Physics of Semiconductor: Lecture # Lec 6

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What we have learnt earlier

Intrinsic semiconductor

$$n = \int_{E_C}^{\infty} Z(E) f(E) dE$$

$$Z(E)dE = \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2} E^{1/2} dE \quad \text{for } E > E_C.$$

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

Electron density available for conduction, $\boxed{n = N_c\, e^{-(Ec - EF)/kT}}$

$$dp = Z(E)[1 - f(E)]dE \qquad (30.31)$$

$$p = N_V e^{-(E_F - E_V)/kT}$$

FERMI LEVEL IN INTRINSIC SEMICONDUCTOR

$$E_F = \frac{E_C + E_V}{2} + \frac{1}{2} kT \; ln \frac{N_V}{N_C}$$

$$\therefore \quad E_F = \frac{E_C + E_V}{2} + \frac{3}{4} kT \; ln\left(\frac{m_h^*}{m_e^*}\right)$$

$$\sigma_i = Ae^{-E_g/2kT}$$

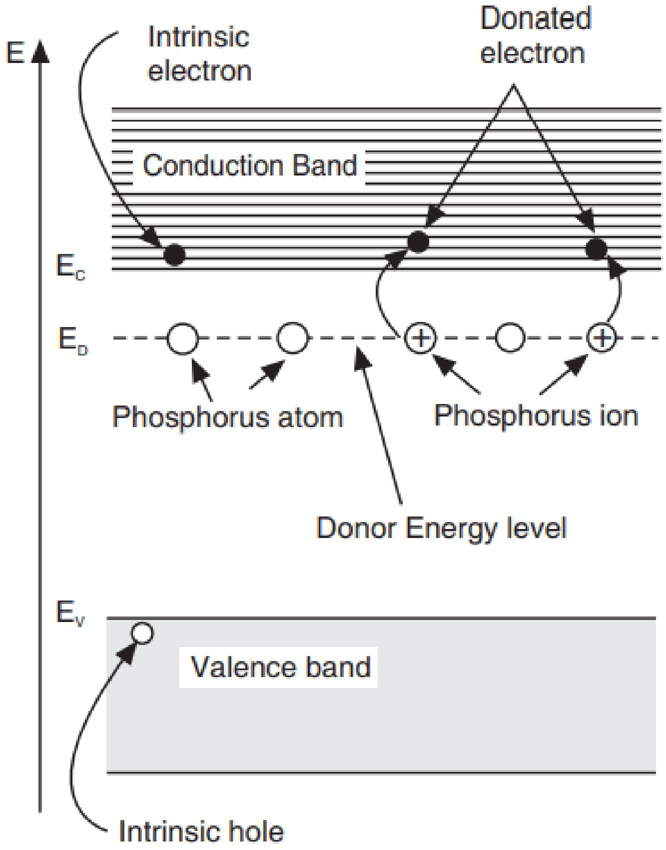
Electron density available for conduction, $\boxed{n = N_c\, e^{-(Ec - EF)/kT}}$

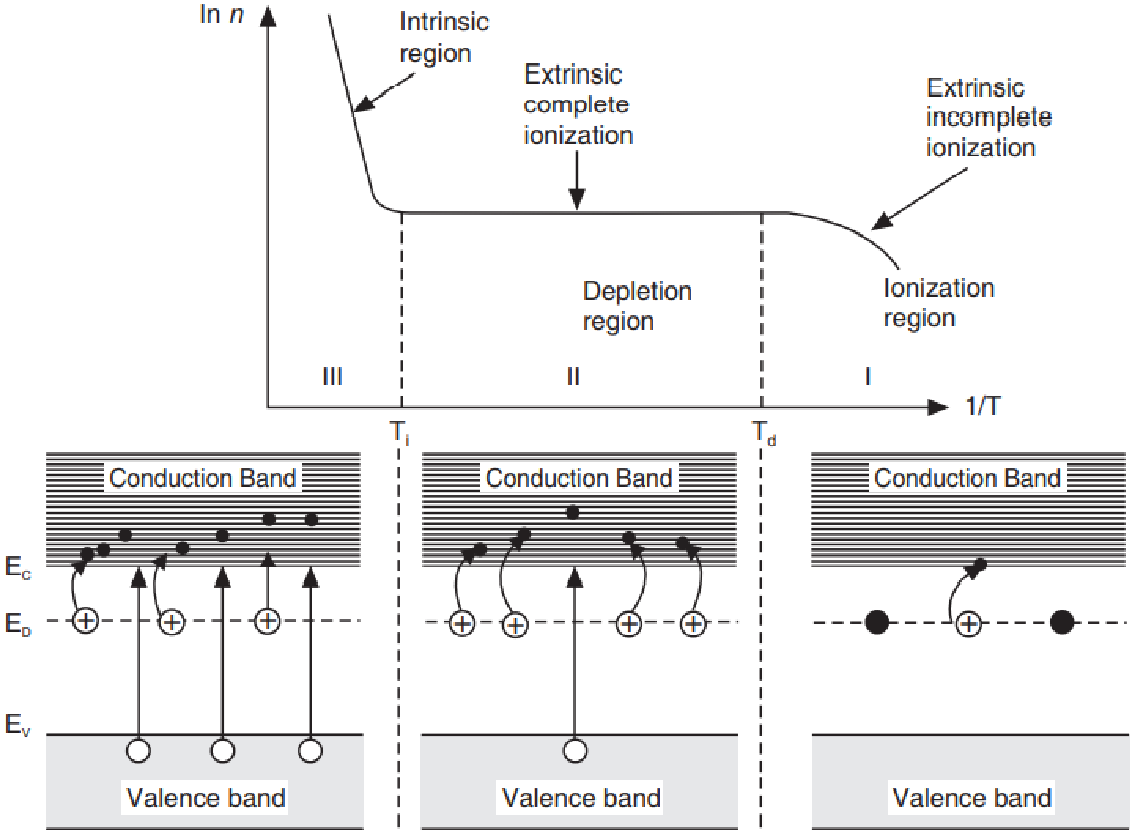
Hole density available for conduction, $\boxed{p = N_v\, e^{-(EF - Ev)/kT}}$

Extrinsic semiconductor

Common Dopant Elements for Silicon and Germanium

n-type	p-type
Phosphorous	Aluminium
Arsenic	Boron
Antimony	Gallium
	Indium

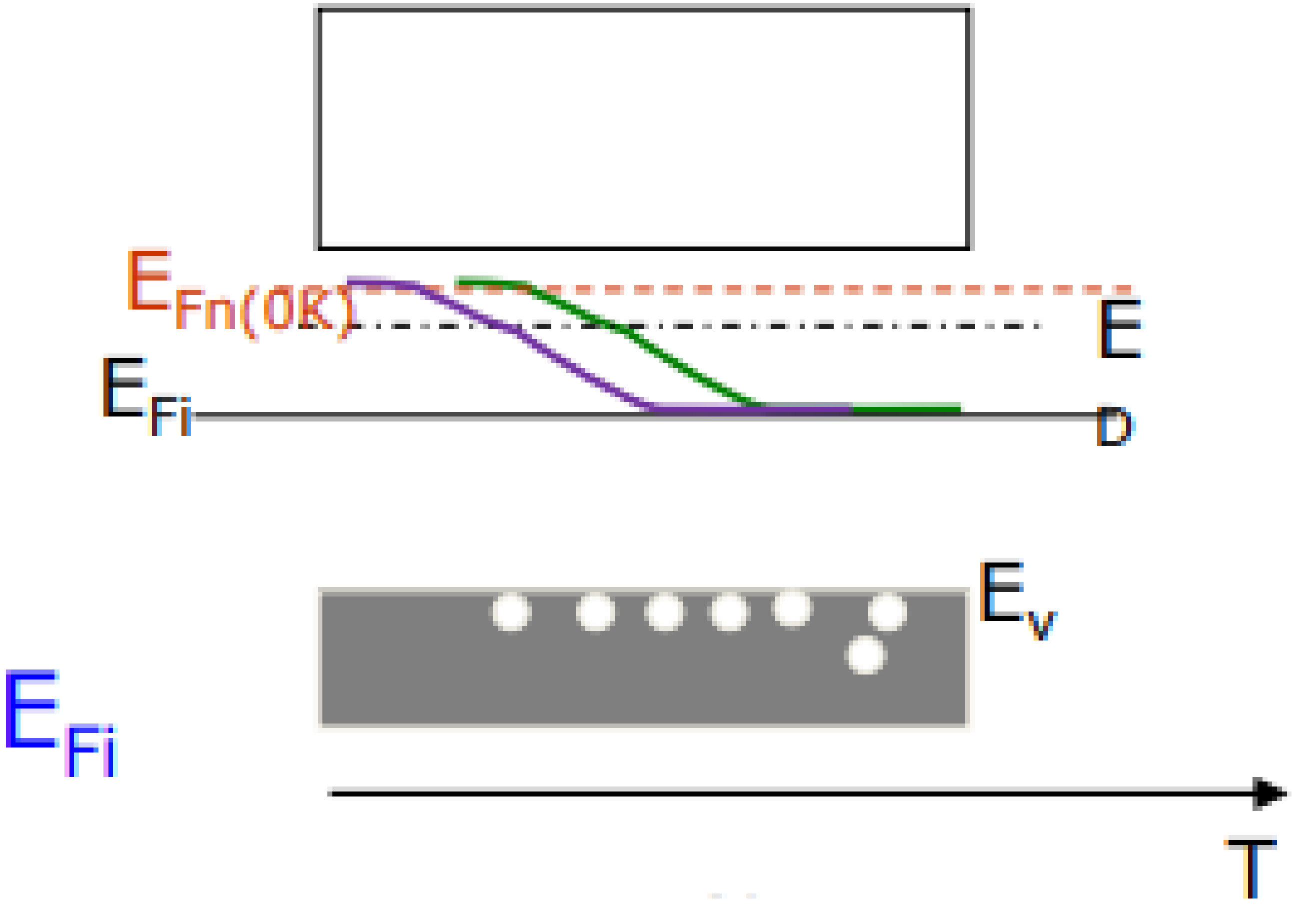




1. @ 0K
2. Then raise temperature
3. @ 100 K all donor atoms are ionized
4. @ high temperature

Extrinsic semiconductor- Fermi level- n type semiconductor

$$E_{Fn} = \frac{E_{cn} + E_D}{2} + \frac{k_B T}{2} ln \left[\frac{N_D}{N_c} \right]$$



Carrier Concentration in n-type semiconductor

The expression for concentration of holes in N-type semiconductors can be obtained by substituting the value of Fermi energy of N-type semiconductors into the expression for no. density of electrons in conduction band

Electron density available for conduction, $\boxed{n = N_c e^{-(E_c - E_F)/kT}}$

No. density of electrons in conduction band of N-type semiconductor , n_n

$$= N_c \times \exp\left(\frac{E_{Fn} - E_{cn}}{k_B T}\right)$$

Substituting $E_{Fn} = \frac{E_{cn} + E_D}{2} + \frac{k_B T}{2} ln\left[\frac{N_D}{N_c}\right]$

$$(E_{Fn} - E_{cn}) = \frac{E_{cn} + E_D}{2} - E_{cn} + (k_B T) ln\sqrt{\frac{N_D}{N_c}} = \frac{E_{cn} + E_D - 2E_{cn}}{2} + (k_B T) ln\sqrt{\frac{N_D}{N_c}}$$

$$\left(\frac{E_{Fn} - E_{cn}}{k_B T}\right) = \left(\frac{E_D - E_{cn}}{2k_B T}\right) + ln\sqrt{\frac{N_D}{N_c}}$$

$$exp\left(\frac{E_{Fn} - E_{cn}}{k_B T}\right) = exp\left(\frac{E_D - E_{cn}}{2k_B T}\right) \times \sqrt{\frac{N_D}{N_c}}$$

$$n_n = N_c \times \exp\left(\frac{E_{Fn} - E_{cn}}{k_B T}\right) = N_c \times \sqrt{\frac{N_D}{N_c}}\, exp\left(\frac{E_D - E_{cn}}{2k_B T}\right) = \sqrt{N_c N_D}\; exp\left(\frac{E_D - E_{cn}}{2k_B T}\right)$$

Carrier Concentration in n-type semiconductor

$$n_n = \sqrt{N_c N_D}\ exp\left(\frac{E_D - E_{cn}}{2k_BT}\right) \qquad N_c = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2}$$

$$= (2N_D)^{1/2}\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/4} exp\left(\frac{E_D - E_{cn}}{2k_BT}\right)$$

i.e For low temperatures, no. density of electrons in N-type semiconductor is proportional to the square-root of donor impurity density

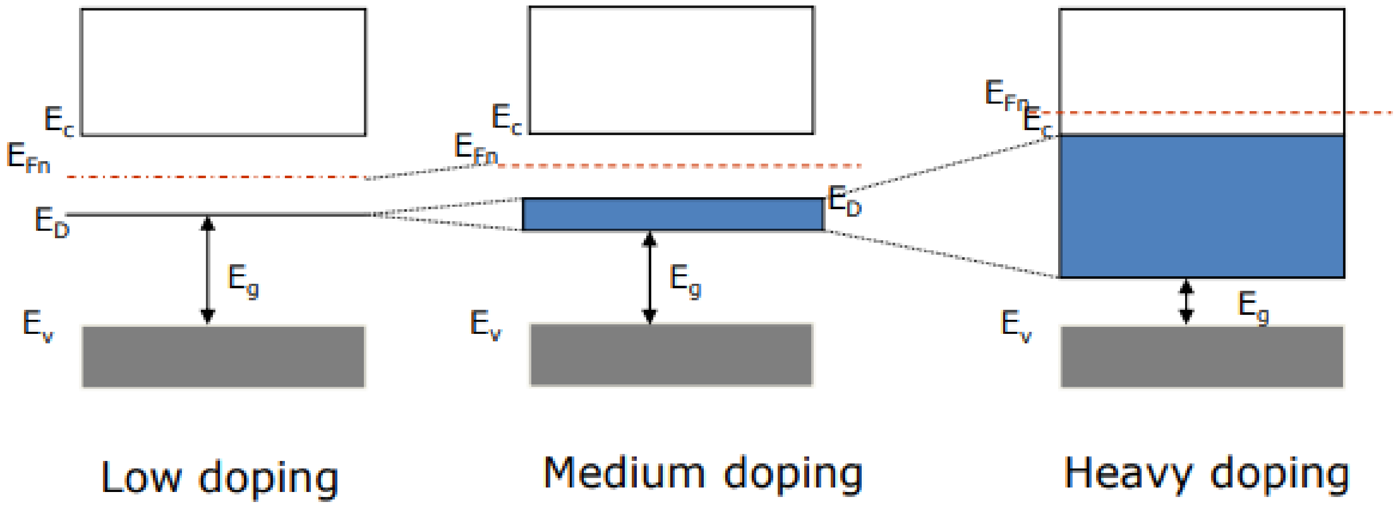
$(E_{cn}-E_D)$ is the ionization energy of the dopant

When all donors are ionized, $n_n \approx N_D$

Effect of doping concentration

Variation of Fermi level, E_{Fn} with dopant concentration:

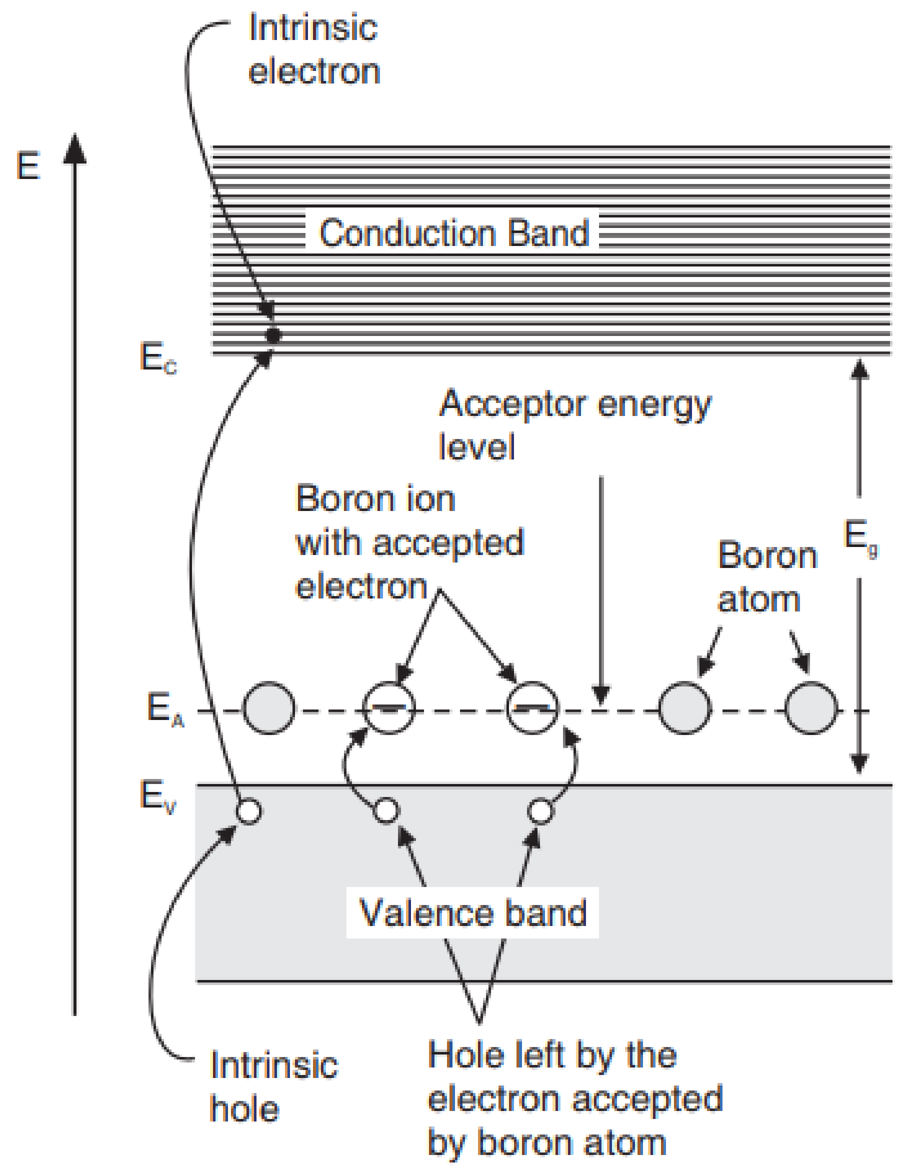
- When dopant concentration increases, dopants come close together and interacts
  - This causes broadening of the donor level and the Fermi level gets pushed up
  - This broadening of the donor level also leads to reduction in bandgap
- If the dopant concentration goes still higher, the Fermi level will go into the conduction band



p- type semiconductor

- A p-type semiconductor is produced when a pure semiconductor is doped with a trivalent impurity such as boron.
- Boron atom has three valence electrons.
- Therefore, it falls short of one electron for completing the four covalent bonds with its neighbours.
- When an electron from a neighbouring atom acquires energy and jumps into the vacancy to form the fourth bond, it leaves behind a hole.
- The boron atom having acquired an additional electron becomes a negative ion.
- The hole can move freely in the valence band whereas the impurity ion is fixed in position by the covalent bonds.
- As the boron atom accepted an electron from the valence band, it is called an acceptor atom.
- The acceptor impurity atoms produce holes without the simultaneous generation of the electrons in the conduction band

p- type semiconductor



Fermi level- p type semiconductor

Carrier Concentration in p-type Semiconductor at Low Temperatures : (In the Ionization Region)

$$p = N_A^-$$

The concentration of ionized acceptors $N_A^- = N_A f(E_A) = N_A \exp\left(\frac{E_F - E_A}{kT}\right)$

$$p = N_A \exp\left(\frac{E_F - E_A}{kT}\right) \qquad p = N_V e^{-(E_F - E_V)/kT} = N_V \exp\left(\frac{E_V - E_F}{kT}\right)$$

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

Taking logarithm and rearranging the terms we get

$$\left(\frac{E_F - E_A}{kT}\right) - \left(\frac{E_V - E_F}{kT}\right) = ln\,\frac{N_V}{N_A}$$

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

$$E_F = \frac{E_V + E_A}{2} + \left(\frac{kT}{2}\right) ln\,\frac{N_V}{N_A}$$

$$E_F = \frac{E_V + E_A}{2} - \left(\frac{kT}{2}\right) ln\,\frac{N_A}{N_V}$$

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

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

Carrier Concentration in p-type semiconductor

$$\exp\left[\frac{E_V - E_F}{kT}\right] = \exp\left[\frac{E_V}{kT} - \frac{E_V + E_A}{2kT} + \left(\frac{1}{2}\right) ln\ \frac{N_A}{2\left(2\pi m_h^* kT/h^2\right)^{3/2}}\right]$$

$$= \exp\left[\frac{E_V - E_A}{2kT} + \left(\frac{1}{2}\right) ln\ \frac{N_A}{2\left(2\pi m_h^* kT/h^2\right)^{3/2}}\right]$$

$$= \exp\left[\frac{E_V - E_A}{2kT} + ln\sqrt{\frac{N_A}{2\left(2\pi m_h^* kT/h^2\right)^{3/2}}}\right] \qquad \left[\because \frac{1}{2} ln\, x = ln\sqrt{x}\right]$$

$$= \exp\left[\left(\frac{E_V = E_A}{2kT}\right)\right] \cdot \exp\left[ln\sqrt{\frac{N_A}{2\left(2\pi\ m_h^* kT/h^2\right)^{3/2}}}\right] \qquad \left[\begin{array}{l}\because \exp\ (a+b) = \\ \exp(a) + \exp(b)\end{array}\right]$$

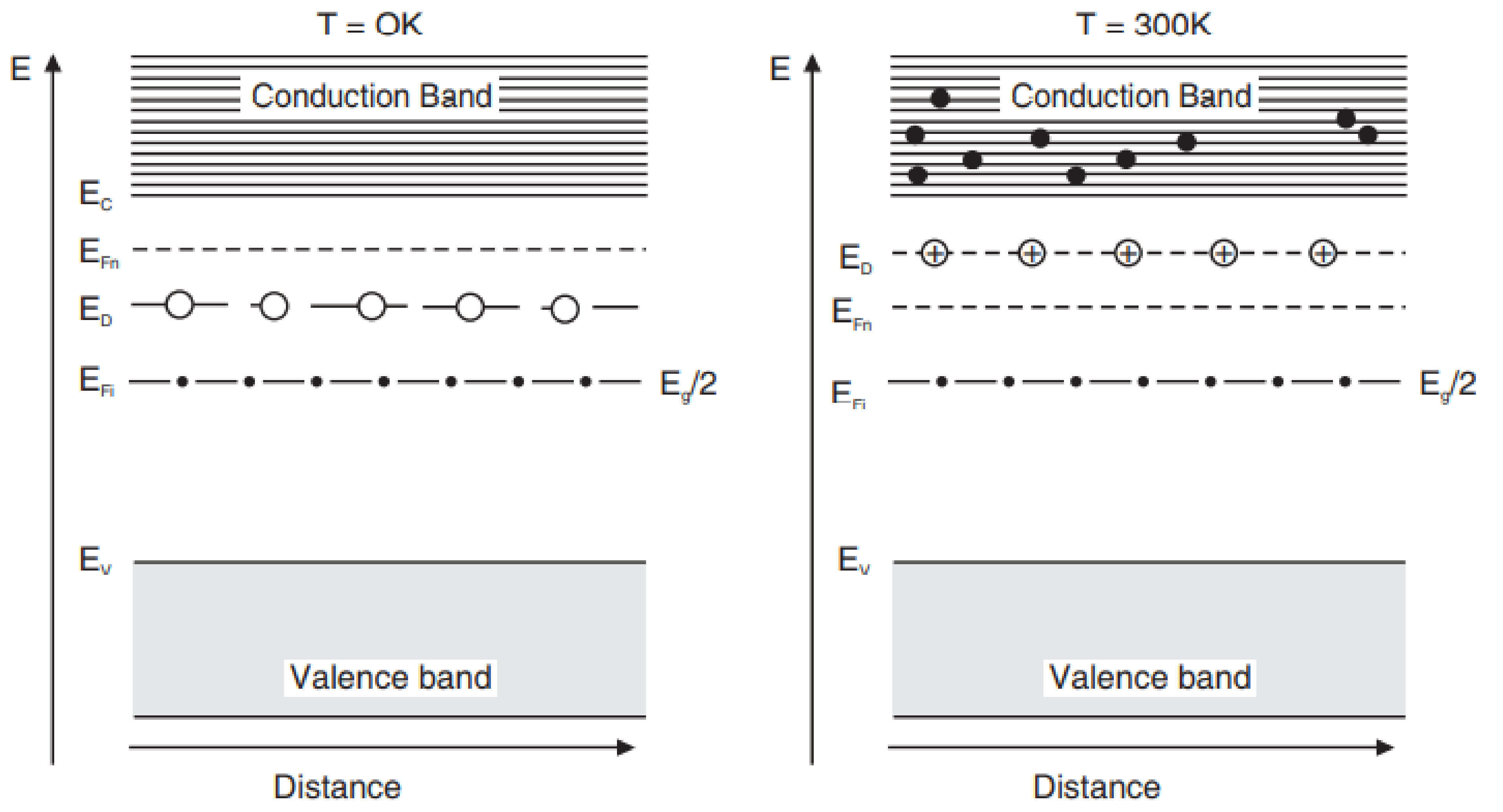
$$= \exp\left[\left(\frac{E_V - E_A}{2kT}\right)\right] \cdot \left[\sqrt{\frac{N_A}{2\left(2\pi\ m_h^* kT/h^2\right)^{3/2}}}\right] \qquad \left[\because \exp\ (ln\, x) = x\right]$$

$$\therefore \quad p = N_V \exp\left[\frac{E_V - E_A}{kT}\right] = 2\left[\frac{2\pi\ m_h^* kT}{h^2}\right]^{3/2} \exp\left[\left(\frac{E_V - E_A}{2kT}\right)\right] \cdot \left[\sqrt{\frac{N_A}{2\left(2\pi\ m_h^* kT/h^2\right)^{3/2}}}\right]$$

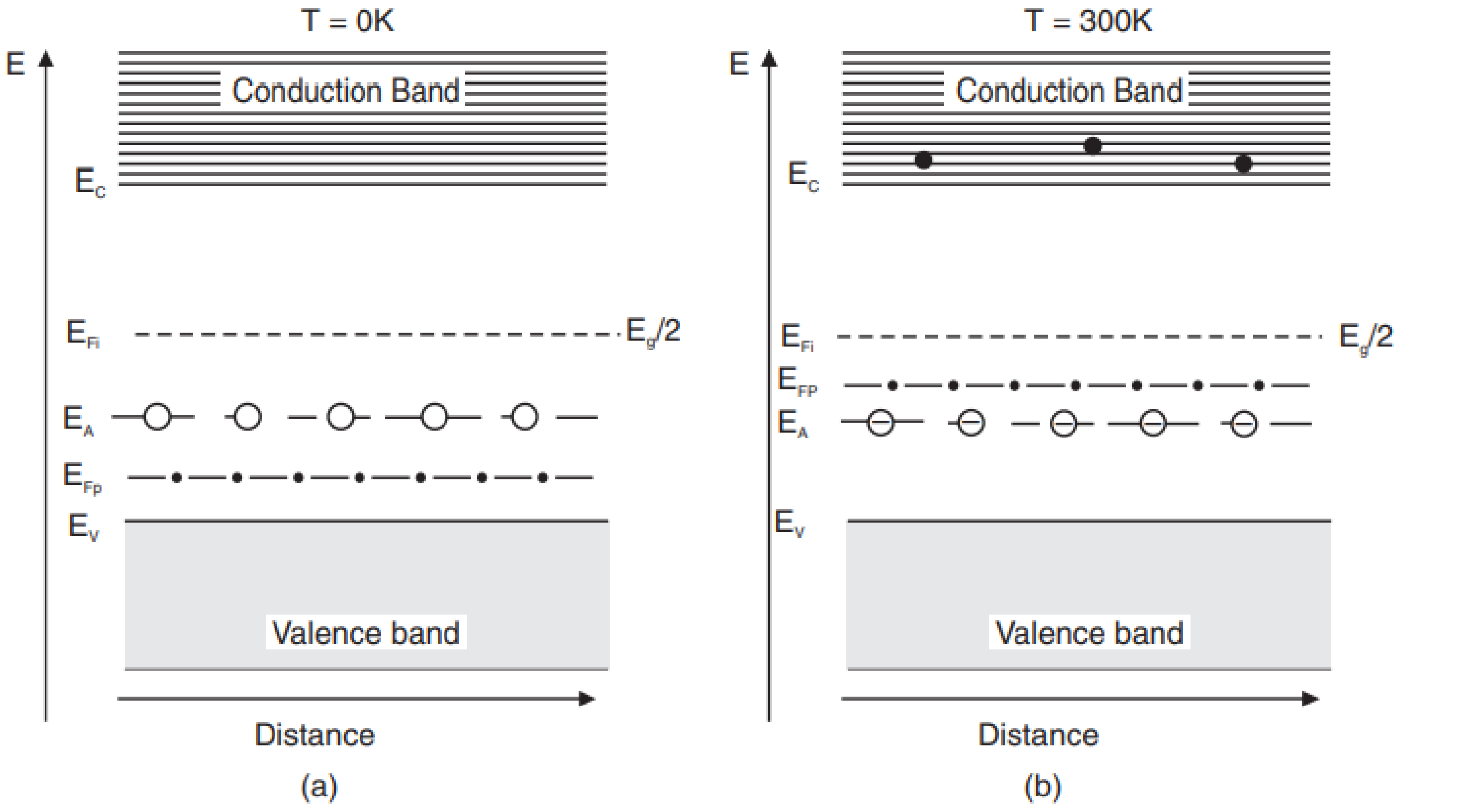
or

$$p = (2N_A)^{\frac{1}{2}}\left[\frac{2\pi\ m_h^* kT}{h^2}\right]^{3/4} \exp\left[\left(\frac{E_V - E_A}{2kT}\right)\right] \qquad (30.76)$$

BAND DIAGRAMS OF EXTRINSIC SEMICONDUCTORS AT 0K AND 300K



BAND DIAGRAMS OF EXTRINSIC SEMICONDUCTORS AT 0K AND 300K

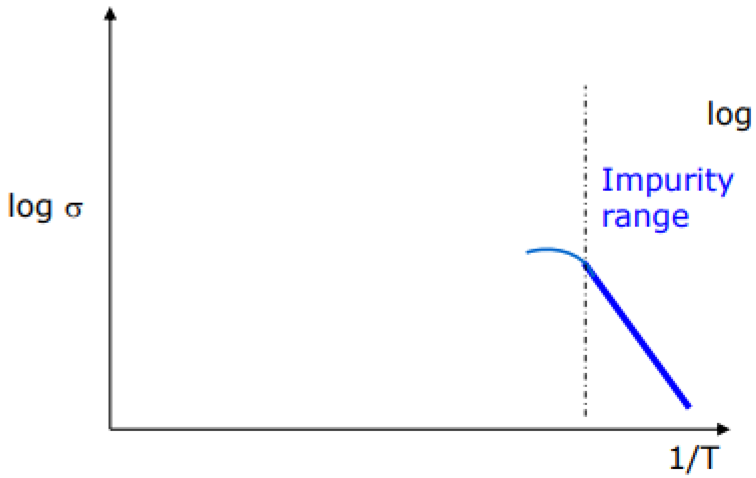


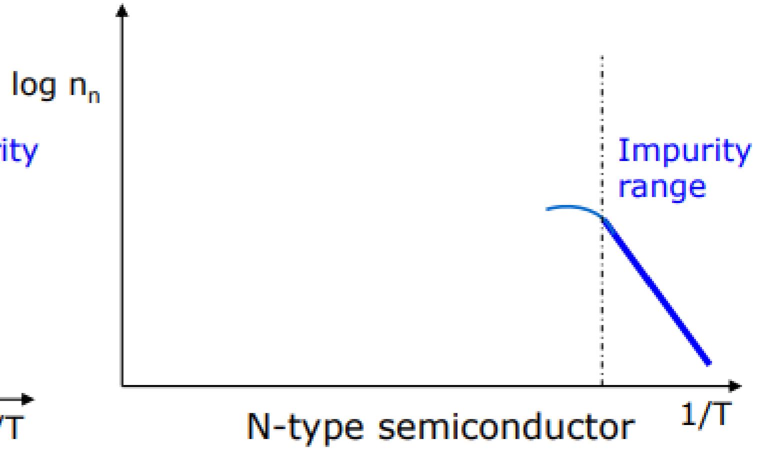
EXTRINSIC CONDUCTIVITY

Conductivity σ in semiconductors $= Ne\mu = ne\mu_e + pe\mu_h$

- At OK, there are no carriers either in the conduction band or valence band and hence conductivity is also zero

- At low temperatures, impurity atoms get ionized releasing carriers for conduction. (N type-Donors release electrons, P-type-acceptors release holes. Therefore no. of charge carriers and hence conductivity increases with temperature. This region is called impurity range in the carrier concentration /conductivity versus 1/T curve





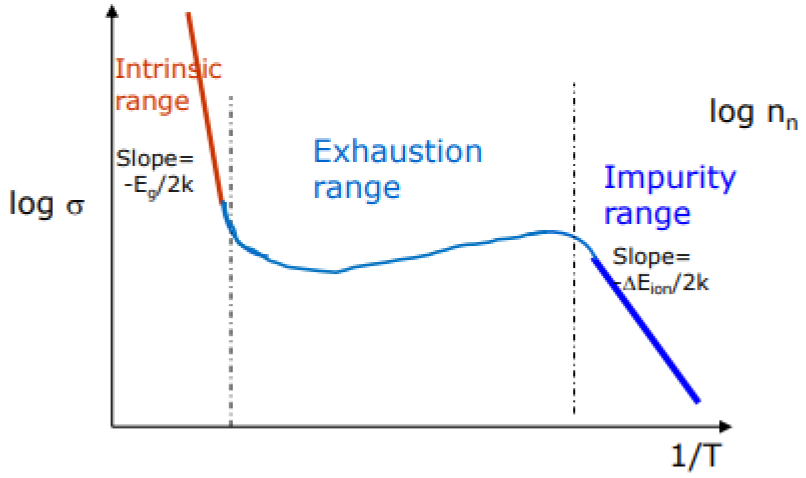
N-type semiconductor

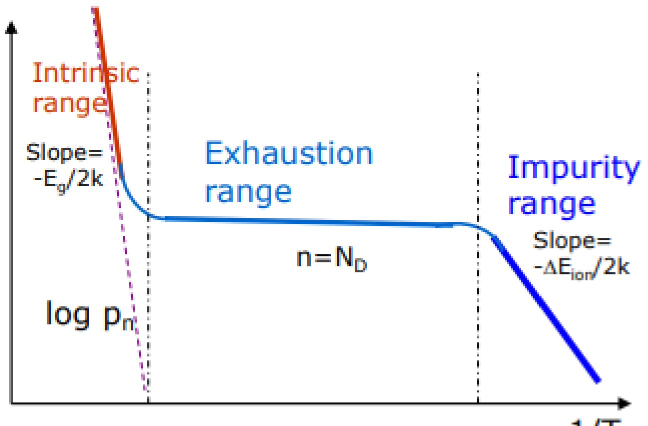
$$n_n = (2N_D)^{1/2}\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/4} exp\left(\frac{E_D - E_{cn}}{2k_B T}\right) \quad p = (2N_A)^{\frac{1}{2}}\left[\frac{2\pi\, m_h^* kT}{h^2}\right]^{3/4} \exp\left[\left(\frac{E_V - E_A}{2kT}\right)\right]$$

EXTRINSIC CONDUCTIVITY

- As temperature increases further, thermal ionization results in addition of holes in the valence band and an equal no. of electrons in the conduction band and the material now behaves like an intrinsic semiconductor. This region is called the intrinsic region

- In the intrinsic region, conductivity increases with temperature with the same slope as that in intrinsic semiconductor. Slope of the lnσ vs 1/T curve in this region is $-E_g/2k$





N-type semiconductor

Mass action law

Product of carrier densities in an extrinsic semiconductors is a constant and equal to square of intrinsic carrier density, n_i

In N type

$$n_n p_n = N_c e^{\frac{(E_{Fn}-E_{cn})}{kT}} . N_v e^{\frac{(E_{vn}-E_{Fn})}{kT}} = N_c N_v e^{\frac{(E_{Fn}-E_{cn}+E_{vn}-E_{Fn})}{kT}}$$

$$= N_c N_v e^{\frac{(-E_{cn}+E_{vn})}{kT}} = N_c N_v e^{\frac{-(E_{cn}-E_{vn})}{kT}} = N_c N_v e^{\frac{-(E_g)}{kT}}$$

$$= n_i^2$$

Similarly for P-type $p_p n_p = n_i^2$

Law of mass action - $\boxed{p_p n_p = n_n p_n = n_i^2}$

In exhaustion region, using law of mass action,

P-type

$$p_p = N_A, \quad n_p = \frac{n_i^2}{N_A}$$

N-type

$$n_n = N_D, \quad p_n = \frac{n_i^2}{N_D}$$

(a) Variation of Fermi Level with Temperature in an *n*-type Semiconductor

$$E_{Fn} = \frac{E_C + E_D}{2} \text{ at } T = 0\ K$$

As the temperature increases the donor levels gradually get depleted and the Fermi level moves downward. At the temperature of complete depletion of donor levels, T_d, the Fermi level coincides with the donor level E_D. Thus

$$E_{Fn} = E_D \text{ at } T = T_d \qquad (30.92)$$

(a) Variation of Fermi Level with Temperature in an *n*-type Semiconductor

As the temperature grows further above T_d, the Fermi level shifts downward in an approximately linear fashion. At a temperature T_i, the intrinsic process contributes to electron concentration significantly. At higher temperatures, the *n*-type semiconductor loses its extrinsic character and behaves as an intrinsic semiconductor. In the intrinsic region, the electron concentration in conduction band increases exponentially and the Fermi level approaches the intrinsic value. Thus,

$$E_{Fn} = E_{Fi} = \frac{E_g}{2} \qquad \text{at } T \geq T_i \qquad (30.93)$$

The variation of Fermi level E_{Fn} in an *n*-type semiconductor with temperature is illustrated in Fig. 30.19.

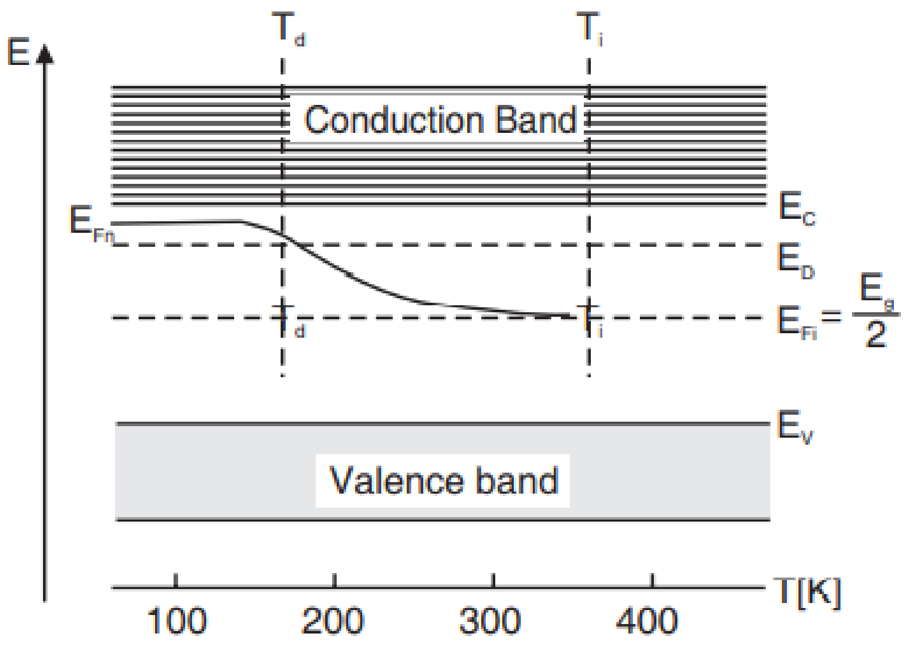


Fig. 30.19: Qualitative dependence of Fermi level on temperature in an *n*-type semiconductor

Variation of Fermi Level with Temperature in a p-type Semiconductor

In case of *p*-type semiconductor, in the low temperature region, holes in the valence band are only due to the transitions of electrons from the valence band to the acceptor levels. As the valence band is the source of electrons and the acceptor levels are the recipients for them, the Fermi level must lie between the top of the valence band and the impurity acceptor levels. When $T = 0$, Fermi level lies midway between the acceptor levels and the top of the valence band. Thus,

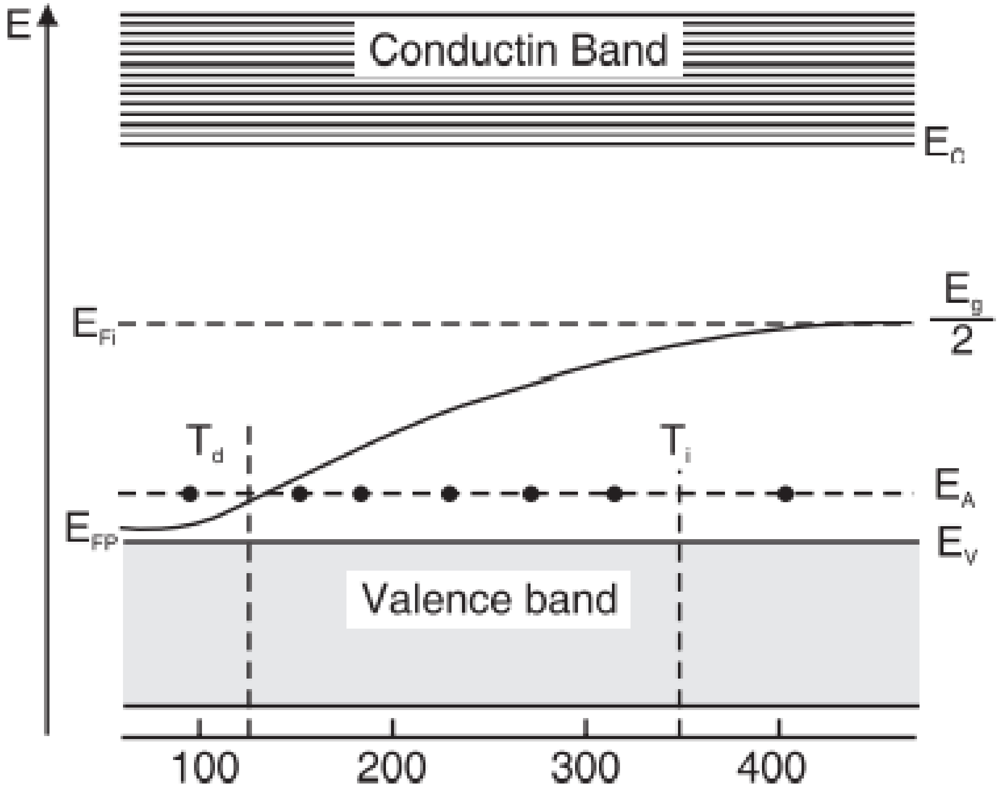


Fig. 30.20: Qualitative dependence of Fermi level on temperature in a *p*-type semiconductor

$$E_{FP} = \frac{E_V + E_A}{2} \tag{30.94}$$

FERMI LEVEL IN EXTRINSIC SEMICONDUCTORS

As the temperature increases the acceptor levels gradually get filled and the Fermi level moves upward. At the temperature of saturation T_s, the Fermi level coincides with the acceptor level E_A. Thus,

$$E_{FP} = E_A \quad \text{at } T = T_s \tag{30.95}$$

As the temperature grows above T_s, the Fermi level shifts upward in an approximately linear fashion.

At a temperature T_i intrinsic behaviour sets in. At higher temperatures, the *p*-type semiconductor loses its extrinsic character and behaves as an intrinsic semiconductor. In the intrinsic region, the hole concentration in the valence band increases exponentially and the Fermi level approaches the intrinsic value. Thus

$$E_{FP} = E_i = \frac{E_g}{2} \quad \text{at } T = T_i \tag{30.96}$$

The variation of Fermi level E_{Fn} in an *p*-type semiconductor with temperature is illustrated in Fig. 30.20.