution:

$$\boxed{n_o = N_C \exp\frac{-(E_C - E_f)}{kT}}$$

majority carrier

$$n_o = 2.8\times10^{19}\exp\left(\frac{-0.20}{0.0259}\right) = 1.24\times10^{16}\,\text{cm}^{-3}$$

$$\because n_o = N_d - N_a$$

$$N_d = 1.24\times10^{16} + 10^{16} = 2.24\times10^{16}\,\text{cm}^{-3}$$