



## $n_0$ equations

$$n_0 = \int g_c(E) f_F(E) dE$$

For electrons in the conduction band, we have  $E > E_c$ . If  $(E_c - E_f) \gg kT$ , then  $(E - E_f) \gg kT$ ,

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_f}{kT}\right)} \approx \exp\left[\frac{-(E - E_f)}{kT}\right]$$

$$n_0 = \int_{E_c}^{\infty} \frac{4\pi(2m_n^*)^{3/2}}{h^3} \sqrt{E - E_c} \exp\left[\frac{-(E - E_f)}{kT}\right] dE$$

$$n_0 = N_c \exp\left[\frac{-(E_c - E_f)}{kT}\right] \quad \text{where} \quad N_c = 2 \left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

*effective density of states function in the conduction band*

## $p_0$ equations

$$p_0 = \int g_v(E) [1 - f_F(E)] dE$$

For energy states in the valence band,  $E < E_v$ . If  $(E_f - E_v) \gg kT$

$$1 - f_F(E) = \frac{1}{1 + \exp\left(\frac{E_f - E}{kT}\right)} \approx \exp\left[\frac{-(E_f - E)}{kT}\right]$$

$$p_0 = \int_{-\infty}^{E_v} \frac{4\pi(2m_p^*)^{3/2}}{h^3} \sqrt{E_v - E} \exp\left[\frac{-(E_f - E)}{kT}\right] dE$$

$$p_0 = N_v \exp\left[\frac{-(E_f - E_v)}{kT}\right] \quad \text{where} \quad N_v = 2 \left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

*effective density of states function in the valence band*

## Effective density of states function and effective mass values

	$N_c$ (cm <sup>-3</sup> )	$N_v$ (cm <sup>-3</sup> )	$m_n^*/m_0$	$m_p^*/m_0$
Silicon	$2.8 \times 10^{19}$	$1.04 \times 10^{19}$	1.08	0.56
Gallium arsenide	$4.7 \times 10^{17}$	$7.0 \times 10^{18}$	0.067	0.48
Germanium	$1.04 \times 10^{19}$	$6.0 \times 10^{18}$	0.55	0.37

## Intrinsic Carrier Concentration

For an intrinsic semiconductor, the concentration of electrons in the conduction band is equal to the concentration of holes in the valence band.

→  $n_0 = p_0 \equiv n_i$  → intrinsic semiconductor

Let  $E_F = E_{Fi}$

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

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

$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_v)}{kT}\right] = N_c N_v \exp\left[\frac{-E_g}{kT}\right]$$

## Intrinsic Fermi-Level Position

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

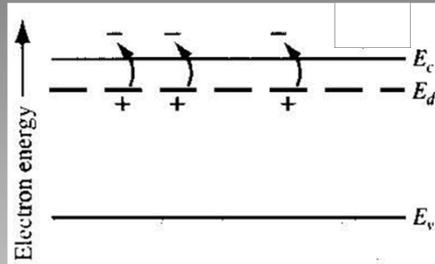
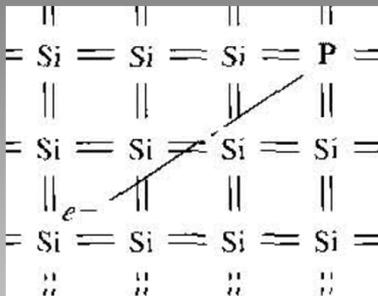
If we take the natural log of both sides of this equation and solve for  $E_{Fi}$ , we got

$$E_{Fi} - E_{\text{midgap}} = \frac{3}{4} kT \ln \left( \frac{m_p^*}{m_n^*} \right)$$

where  $\frac{1}{2}(E_c + E_v) = E_{\text{midgap}}$

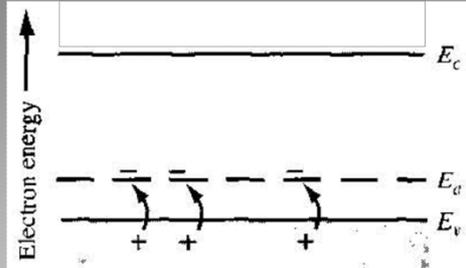
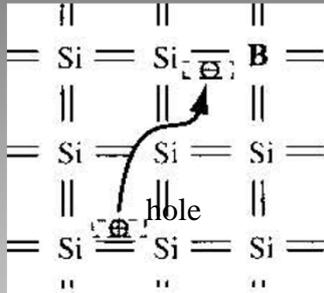
$$m_p^* =, >, < m_n^*$$

## N-type semiconductor



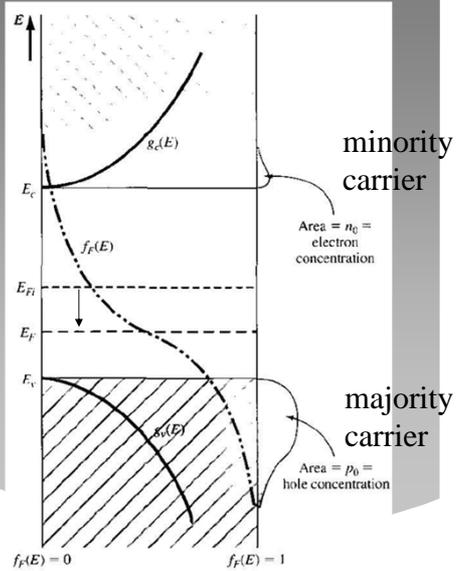
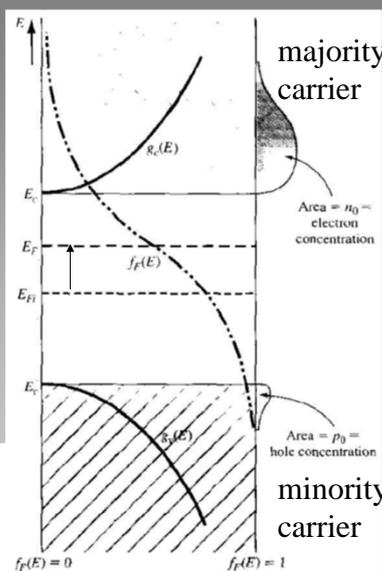
Extrinsic semiconductor  
group V element  
Donor impurity atom

# P-type semiconductor



group III element  
acceptor impurity atom

# Extrinsic semiconductor



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

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

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

Intrinsic carrier concentration

$E_F > E_{Fi} \rightarrow n_0 > p_0 \rightarrow$  n-type semi.

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

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

$E_F < E_{Fi} \rightarrow p_0 > n_i$ , and  $n_0 < n_i \rightarrow p_0 > n_0 \rightarrow$  p-type semi.

## $n_0 p_0$ Product

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

$$= N_c N_v \exp\left[\frac{-E_g}{kT}\right]$$

$$= n_i^2$$

The product of  $n_0$  and  $p_0$  is always a constant for a given semiconductor material at a given temperature.

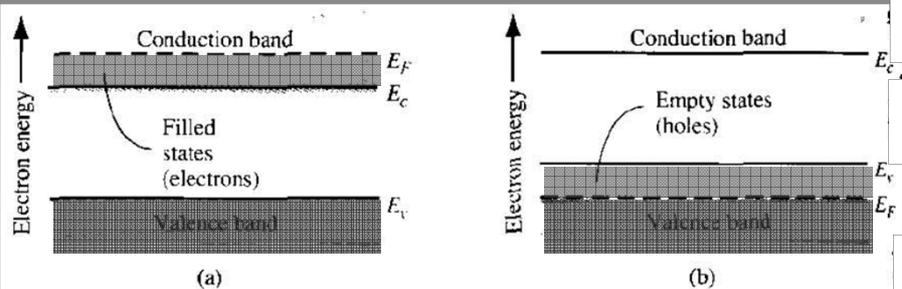
## Nondegenerate Semiconductors

In our discussion of adding dopant atoms to a semiconductor, we have implicitly assumed that the concentration of dopant atoms added is small when compared to the density of host or semiconductor atoms. The small number of impurity atoms are spread far *enough* apart so that there is no interaction between donor electrons. These types of semiconductors are referred to as nondegenerate semiconductors.

## Degenerate Semiconductors

If the impurity concentration increases, the distance between the impurity atoms decreases and a point will be reached when donor electrons, for example, will begin to interact with each other. When this occurs, the single discrete donor energy will split into a band of energies. As the donor concentration further increases, the band of donor states widens and may overlap the bottom of the conduction band. This overlap occurs when the donor concentration becomes comparable with the effective density of states. When the concentration of electrons in the conduction band exceeds the density of states  $N_c$ , the Fermi energy lies within the conduction band. This type of semiconductor is called a degenerate n-type semiconductor.

degenerate p-type semiconductor



**Figure 4.11** | Simplified energy-band diagrams for degenerately doped (a) n-type and (b) p-type semiconductors.

# Compensated Semiconductors

A *compensated semiconductor* is one that contains both donor and acceptor impurity atoms in the same region.

n-type compensated semiconductor:  $N_d > N_a$

p-type compensated semiconductor:  $N_a > N_d$

completely compensated semiconductor:  $N_a = N_d$

intrinsic material

$$n_0 + N_a^- = p_0 + N_d^+$$

$$n_0 + (N_a - p_a) = p_0 + (N_d - n_d)$$

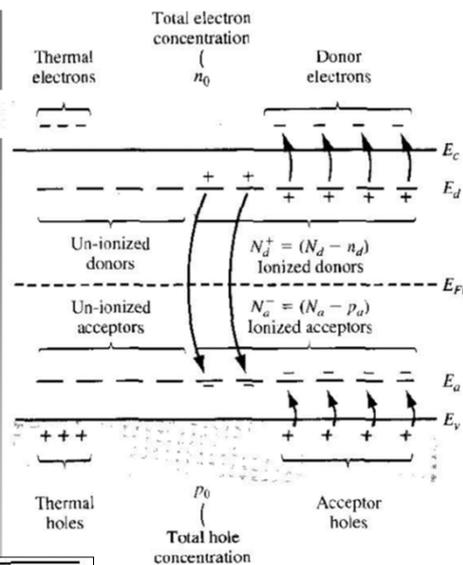
If we assume complete ionization,  $n_d$  and  $p_a$  are both zero.

$$n_0 + N_a = p_0 + N_d$$

$$n_0 + N_a = \frac{n_i^2}{n_0} + N_d$$

$$n_0^2 - (N_d - N_a)n_0 - n_i^2 = 0$$

$$n_0 = \frac{(N_d - N_a)}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$



express  $n_0$  as  $n_i^2/p_0$

$$\frac{n_i^2}{p_0} + N_a = p_0 + N_d$$

$$p_0^2 - (N_a - N_d)p_0 - n_i^2 = 0$$

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$$

## POSITION OF FERMI ENERGY LEVEL

from  $n_0 = N_c \exp[-(E_c - E_F)/kT]$

$$\rightarrow E_c - E_F = kT \ln\left(\frac{N_c}{n_0}\right)$$

where  $n_0 = \frac{(N_d - N_a)}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$

For n-type semi.,  $N_d \gg n_i \rightarrow n_0 \sim N_d$

$$E_c - E_F = kT \ln\left(\frac{N_c}{N_d}\right)$$

For p-type semi.,

$$p_0 = N_v \exp [-(E_F - E_v)/kT]$$

$$E_F - E_v = kT \ln \left( \frac{N_v}{p_0} \right)$$

where 
$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left( \frac{N_a - N_d}{2} \right)^2 + n_i^2}$$

If  $N_a \gg n_i$ ,

$$E_F - E_v = kT \ln \left( \frac{N_v}{N_a} \right)$$

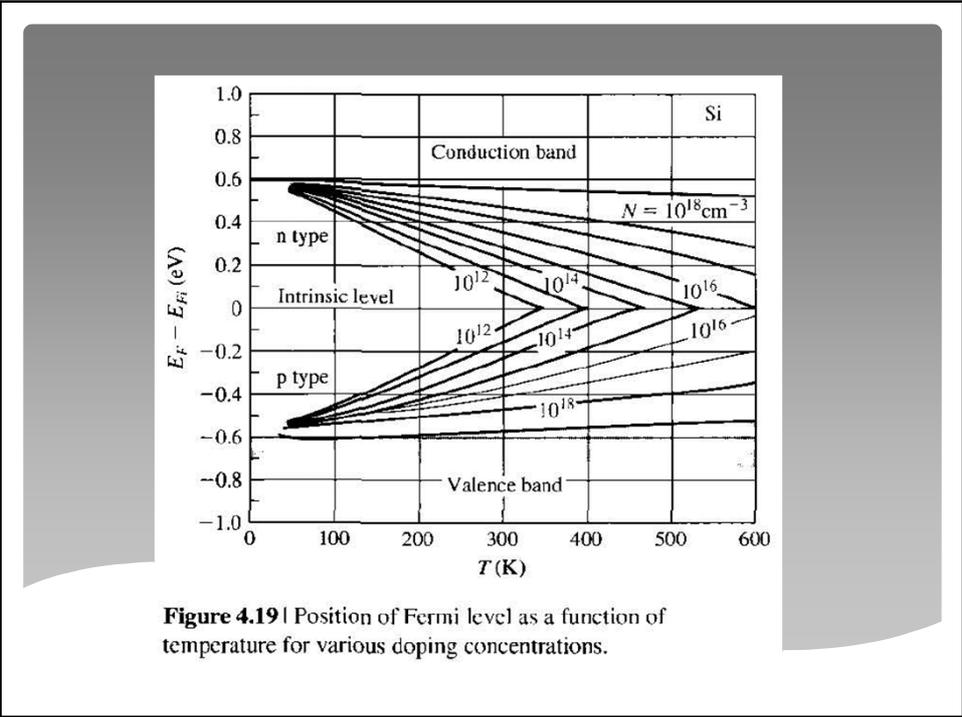
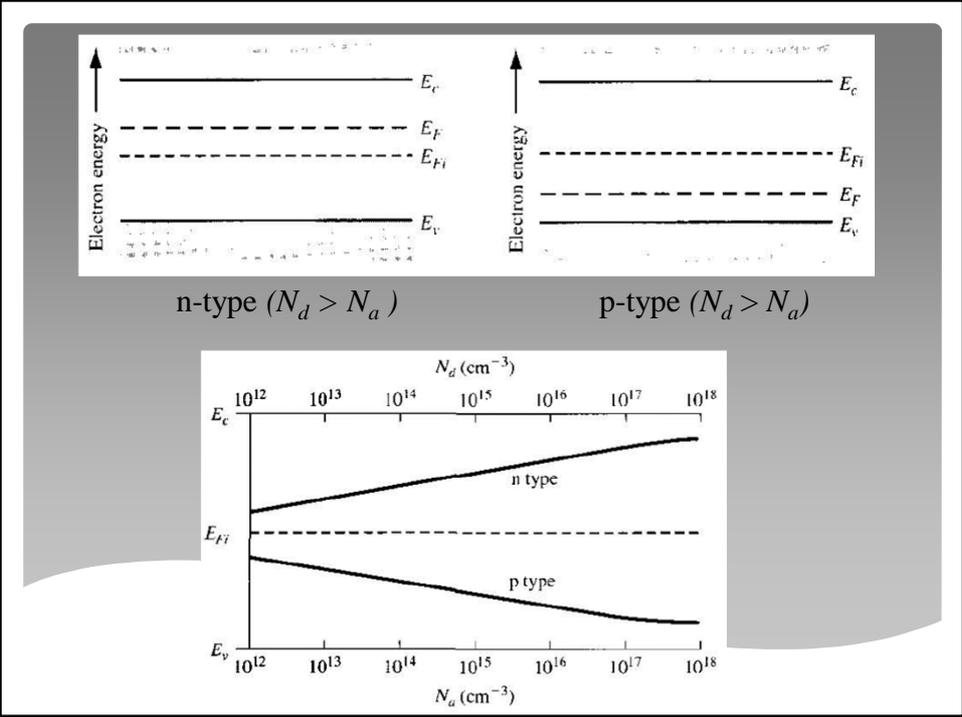
## Another way

$$n_0 = n_i \exp \{ (E_F - E_{Fi}) / kT \}$$

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

$$p_0 = n_i \exp [-(E_F - E_{Fi}) / kT]$$

$$E_{Fi} - E_F = kT \ln \left( \frac{p_0}{n_i} \right)$$



**Figure 4.19** | Position of Fermi level as a function of temperature for various doping concentrations.