Semiconductor Devices

THIRD EDITION

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Chapter 1

Energy Bands and Carrier Concentration in Thermal Equilibrium

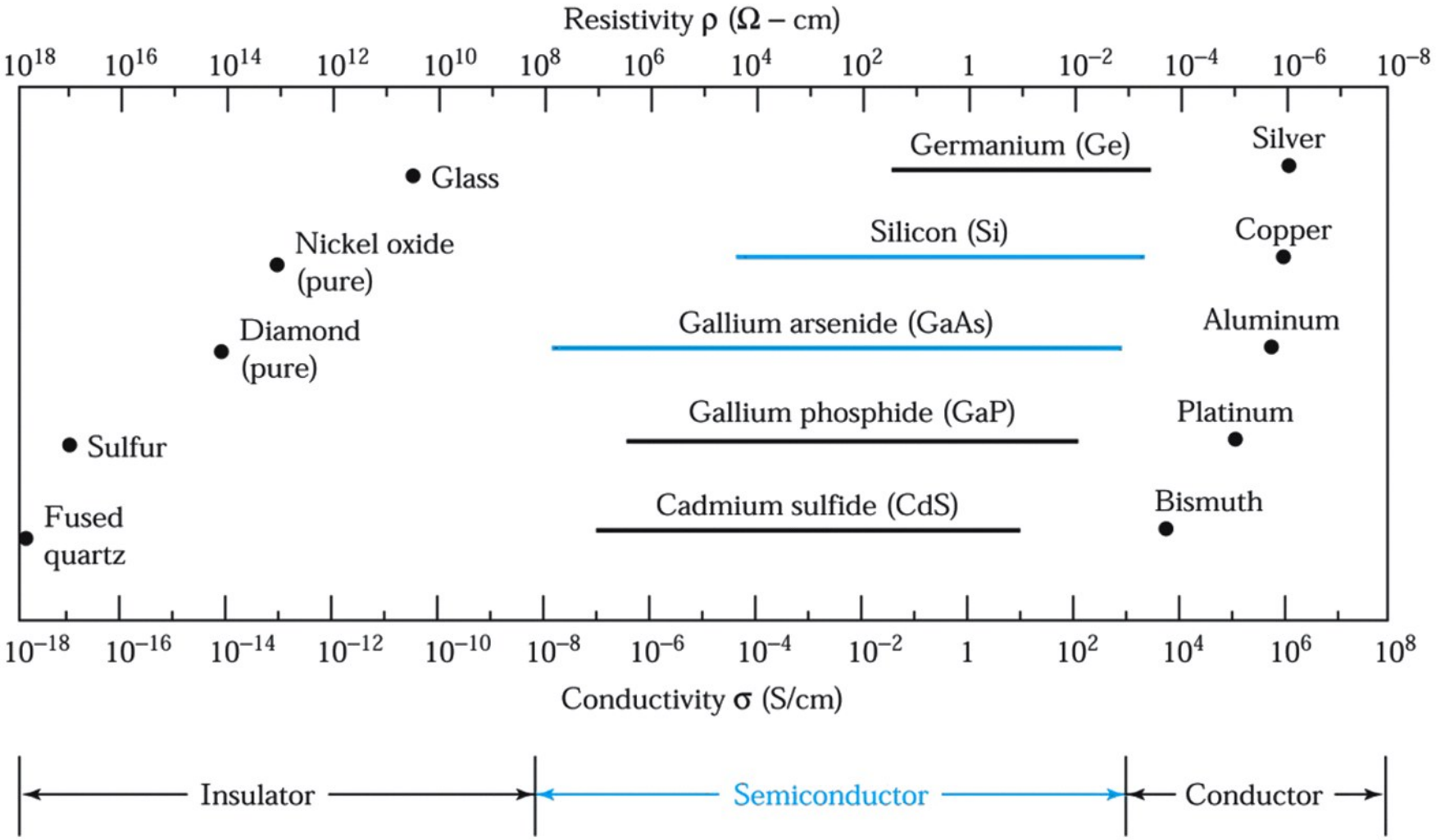


Figure 1.1

Typical range of conductivities for insulators, semiconductors, and conductors.

Si is abundant and has very good SiO_2

Semiconductor is promising due to high sensitivity in ρ

TABLE 1 Portion of the Periodic Table Related to Semiconductors

Period	Column II	III	IV	V	VI
2		B Boron	C Carbon	N Nitrogen	O Oxygen
3	Mg Magnesium	Al Aluminum	Si Silicon	P Phosphorus	S Sulfur
4	Zn Zinc	Ga Gallium	Ge Germanium	As Arsenic	Se Selenium
5	Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium
6	Hg Mercury		Pb Lead		

Table 1.1

TABLE 2 Semiconductor Materials[2]

General Classification	Semiconductor	
	Symbol	Name
Element	Si	Silicon
	Ge	Germanium
Binary compound		
IV-IV ----------	SiC	Silicon carbide
III-V ----------	AlP	Aluminum phosphide
	AlAs	Aluminum arsenide
	AlSb	Aluminum antimonide
	GaN	Gallium nitride
	GaP	Gallium phosphide
	GaAs	Gallium arsenide
	GaSb	Gallium antimonide
	InP	Indium phosphide
	InAs	Indium arsenide
	InSb	Indium antimonide
II-VI ----------	ZnO	Zinc oxide
	ZnS	Zinc sulfide
	ZnSe	Zinc selenide
	ZnTe	Zinc telluride
	CdS	Cadmium sulfide
	CdSe	Cadmium selenide
	CdTe	Cadmium telluride
	HgS	Mercury sulfide
IV-VI ----------	PbS	Lead sulfide
	PbSe	Lead selenide
	PbTe	Lead telluride
Ternary compound	$Al_xGa_{1-x}As$	Aluminum gallium arsenide
	$Al_xIn_{1-x}As$	Aluminum indium arsenide
	$GaAs_{1-x}P_x$	Gallium arsenic phosphide
	$Ga_xIn_{1-x}N$	Gallium indium nitride
	$Ga_xIn_{1-x}As$	Gallium indium arsenide
	$Ga_xIn_{1-x}P$	Gallium indium phosphide
Quaternary compound	$Al_xGa_{1-x}As_ySb_{1-y}$	Aluminum gallium arsenic antimonide
	$Ga_xIn_{1-x}As_{1-y}P_y$	Gallium indium arsenic phosphide

Table 1.2

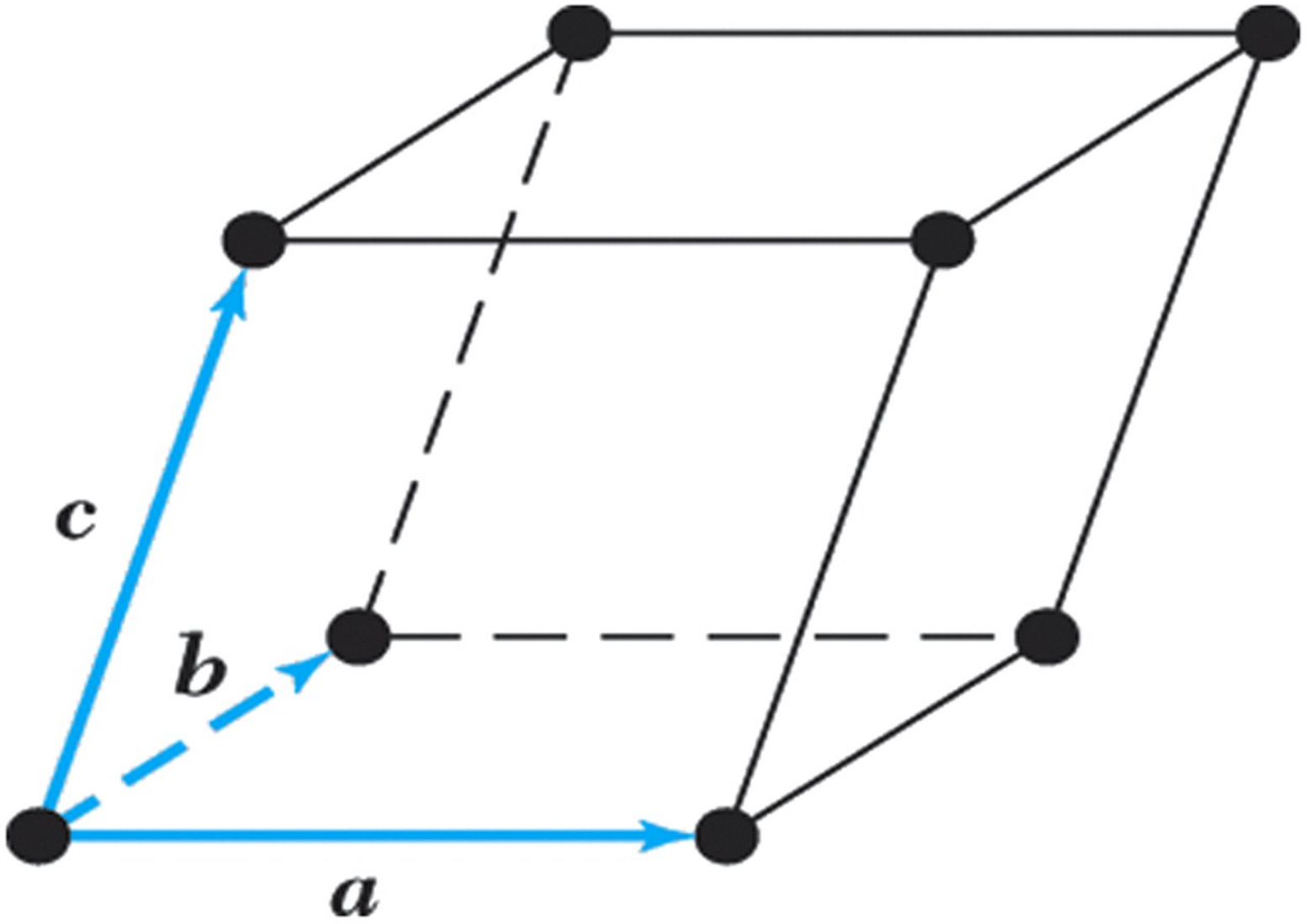


Figure 1.2

Figure 1.2. A generalized primitive unit cell.

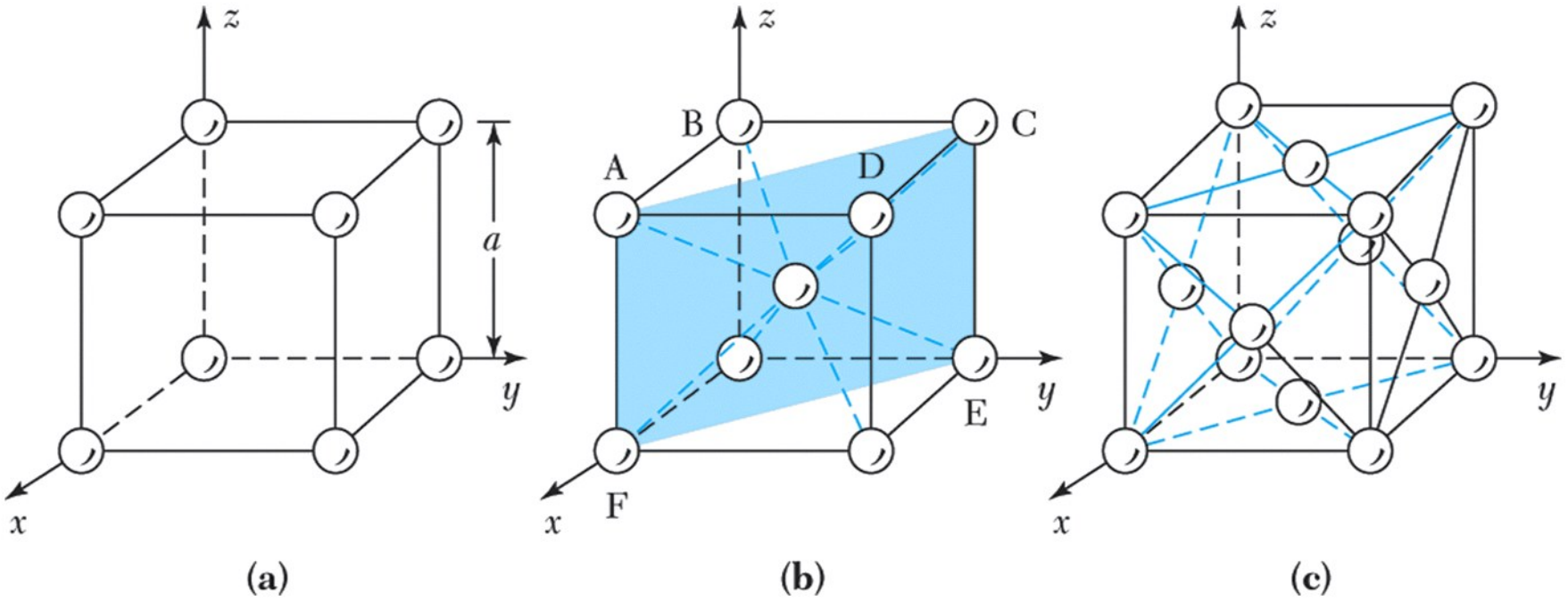
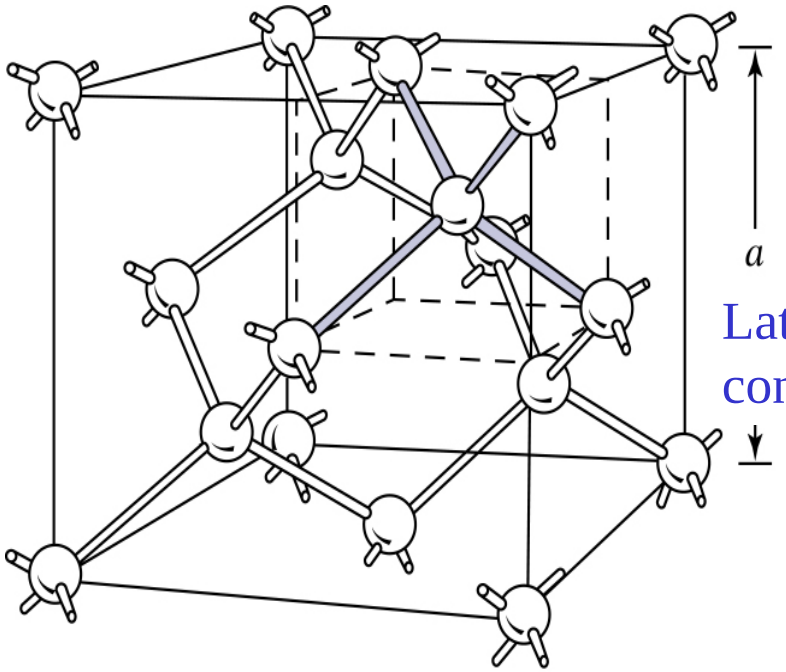
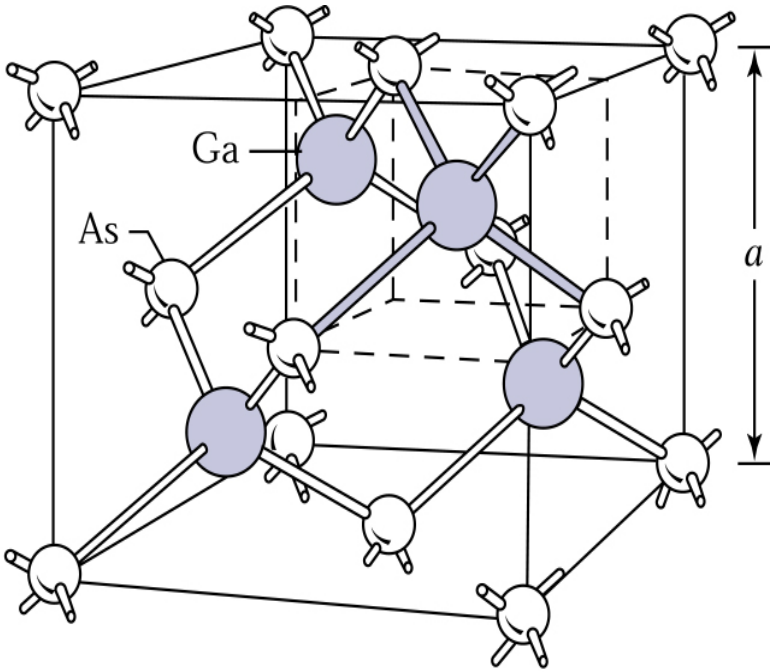


Figure 1.3

Three cubic-crystal unit cells. (*a*) Simple cubic. (*b*) Body-centered cubic. (*c*) Face-centered cubic.

＊半導體為 Single crystal　Periodic 排列為 Lattice (晶格)



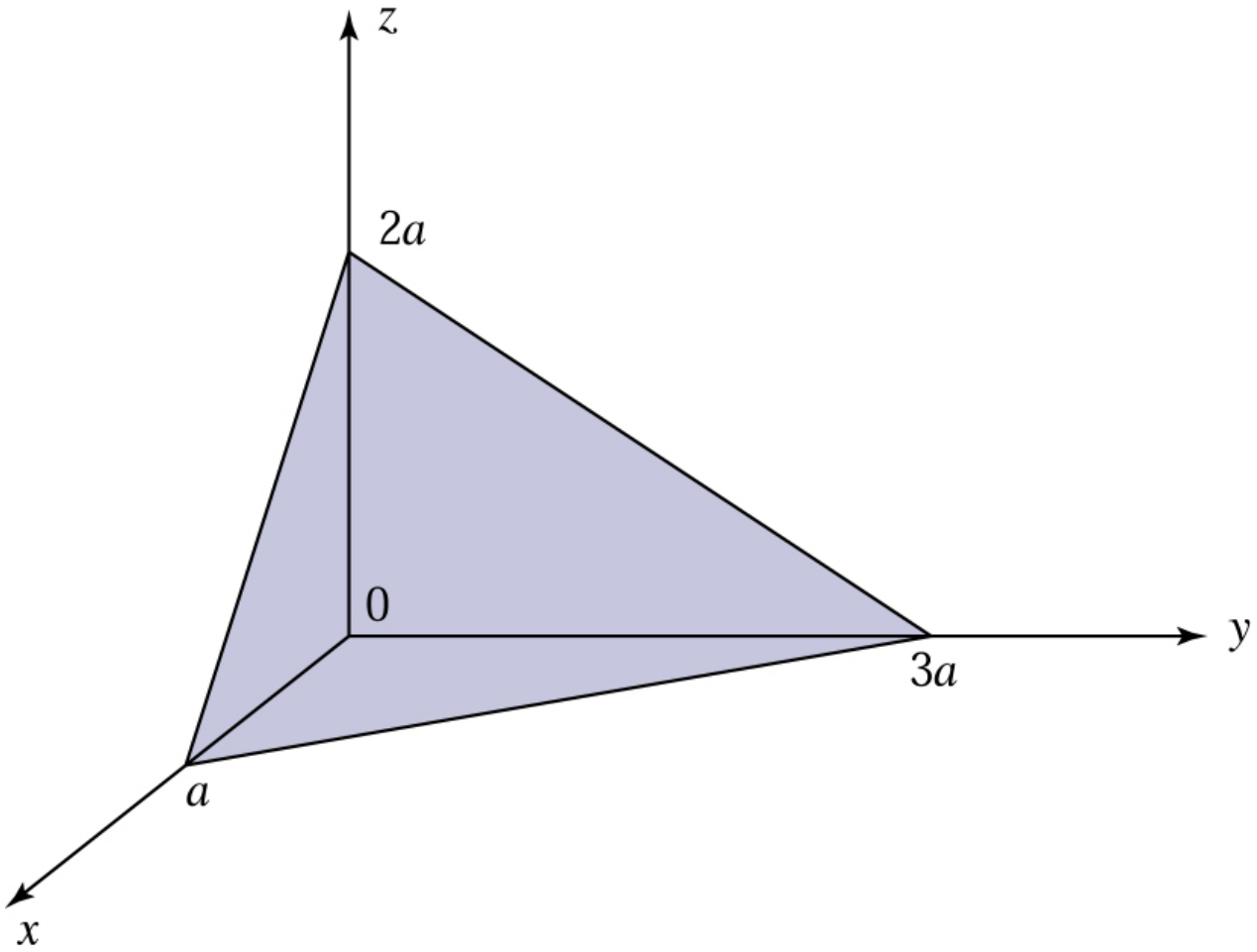


(a) Si ,Ge 之 lattice　　(b) III-V 之 Lattice

Like two interpenetrating fcc sublattices

Si 之濃度 $5 \times 10^{22}\ \#/cm^3$

Figure 1.4. (*a*) Diamond lattice. (*b*) Zincblende lattice.



Normal vector (1/a,1/3a,1/2a)

Figure 1.5. A (623)-crystal plane.

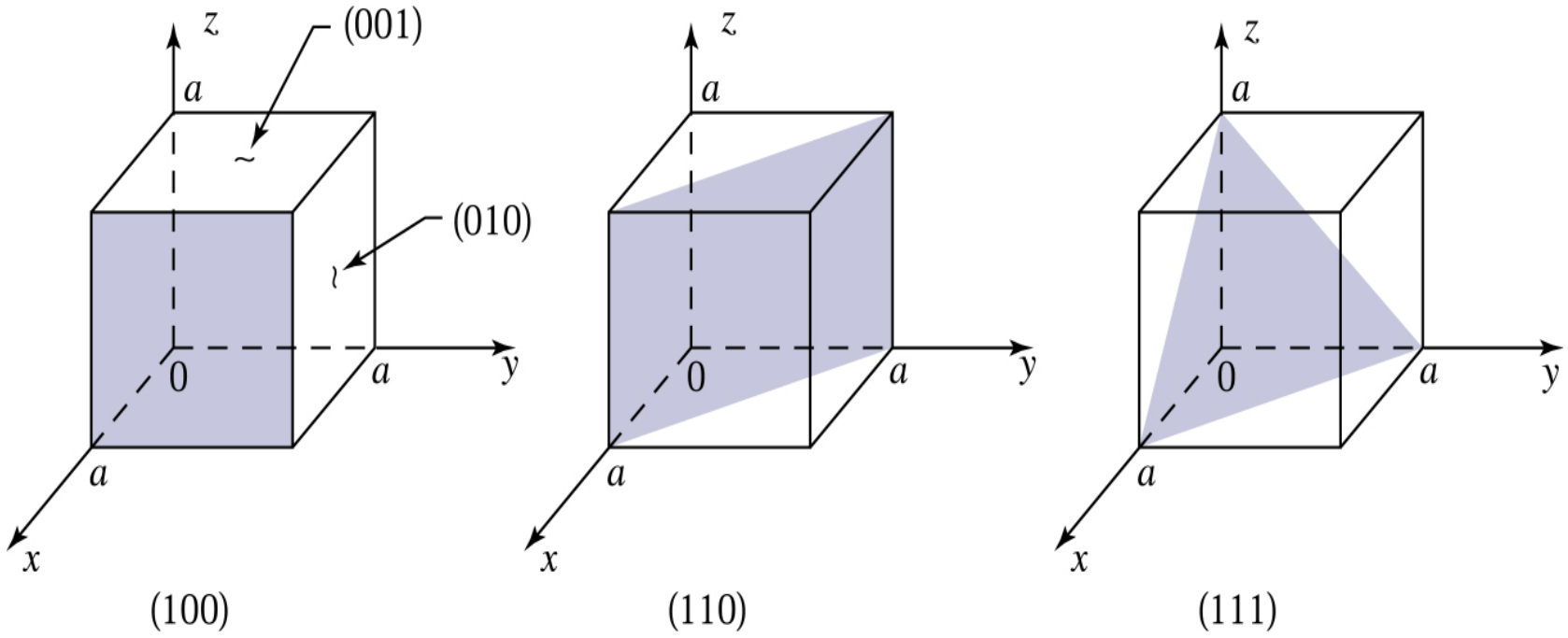
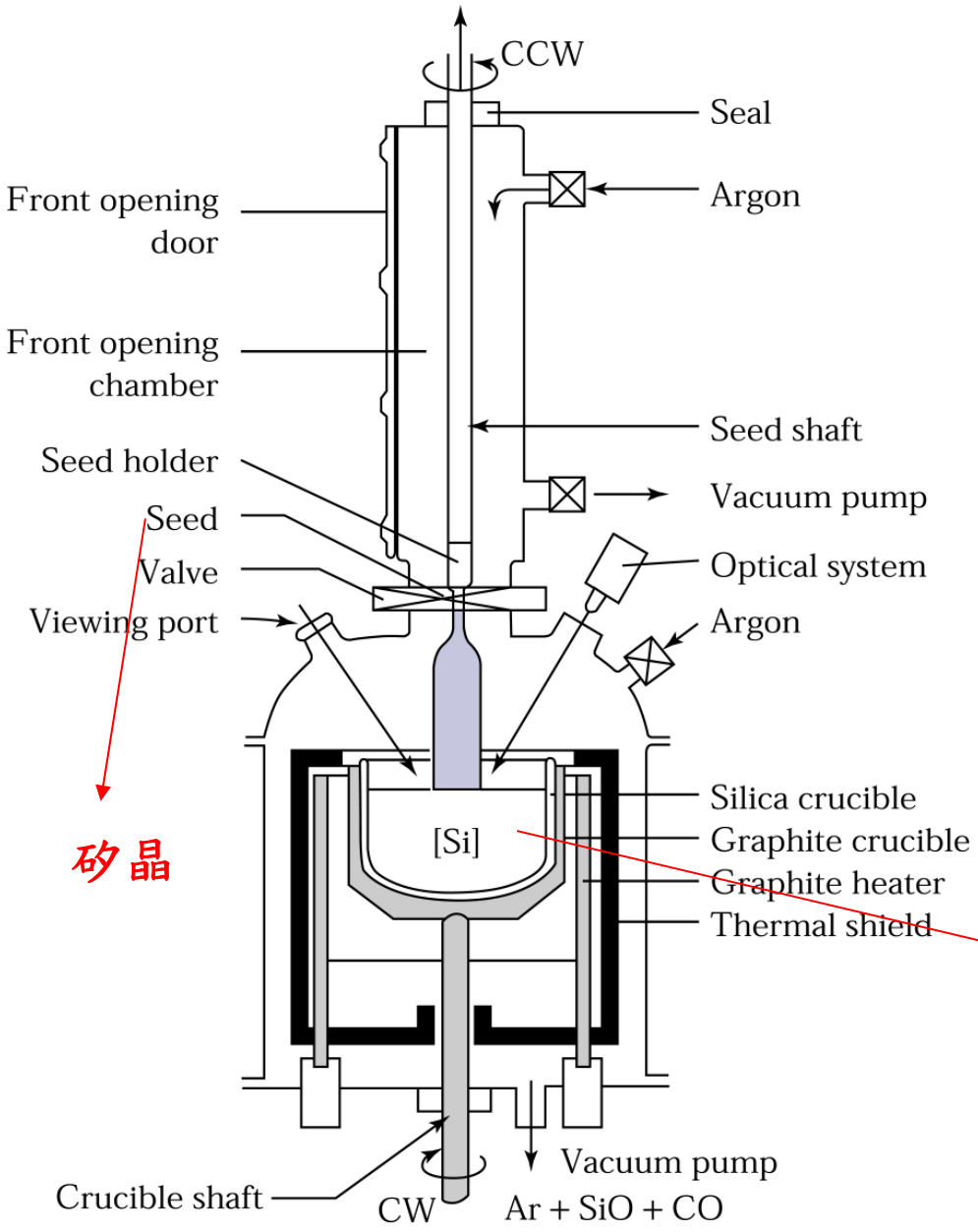


Figure 1.6. Miller indices of some important planes in a cubic crystal.



Simplified schematic drawing of the **Czochralski** puller. Clockwise (CW), counterclockwise (CCW).

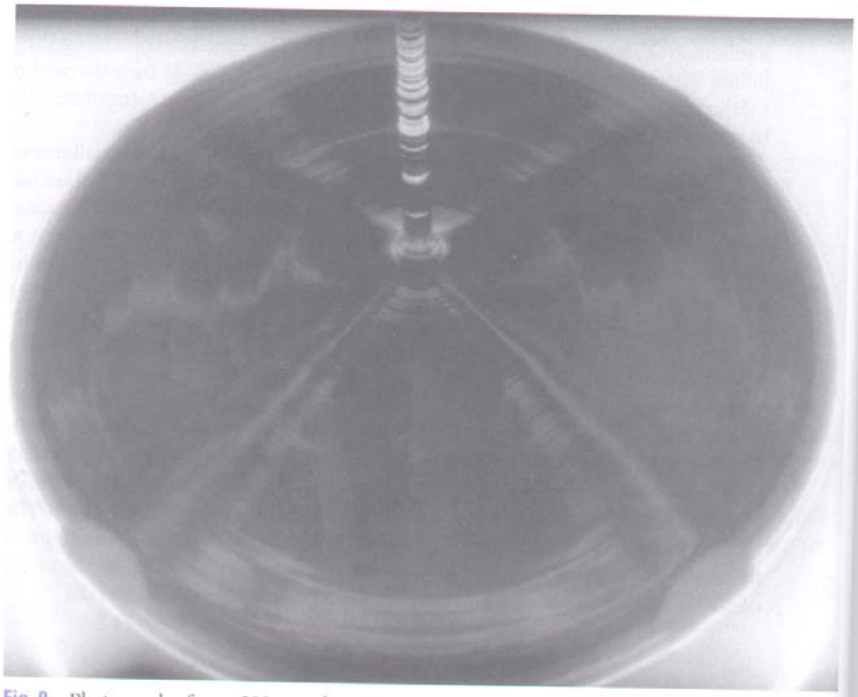


Fig. 9 Photograph of an a 200 mm diameter, (100)-oriented Si crystal being pulled from the melt. (Photograph courtesy of Taisil Electronic Materials Corp., Taiwan.)

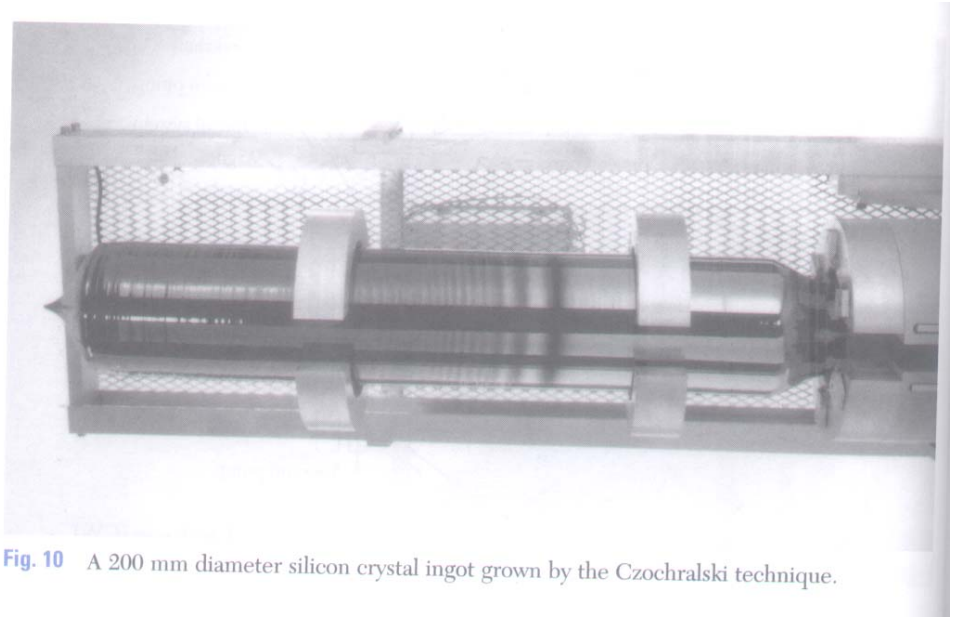
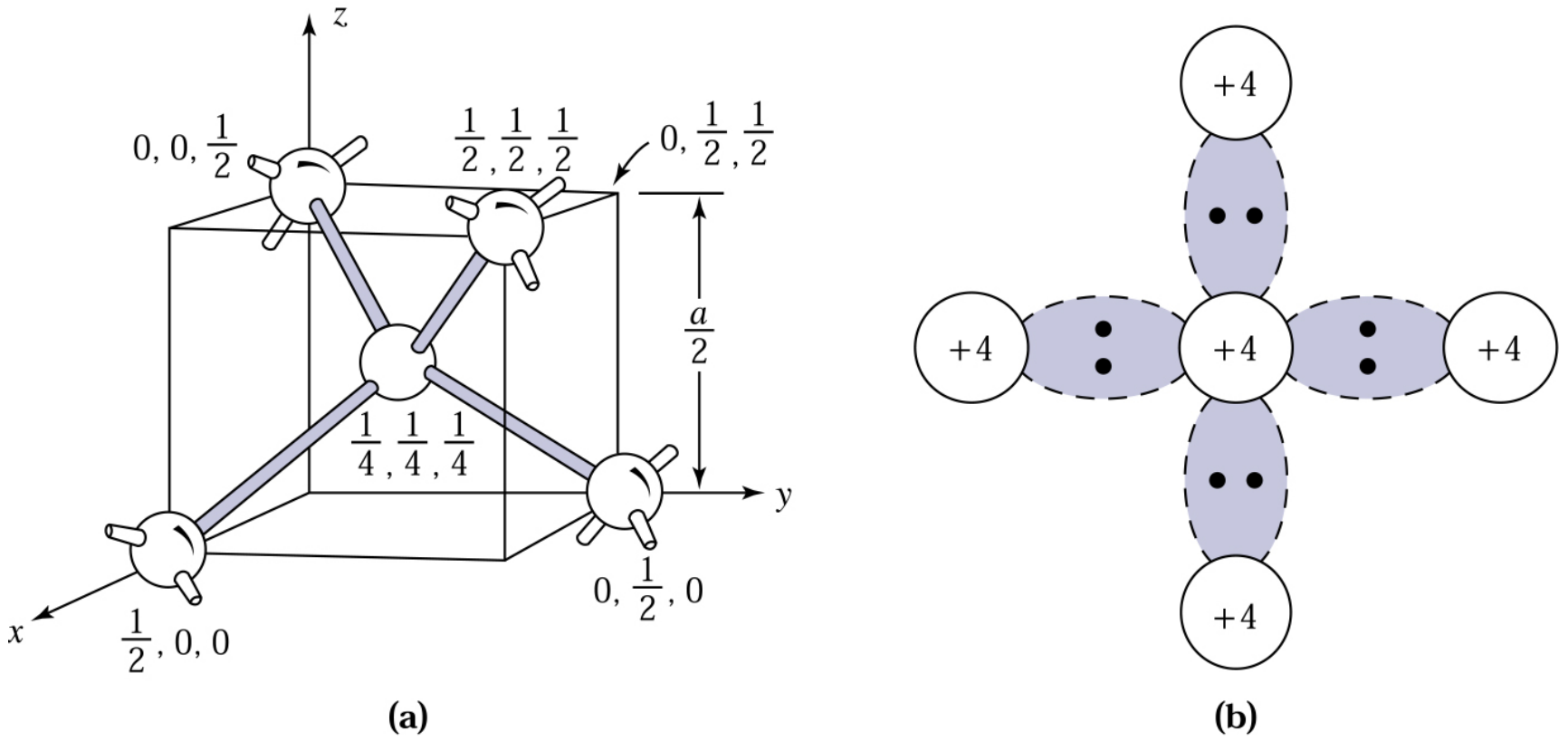


Fig. 10 A 200 mm diameter silicon crystal ingot grown by the Czochralski technique.



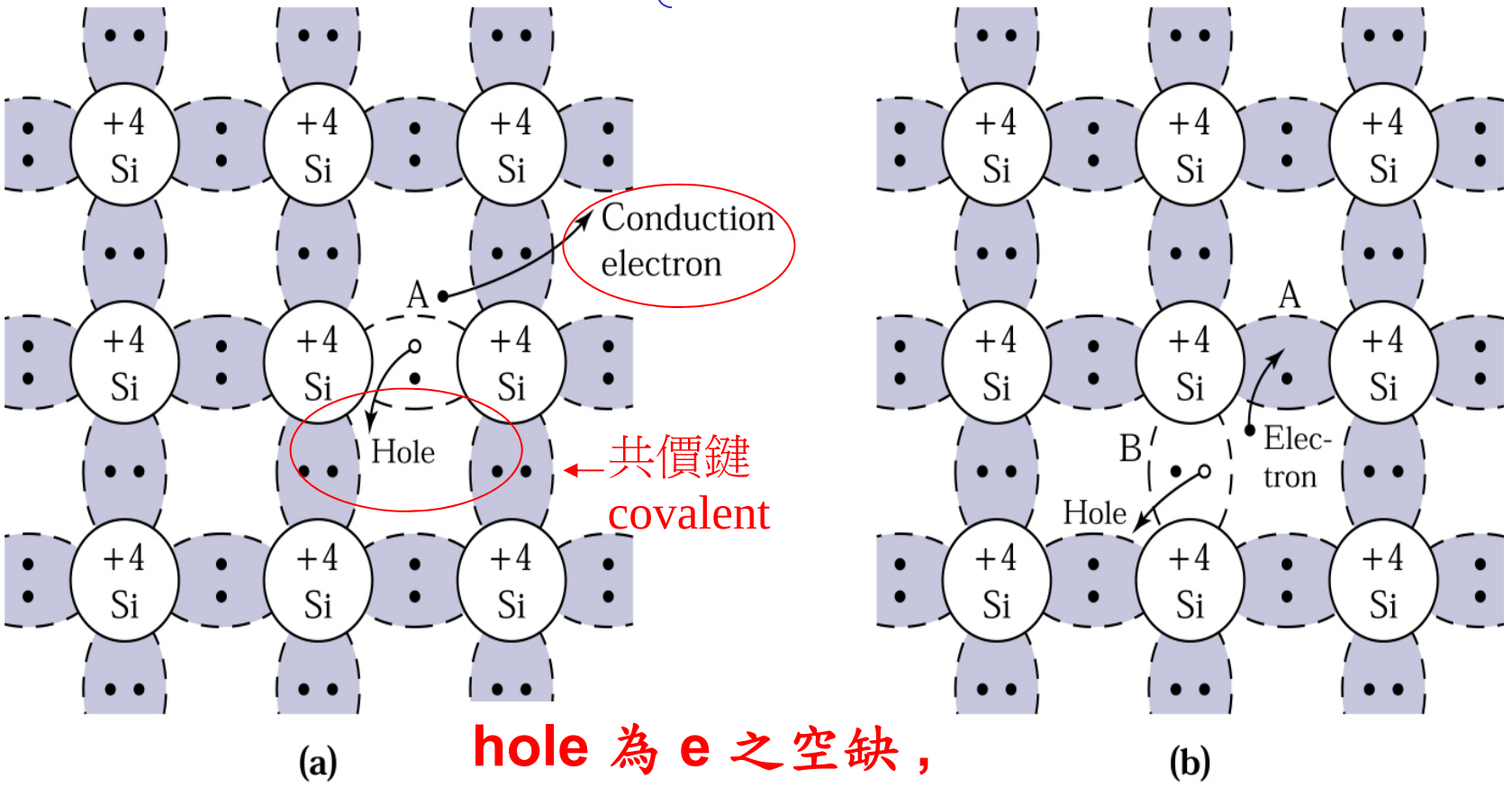
四面體

Figure 1.7 (*a*) A tetrahedron bond. (*b*) Schematic two-dimensional representation of a tetrahedron bond.

Si : 10^{22} #/cm^3

電子濃度 n　Intrinsic(本質) n=p=ni

電洞濃度 p　≒1.5×10^{10}



hole 為 e 之空缺，正電,與e反向

Figure 1.8 The basic bond representation of intrinsic silicon. (*a*) A broken bond at Position A, resulting in a conduction electron and a hole. (*b*) A broken bond at position B.

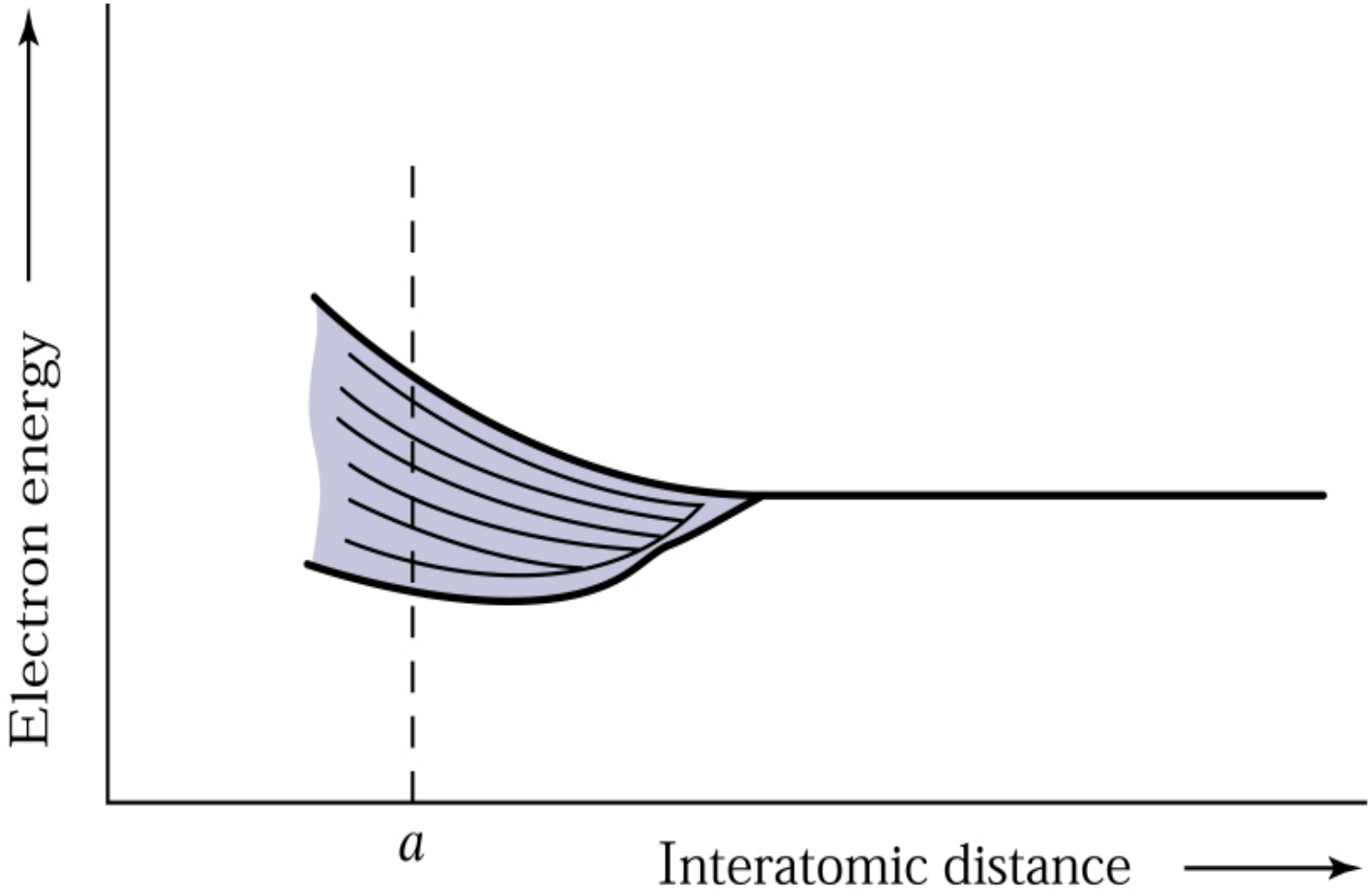


Figure 1.9 The splitting of a degenerate state into a band of allowed energies.

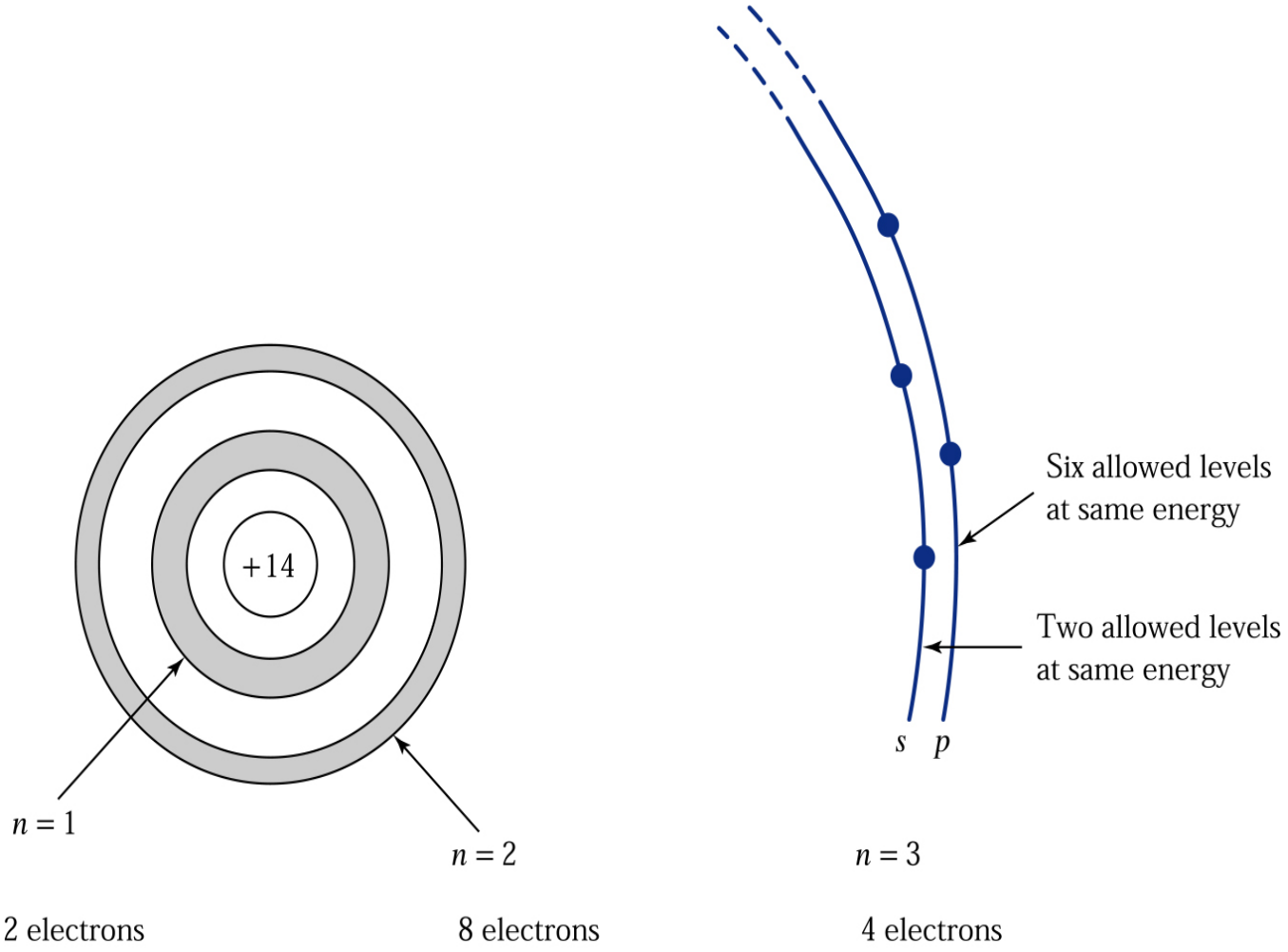
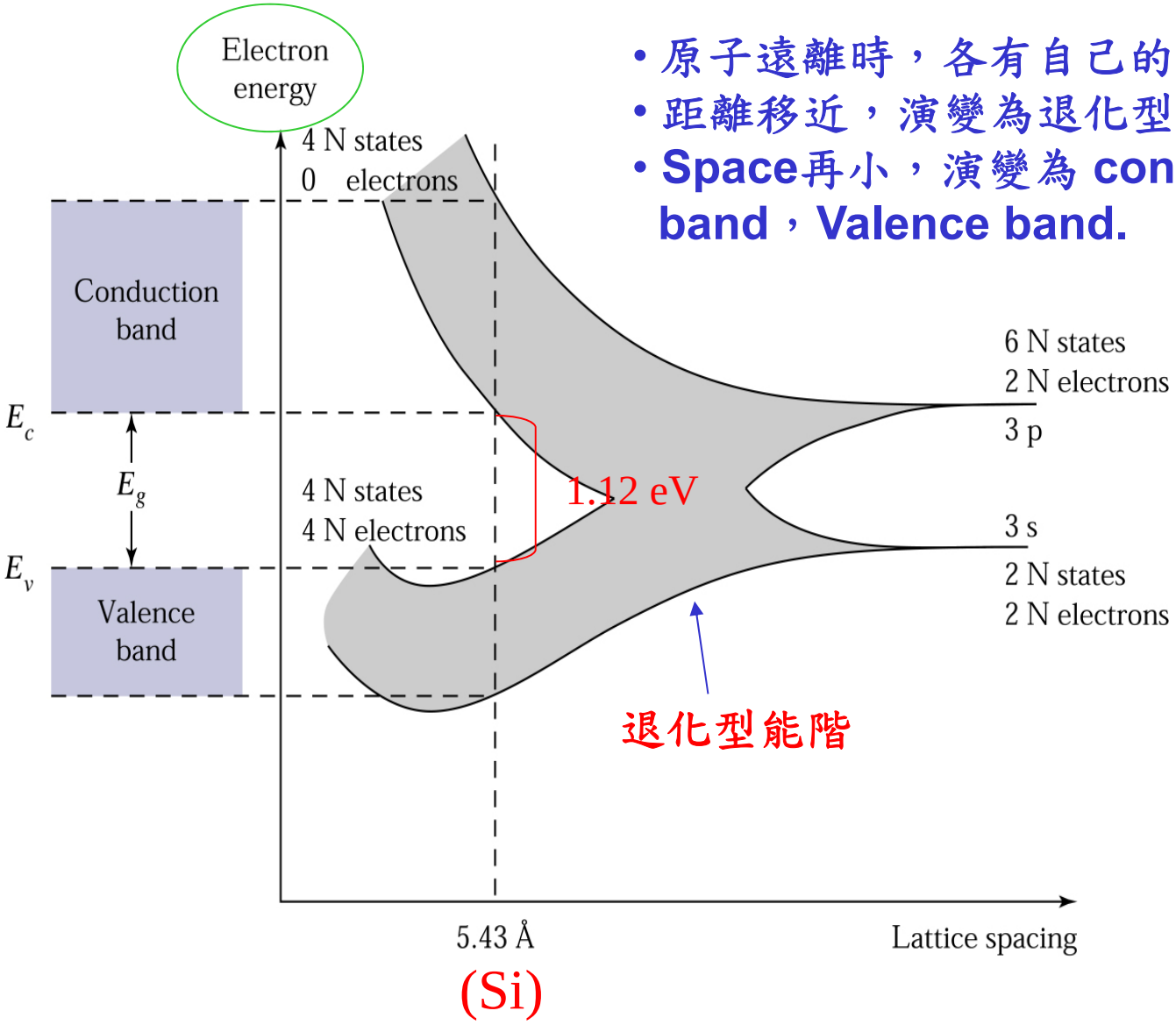


Figure 1.10 Schematic representation of an isolated silicon atom.

$1S^2$ $2S^2$ $2P^6$ $3S^2 3P^2$



- 原子遠離時，各有自己的能階.
- 距離移近，演變為退化型能階.
- Space再小，演變為 conduction band，Valence band.

Figure 1.11 Formation of energy bands as a diamond lattice crystal is formed by bringing isolated silicon atoms together.

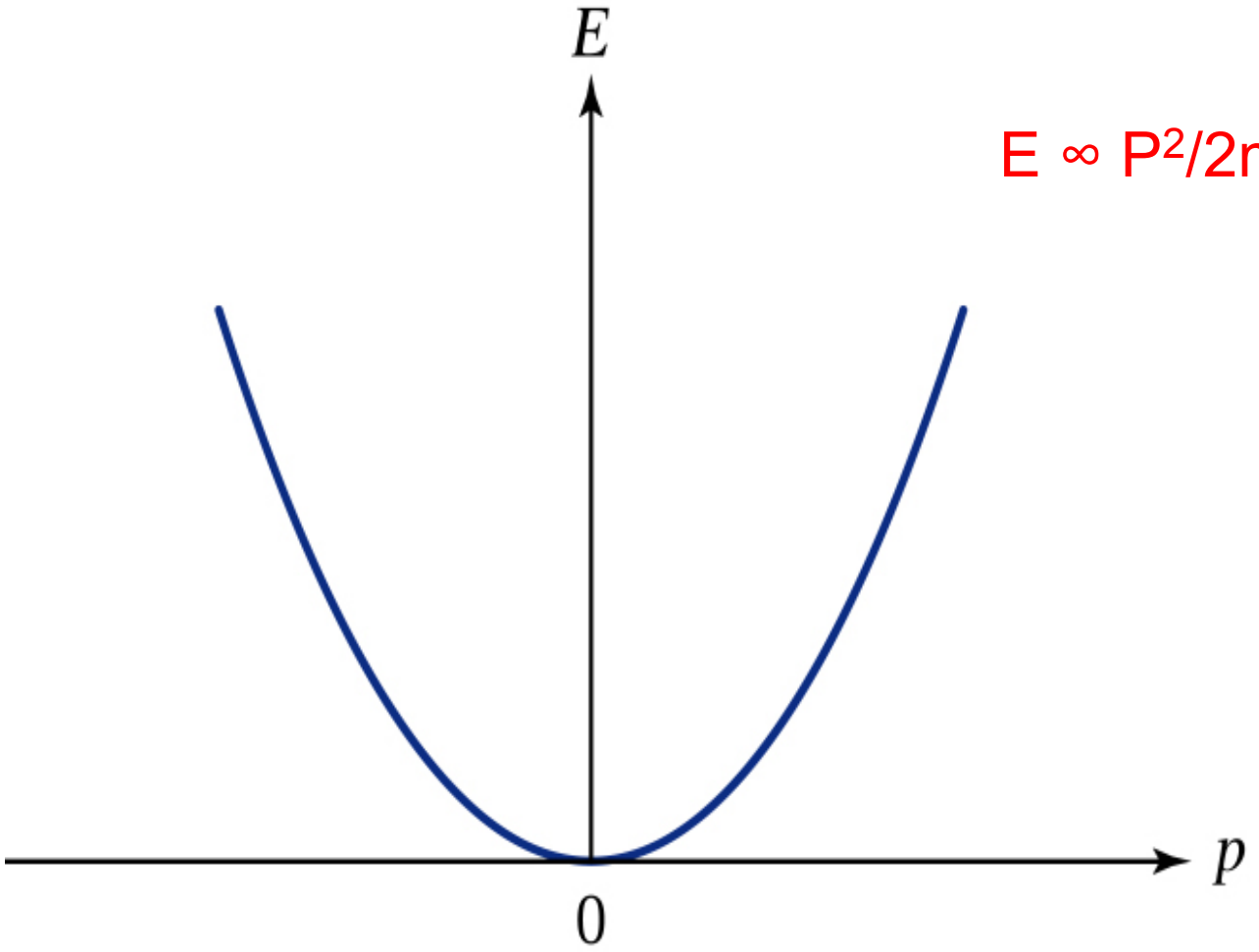


Figure 1.12 The parabolic energy (*E*) vs. momentum (*p*) curve for a free electron.

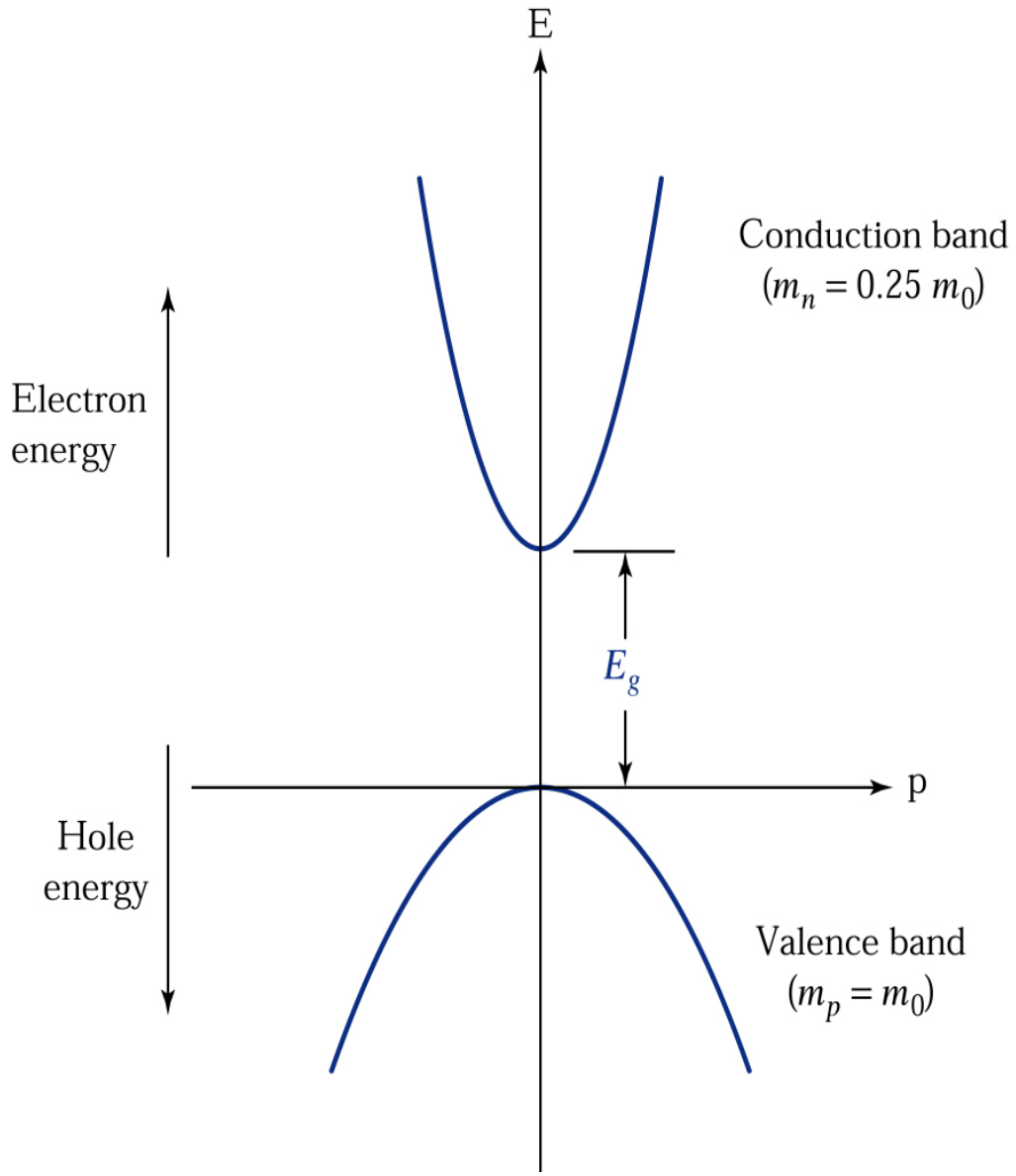


Figure 1.13
A schematic **energy-momentum** diagram for a special semiconductor with $m_n = 0.25\ m_0$ and $m_p = m_0$.

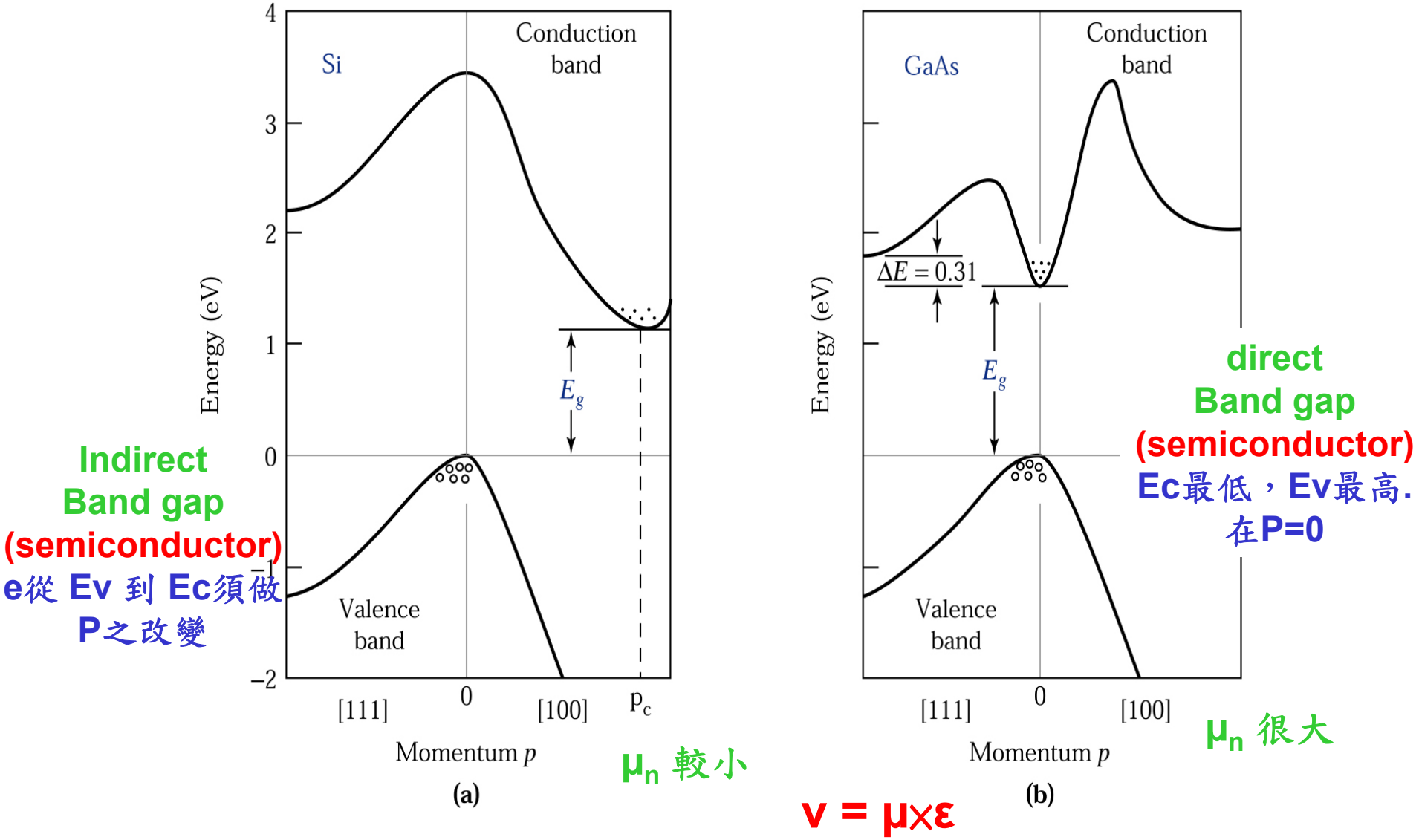


Figure 1.14 Energy band structures of Si and GaAs. Circles (°) indicate holes in the valence bands and dots (•) indicate electrons in the conduction bands.

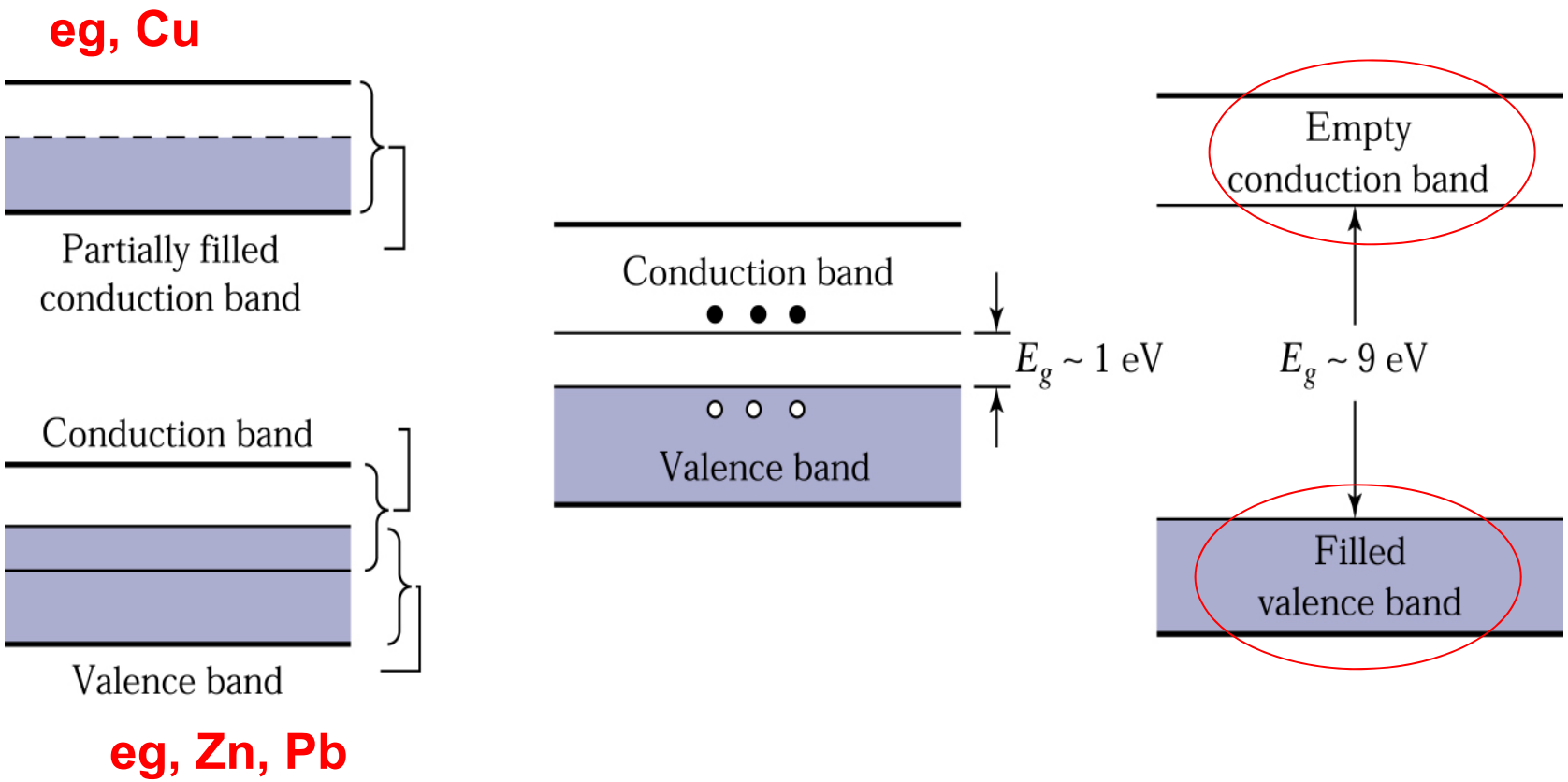


Figure 1.15 Schematic energy band representations of (*a*) **a conductor with two possibilities (either the partially filled conduction band shown at the upper portion or the overlapping bands shown at the lower portion),** (*b*) a **semiconductor**, and (*c*) an insulator.

Intrinsic semiconductor : impurity 所產生之e,p << thermal 之 e,p

Fermi-Dirac distribution function

$$n = \int_0^{E_{top}} n(E)dE = \int_0^{E_{top}} N(E)F(E)dE \qquad (9)$$

電子濃度　濃度　能態密度

$$F(E) = \frac{1}{1 + e^{(E - E_F)/kT}} \qquad (10)$$

→ 能量E態位被佔據的機率

E_F : Fermi Level，被電子佔據的機率為1/2的能量

Density of state N(E)與$E^{1/2}$ 成正比

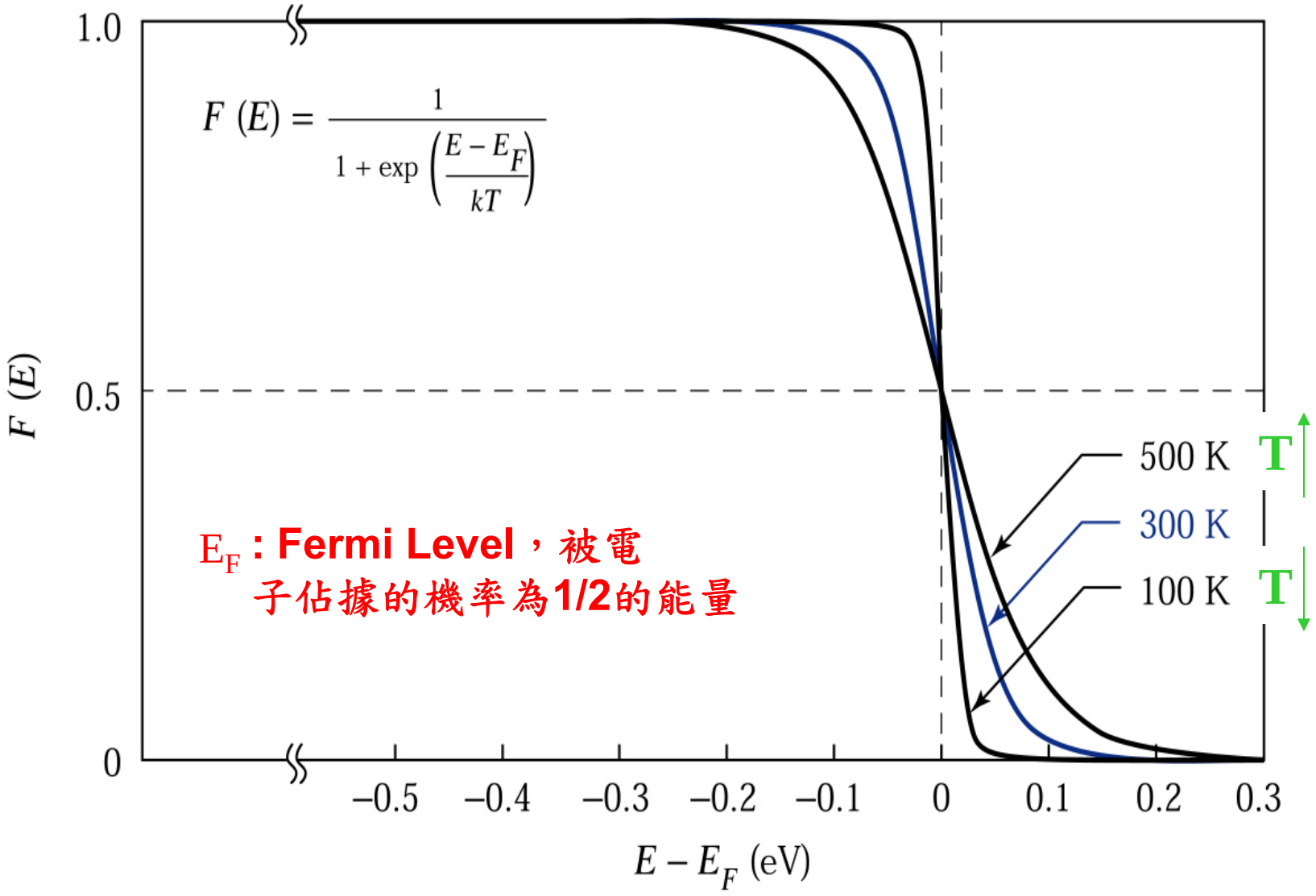


Figure 1.16 Fermi distribution function $F(E)$ versus $(E - E_F)$ for various temperatures.

n(E)=N(E)×F(E)

p(E)=P(E)×F(E)

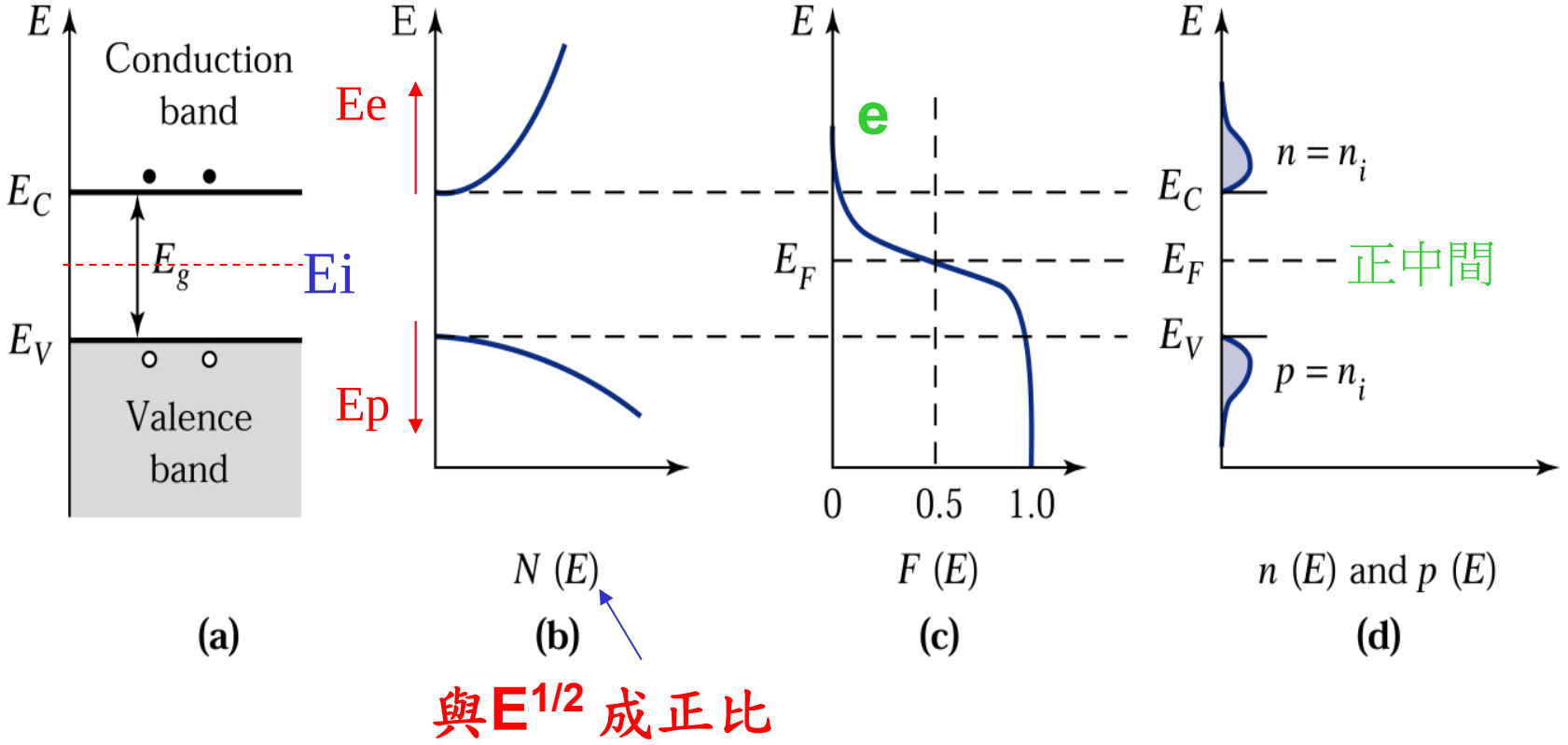


Figure 1.17 Intrinsic semiconductor. (*a*) Schematic band diagram. (*b*) Density of states. (*c*) Fermi distribution function. (*d*) Carrier concentration.

effective density of state

$$N_C \equiv 2(2\pi m_n kT / h^2)^{3/2} \qquad (13a)$$

$2.86\times10^{19} cm^{-3}$

For silicon

☆ $$n = Nc \cdot exp\left[-\frac{(E_C - E_F)}{kT}\right] \qquad (16)$$

$$N_V \equiv 2(2\pi m_P kT / h^2)^{3/2} \qquad (18) \rightarrow 2.66\times10^{19} cm^{-3}$$

For silicon

☆ $$p = N_V \cdot \exp\left[-\frac{(E_F - E_V)}{kT}\right] \qquad (17)$$

Ei : intrinsic fermi level ，**band gap 中間** 。

ni : intrinsic carrier density ⟶ (Si) $1.45 \times 10^{10}\ \#/cm^3$

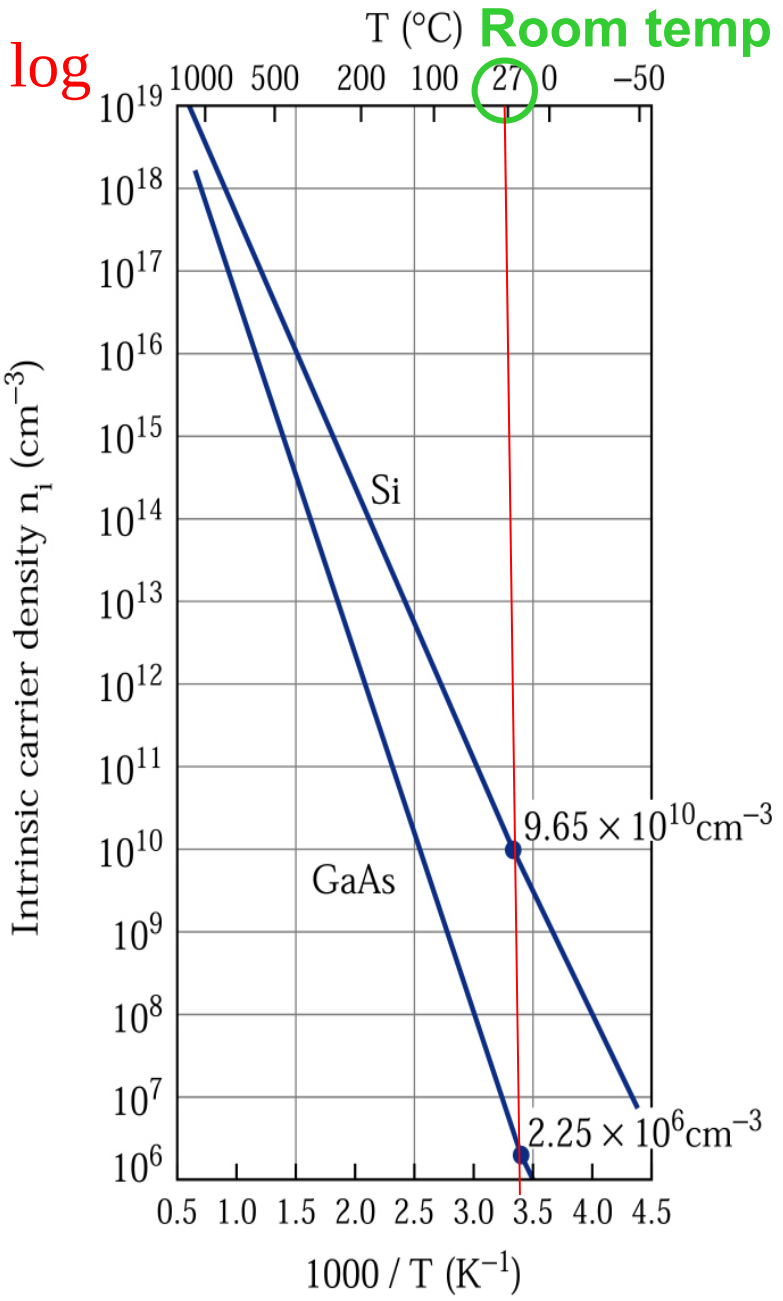
Intrinsic semiconductor n=p=ni

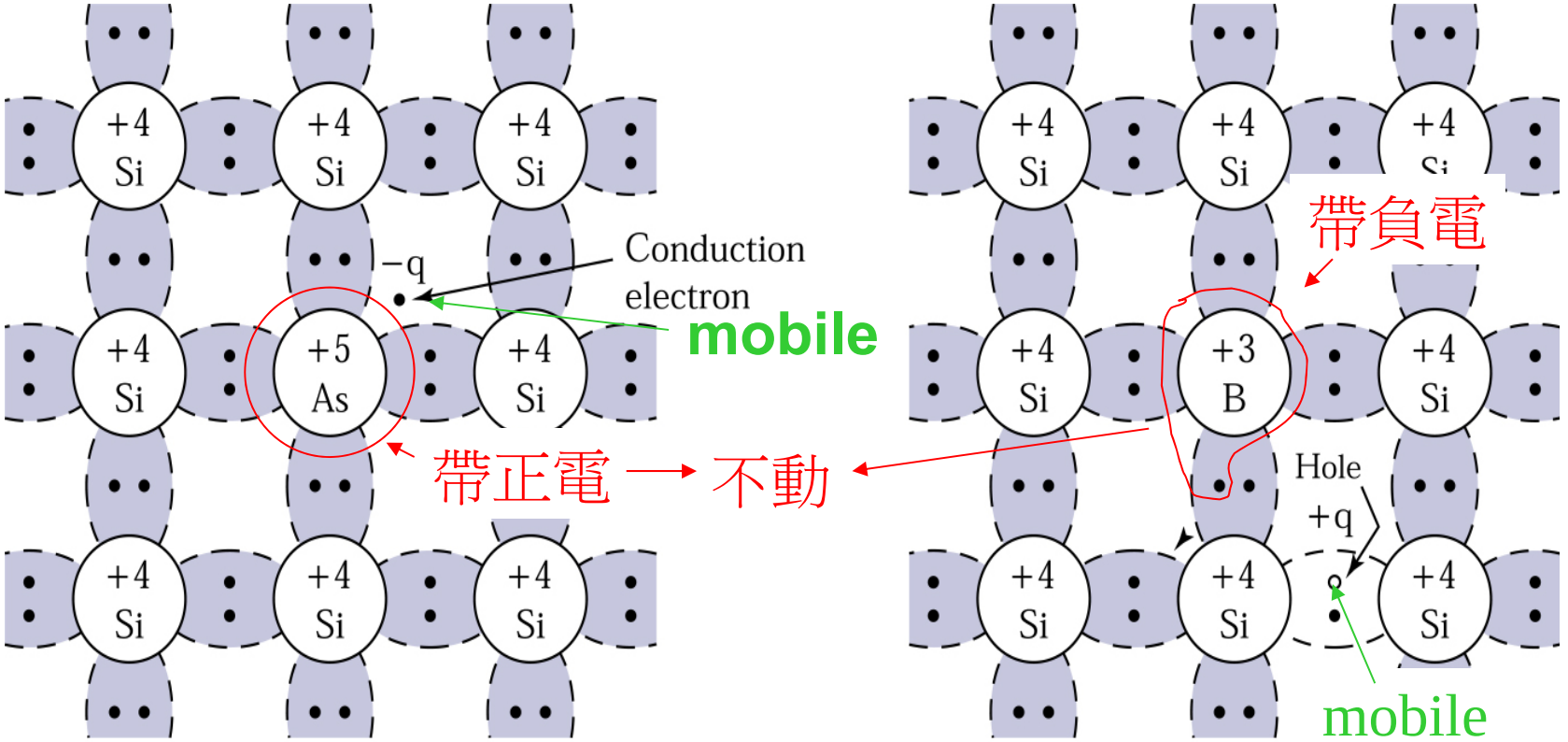
$$np = n_i^2$$ **Mass action law** (20) { **Intrinsic,** **Extrinsic 皆可用**

$$n_i^2 = N_C N_V \exp\left[-\frac{E_g}{kT}\right]$$ Eg=Ec-Ev (21)

$$n_i = \sqrt{N_C N_V}\exp\left[-\frac{E_g}{2kT}\right]$$ (22) **可得ni**

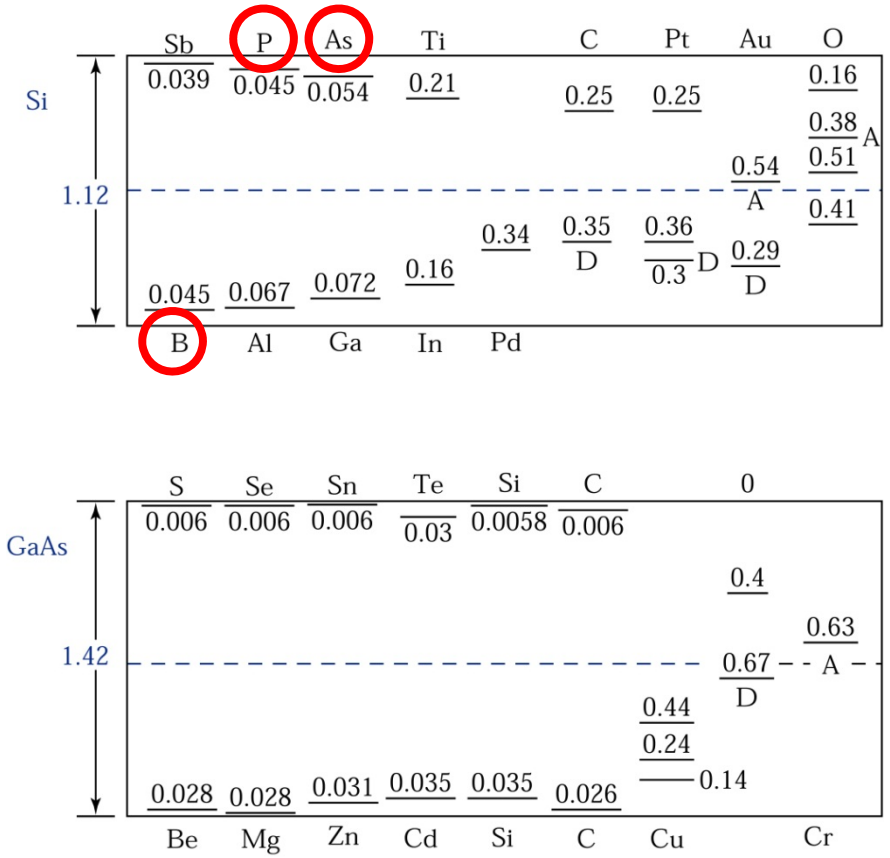
Figure 1.18
Intrinsic carrier densities in Si and GaAs as a function of the reciprocal of temperature. [5-7]





extrinsic { Donor （Ⅴ） As ,Ph n type
Acceptor （Ⅲ） B p type

Figure 1.19 Schematic bond pictures for (*a*) *n*-type Si with donor (arsenic) and (*b*) *p*-type Si with acceptor (boron).



E_D : ionization of donor

Complete ionization : for Si ，

常溫下已有足夠的熱能提供E_D

$$n = N_D \qquad (24) \qquad n = N_C \cdot e^{-\frac{E_C - E_F}{kT}}$$

$$E_C - E_F = kT\, ln\left[\frac{N_C}{N_D}\right] \qquad (25)$$

$$p = N_A \qquad (26)$$

$$E_F - E_V = kT\, ln\left[\frac{N_V}{N_A}\right] \qquad (27)$$

Figure 1.20 Measured ionization energies (in eV) for various impurities in **Si and GaAs**. The levels below the gap center are measured from the top of the valence band and are acceptor levels unless indicated by *D* for donor level. The levels above the gap center are measured from the bottom of the conduction band and are donor levels unless indicated by *A* for acceptor level.[8]

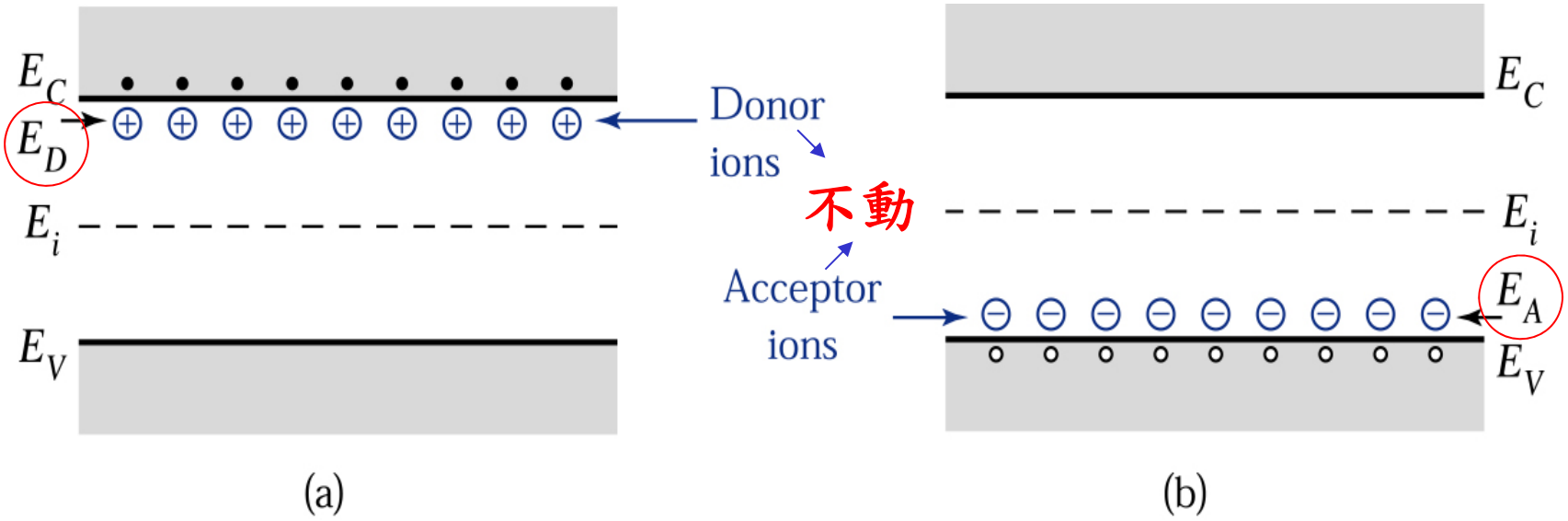
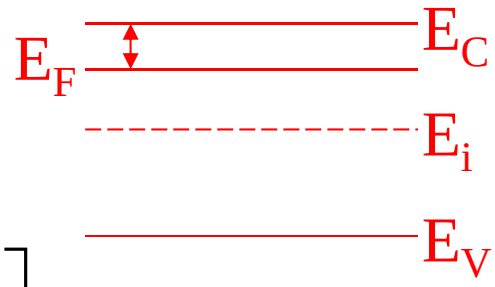


Figure 1.21 Schematic energy band representation of extrinsic semiconductors with (*a*) donor ions and (*b*) acceptor ions.

$$n = Nc \cdot exp\left[-\frac{E_C - E_F}{kT}\right]$$



$$= Nc \cdot exp\left[-\frac{(E_C - E_i)}{kT}\right] \cdot exp\left[\frac{(E_F - E_i)}{kT}\right]$$

☆ $$n = n_i \cdot exp\left[\frac{(E_F - E_i)}{kT}\right] \qquad (28)$$

similarly

☆ $$p = n_i \cdot exp\left[\frac{(E_i - E_F)}{kT}\right] \qquad (29)$$

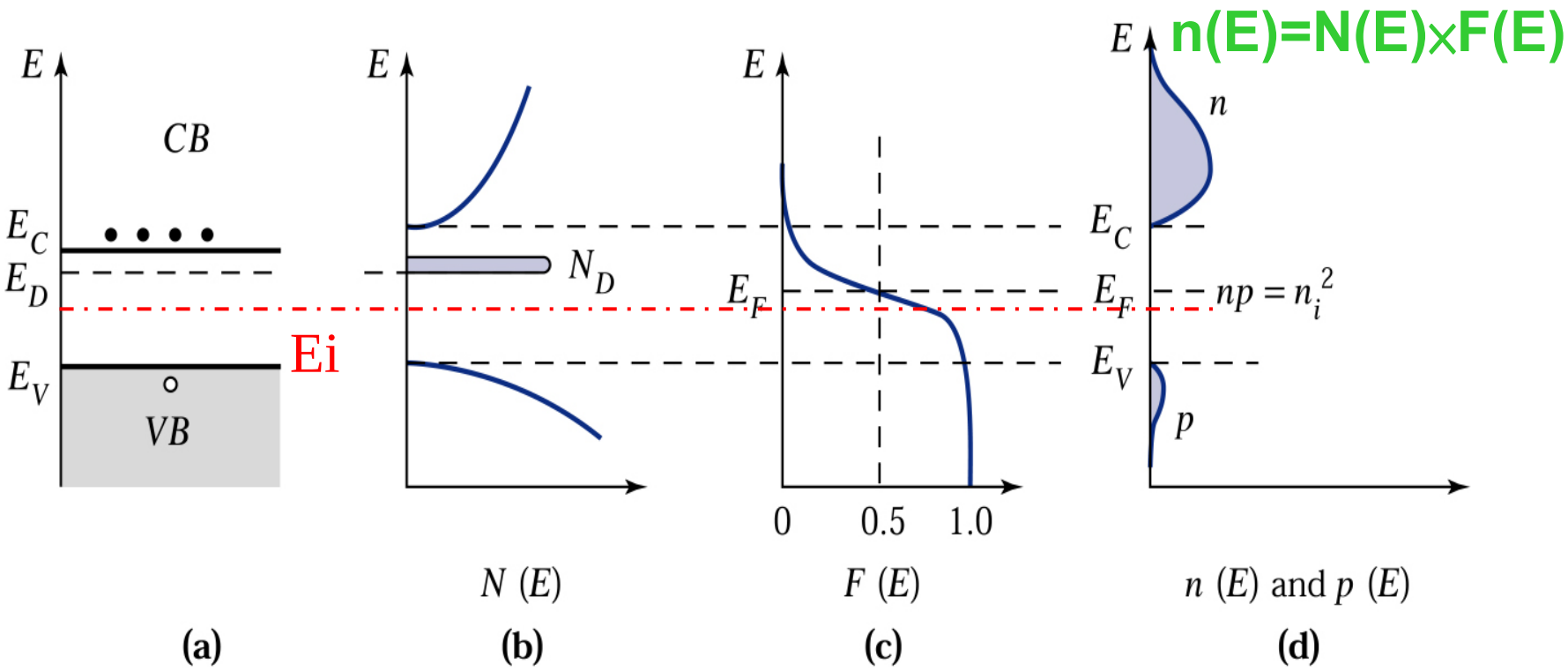


Figure 1.22 *n*-Type semiconductor. (*a*) Schematic band diagram. (*b*) Density of states. (*c*) Fermi distribution function (*d*) Carrier concentration. Note that $np = n_i^2$.

EXAMPLE 4

A silicon ingot is doped with 10^{16} arsenic atoms/cm^3. Find the carrier concentrations and the Fermi level at room temperature (300 K).

SOLUTION At 300 K, we can assume complete ionization of impurity atoms. We have

$$n \approx N_D = 10^{16}\,\text{cm}^{-3}.$$

From Eq. 20, $$p \approx n_i^2/N_D = (9.65 \times 10^9)^2/10^{16} = 9.3 \times 10^3\,\text{cm}^{-3}.$$

The Fermi level measured from the bottom of the conduction band is given by Eq. 25:

$$E_C - E_F = kT \ln(N_C/N_D)$$
$$= 0.0259 \ln(2.86 \times 10^{19}/10^{10}) = 0.205\ \text{eV}.$$

The Fermi level measured from the intrinsic Fermi level is given by Eq. 28:

$$E_F - E_i = kT \ln(N_D/n_i) \approx kT \ln(N_D/n_i)$$
$$= 0.0259 \ln (10^{16}/9.65 \times 10^9) = 0.358\ \text{eV}.$$

These results are shown graphically in Fig. 27.

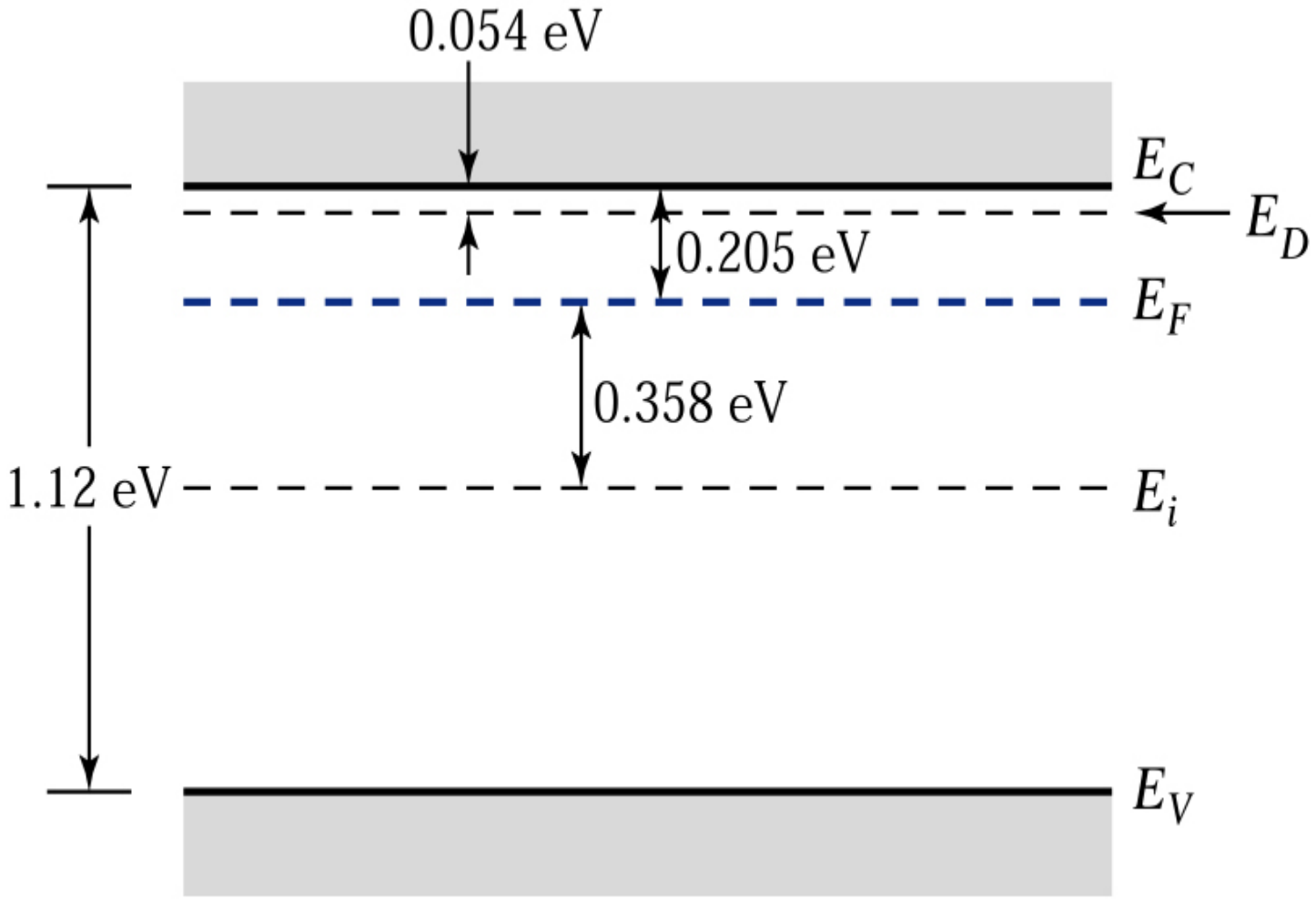


Figure 1.23 Band diagram showing Fermi level E_F and intrinsic Fermi level E_i.

Figure 1.24
Fermi level for Si and GaAs as a function of temperature and impurity concentration. The dependence of the bandgap on temperature is shown.[9]

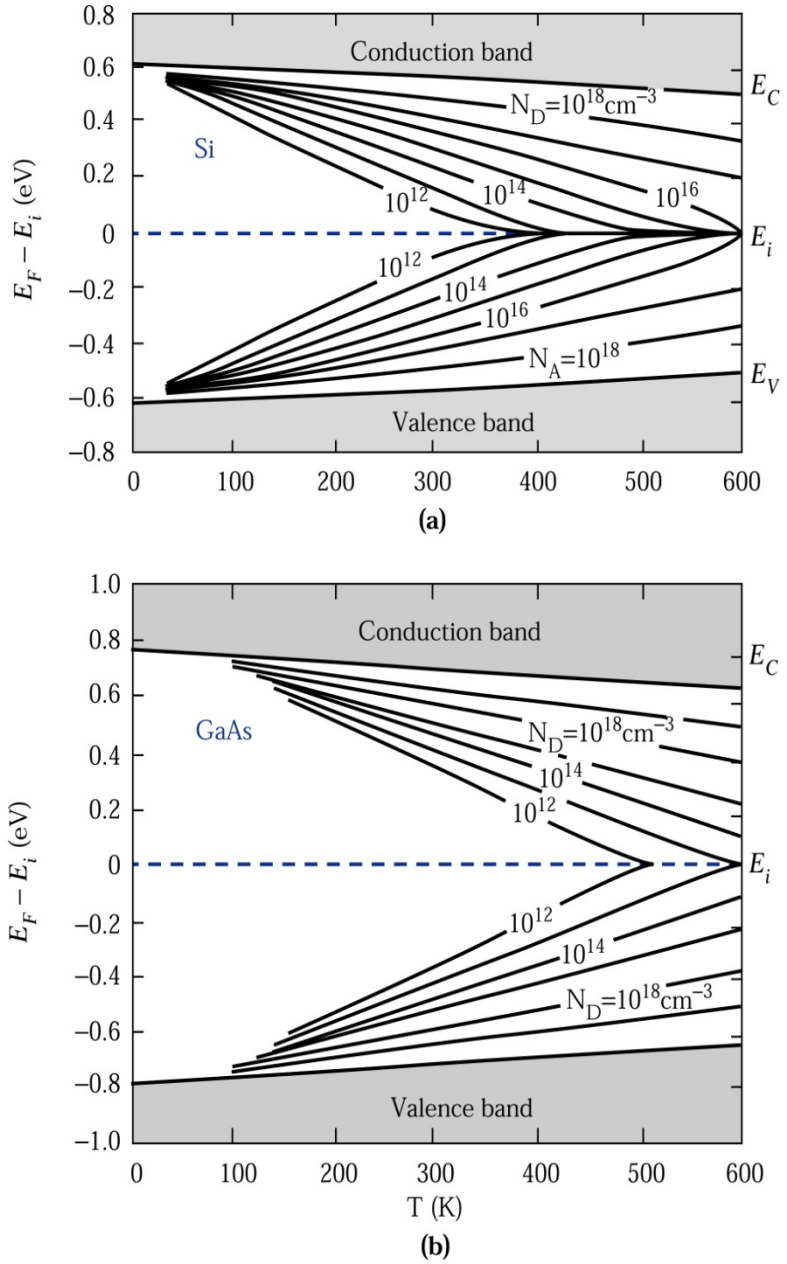


Figure 1.25
Electron density as a function of temperature for a Si sample with a donor concentration of 10^{15} cm^{-3}.