Semiconductor Devices

Chapter 4 Semiconductor in Equilibrium

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Density of state (DOS) function

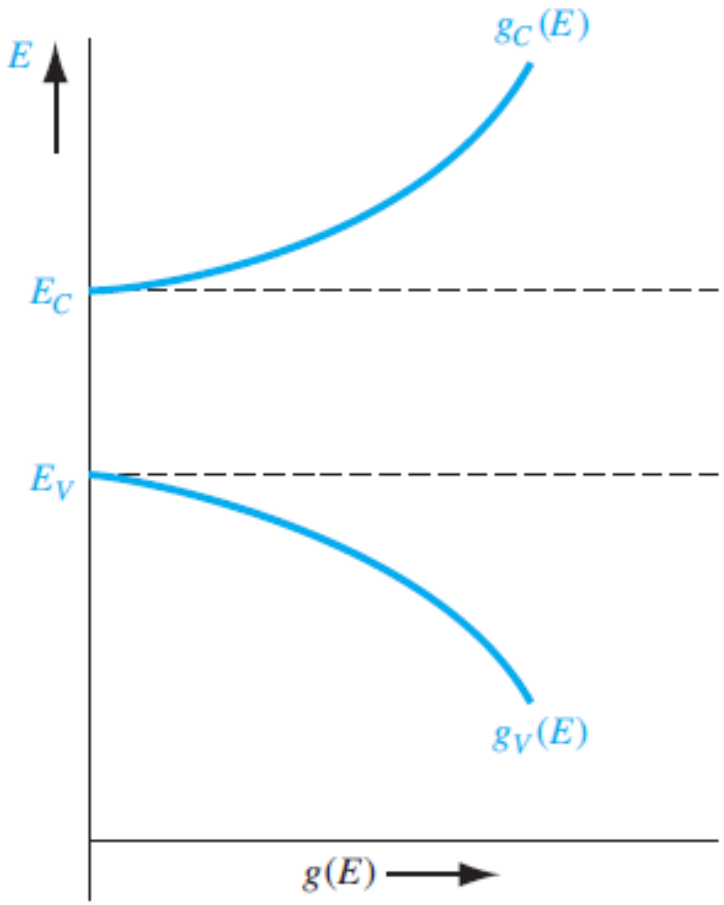


Figure 3.27 | The density of energy states in the conduction band and the density of energy states in the valence band as a function of energy.

$$g_c(E) = \frac{4\pi(2m_n{}^*)^{3/2}}{h^3}\sqrt{E - E_c} \qquad (3.72)$$

$$g_v(E) = \frac{4\pi(2m_p{}^*)^{3/2}}{h^3}\sqrt{E_v - E} \qquad (3.75)$$

Fermi-Dirac distribution function

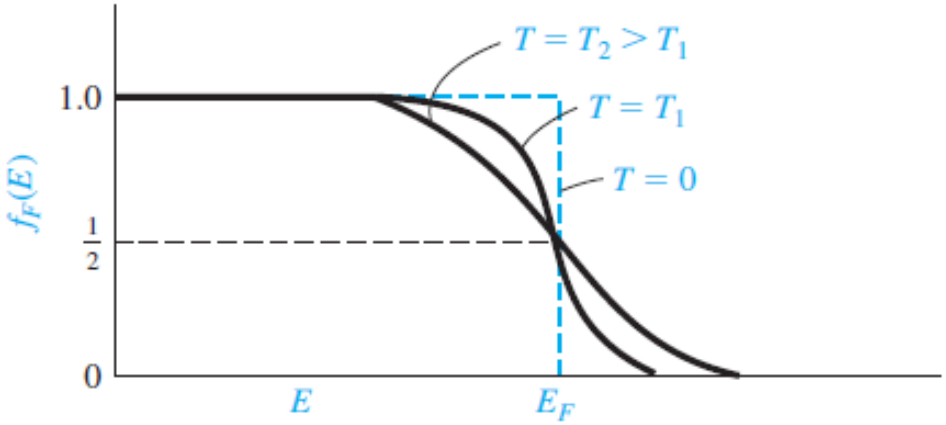


Figure 3.33 | The Fermi probability function versus energy for different temperatures.

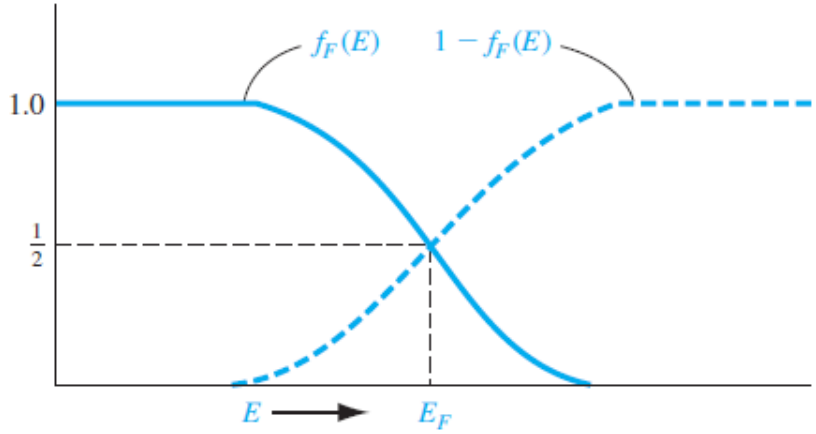


Figure 3.34 | The probability of a state being occupied, $f_F(E)$, and the probability of a state being empty, $1 - f_F(E)$.

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \qquad (3.79)$$

when $T > 0$ K

$$f_F(E) \neq 1, \quad f_F(E) \neq 0$$

when $E = E_F$

$$f_F(E) = \frac{1}{1 + \exp(0)} = \frac{1}{2}$$

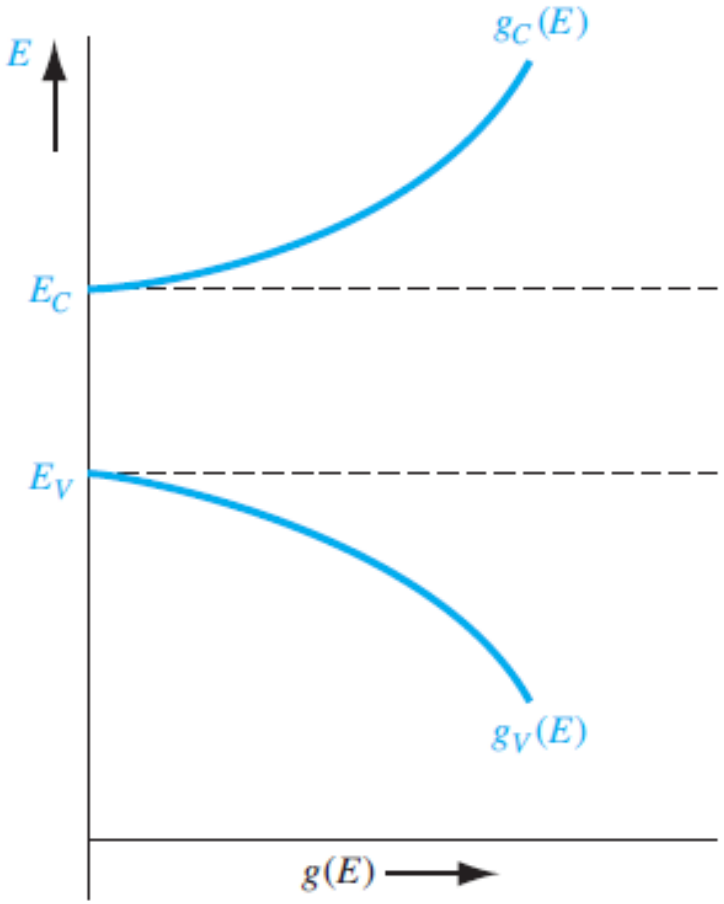
Boltzmann approximation

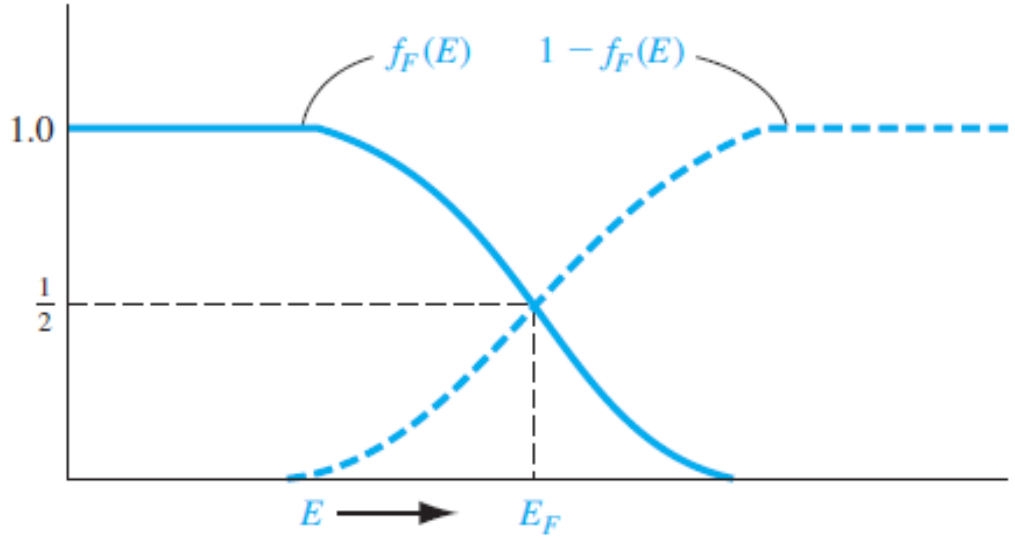
$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \tag{3.79}$$

when $E - E_F >> kT$ $\exp((E - E_F)/kT) >> 1$

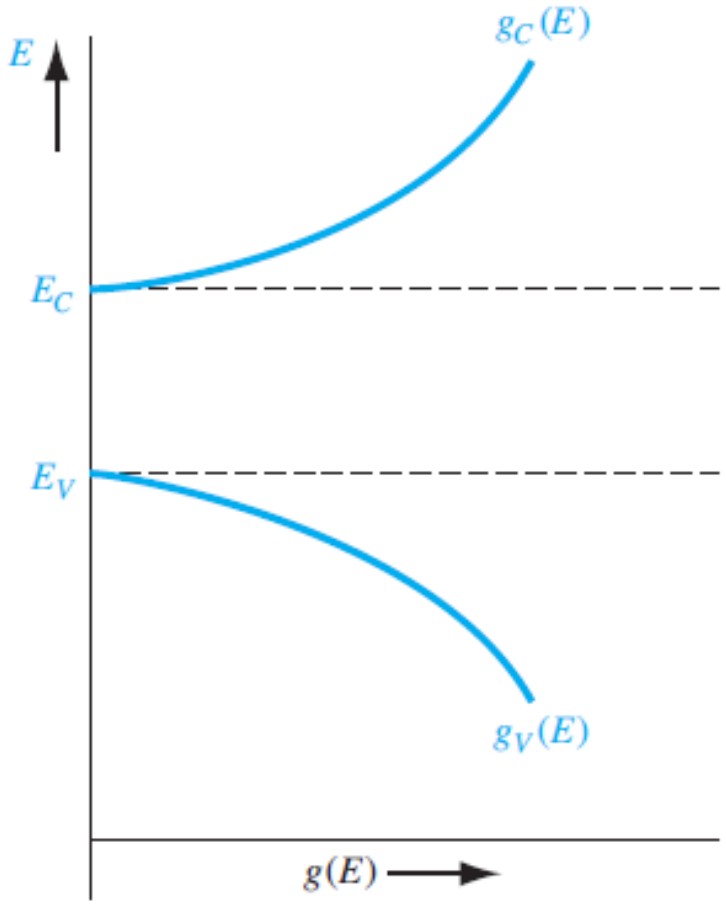
$$f_F(E) \approx \frac{1}{\exp\left(\frac{E - E_F}{kT}\right)} \approx \exp\left[\frac{-(E - E_F)}{kT}\right] \tag{3.80}$$

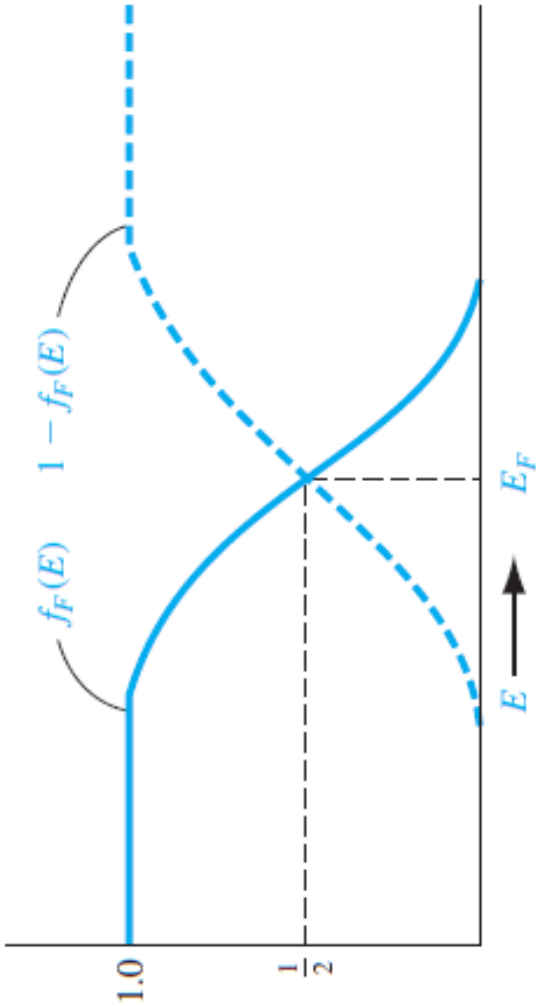
Thermal Equilibrium Distribution of Electrons and Holes



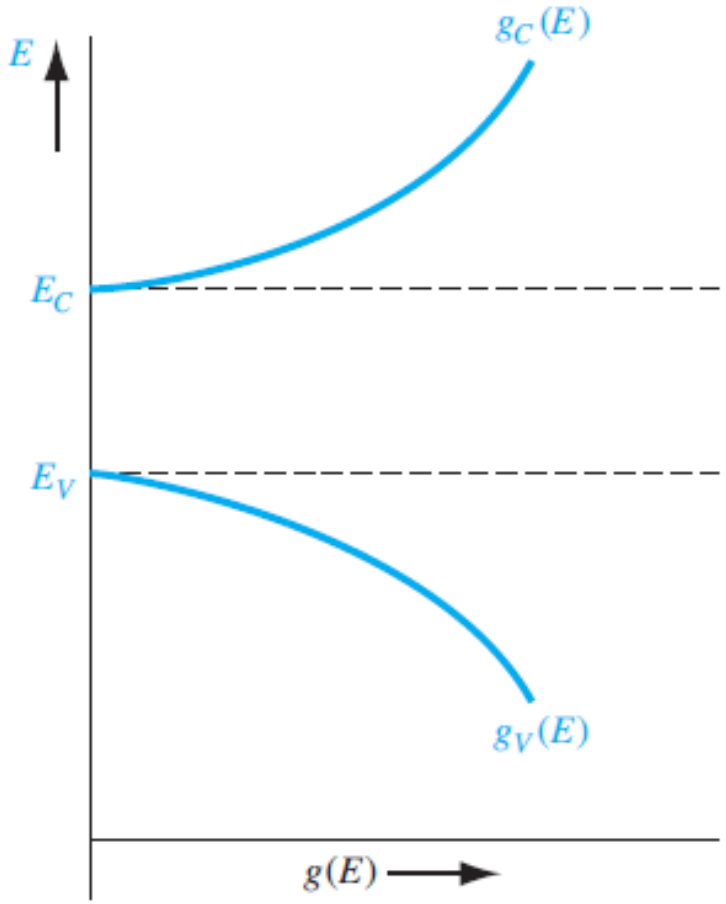


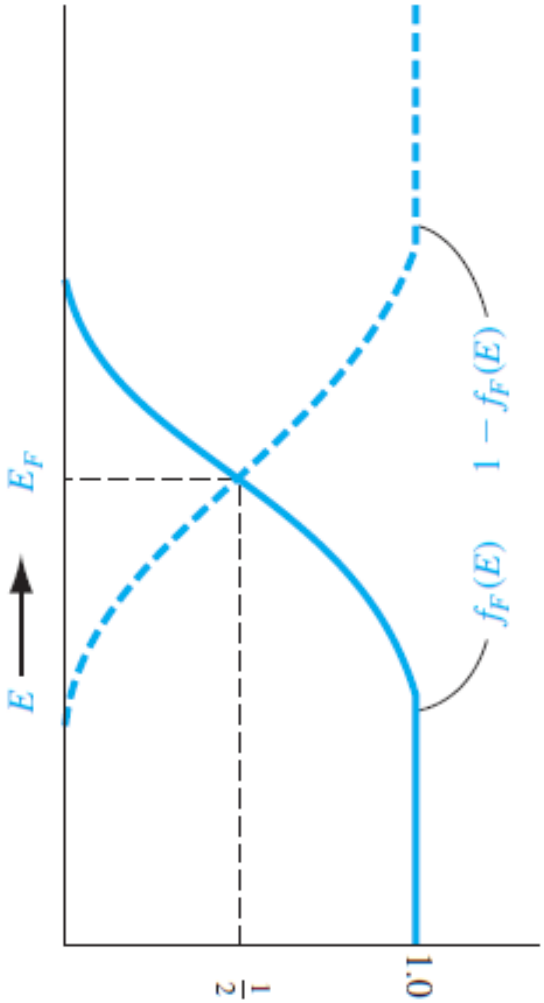
Thermal Equilibrium Distribution of Electrons and Holes



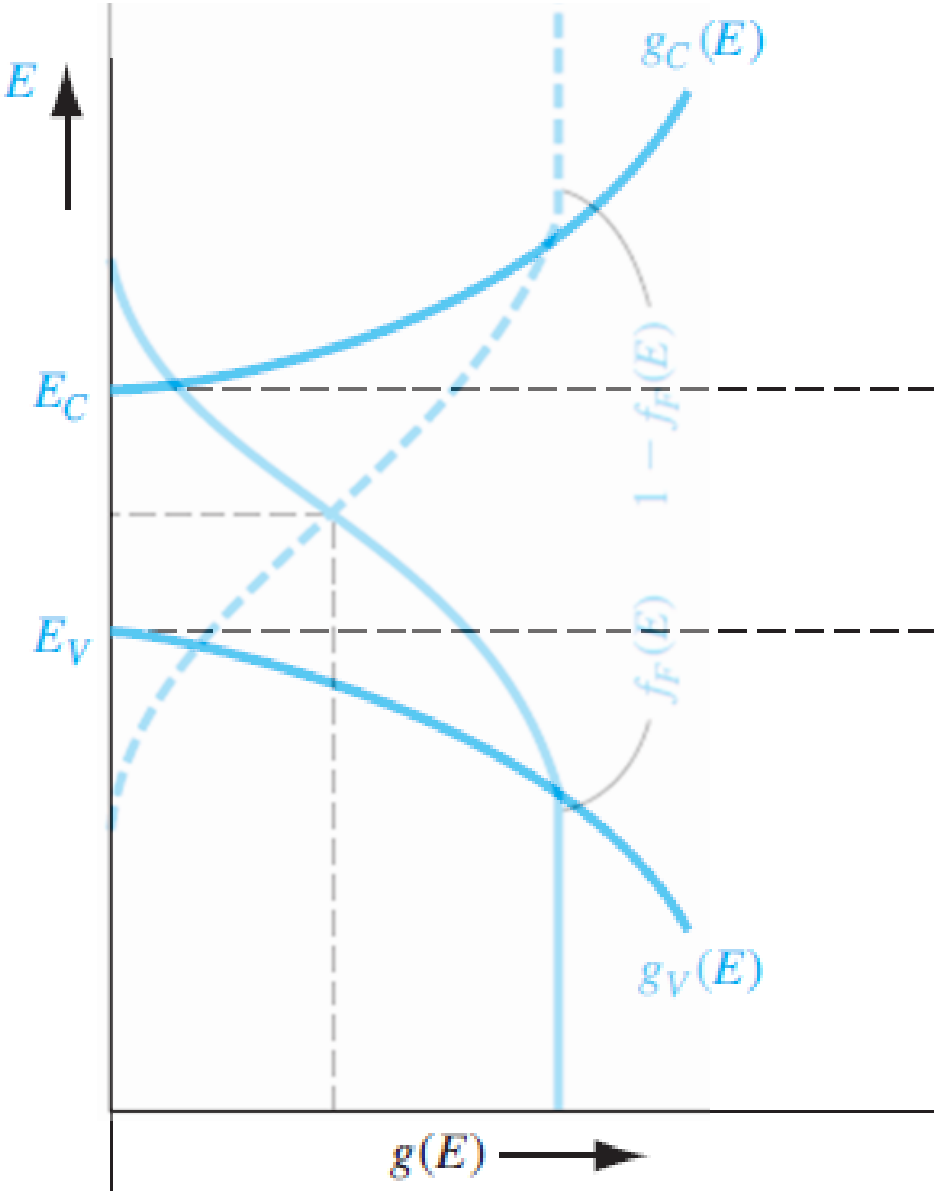


Thermal Equilibrium Distribution of Electrons and Holes





Thermal Equilibrium Distribution of Electrons and Holes



Thermal Equilibrium Distribution of Electrons and Holes

$$n(E) = g_c(E) f_F(E) \quad (4.1)$$

$$p(E) = g_v(E)[1 - f_F(E)] \quad (4.2)$$

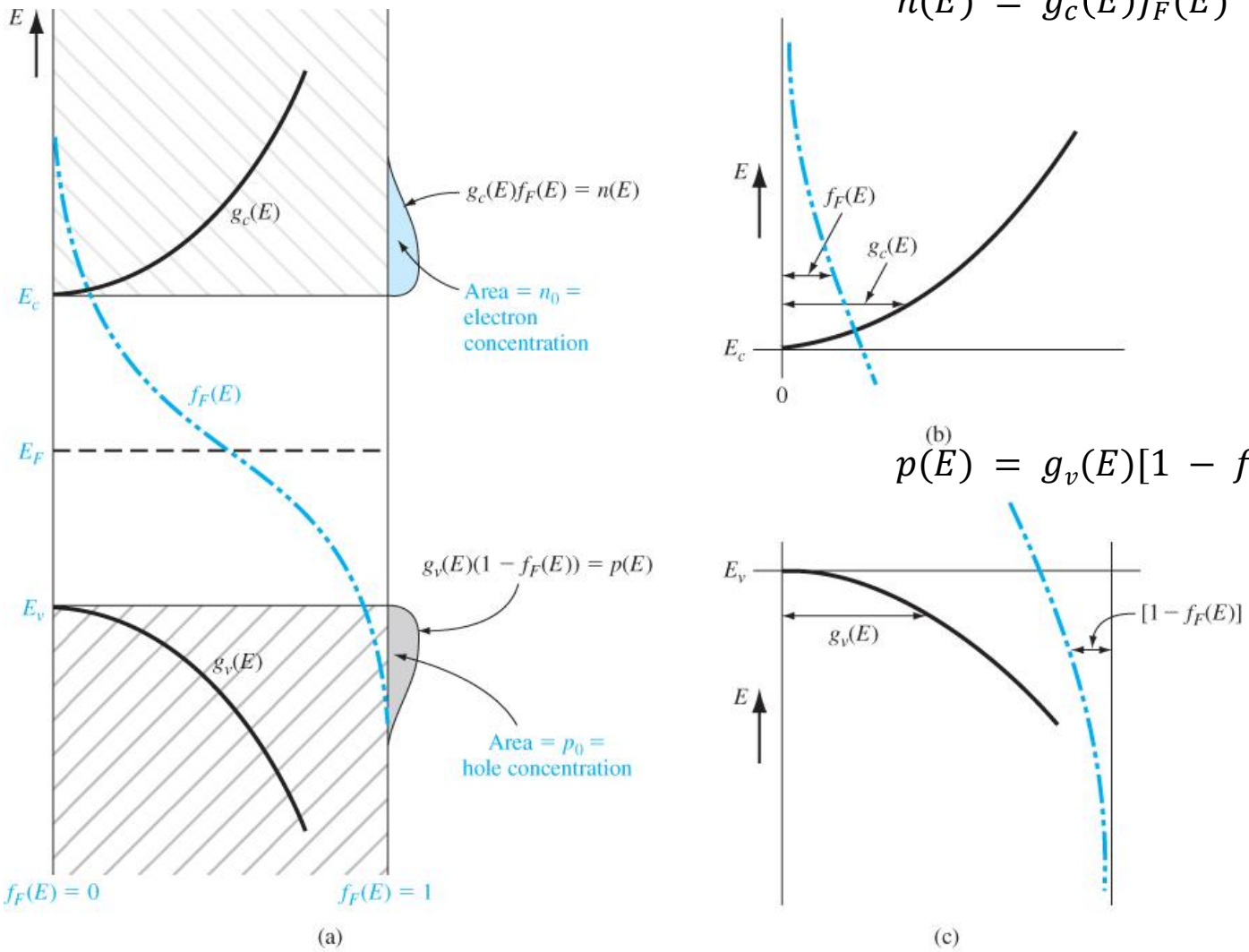


Figure 4.1 | (a) Density of states functions, Fermi–Dirac probability function, and areas representing electron and hole concentrations for the case when E_F is near the midgap energy; (b) expanded view near the conduction-band energy; and (c) expanded view near the valence-band energy.

The n_0 and p_0 Equations

Thermal equilibrium concentration of electrons

$$n_0 = \int_{E_c}^{\infty} g_c(E) f_F(E) dE \qquad (4.3)$$

$$g_c(E) = \frac{4\pi(2m_n{}^*)^{3/2}}{h^3}\sqrt{E - E_c} \qquad f_F(E) = \frac{1}{1 + \exp\dfrac{(E - E_F)}{kT}} \approx \exp\left[\frac{-(E - E_F)}{kT}\right]$$

Boltzmann approximation, $(E_c - E_F) >> kT$

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

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$$\Downarrow \qquad \exp\left[\frac{-(E - E_F)}{kT}\right] = \exp\left[\frac{-(E - E_c + E_c - E_F)}{kT}\right] = \exp\left[\frac{-(E - E_c)}{kT}\right]\exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

$$n_0 = \int_{E_c}^{\infty} \frac{4\pi(2m_n{}^*)^{3/2}}{h^3}(E - E_c)^{\frac{1}{2}}\exp\left[\frac{-(E - E_c)}{kT}\right]\exp\left[\frac{-(E_c - E_F)}{kT}\right] dE$$

The n_0 and p_0 Equations

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

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$$n_0 = \int_{E_c}^{\infty} \frac{4\pi(2m_n{}^*)^{3/2}}{h^3}(E - E_c)^{\frac{1}{2}}\exp\left[\frac{-(E - E_c)}{kT}\right]\exp\left[\frac{-(E_c - E_F)}{kT}\right] dE$$

$$\Downarrow \qquad \eta = \frac{E - E_c}{kT} \quad d\eta = \frac{dE}{kT} \quad \eta^{\frac{1}{2}} = \left(\frac{E - E_c}{kT}\right)^{\frac{1}{2}}$$

$$n_0 = \frac{4\pi(2m_n{}^* kT)^{3/2}}{h^3}\exp\left[\frac{-(E_c - E_F)}{kT}\right]\int_0^{\infty} \eta^{\frac{1}{2}}\exp(-\eta) d\eta$$

The n_0 and p_0 Equations

Thermal equilibrium concentration of electrons

$$n_0 = \frac{4\pi(2m_n{}^* kT)^{3/2}}{h^3} \exp\left[\frac{-(E_c - E_F)}{kT}\right] \int_0^\infty \eta^{\frac{1}{2}} \exp(-\eta) d\eta$$

$$\Downarrow \qquad \int_0^\infty \eta^{\frac{1}{2}} \exp(-\eta) d\eta = \frac{1}{2}\sqrt{\pi}$$

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

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

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

N_c : effective density of states function in the conduction band

The n_0 and p_0 Equations

Thermal equilibrium concentration of holes

$$p_0 = \int_{-\infty}^{E_v} g_v(E)[1 - f_F(E)]dE \qquad (4.3)$$

$$g_v(E) = \frac{4\pi(2m_p{}^*)^{3/2}}{h^3}\sqrt{E_v - E} \qquad 1 - f_F(E) = \frac{1}{1 + \exp\dfrac{(E_F - E)}{kT}} \approx \exp\left[\frac{-(E_F - E)}{kT}\right]$$

Boltzmann approximation, $(E_F - E_v) >> kT$

$$p_0 = \int_{-\infty}^{E_v} g_v(E)[1 - f_F(E)]dE = \int_{-\infty}^{E_v} \frac{4\pi(2m_p{}^*)^{3/2}}{h^3}\sqrt{E_v - E}\exp\left[\frac{-(E_F - E)}{kT}\right]dE$$

$$\Downarrow \qquad \exp\left[\frac{-(E_F - E)}{kT}\right] = \exp\left[\frac{-(E_F - E_v + E_v - E)}{kT}\right] = \exp\left[\frac{-(E_F - E_v)}{kT}\right]\exp\left[\frac{-(E_v - E)}{kT}\right]$$

$$p_0 = \int_{-\infty}^{E_v} \frac{4\pi(2m_p{}^*)^{3/2}}{h^3}(E_v - E)^{\frac{1}{2}}\exp\left[\frac{-(E_F - E_v)}{kT}\right]\exp\left[\frac{-(E_v - E)}{kT}\right]dE$$

$$\Downarrow \qquad \eta' = \frac{E_v - E}{kT} \qquad d\eta' = -\frac{dE}{kT} \qquad \eta'^{\frac{1}{2}} = \left(\frac{E_v - E}{kT}\right)^{\frac{1}{2}}$$

$$p_0 = \frac{4\pi(2m_p{}^*kT)^{3/2}}{h^3}\exp\left[\frac{-(E_F - E_v)}{kT}\right]\int_0^{\infty} \eta'^{\frac{1}{2}}\exp(-\eta')d\eta'$$

The n_0 and p_0 Equations

Thermal equilibrium concentration of holes

$$p_0 = \frac{4\pi(2m_p{}^* kT)^{3/2}}{h^3} \exp\left[\frac{-(E_F - E_v)}{kT}\right] \int_0^\infty \eta'^{\frac{1}{2}} \exp(-\eta') d\eta'$$

$$\Downarrow \qquad \int_0^\infty \eta'^{\frac{1}{2}} \exp(-\eta') d\eta' = \frac{1}{2}\sqrt{\pi}$$

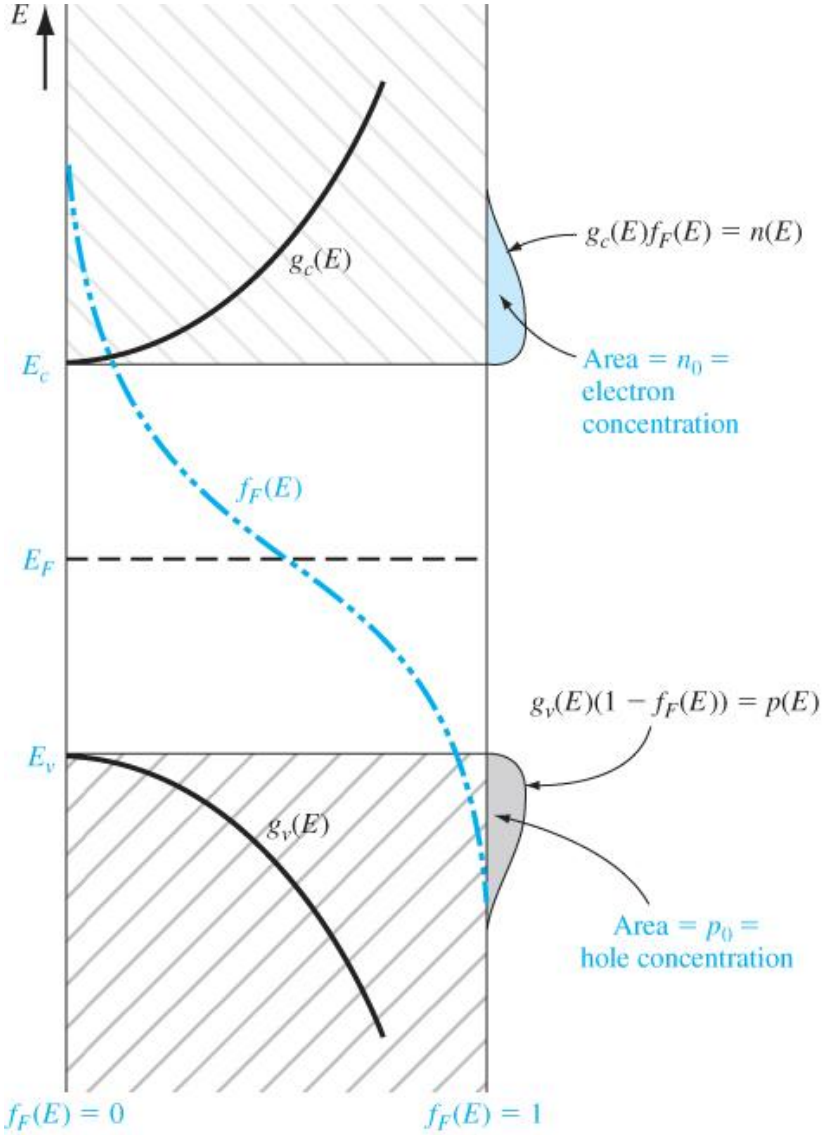
$$p_0 = \frac{2(2\pi m_p{}^* kT)^{3/2}}{h^3} \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

$$\Downarrow \qquad N_v = \frac{2(2\pi m_p{}^* kT)^{3/2}}{h^3}$$

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

N_v : effective density of states function in the valence band

The n_0 and p_0 Equations



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

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

N_c : effective density of states function in the conduction band

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

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

N_v : effective density of states function in the valence band

The n_0 and p_0 Equations

Table 4.1 | Effective density of states function and density of states effective mass values

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

m_0 = Electron mass in free space = 9.109×10^{-31} kg

The Intrinsic Carrier Concentration

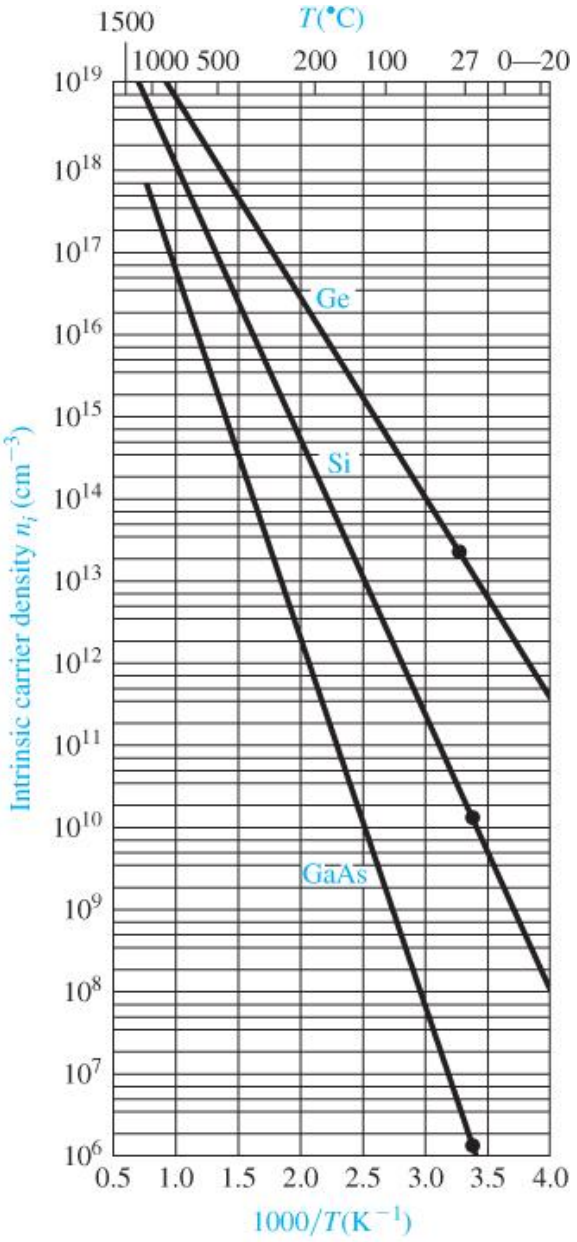
$$n_0 p_0 = n_i p_i = {n_i}^2 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$
$$= N_c N_v \exp\left[\frac{-(E_c - E_v)}{kT}\right] = N_c N_v \exp\left[\frac{-E_g}{kT}\right]$$

Table 4.2 | Commonly accepted values of n_i at $T = 300$ K

Silicon	$n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$
Gallium arsenide	$n_i = 1.8 \times 10^{6}\ \text{cm}^{-3}$
Germanium	$n_i = 2.4 \times 10^{13}\ \text{cm}^{-3}$

The intrinsic carrier concentration (n_i) of Si at room temperature are between 1×10^{10} and 1.5×10^{10} cm^{-3}.
n_i =1.08×10^{10} cm^{-3} (Green, 1990)

The Intrinsic Carrier Concentration



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

$$n_i = \sqrt{N_c N_v}\exp\left[\frac{-E_g}{2kT}\right]$$

$$\ln(n_i) = \ln\left(\sqrt{N_c N_v}\right) + \frac{-E_g}{2kT}$$

$$\ln(n_i) \propto -\frac{1}{T}$$

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

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

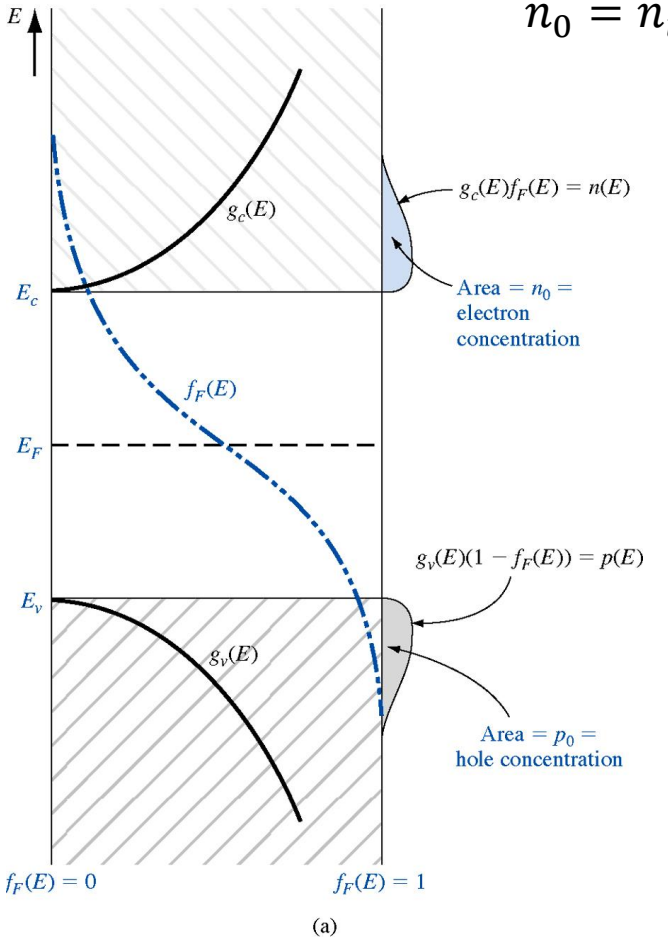
$$E_{g_{\text{GaAs}}} > E_{g_{\text{Si}}} > E_{g_{\text{Ge}}}$$

$$n_{i_{\text{GaAs}}} < n_{i_{\text{Si}}} < n_{i_{\text{Ge}}}$$

	Si	Ge	GaAs
Bandgap type	Indirect	Indirect	Direct
Bandgap (Eg) @ 300K	1.12 eV	0.66 eV	1.42 eV

Figure 4.2 | The intrinsic carrier concentration of Ge, Si, and GaAs as a function of temperature. *(From Sze [14].)*

The Intrinsic Fermi Level Position



(a)

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

⇩

$$\exp\left[\frac{-(E_c + E_v - 2E_F)}{kT}\right] = \frac{N_v}{N_c} = \left(\frac{m_p{}^*}{m_n{}^*}\right)^{3/2}$$

$$N_c = \frac{2(2\pi m_n{}^* kT)^{3/2}}{h^3} \qquad N_v = \frac{2(2\pi m_p{}^* kT)^{3/2}}{h^3}$$

⇩

$$-\frac{(E_c + E_v - 2E_{Fi})}{kT} = \frac{3}{2}\ln\left(\frac{m_p{}^*}{m_n{}^*}\right)$$

⇩

$$E_{Fi} - \frac{E_c + E_v}{2} = E_{Fi} - E_{midgap} = \frac{3}{4}kT\ln\left(\frac{m_p{}^*}{m_n{}^*}\right)$$

- $m_p{}^* \neq m_n{}^*$ 이므로 energy gap의 중앙에 위치하지 않는다.
- $m_p{}^* > m_n{}^*$ 이면 중앙보다 약간 위
- $m_p{}^* < m_n{}^*$ 이면 중앙보다 약간 아래

$kT = 0.026\ eV\ (T = 300\ \mathrm{K})$
$Bandgap\ of\ \mathrm{Si} = 1.12\ eV \approx 43kT$

Dopant atoms and Energy levels

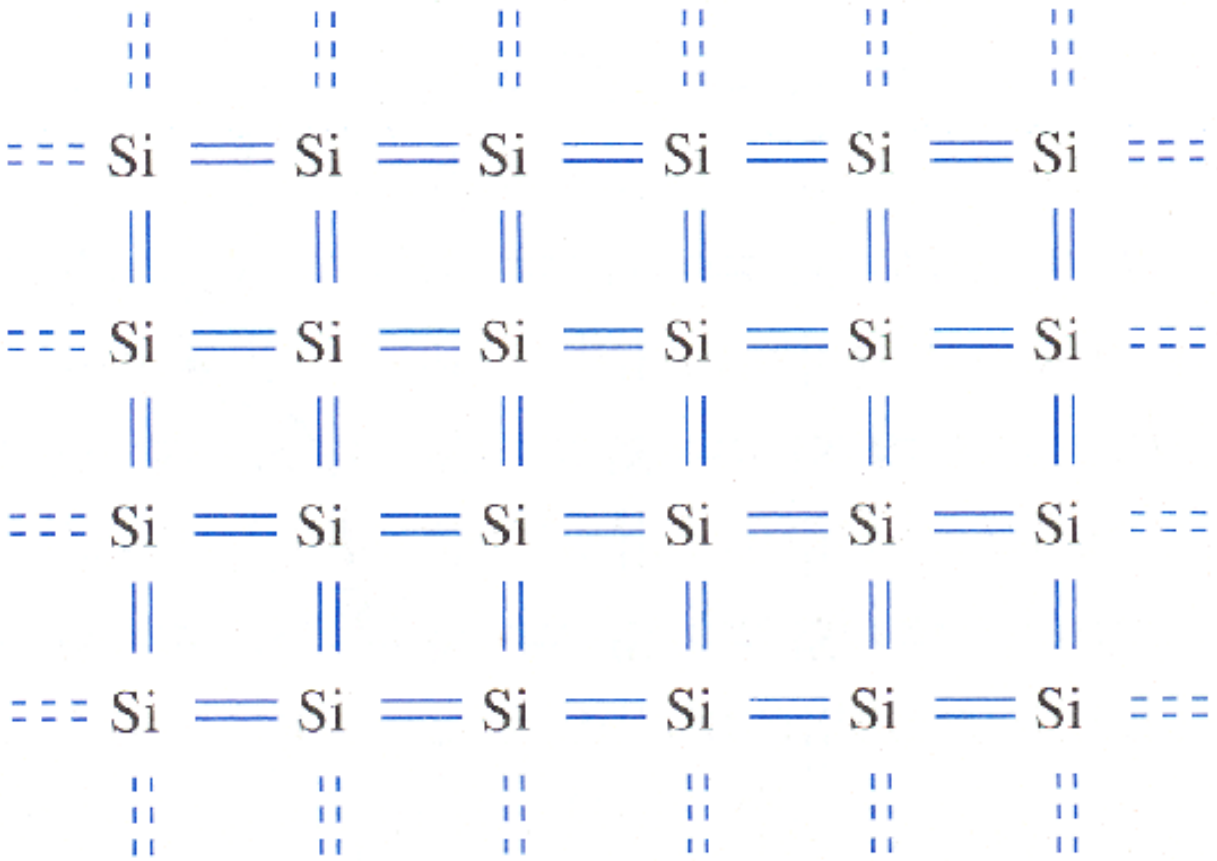
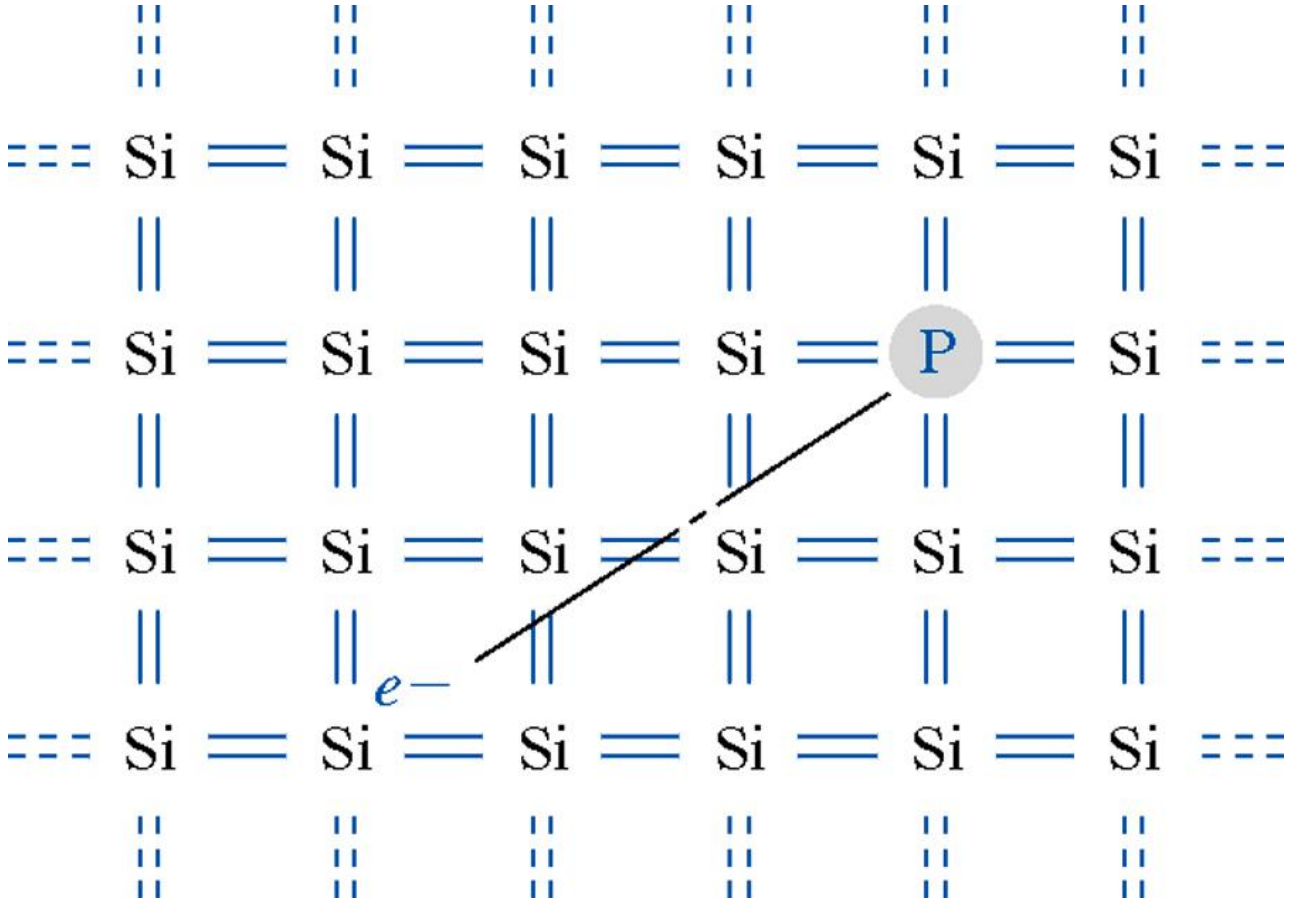


Figure 4.3 | Two-dimensional representation of the intrinsic silicon lattice.

Dopant atoms and Energy levels

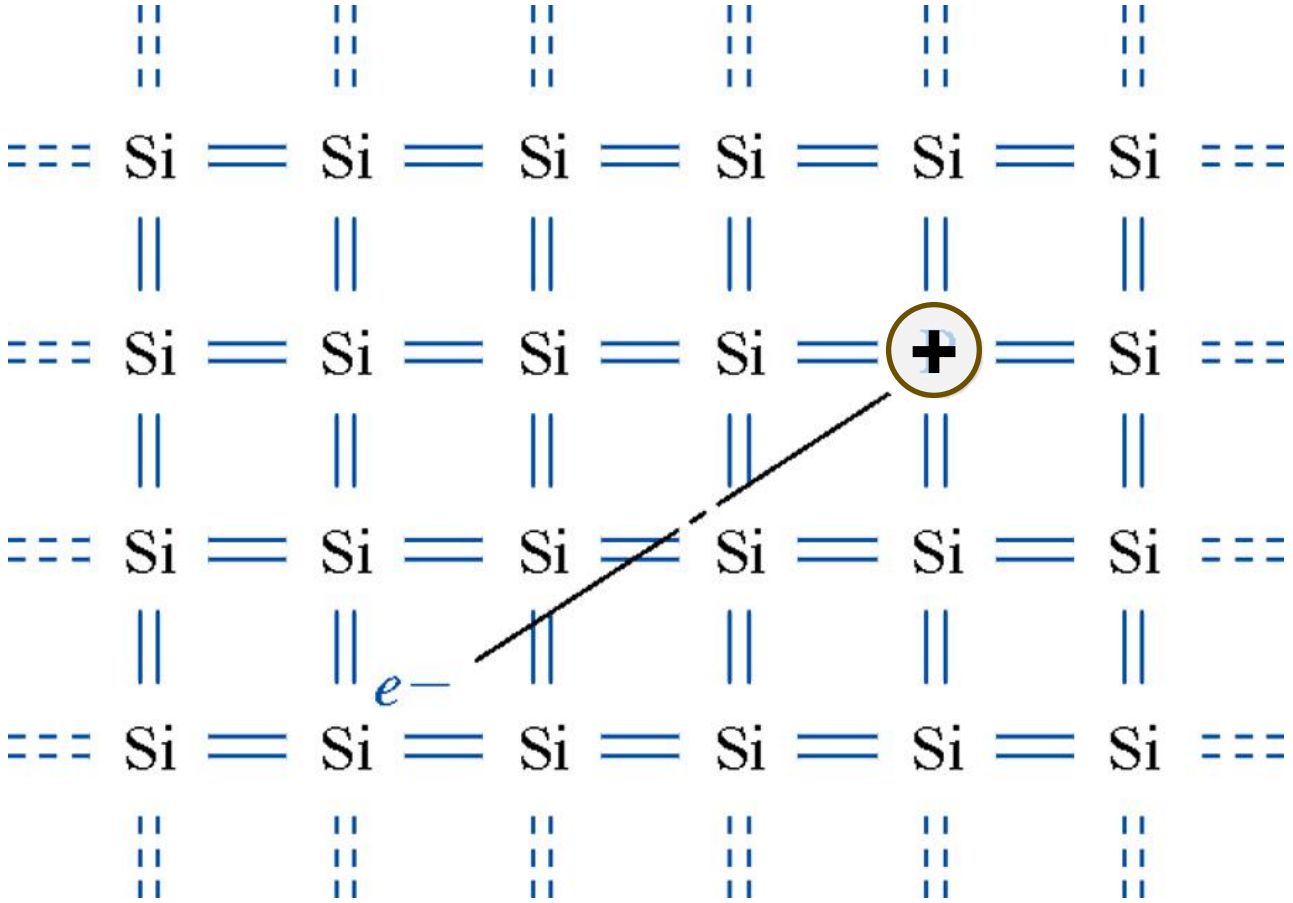


Donor impurity atom has more electrons and turns to fixed positive charge after activated.

Figure 4.4

P, As (Group 15 elements) = Donor = N type dopant

Dopant atoms and Energy levels



Donor impurity atom has more electrons and turns to fixed positive charge after activated.

P, As (Group 15 elements) = Donor = N type dopant

Concentration of donor atoms = N_d

Figure 4.4

Dopant atoms and Energy levels

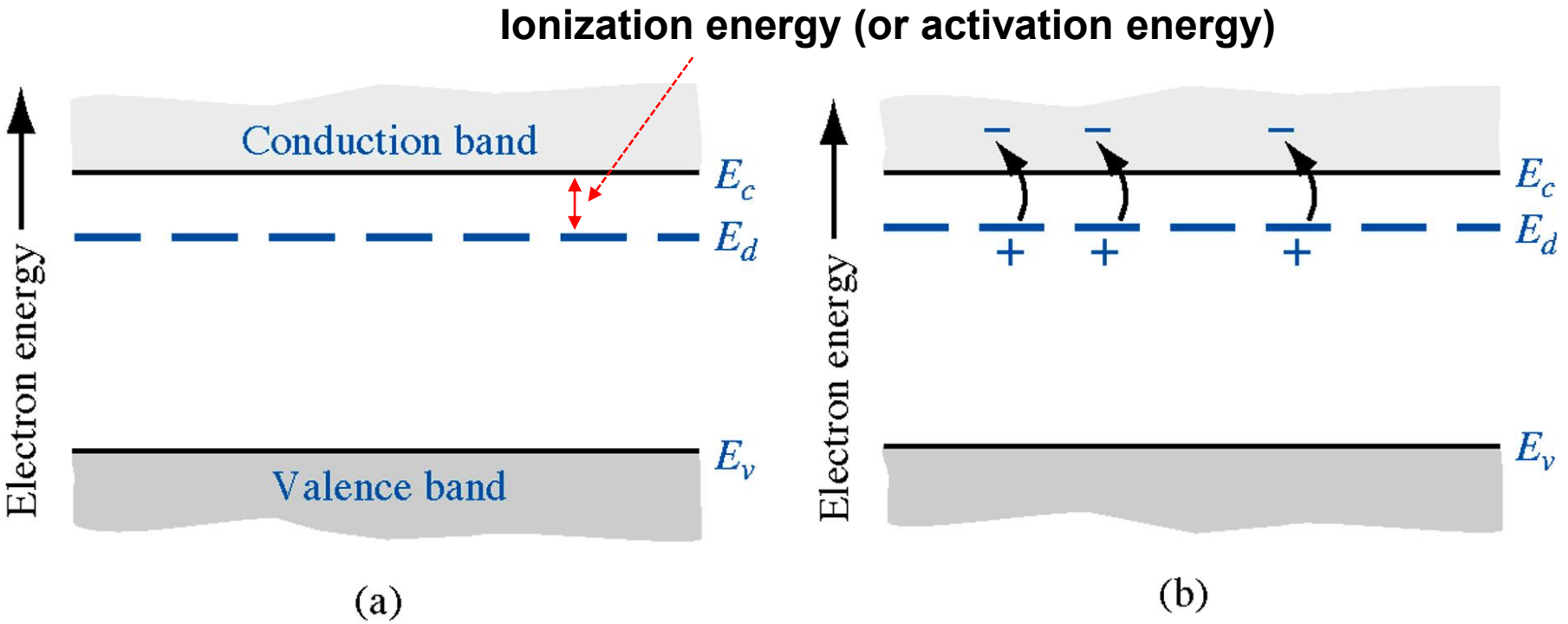


Figure 4.5

Dopant atoms and Energy levels

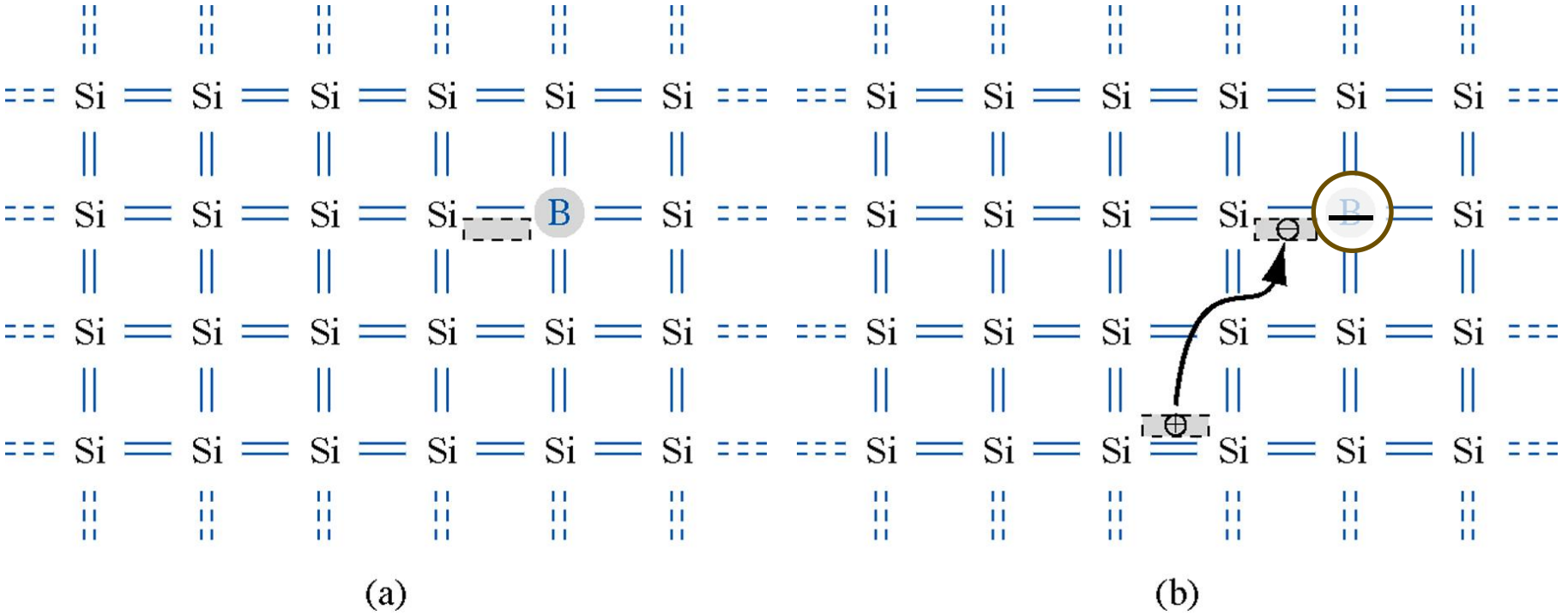


Figure 4.6

Acceptor impurity atom has less electrons and turns to fixed negative charge after activated.

B, Al (Group 13 elements) = Acceptor = P type dopant

Concentration of donor atoms = N_a

Dopant atoms and Energy levels

Ionization energy (or activation energy)

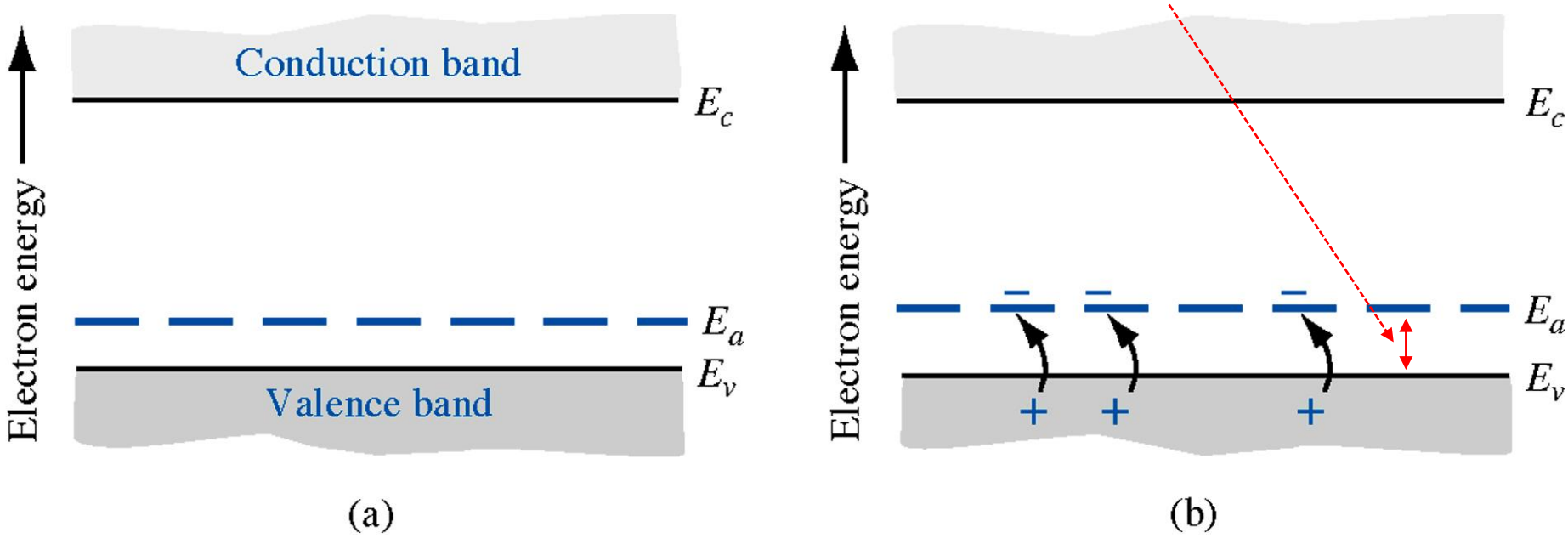


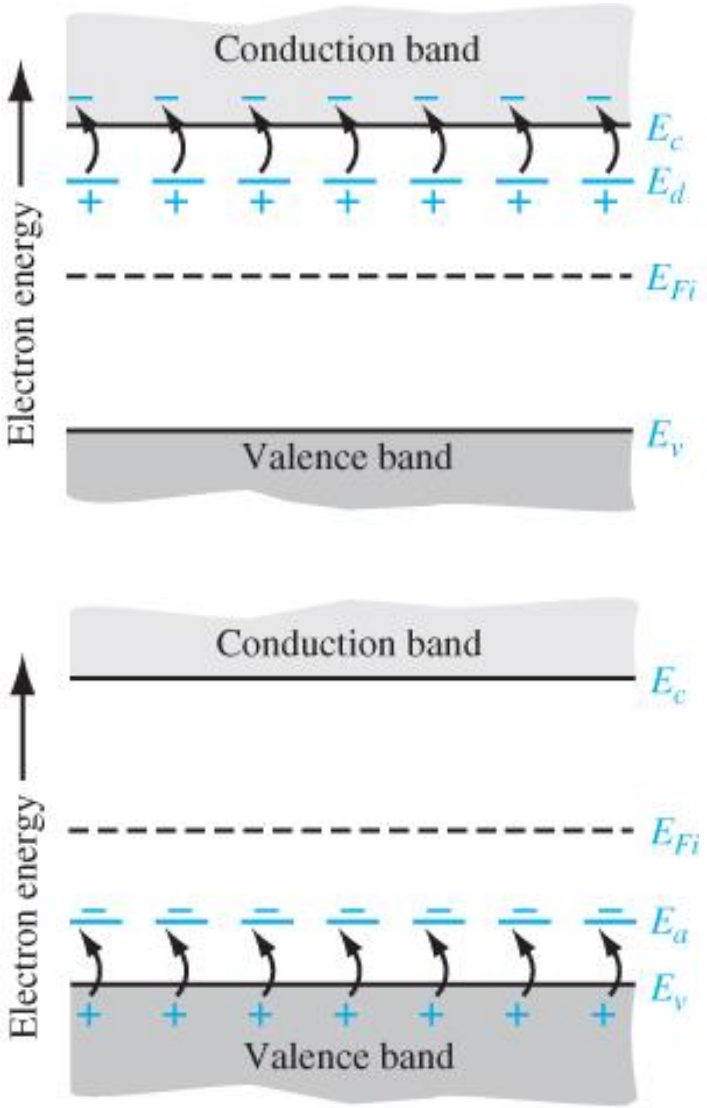
Figure 4.7

Ionization Energy

Table 4.3 | Impurity ionization energies in silicon and germanium

Impurity	Ionization energy (eV) Si	Ge
Donors		
Phosphorus	0.045	0.012
Arsenic	0.05	0.0127
Acceptors		
Boron	0.045	0.0104
Aluminum	0.06	0.0102

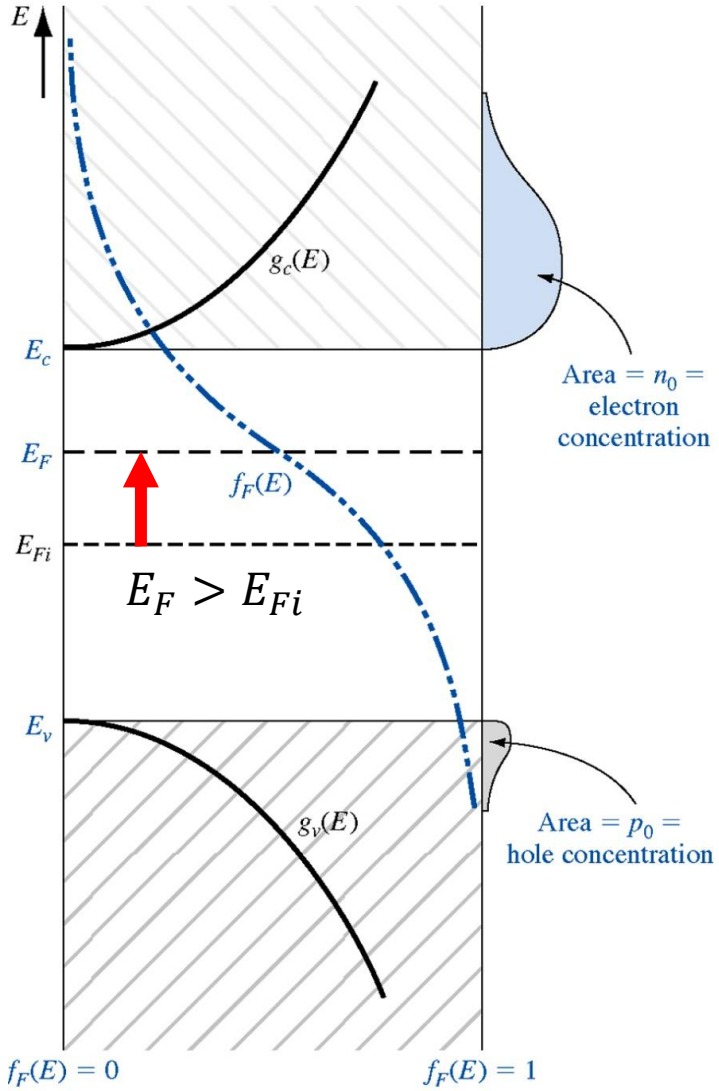
$$kT = 0.026\ eV\ (T = 300\ K)$$



Assume complete (=100%) ionization

Extrinsic semiconductor

N type



P type

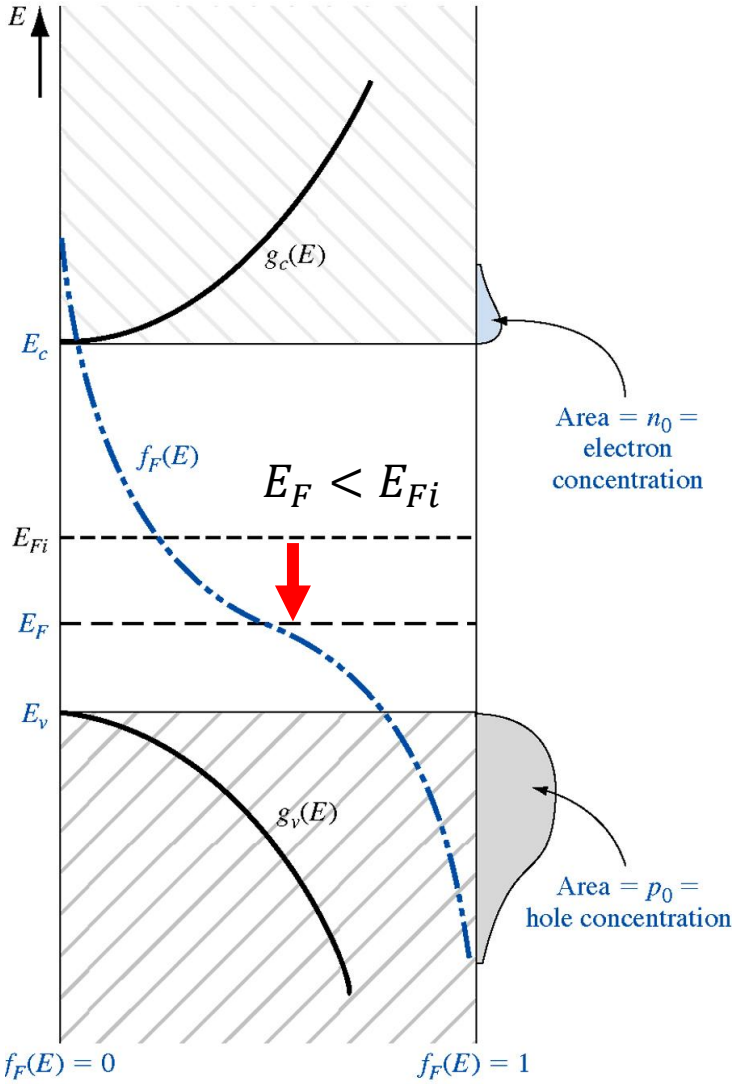


Figure 4.8 & Figure 4.9

Extrinsic semiconductor

Majority & Minority carrier concentration

N type

$N_d > 0, \quad N_a = 0$

Majority carrier: electron

Minority carrier: hole

$n_0 \approx N_d \approx (n_i + N_d)$

$p_0 = ?$

P type

$N_d = 0, \quad N_a > 0$

Majority carrier: hole

Minority carrier: electron

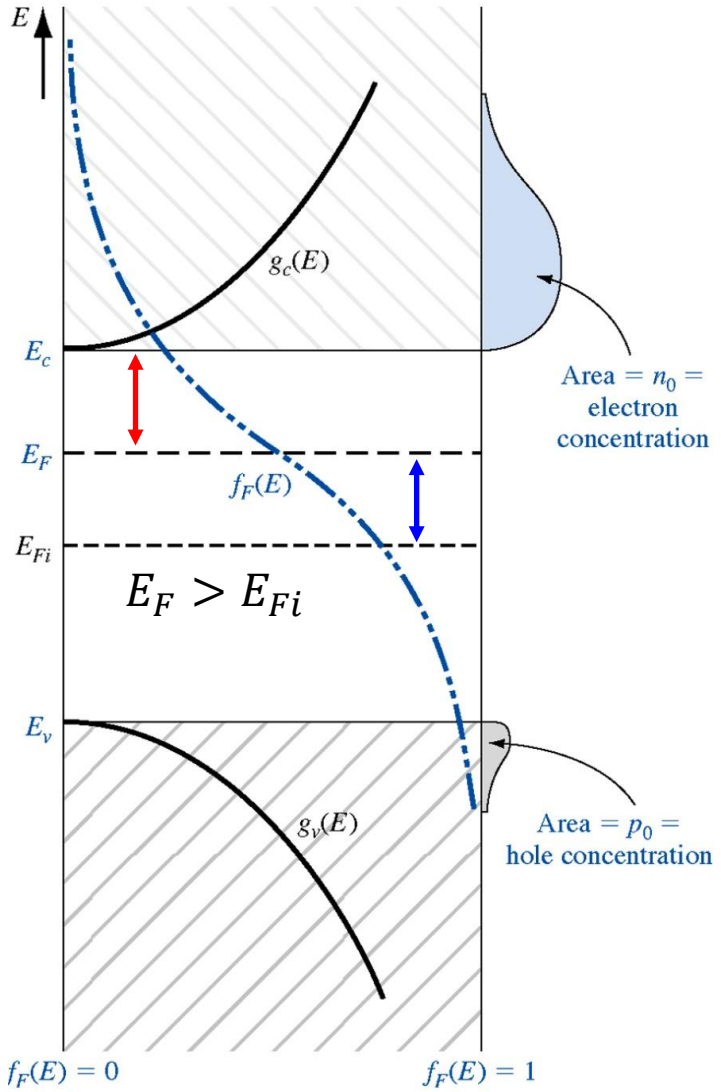
$p_0 \approx N_a \approx (n_i + N_a)$

$n_0 = ?$

$n_i = 1.5 \times 10^{10} [cm^{-3}]$

Extrinsic semiconductor

N type



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

$$\Downarrow$$

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

$$\Downarrow$$

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

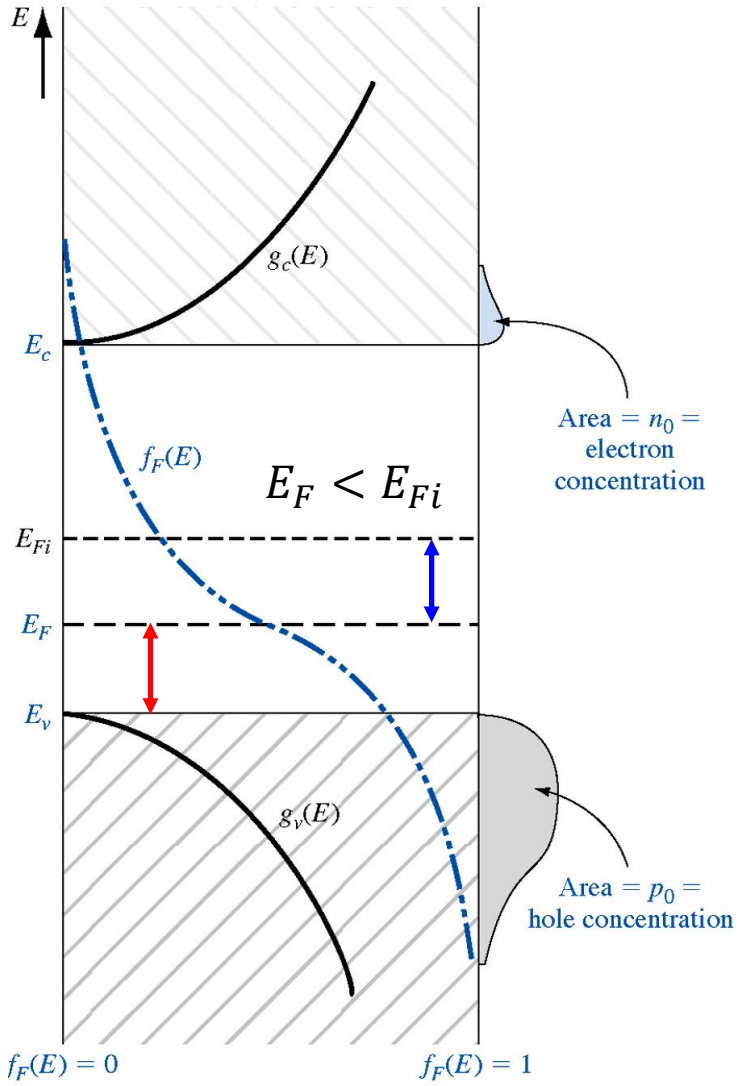
$$\Downarrow$$

$$n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right] \approx N_d$$

Figure 4.8 & Figure 4.9

Extrinsic semiconductor

P type



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

$$\Downarrow$$

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

$$\Downarrow$$

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

$$\Downarrow$$

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

Figure 4.8 & Figure 4.9

Extrinsic semiconductor

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

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

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

$$\boldsymbol{n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]}$$

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

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

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

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

$$n_0 p_0 = N_c N_v \exp\left[\frac{-(E_c - E_F)}{kT}\right] \exp\left[\frac{-(E_F - E_v)}{kT}\right] = N_c N_v \exp\left[\frac{-E_g}{kT}\right] = n_i^2$$

$$n_0 p_0 = n_i^2$$

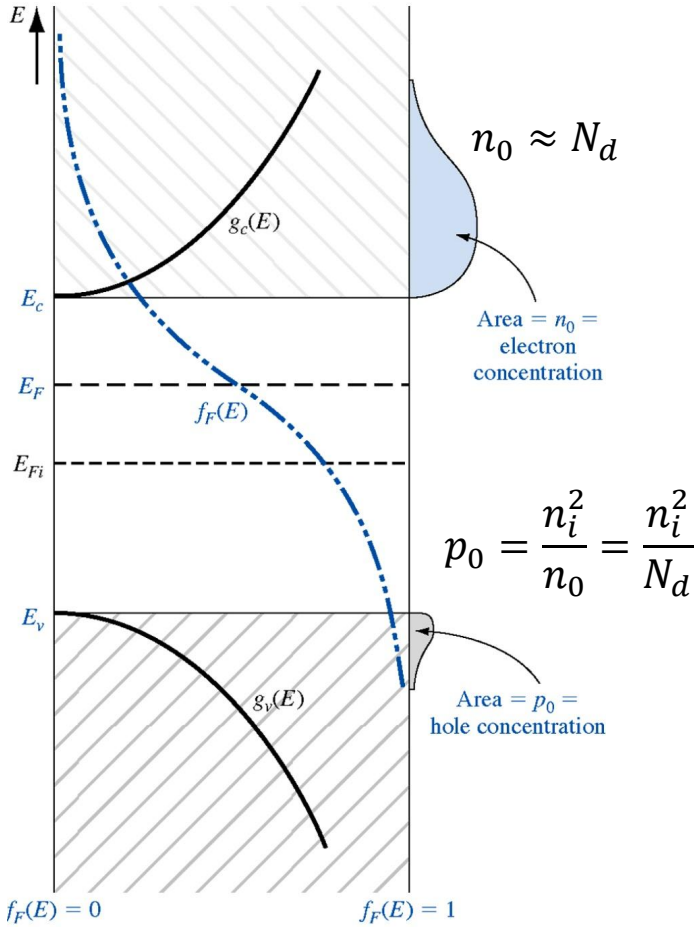
Mass-action law in thermal equilibrium

:np product is always constant at thermal equilibirim state

Extrinsic semiconductor

$$n_0 p_0 = n_i^2$$ *Mass-action law in thermal equilibrium*

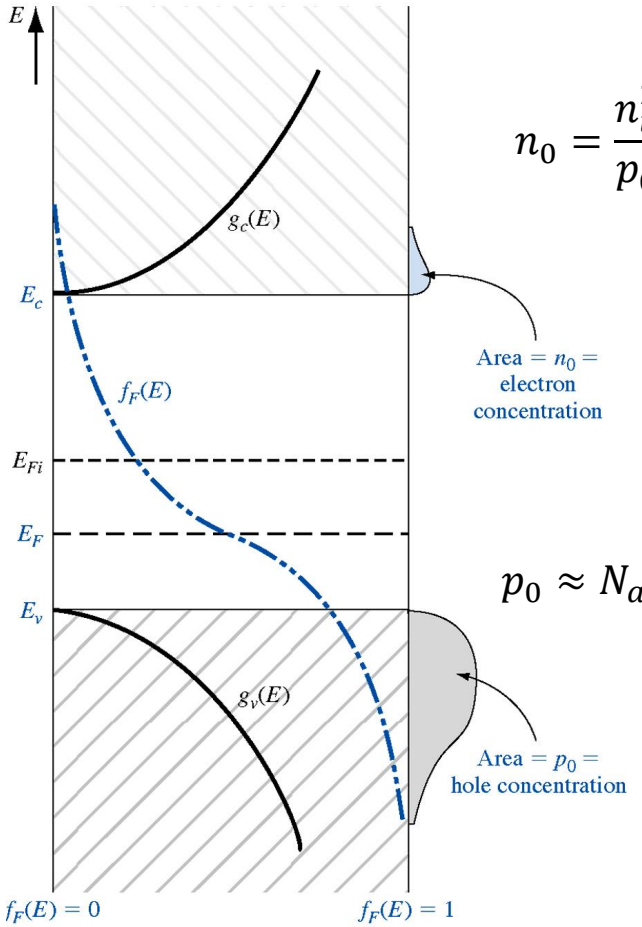
N type



$$n_0 \approx N_d$$

$$p_0 = \frac{n_i^2}{n_0} = \frac{n_i^2}{N_d}$$

P type



$$n_0 = \frac{n_i^2}{p_0} = \frac{n_i^2}{N_a}$$

$$p_0 \approx N_a$$

Extrinsic semiconductor

Majority & Minority carrier concentration

N type

$N_d = 10^{16}, \quad N_a = 0$

Majority carrier: electron

Minority carrier: hole

$n_0 \approx N_d \approx (n_i + N_d)$

$p_0 =$

P type

$N_d = 0, \quad N_a = 10^{16}$

Majority carrier: hole

Minority carrier: electron

$p_0 \approx N_a \approx (n_i + N_a)$

$n_0 =$

$n_i = 1.5 \times 10^{10} [cm^{-3}]$

Charge Neutrality

$$p_0 - n_0 + N_d - N_a = 0$$

$p_0 = positive\ mobile\ charges$

$n_0 = negative\ mobile\ charges$

$N_d = positive\ fixed\ charges$

$N_a = negative\ fixed\ charges$

$n_0 p_0 = n_i^2$
$mass - action\ law$

Charge Neutrality

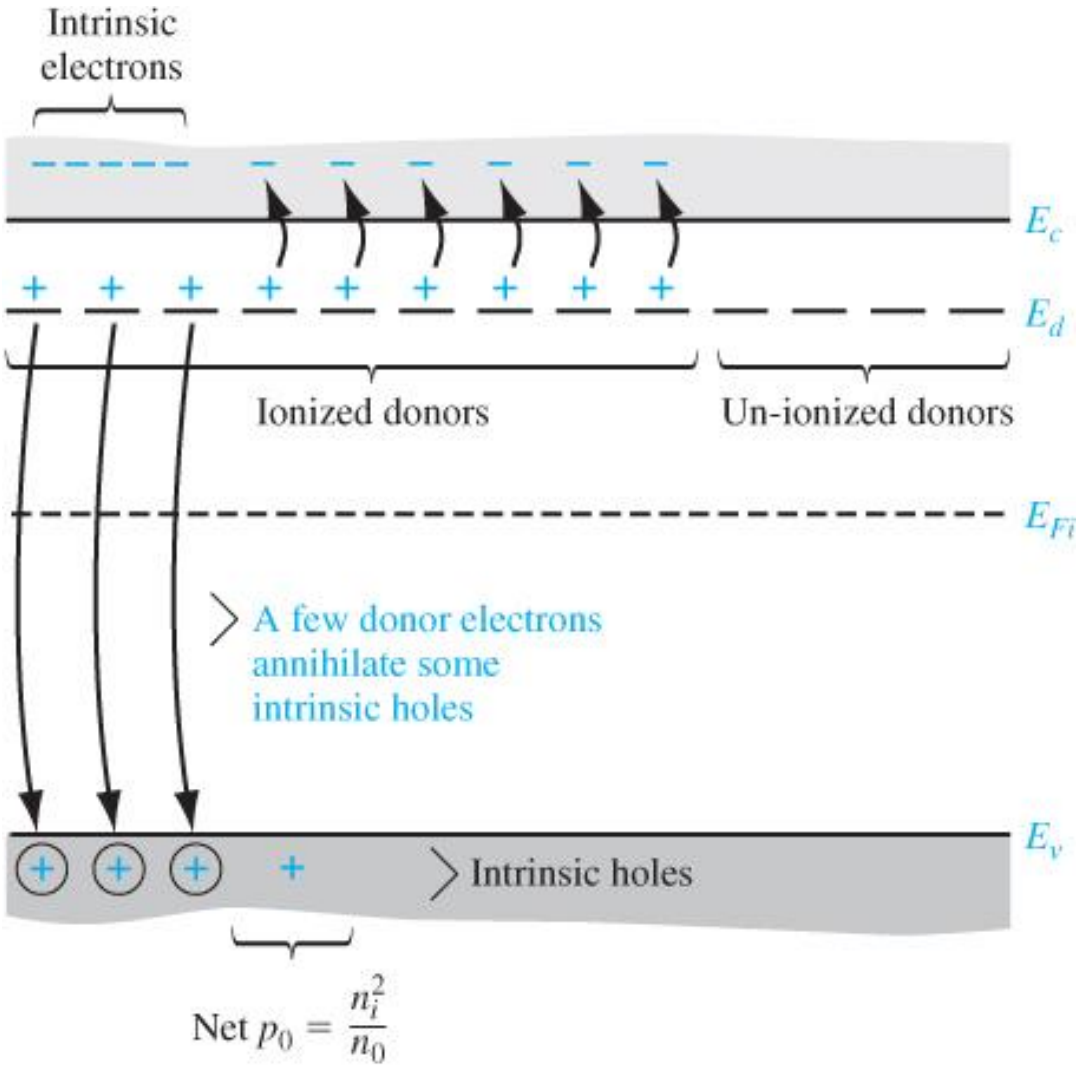


Figure 4.15 | Energy-band diagram showing the redistribution of electrons when donors are added.

Degenerated semiconductor

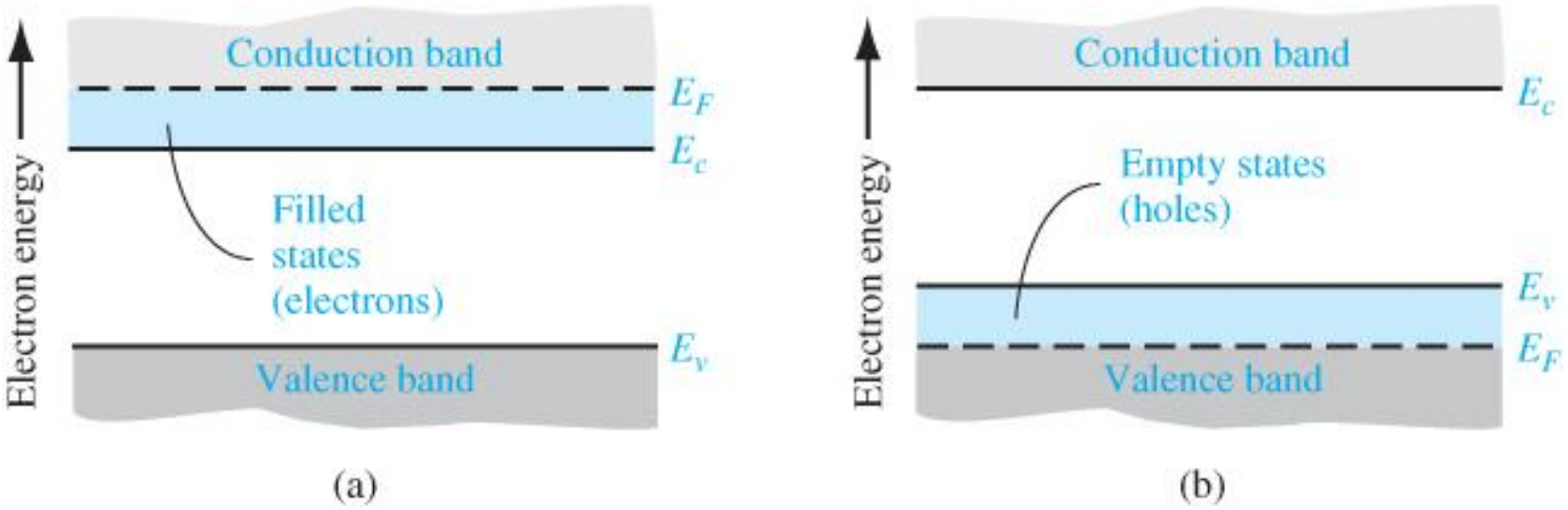


Figure 4.11 | Simplified energy-band diagrams for degenerately doped (a) n-type and (b) p-type semiconductors.

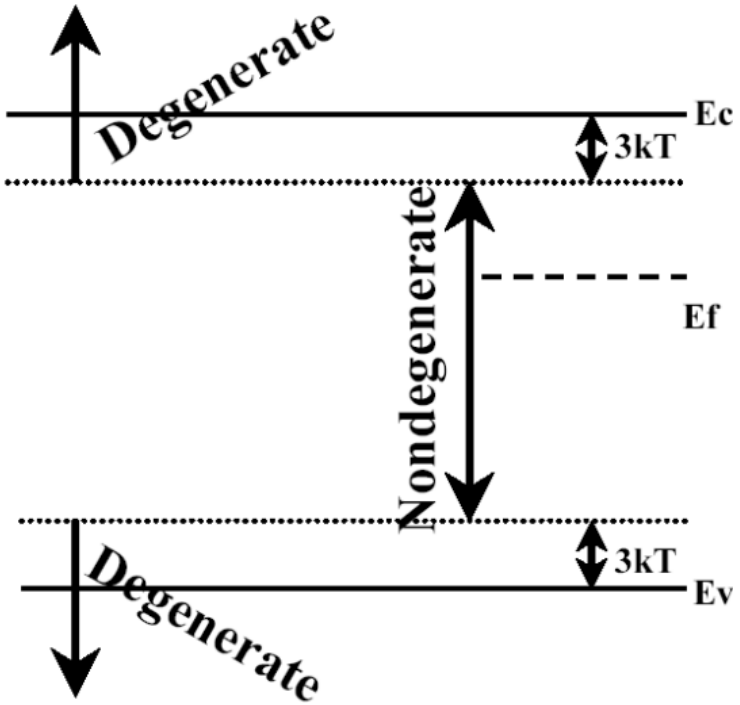
$$f_F(E) = \frac{1}{1+\exp\dfrac{(E-E_F)}{kT}} \approx \exp\left[\frac{-(E-E_F)}{kT}\right]$$

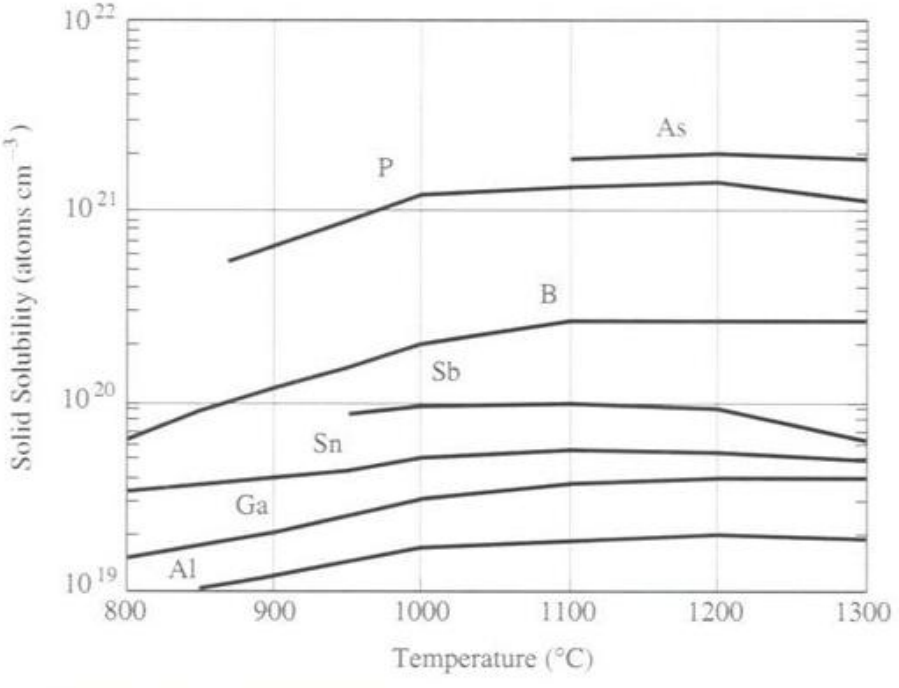
Boltzmann approximation, $(E_c - E_F) >> kT$

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

Boltzmann approximation, $(E_F - E_v) >> kT$

Degenerated semiconductor





- ✓ Non-degenerate semiconductor: E_F is at least 3kT below E_c and at least 3kT above E_v.

- ✓ Density of Si atoms: ~5×10^{22}
- ✓ Solid solubility in Silicon: ~10^{20} is maximum.

$$N_d \;\&\; N_a \leq 10^{20}$$

$$N_d \;\&\; N_a = 10^{15}\sim10^{20}$$

Compensated semiconductor

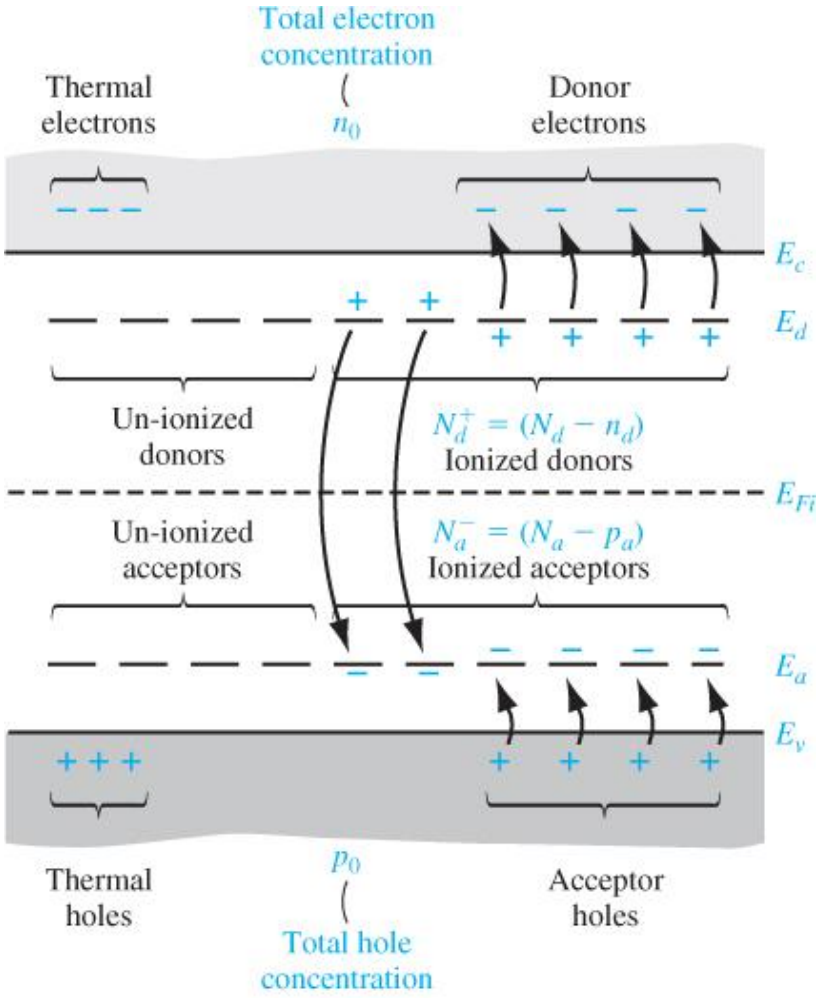


Figure 4.14 | Energy-band diagram of a compensated semiconductor showing ionized and un-ionized donors and acceptors.

$N_d > N_a$ n-type

$N_a > N_d$ p-type

$N_a = N_d$ intrinsic

Compensated semiconductor

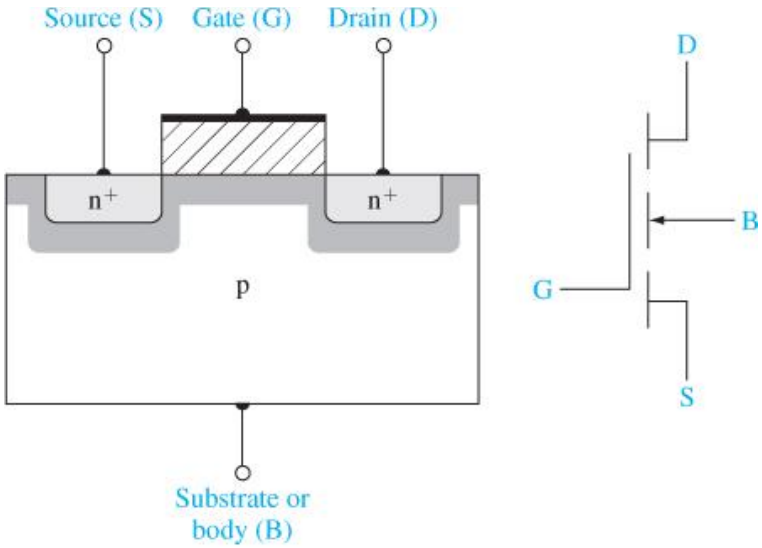
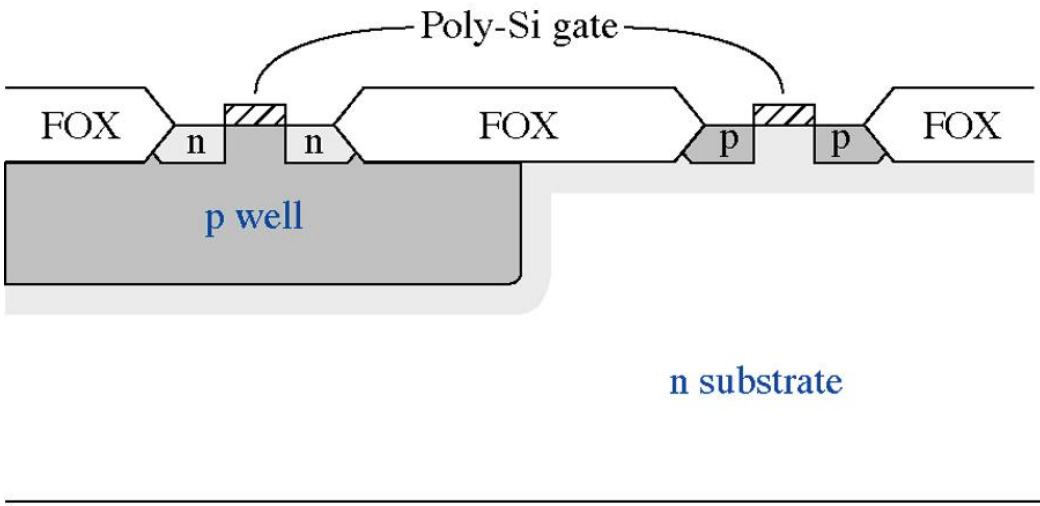


Figure 10.34 | Cross section and circuit symbol for an n-channel enhancement mode MOSFET.

< **MOSFET** >



(a)

< **CMOS** >

General theory of n_0 and p_0

$$n_0 = \frac{N_d - N_a}{2} + \left[\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2\right]^{\frac{1}{2}}$$

$$p_0 = \frac{N_a - N_d}{2} + \left[\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2\right]^{\frac{1}{2}}$$

N type

$N_d = 10^{16}, \quad N_a = 10^{13}$

$N_d - N_a \gg n_i$

Majority carrier: electron

Minority carrier: hole

$n_0 = N_d - N_a \approx N_d$

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

P type

$N_d = 10^{13}, \quad N_a = 10^{16}$

$N_a - N_d \gg n_i$

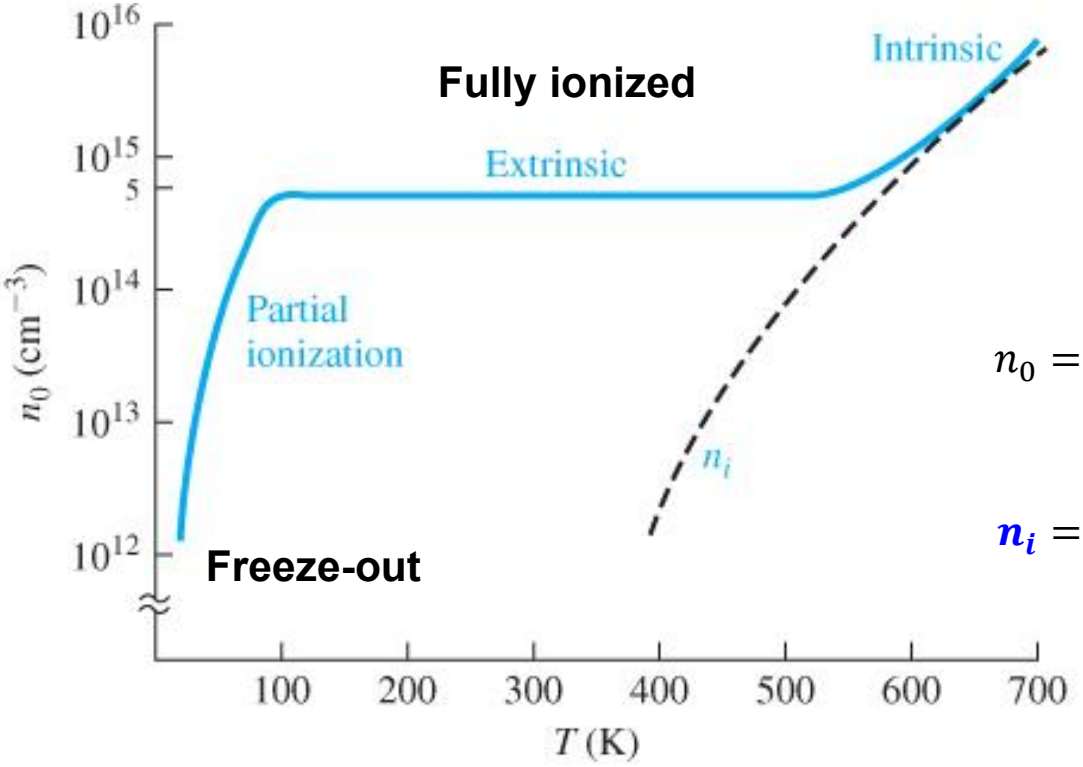
Majority carrier: hole

Minority carrier: electron

$p_0 = N_a - N_d \approx N_a$

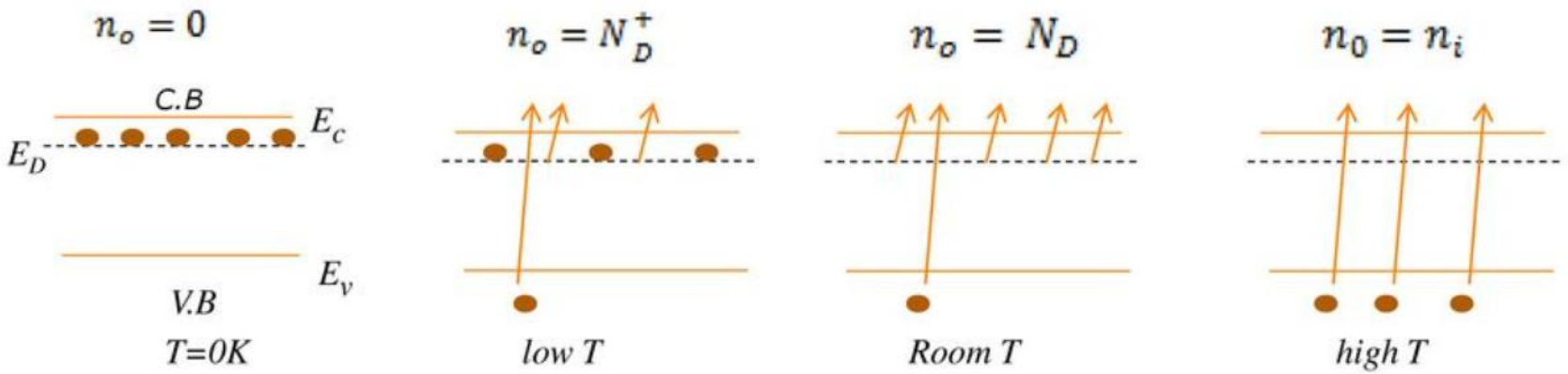
$n_0 = \frac{n_i^2}{N_a}$

Carrier concentrations according to Temperature(*T*)



$$n_0 = \frac{N_d - N_a}{2} + \left[\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2\right]^{\frac{1}{2}}$$

$$n_i = \sqrt{N_c N_v}\exp\left[\frac{-E_g}{2kT}\right]$$



Position of Fermi Energy Level

N type

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

P type

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

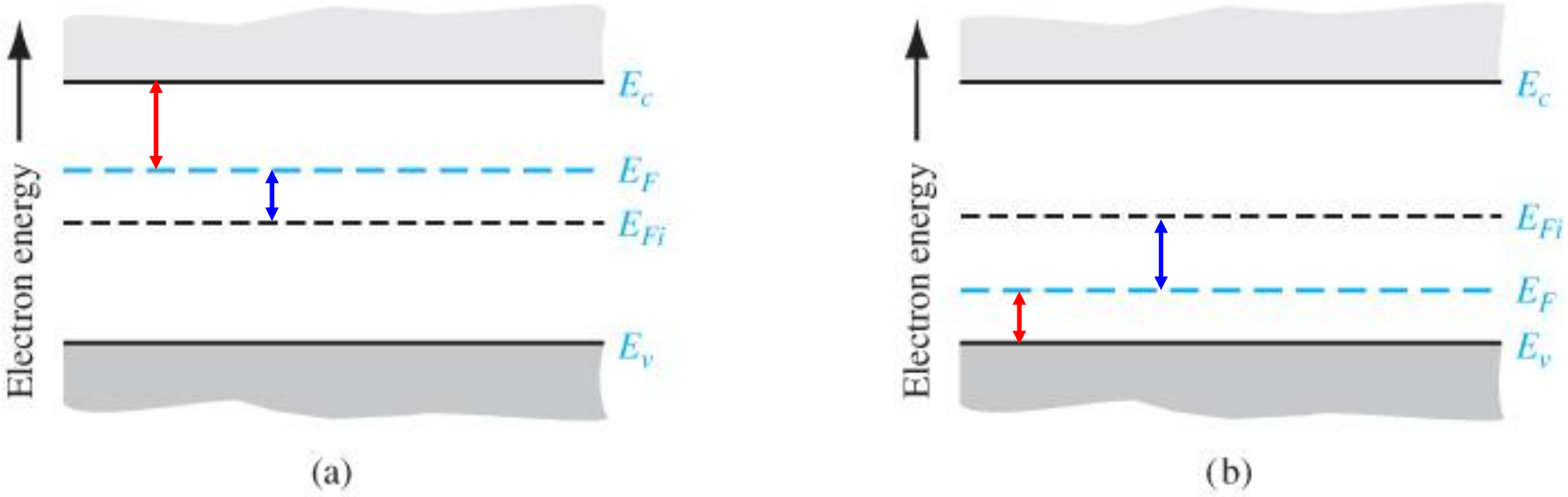


Figure 4.17 | Position of Fermi level for an (a) n-type ($N_d > N_a$) and (b) p-type ($N_d \lesssim N_a$) semiconductor.

Position of Fermi Energy Level

N type

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

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

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

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

P type

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

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

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

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

Variation of E_F with Doping Concentration and Temperature

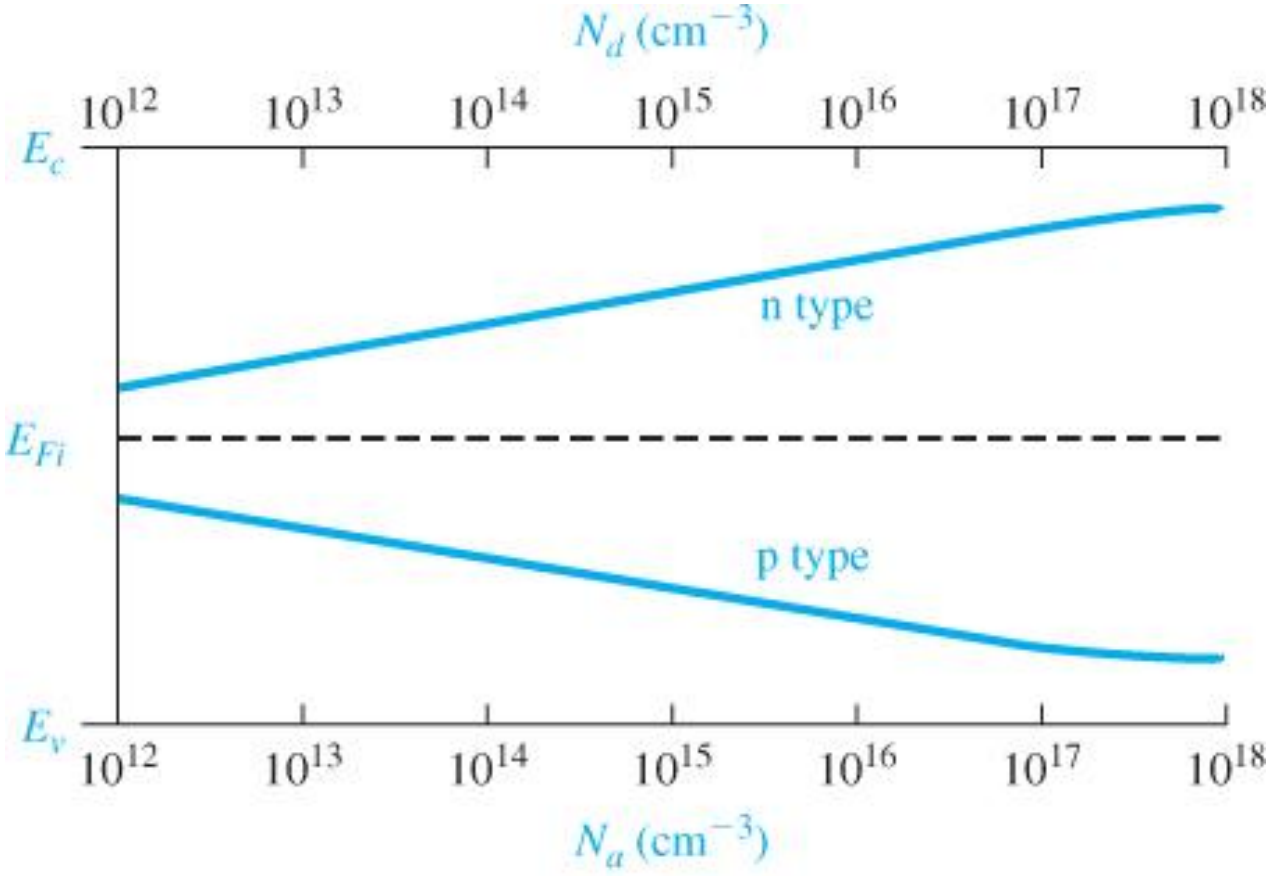


Figure 4.18 | Position of Fermi level as a function of donor concentration (n type) and acceptor concentration (p type).

N type

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

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

$$\boldsymbol{n_0 \approx N_d}$$

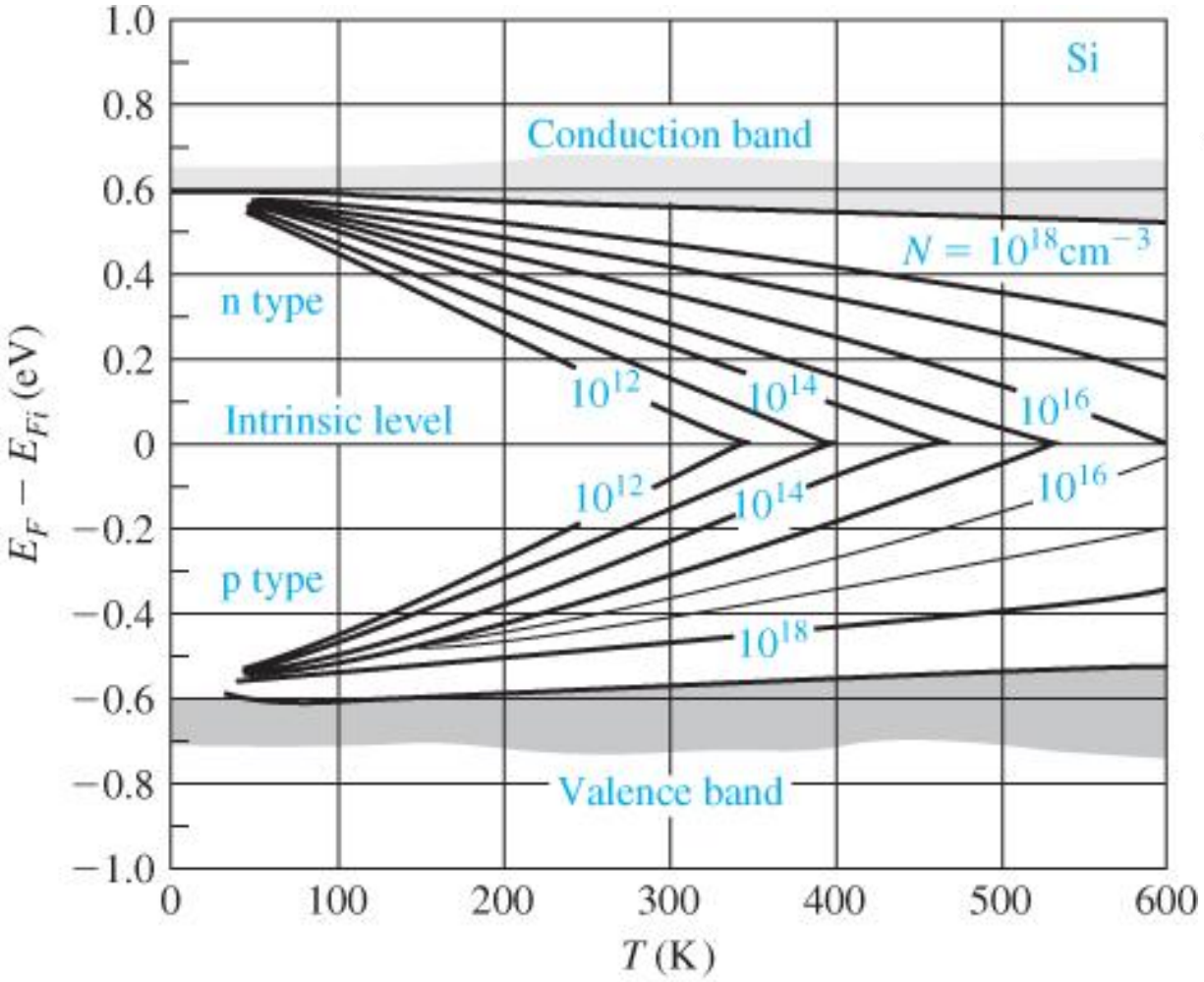
P type

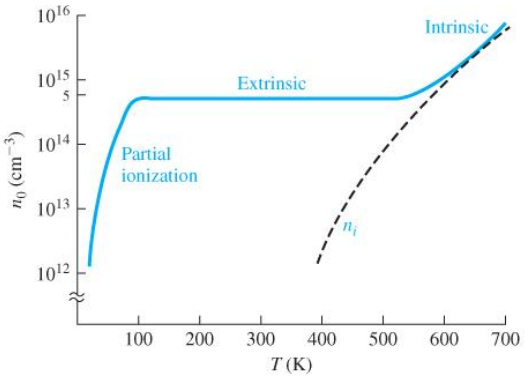
$$E_{Fi} - E_F = kT \ln\left(\frac{p_0}{n_i}\right)$$

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

$$\boldsymbol{p_0 \approx N_a}$$

Variation of E_F with Doping Concentration and Temperature





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

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

$$n_i = \sqrt{N_c N_v}\, exp\left[\frac{-E_g}{2kT}\right]$$

Fermi level at equilibrium state

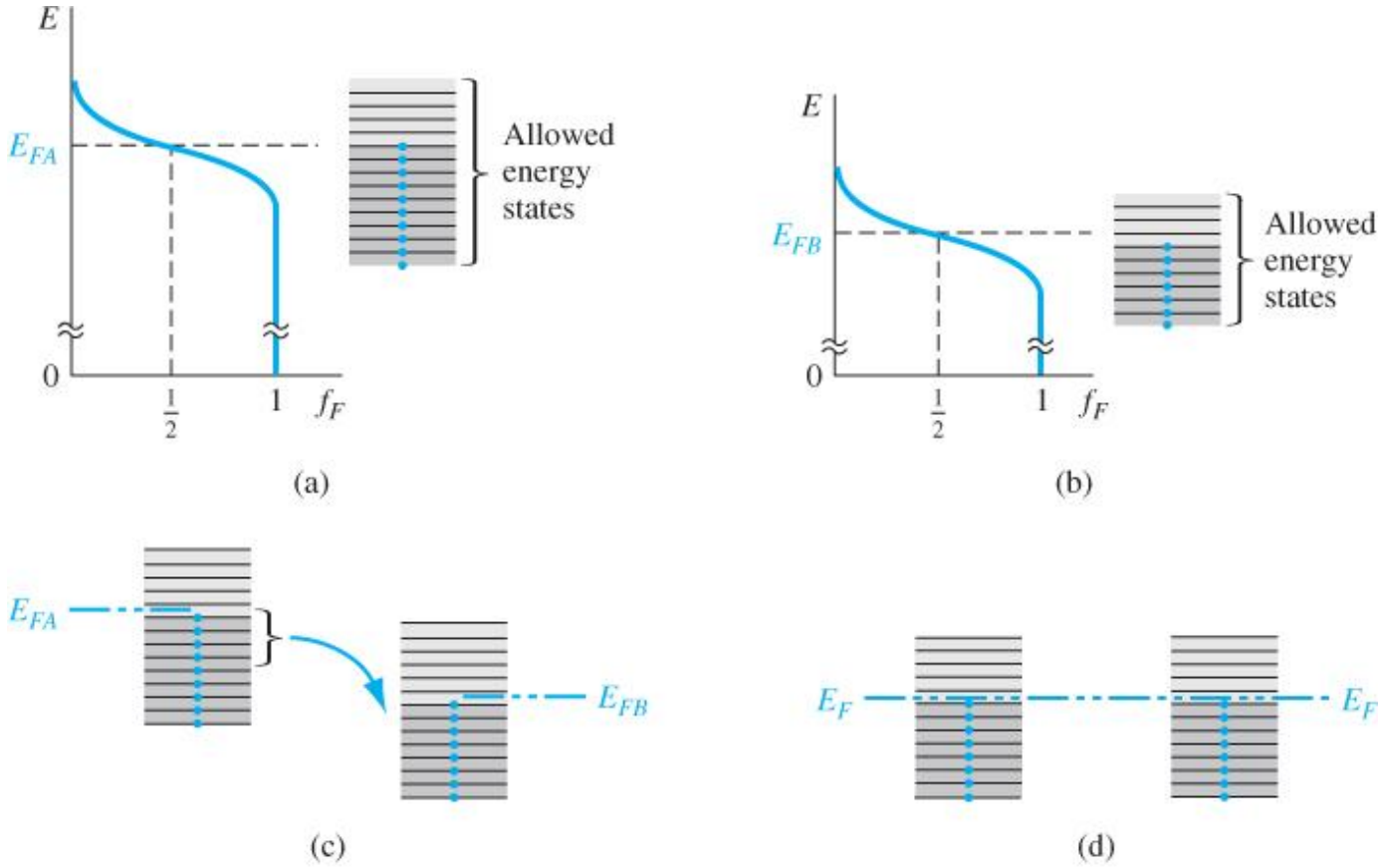


Figure 4.20 | The Fermi energy of (a) material A in thermal equilibrium, (b) material B in thermal equilibrium, (c) materials A and B at the instant they are placed in contact, and (d) materials A and B in contact at thermal equilibrium.

An important point is that, in thermal equilibrium, the Fermi energy level is a **constant** throughout a system.