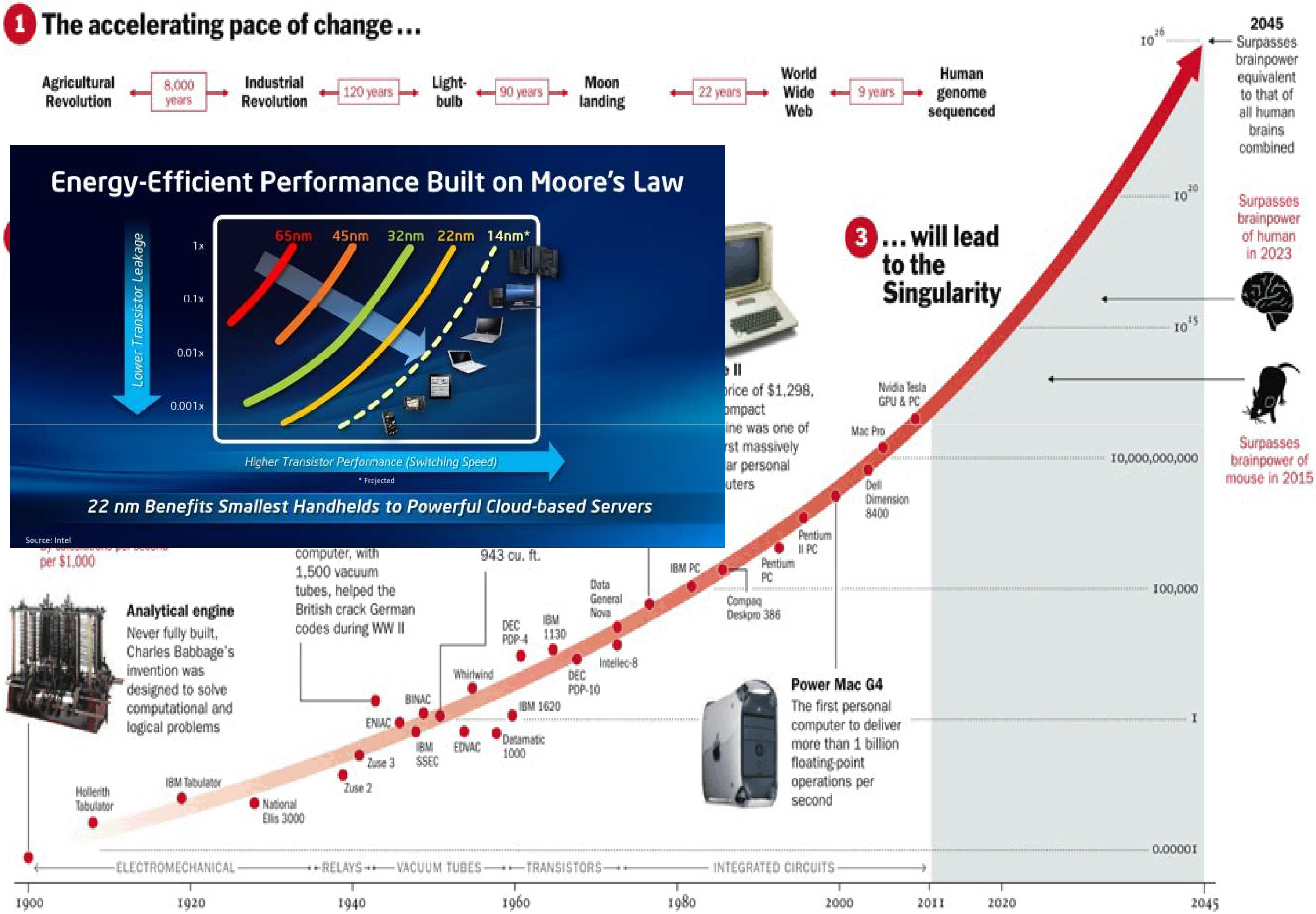

1 The accelerating pace of change ...
Agricultural Revolution
8,000 years
Industrial Revolution
120 years
Light-bulb
90 years
Moon landing
22 years
World Wide Web
9 years
Human genome sequenced
2045
Surpasses brainpower equivalent to that of all human brains combined
Surpasses brainpower of human in 2023
Surpasses brainpower of mouse in 2015
3 ... will lead to the Singularity
Energy-Efficient Performance Built on Moore's Law
65nm
45nm
32nm
22nm
14nm*
1x
0.1x
0.01x
0.001x
Lower Transistor Leakage
Higher Transistor Performance (Switching Speed)
* Projected
22 nm Benefits Smallest Handhelds to Powerful Cloud-based Servers
Source: Intel
per $1,000
Analytical engine
Never fully built, Charles Babbage's invention was designed to solve computational and logical problems
computer, with 1,500 vacuum tubes, helped the British crack German codes during WW II
943 cu. ft.
rice of $1,298, ompact ine was one of rst massively ar personal uters
Power Mac G4
The first personal computer to deliver more than 1 billion floating-point operations per second
Hollerith Tabulator
IBM Tabulator
National Ellis 3000
Zuse 2
Zuse 3
ENIAC
IBM SSEC
BINAC
EDVAC
Whirlwind
Datamatic 1000
IBM 1620
DEC PDP-4
IBM 1130
DEC PDP-10
Intellec-8
Data General Nova
IBM PC
Compaq Deskpro 386
Pentium PC
Pentium II PC
Dell Dimension 8400
Mac Pro
Nvidia Tesla GPU & PC
10^{26}
10^{20}
10^{15}
10,000,000,000
100,000
1
0.00001
ELECTROMECHANICAL
RELAYS
VACUUM TUBES
TRANSISTORS
INTEGRATED CIRCUITS
1900
1920
1940
1960
1980
2000
2011
2020
2045

Recap

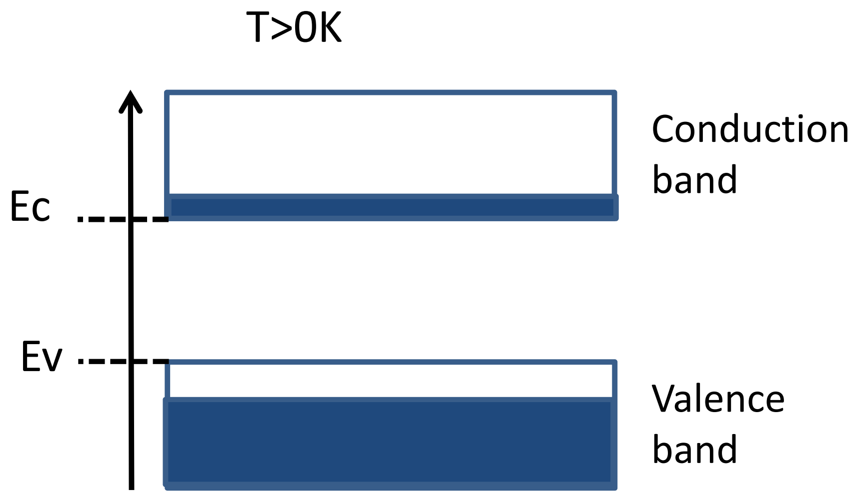
Effective Mass of an electron

$$m^* = \frac{[h/(2\pi)]^2}{d^2E/dk^2}$$

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

Recap



➢Particles that can freely move and contribute to the current flow (conduction)

carrier

1. Electron in conduction band
2. Hole in valence band

Recap

- **How to count number of carriers,n?**

Assumption; Pauli exclusion principle

If we know

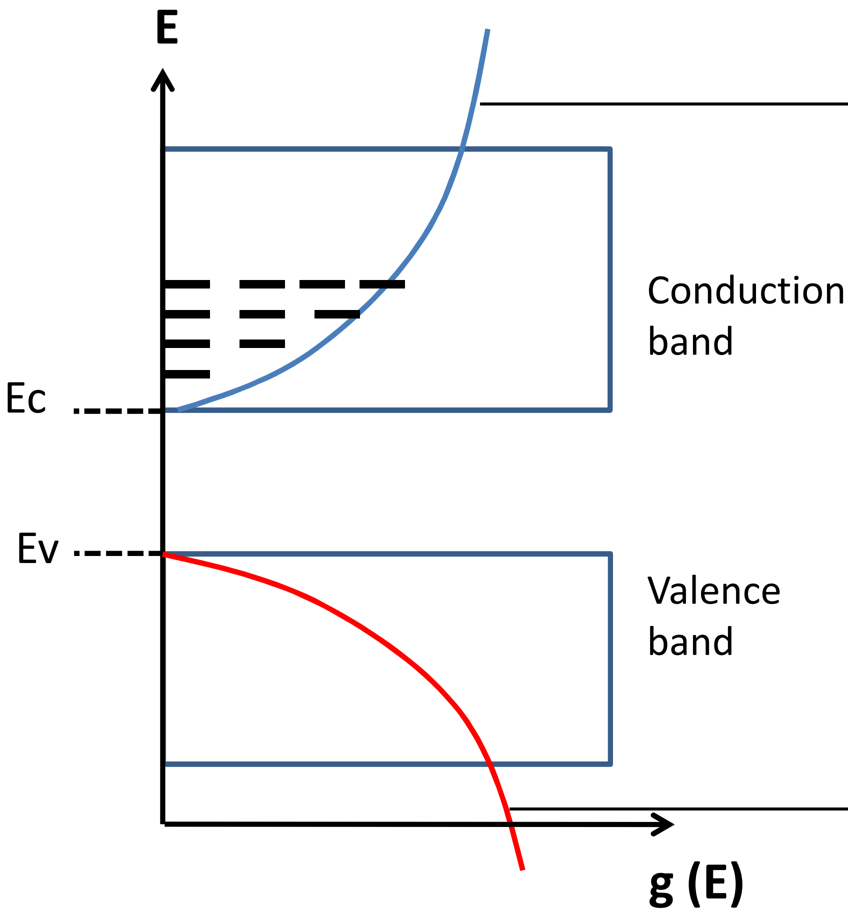
1. No. of energy states $\Rightarrow$ Density of states (DOS)

2. Occupied energy states $\Rightarrow$ The probability that energy states is occupied
"Fermi-Dirac distribution function"

n = DOS x "Fermi-Dirac distribution function"

Recap

Density of state



No of states (seats) above EC for electron

$$g(E) = \frac{4\pi(2m^*)^{3/2}}{h^3}\sqrt{E - E_C}$$

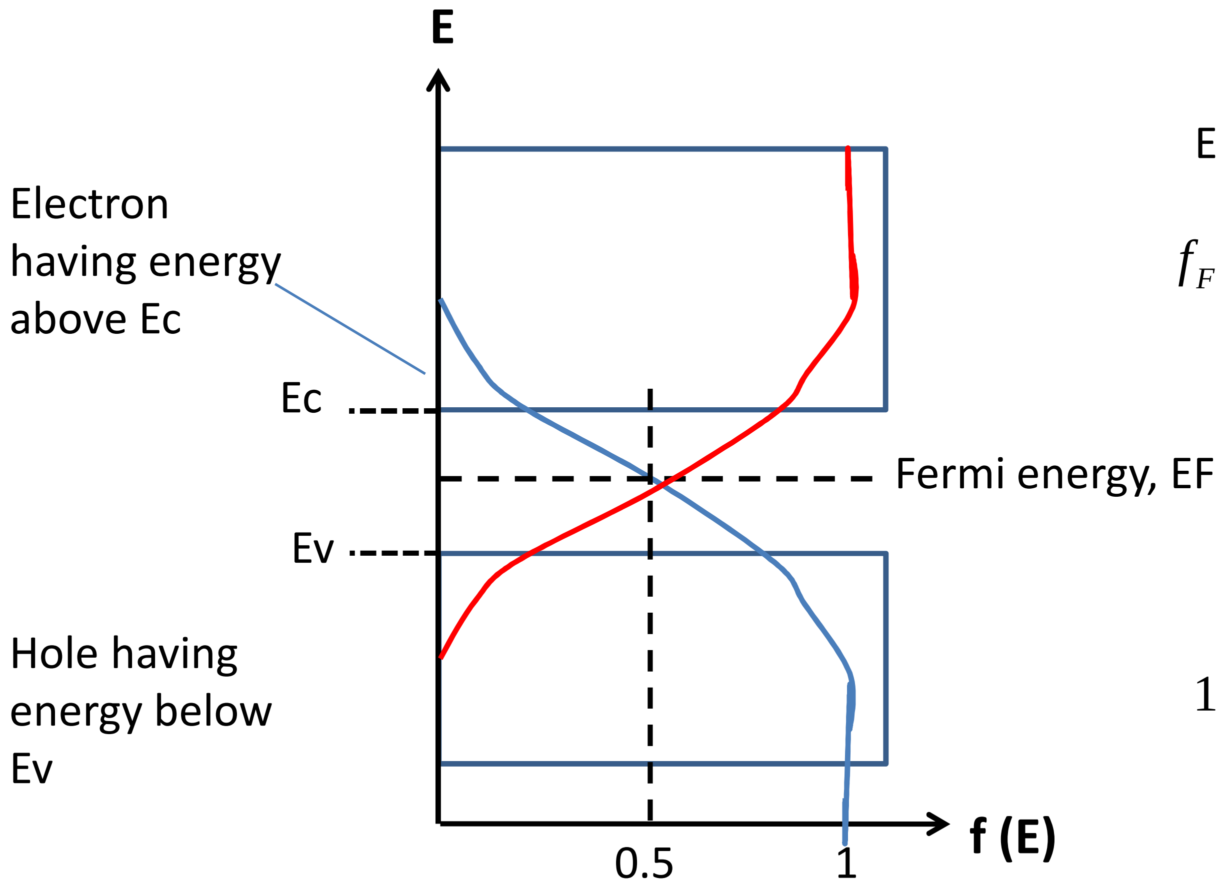
No of states (seats) below Ev for hole

$$g(E) = \frac{4\pi(2m^*)^{3/2}}{h^3}\sqrt{E_v - E}$$

Recap

Fermi-Dirac distribution

Probability of electron having certain energy



Electron (blue line)

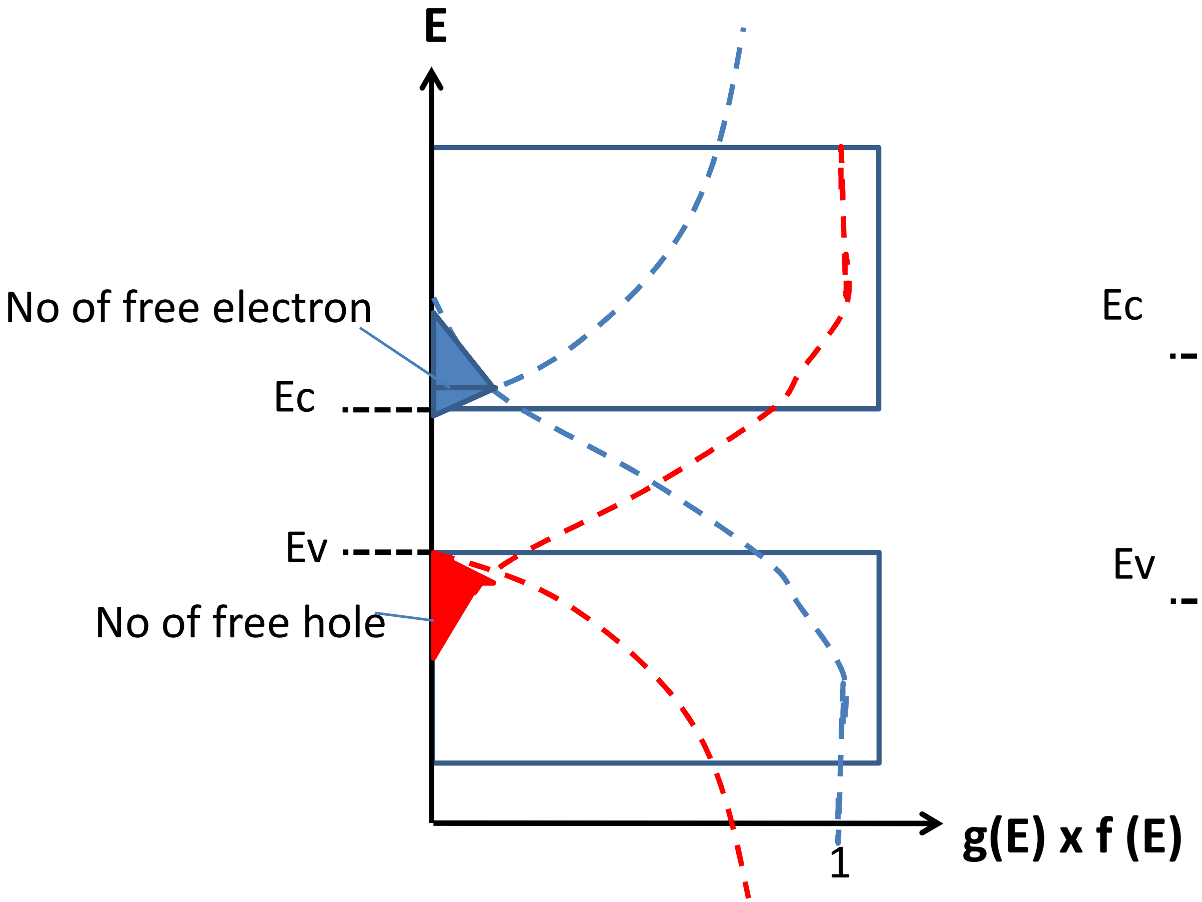
$$f_F(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}$$

hole (red line)

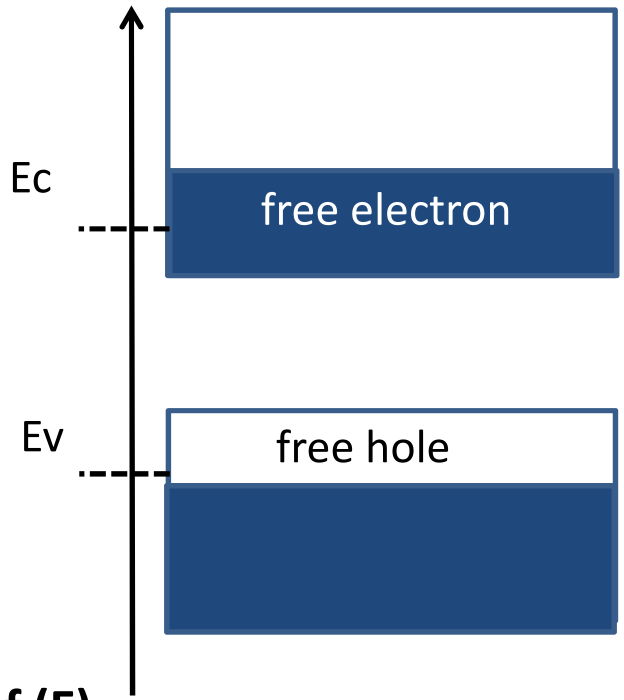
$$1-\frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}$$

EF; the energy below which all states are filled with electron and above which all states are empty at 0K

No of carrier



Recap



Semiconductor in Equilibrium

Equilibrium; no external forces such as voltages, electrical fields, magnetic fields, or temperature gradients are acting on the semiconductor

CHARGE CARRIERS IN SEMICONDUCTORS

4.1.1 Equilibrium Distribution of Electrons and Holes

The distribution (with respect to energy) of electrons in the conduction band is given by the density of allowed quantum states times the probability that a state is occupied by an electron. This statement is written in equation form as

$$n(E) = g_c(E)f_F(E) \tag{4.1}$$

where $f_F(E)$ is the Fermi–Dirac probability function and $g_c(E)$ is the density of quantum states in the conduction band. The total electron concentration per unit volume

ability that a state is *not* occupied by an electron. We may express this as

$$p(E) = g_v(E)[1 - f_F(E)] \tag{4.2}$$

Thermal equilibrium concentration of electron, n_o

$$n_o = \int_{E_C}^{\infty} g_c(E) f(E) dE$$

$$g_c(E) = \frac{4\pi(2m^*)^{3/2}}{h^3}\sqrt{E - E_C}$$

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

Boltzmann approximation

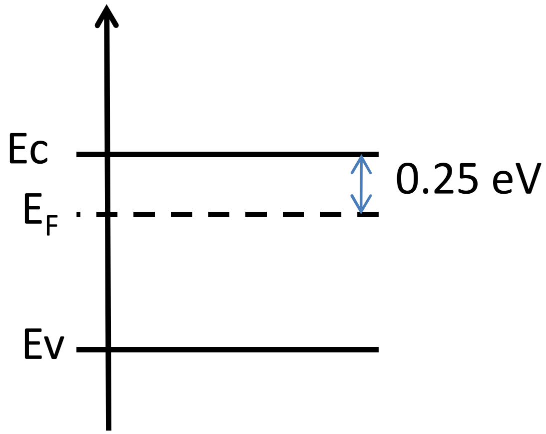
$$n_o = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \exp\left[\frac{-(E_C - E_F)}{kT}\right]$$

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

N_C; effective density of states function in conduction band

Ex. 1

Calculate the thermal equilibrium electron concentration in Si at T= 300K.
Assume that Fermi energy is 0.25 eV below the conduction band. The value of Nc for Si at T=300 K is 2.8 x 10^{19} cm^{-3}.



$$n_o = N_C \exp\left[\frac{-(E_C - E_F)}{kT}\right]$$

$$= 2.8\times10^{19} \cdot \exp\left[\frac{-(E_C - E_C + 0.25)}{0.0259}\right]$$

$$= 1.8\times10^{15}\, cm^{-3}$$

Thermal equilibrium concentration of hole, p_o

$$p_o = \int_{\infty}^{Ev} g_v(E)[1 - f(E)]dE$$

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

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

Boltzmann approximation

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

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

N_v; effective density of states function in valence band

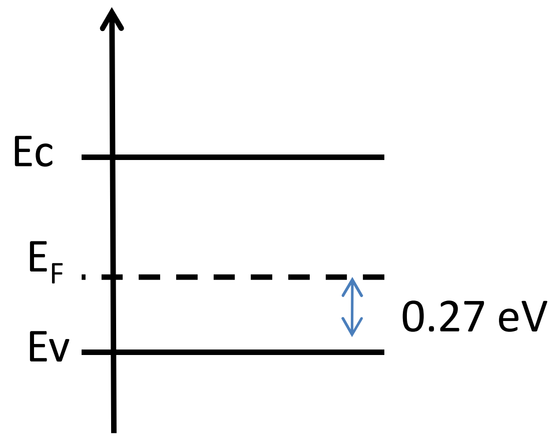
Boltzmann's Constant

Values of *k*[1]	Units
$1.380\,648\,8(13) \times 10^{-23}$	$J\,K^{-1}$
$8.617\,3324(78) \times 10^{-5}$	$eV\,K^{-1}$
$1.380\,648\,8(13) \times 10^{-16}$	$erg\,K^{-1}$
For details, see Value in different units below.	

In physics, the **electron volt** (symbol **eV**; also written **electronvolt**) is a unit of energy equal to approximately 1.6×10^{-19} joule (symbol J). By definition, it is the amount of energy gained (or lost) by the charge of a single electron moved across an electric potential difference of one volt.

Ex.2

Calculate the thermal equilibrium hole concentration in Si at T= 300K.
Assume that Fermi energy is 0.27 eV above the valence band. The value of Nv for Si at T=300 K is 1.04 x 10^{19} cm^{-3}.



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

$$= 1.04 \times 10^{19} \cdot \exp\left[\frac{-(E_v + 0.27 - E_V)}{0.0259}\right]$$

$$= 3.09 \times 10^{14}\, cm^{-3}$$

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

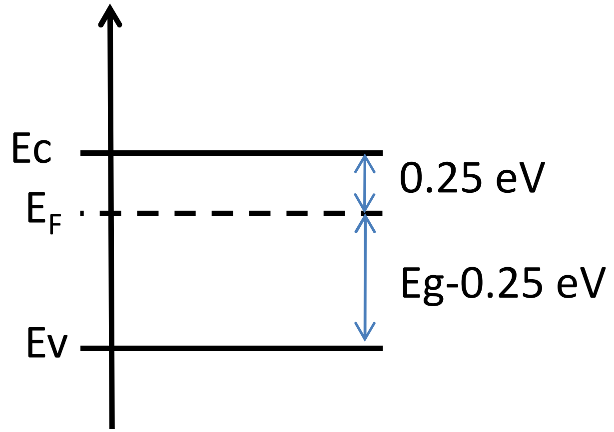
$$p_o = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} \exp\left[\frac{-(E_F - E_v)}{kT}\right] = N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

- N_C and N_v are constant for a given material (effective mass) and temperature
- Position of Fermi energy is important

If E_F is closer to E_C than to E_v, $n>p$
If E_F is closer to E_v than to E_C, $n<p$

Example

Consider ex. 1



$$n_o = N_C \exp\left[\frac{-(E_C - E_F)}{kT}\right]$$

$$= 2.8\times10^{19} \cdot \exp\left[\frac{-(E_C - E_C + 0.25)}{0.0259}\right]$$

$$= 1.8\times10^{15}\, cm^{-3}$$

Hole concentration

Eg=1.12 eV

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

$$= 1.04\times10^{19} \cdot \exp\left[\frac{-(1.12 - 0.25)}{0.0259}\right]$$

$$= 2.68\times10^{4}\, cm^{-3}$$

problem 1

Calculate the thermal-equilibrium hole concentration in silicon at T=400K. Assume that the Fermi energy is 0.27eV above the valence-band energy. The value of N_v for Silicon at T=300K is $N_v=1.04 \times 10^{19}$ cm^{-3}.

Hints:

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

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

problem 2

Calculate the thermal-equilibrium hole concentration in silicon at T=400K. Assume that the Fermi energy is 0.27eV above the valence-band energy. The value of N_v for Silicon at T=300K is $N_v = 1.04 \times 10^{19}$ cm^{-3}.

The parameter values at T=400K are found to as.

$$N_v = (1.04 \times 10^{19}) \left(\frac{400}{300} \right)^{\frac{3}{2}} = 1.60 \times 10^{19}\,\text{cm}^{-3}$$

$$\text{and } kT = 0.0259 \left(\frac{400}{300} \right) = 0.03453\,\text{eV}$$

The hole concentration is then .

$$p_0 = N_v \exp\left[-\frac{(E_F - E_V)}{kT} \right] = (1.60 \times 10^{19}) \exp\left[-\frac{0.27}{0.03453} \right]$$

$$= 6.43 \times 10^{15}\,\text{cm}^{-3}$$

Intrinsic semiconductor; A pure semiconductor with no impurity atoms and no lattice defects in crystal

1. Carrier concentration(n_i, p_i)
2. Position of E_{Fi}

1. Intrinsic carrier concentration

Concentration of electron in in conduction band, ni

$\parallel$

Concentration of hole in in valence band, pi

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

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

Independent of Fermi energy

Example

Calculate the intrinsic carrier concentration in gallium arsenide (GaAs) at room temperature (T=300K). Energy gap, Eg, of GaAs is 1.42 eV.

The value of N_c and N_v at T=300 K are 4.7 x 10^{17} cm^{-3} and 7.0 x 10^{18} cm^{-3}, respectively.

$$n_i^2 = (4.7\times10^{17})(7.0\times10^{18})\exp\left[\frac{-1.42}{0.0259}\right] = 5.09\times10^{12}$$

$$n_i = 2.26\times10^{6}\,cm^{-3}$$

problem 3

Calculate the instrinsic carrier concentration in GaAs at T=400K and at T=250K. Assume that Eg=1.42 eV is constant over this temperature range. Then, get the ratio of n_i at T=400K to that at T=250K

$$T = 400$$

$$n_i^2 = \left(4.7\times10^{17}\right)\left(7\times10^{18}\right)\left(\frac{400}{300}\right)^3 \times \exp\left[\frac{-1.42}{(0.0259)(400/300)}\right] = 1.081\times10^{19}$$

$$n_i = 3.29\times10^9 \text{ cm}^{-3}$$

$$T = 250$$

$$n_i^2 = \left(4.7\times10^{17}\right)\left(7\times10^{18}\right)\left(\frac{250}{300}\right)^3 \times \exp\left[\frac{-1.42}{(0.0259)(250/300)}\right] = 5.09\times10^7$$

$$n_i = 7.13\times10^3 \text{ cm}^{-3}$$

$$\text{Ratio, } \frac{n_i(400)}{n_i(250)} = \frac{3.288\times10^9}{7.135\times10^3} = 4.61\times10^5$$

2. Intrinsic Fermi level position, E_{Fi}

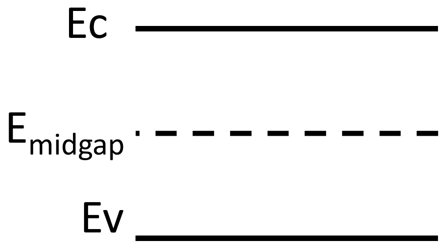
If E_F closer to Ec, n>p
If E_F closer to Ev, n<p

Intrinsic; n=p

E_F is located near the center of the forbidden bandgap

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

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



$m_p = m_n$ $\Rightarrow$ $E_{Fi} = E_{midgap}$ =(Ec+Ev)/2

$m_p \neq m_n$ $\Rightarrow$ E_{Fi} shifts slightly from E_{midgap}

Position of instrinsic Fermi Level

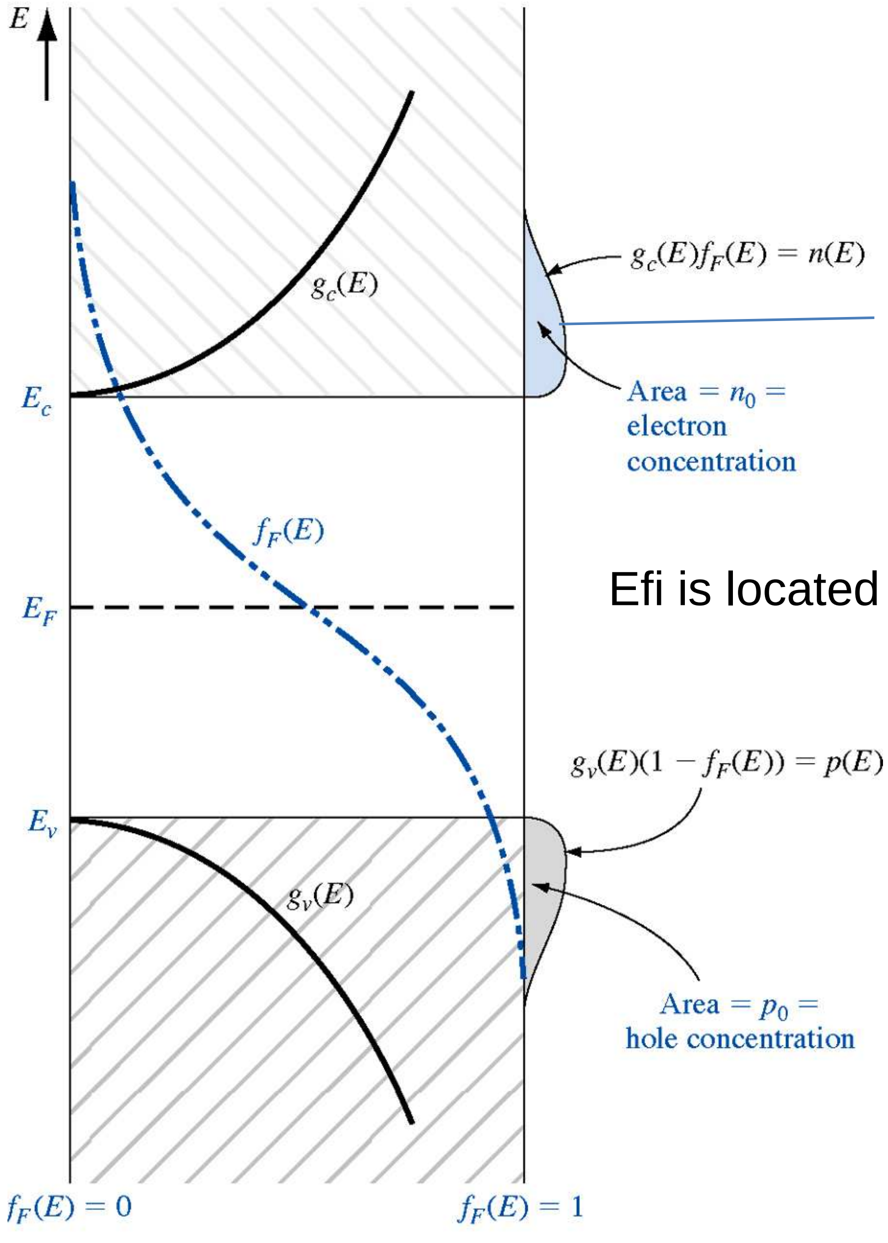
Calculate the position of the instrinsic Fermi level with respect to the center of the bandgap in silicon T=300K. The density of states effective masses in silicon are $m^*_n = 1.08\ m_0$ and $m^*_p = 0.56\ m_0$

The instrinsic Fermi level with respect to the center of the bandgap is

$$E_{Fi} - E_{midgap} = \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right) = \frac{3}{4}(0.0259)\ln\left(\frac{0.56}{1.08}\right) =$$

$$E_{Fi} - E_{midgap} = -0.0128\,\mathrm{eV} = -12.8\,\mathrm{meV}$$

The instrinsic Fermi level in silicon is 12.8 meV below the midgap energy



(a)

$n_o = p_o$

Efi is located near the center of Eg

Extrinsic Semiconductor

Dopant atoms and energy levels

adding small, controlled amounts of specific dopant, or impurity, atoms

Increase no. of carrier (either electron or hole)

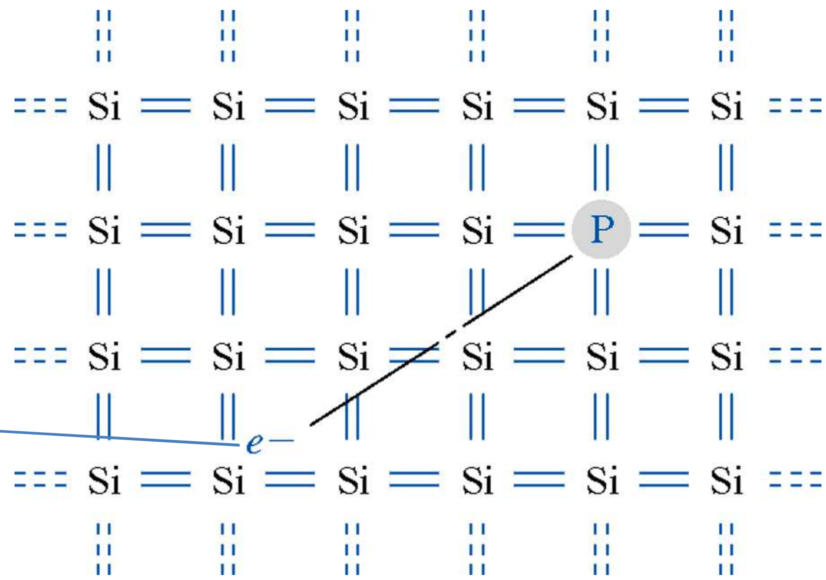
Alter the conductivity of semiconductor

3 valence electrons		5 valence electrons
III	IV	V
B	C	
Al	Si	P
Ga	Ge	As
In		Sb

Consider Phosphorus (P) and boron (B) as impurity atoms in Silicon (Si)

1. P as substitutional impurity (group V element; 5 valence electron)

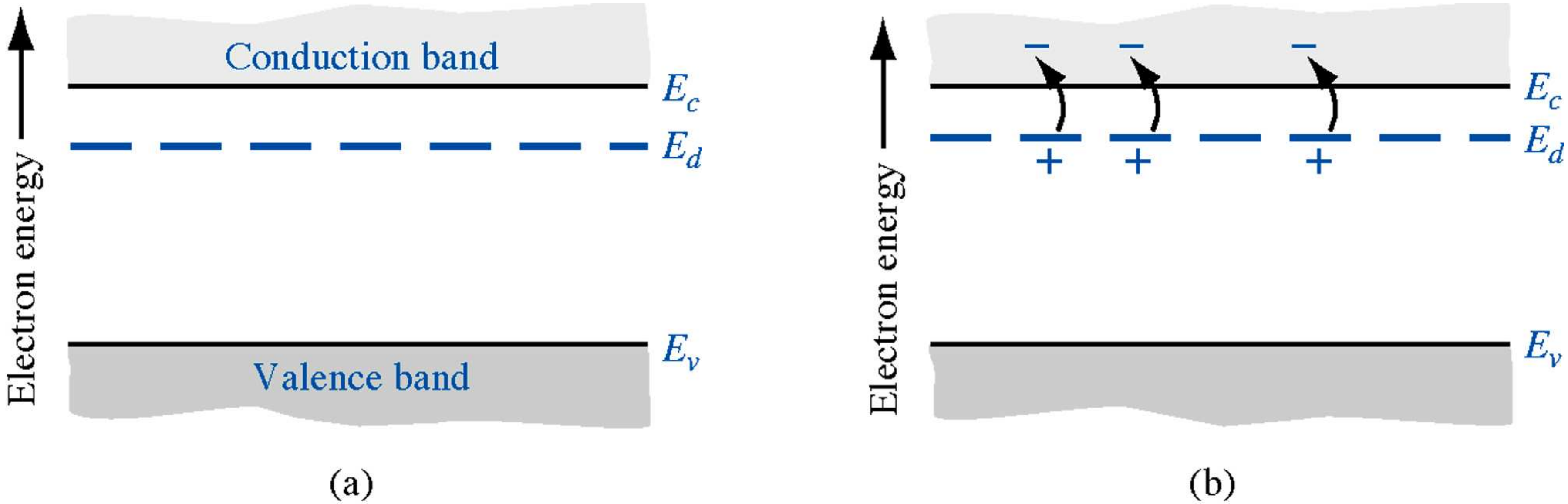
Donor electron



- ➢In intrinsic Si, all 4 valence electrons contribute to covalent bonding.
- ➢In Si doped with P, 4 valence electron of P contribute to covalent bonding and **1 electron loosely bound to P atom (Donor electron).**

can easily break the bond and freely moves

➢Energy to elevate the donor electron into conduction band is less than that for the electron involved in covalent bonding



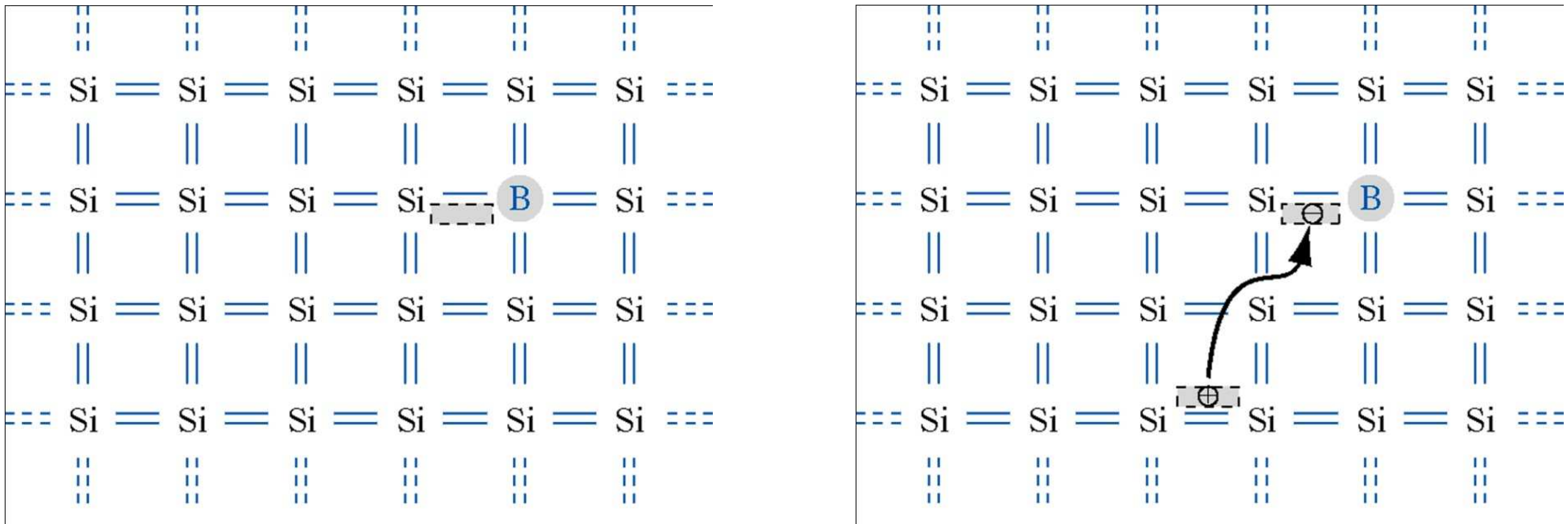
➢Ed(; energy state of the donor electron) is located near Ec

➢When small energy is added, donor electron is elevated to conduction band, leaving behind positively charged P ion

➢P atoms donate electron to conduction band→ P; **donor impurity atom**

➢No. of electron > no. of hole→ **n-type semiconductor** (majority carrier is electron)

2. B as substitutional impurity (group III element; 3 valence electron)



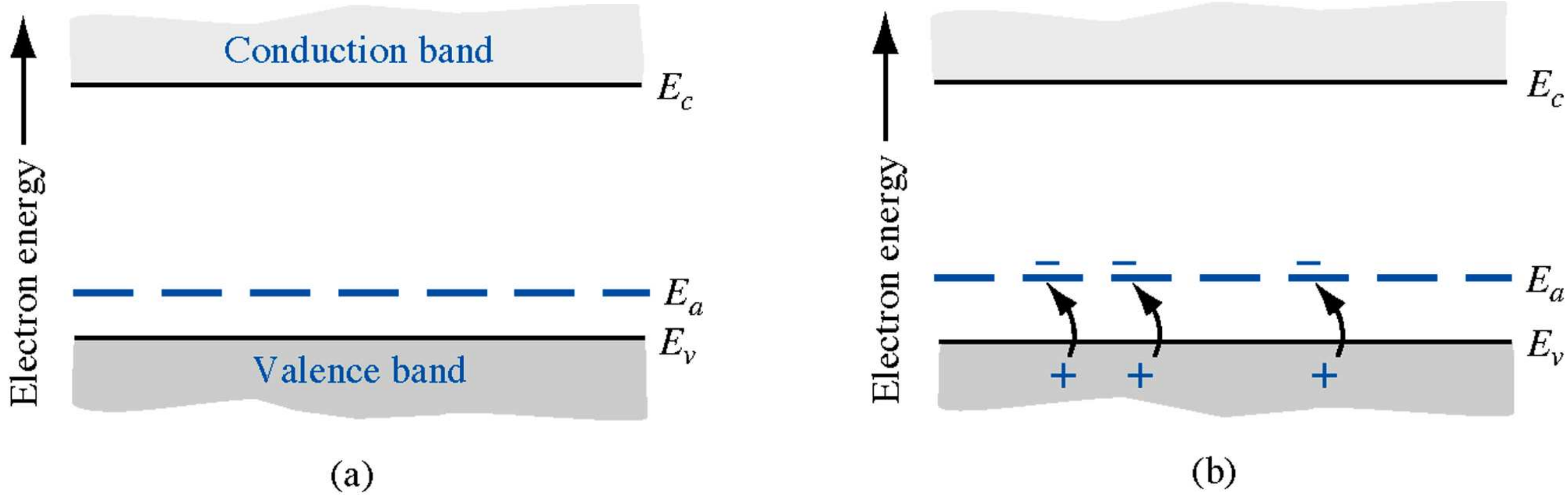
(a) (b)

➢In Si doped with B, all 3 valence electron of B contribute to covalent bonding and one covalent bonding is empty

➢When small energy is added, electron that involved in covalent bond will occupy the empty position **leaving behind empty position** that associated with Si atom

Hole is created

➢Electron occupying the empty state associated with B atom does not have sufficient energy to be in the conduction band→ no free electron is created



➢Ea (;acceptor energy state) is located near Ev

➢When electron from valence band elevate to Ea, hole and negatively charged B are created

➢B accepts electron from valence band→ B; **acceptor impurity atom**

➢No. of hole > no. of electron→ **p-type material** (majority carrier is hole)

- ➢Pure single-crystal semiconductor**; intrinsic semiconductor**

- ➢Semiconductor with dopant atoms; **<u>extrinsic semiconductor</u>**

	<u>n-type</u>	<u>p-type</u>
Dopant atom;	✓Donor impurity atom	✓Acceptor impurity atom
Majority carrier;	✓electron	✓hole

<u>Ionization Energy</u>

The energy that required to elevate donor electron into the conduction (in case of donor impurity atom) or to elevate valence electron into acceptor state (in case of acceptor impurity atom).

III-V semiconductors

GaAs

Group III Group V

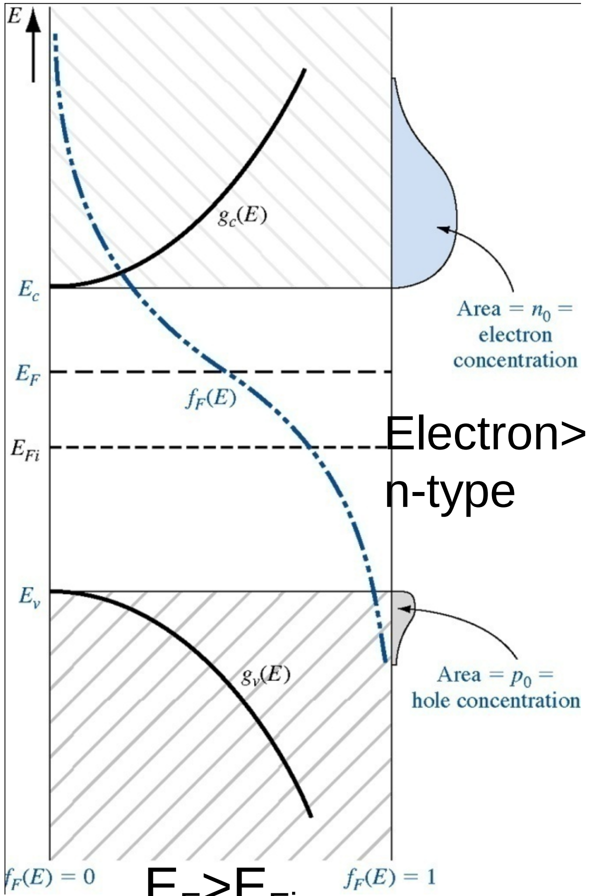
Dopant atoms;

- Group II (beryllium, zinc and cadmium) replacing Ga; acceptor
- Group VI (selenium, tellurium) replacing As; donor
- Group IV (Si and germanium) replacing Ga; donor

  As; acceptor

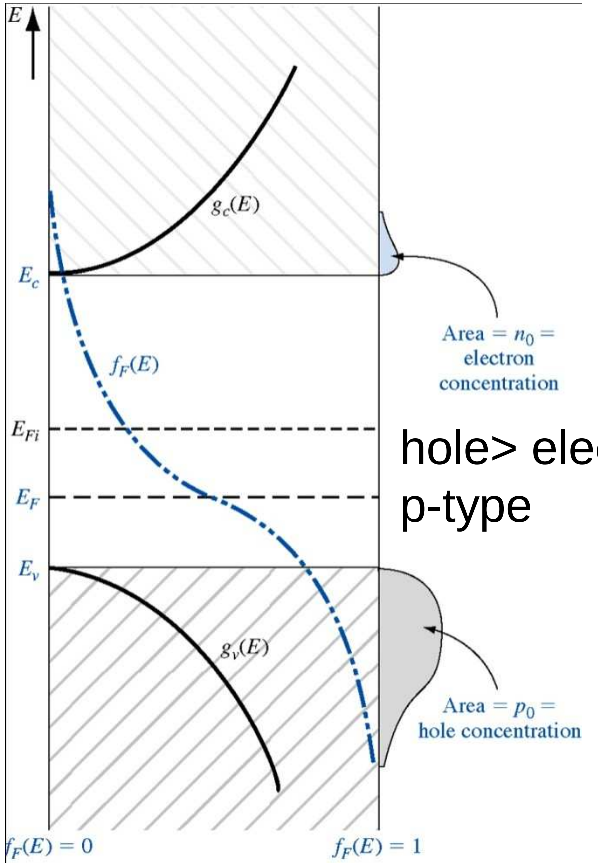
Carrier concentration of extrinsic semiconductor

When dopant atoms are added, Fermi energy and distribution of electron and hole will change.



Electron> hole
n-type

$E_F > E_{Fi}$



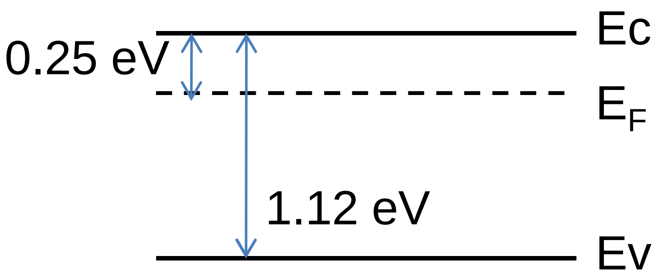
hole> electron
p-type

$E_F < E_{Fi}$

$$n_o = N_C \exp\left[\frac{-(E_C - E_F)}{kT}\right]$$ Thermal equilibrium concentration of electron

$$p_o = N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$ Thermal equilibrium concentration of hole

Ex. 4



Band diagram of Si. At T= 300 K, Nc=$2.8\text{x}10^{19}$cm^{-3} and Nv=$1.04\text{x}10^{19}$cm^{-3}. Calculate n_o and p_o.

$$n_o = (2.8\times10^{19})\exp\left(\frac{-0.25}{0.0259}\right) = 1.8\times10^{15}\,cm^{-3}$$

N-type Si

$$p_o = (1.04\times10^{19})\exp\left(\frac{-(1.12-0.25)}{0.0259}\right) = 2.7\times10^{4}\,cm^{-3}$$

- **Change of Fermi energy causes change of carrier concentration**.

n_o and p_o equation as function of the change of Fermi energy

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

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

n_i; intrinsic carrier concentration
E_{fi}; intrinsic Fermi energy

The $n_o p_o$ product

$$n_o p_o = N_C N_v \exp\left[\frac{-(E_C - E_F)}{kT}\right]\exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

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

$$= n_i^2$$

$$\boxed{n_o p_o = n_i^2}$$

Product of n_o and p_o is always a constant for a given material at a given temperature.

4.3.4 Degenerate and Nondegenerate Semiconductors

- 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 Nc**, the Fermi energy lies within the conduction band. This type of semiconductor is called a **degenerate** n-type semiconductor.
- In the degenerate n-type semiconductor, **the states between EF and Ec are mostly filled with electrons**; thus, the electron concentration in the conduction band is very large.

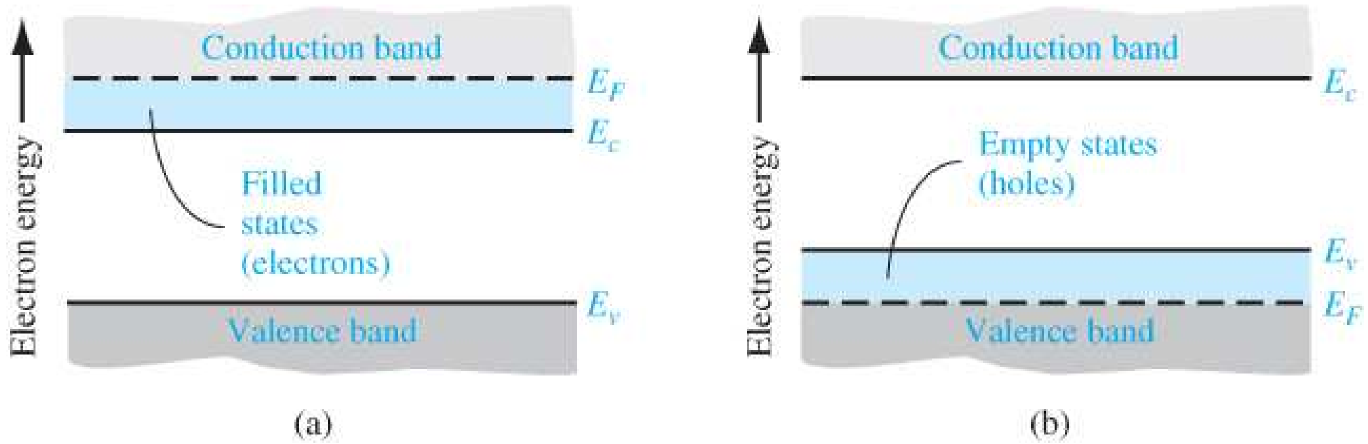


Figure 4.11 | Simplified energy-band diagrams for degenerately doped (a) n-type and (b) p-type semiconductors.

4.4 | STATISTICS OF DONORS AND ACCEPTORS

4.4.1 Probability Function

The probability function of electrons occupying the donor state is

$$n_d = \frac{N_d}{1 + \frac{1}{2}\exp\left(\frac{E_d - E_F}{kT}\right)} \qquad (4.50)$$

where nd is the density of electrons occupying the donor level and Ed is the energy of the donor level. The factor 1/2 in this equation is a direct result of the spin factor just mentioned.

$$n_d = N_d - N_d^+ \qquad (4.51)$$

where N_d^+ is the concentration of ionized donors. In many applications, we will be interested more in the concentration of ionized donors than in the concentration of electrons remaining in the donor states.

4.4.2 Complete Ionization and Freeze-Out

If we assume that $(E_d - E_F) \gg kT$, then

$$n_d \approx \frac{N_d}{\frac{1}{2}\exp\left(\frac{E_d - E_F}{kT}\right)} = 2N_d \exp\left[\frac{-(E_d - E_F)}{kT}\right] \qquad (4.53)$$

$$\frac{n_d}{n_d + n_0} = \frac{1}{1 + \dfrac{N_c}{2N_d} \exp\left[\dfrac{-(E_c - E_d)}{kT}\right]} \tag{4.55}$$

The factor $(E_c - E_d)$ is just the ionization energy of the donor electrons.

Note:

there are very few electrons in the donor state compared with the conduction band. Essentially all of the electrons from the donor states are in the conduction band and, since only about 0.4 percent of the donor states contain electrons, **the donor states are said to be completely ionized**.

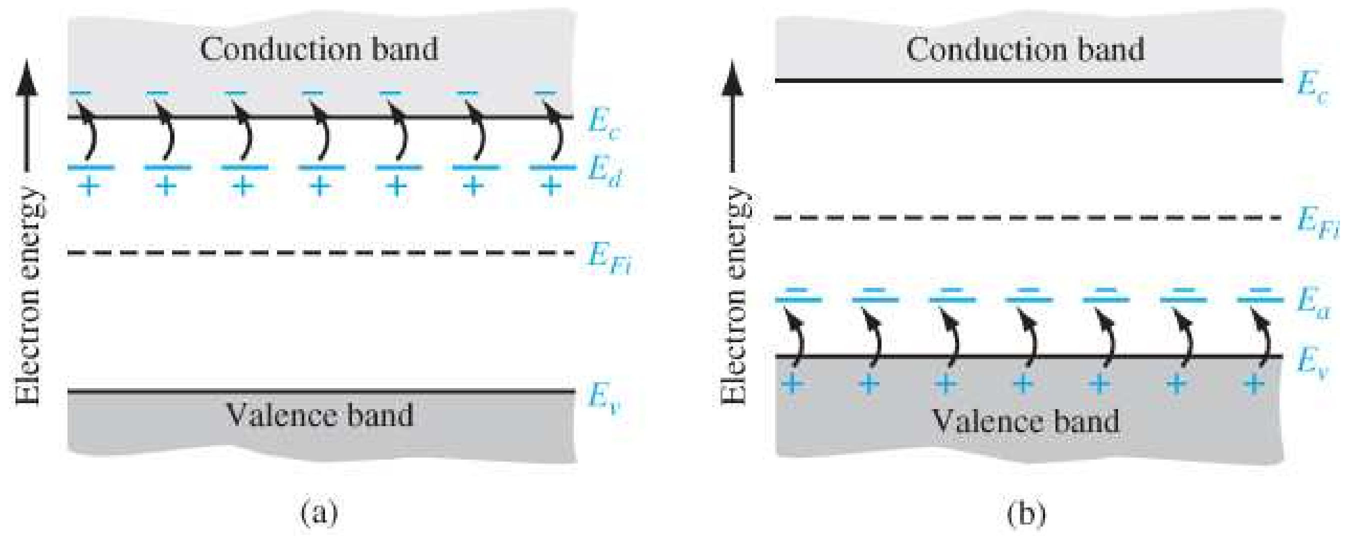


Figure 4.12 | Energy-band diagrams showing complete ionization of (a) donor states and (b) acceptor states.

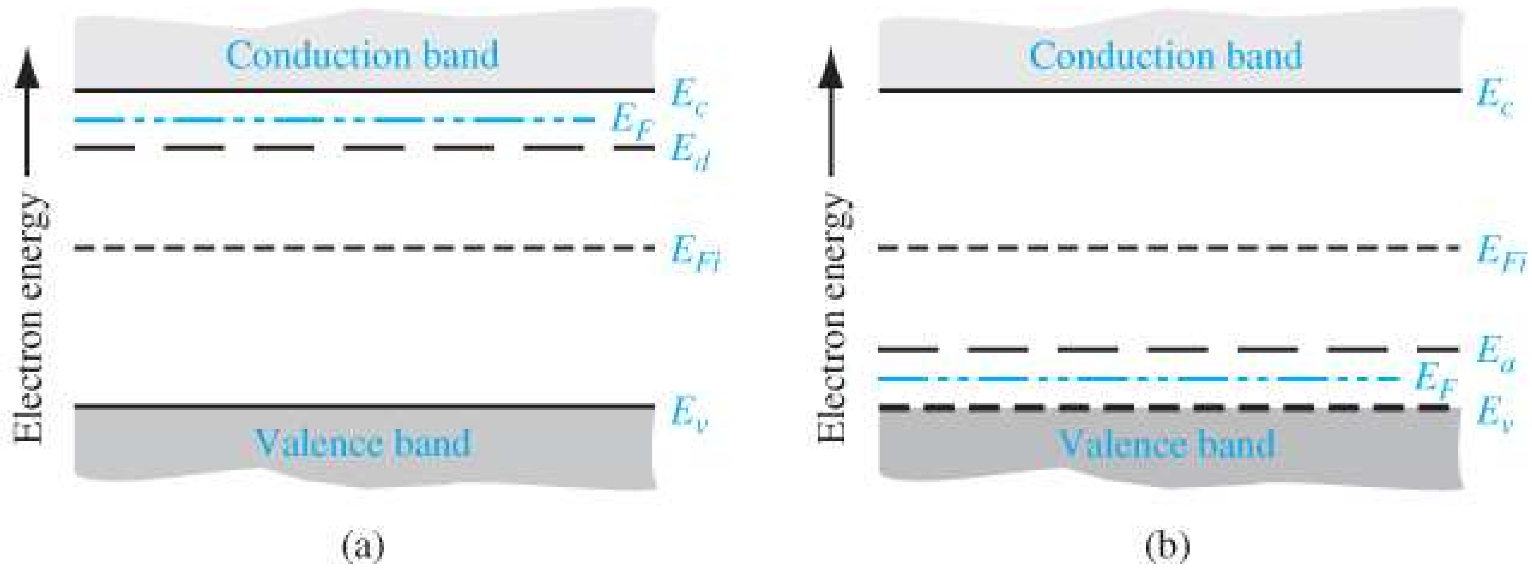


Figure 4.13 | Energy-band diagram at $T = 0$ K for (a) n-type and (b) p-type semiconductors.

at T = 0 K, No electrons from the donor state are thermally elevated into the conduction band; this effect is called freeze-out. Similarly, when no electrons from the valance band are elevated into the acceptor states, the effect is also called freeze-out.

4.5 | CHARGE NEUTRALITY

4.5.1 Compensated Semiconductors

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

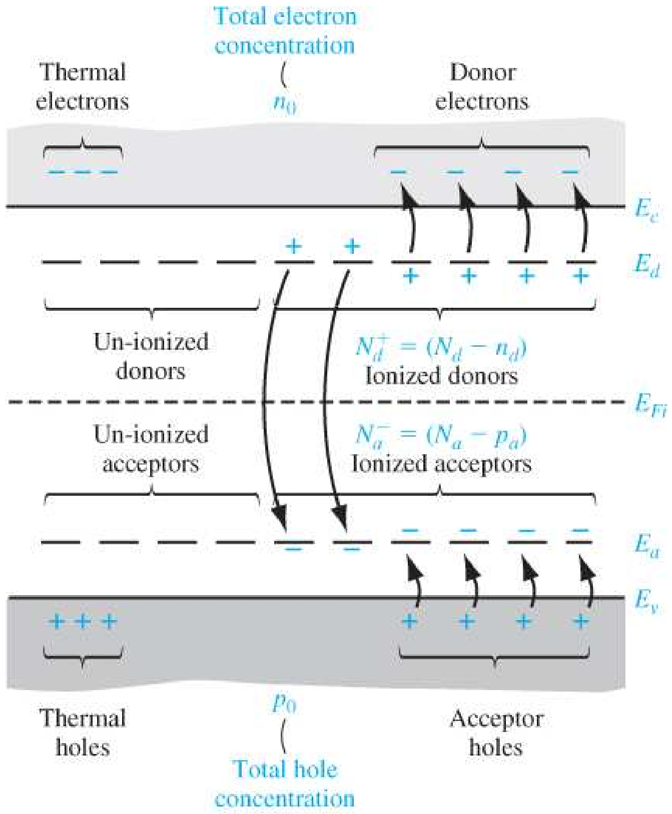


Figure 4.14 | Energy-band diagram of a compensated semiconductor showing ionized and un-ionized donors and acceptors.

4.5.2 Equilibrium Electron and Hole Concentrations

The charge neutrality condition is expressed by equating the density of negative charges to the density of positive charges.

$$n_0 + N_a^- = p_0 + N_d^+ \tag{4.56}$$

Thermal-Equilibrium Electron Concentration If we assume complete ionization, n_d and p_a are both zero, and Equation (4.57) becomes

$$n_0 + N_a = p_0 + n_d \tag{4.58}$$

If we express p_0 as n_i^2/n_0, then Equation (4.58) can be written as

$$n_0 + N_a = \frac{n_i^2}{n_0} + N_d \tag{4.59a}$$

which in turn can be written as

$$n_0^2 - (N_d - N_a)n_0 - n_i^2 = 0 \tag{4.59b}$$

The electron concentration n_0 can be determined using the quadratic formula, or

$$\boxed{n_0 = \frac{(N_d - N_a)}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}} \tag{4.60}$$

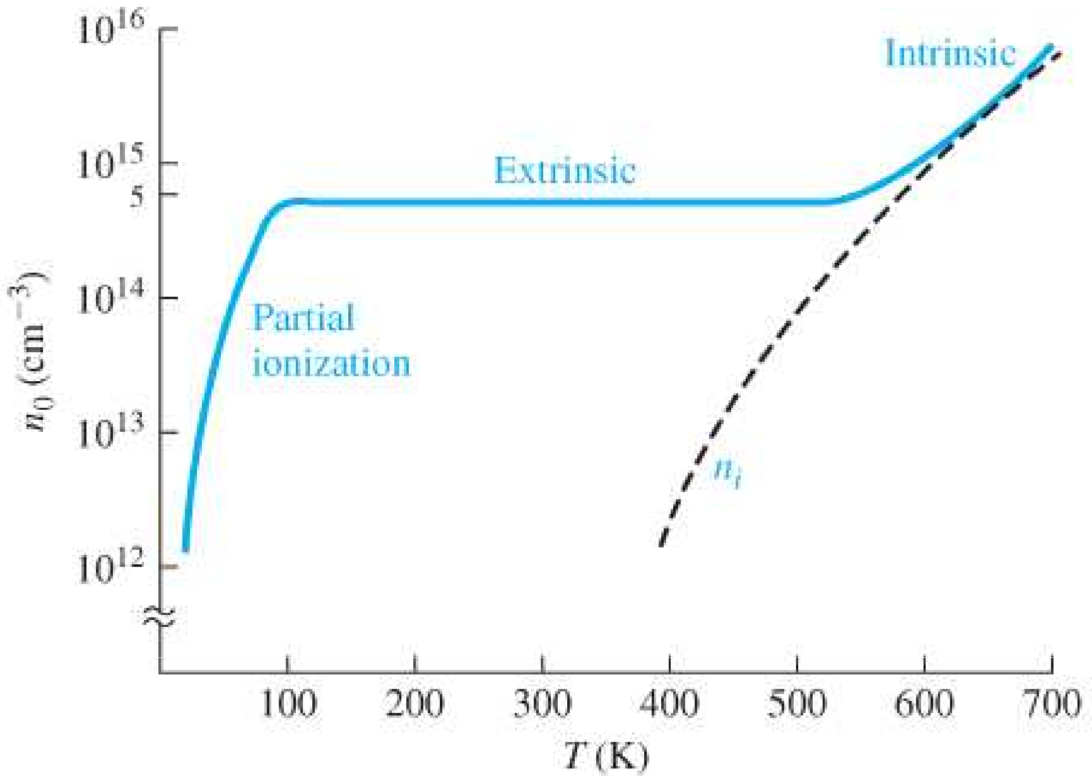


Figure 4.16 | Electron concentration versus temperature showing the three regions: partial ionization, extrinsic, and intrinsic.

Silicon doped with 5 X 10^{14} donors
As the temperature increases, we can see where the intrinsic concentration begins to dominate. Also shown is the partial ionization, or the onset of freeze-out, at the low temperature.

Thermal-Equilibrium Hole Concentration If we reconsider Equation (4.58) and express n_0 as n_i^2/p_0, then we have

$$\frac{n_i^2}{p_0} + N_a = p_0 + N_d \tag{4.61a}$$

$$\boxed{p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}} \tag{4.62}$$

4.6 | POSITION OF FERMI ENERGY LEVEL

4.6.1 Mathematical Derivation

$$\boxed{E_c - E_F = kT \ln\left(\frac{N_c}{n_0}\right)} \tag{4.63}$$

$$E_c - E_F = kT \ln\left(\frac{N_c}{N_d}\right) \tag{4.64}$$

$$\boxed{E_F - E_{Fi} = kT \ln\left(\frac{n_0}{n_i}\right)} \tag{4.65}$$

$$\boxed{E_F - E_v = kT \ln\left(\frac{N_v}{p_0}\right)} \tag{4.66}$$

$$\boxed{E_{Fi} - E_F = kT \ln\left(\frac{p_0}{n_i}\right)} \tag{4.68}$$

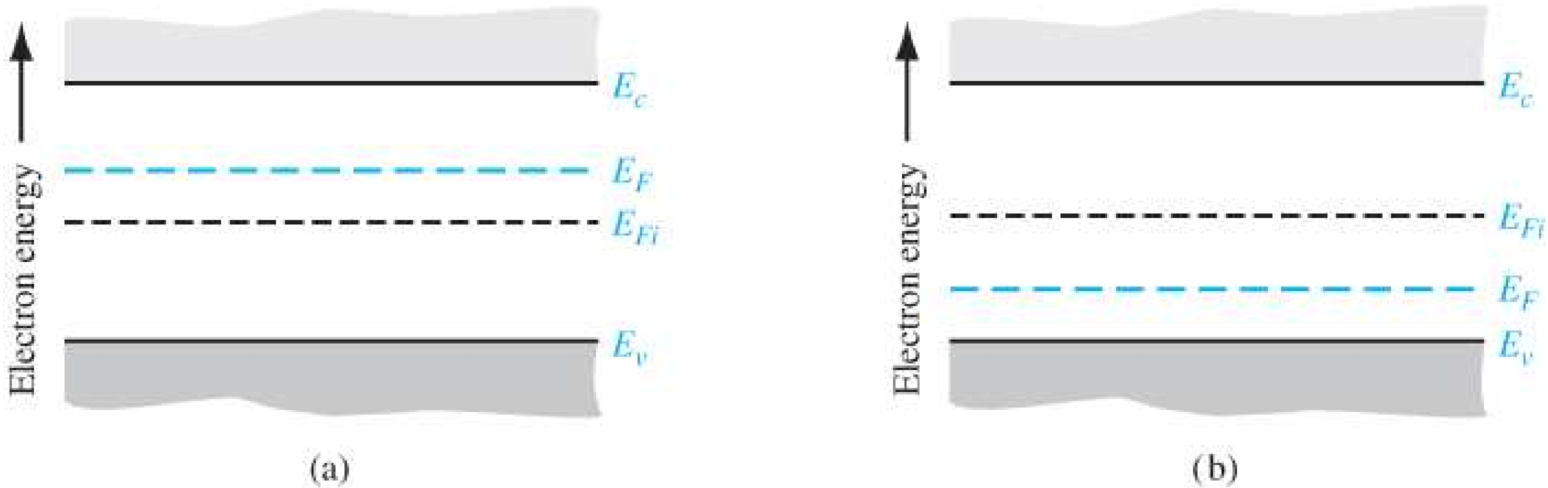


Figure 4.17 | Position of Fermi level for an (a) n-type ($N_d > N_a$) and (b) p-type ($N_a > N_d$) semiconductor.

4.6.2 Variation of E_F with Doping Concentration and Temperature

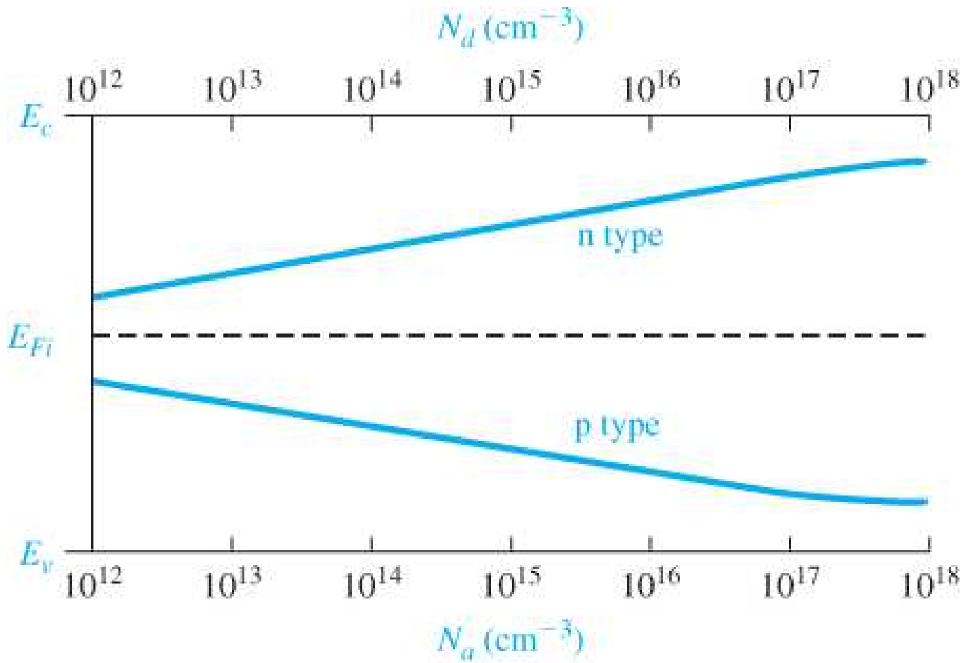


Figure 4.18 | Position of Fermi level as a function of donor concentration (n type) and acceptor concentration (p type).

Comment Ex 4.13

If the acceptor (or donor) concentration in silicon is **greater than approximately 3 X 10^{17} cm^{-3}**, then the Boltzmann approximation of the distribution function **becomes less valid** and the equations for the Fermi-level position are no longer quite as accurate.

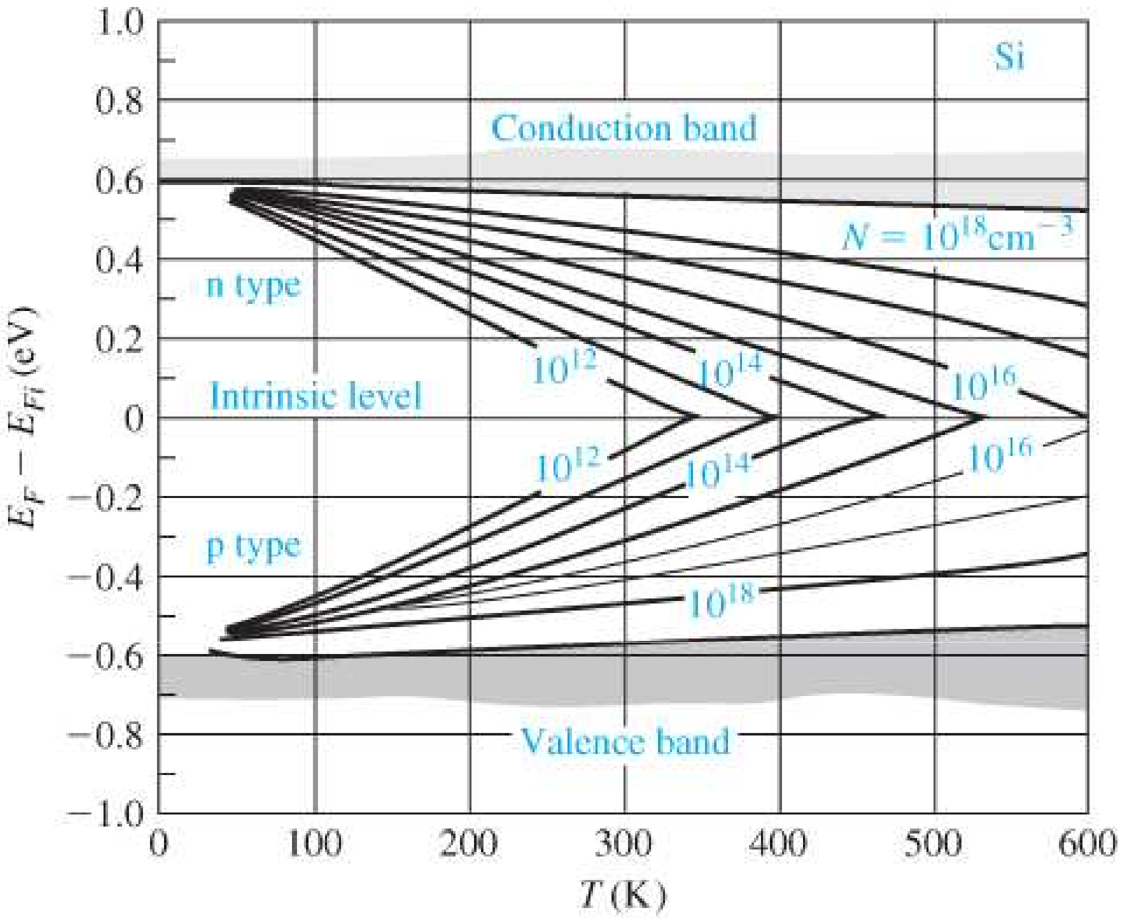


Figure 4.19 | Position of Fermi level as a function of temperature for various doping concentrations.
(From Sze [14].)

At the low temperature where freeze-out occurs, the Fermi level goes above Ed for the n-type material and below Ea for the p-type material.

in thermal equilibrium, the Fermi energy level is a constant throughout a system.

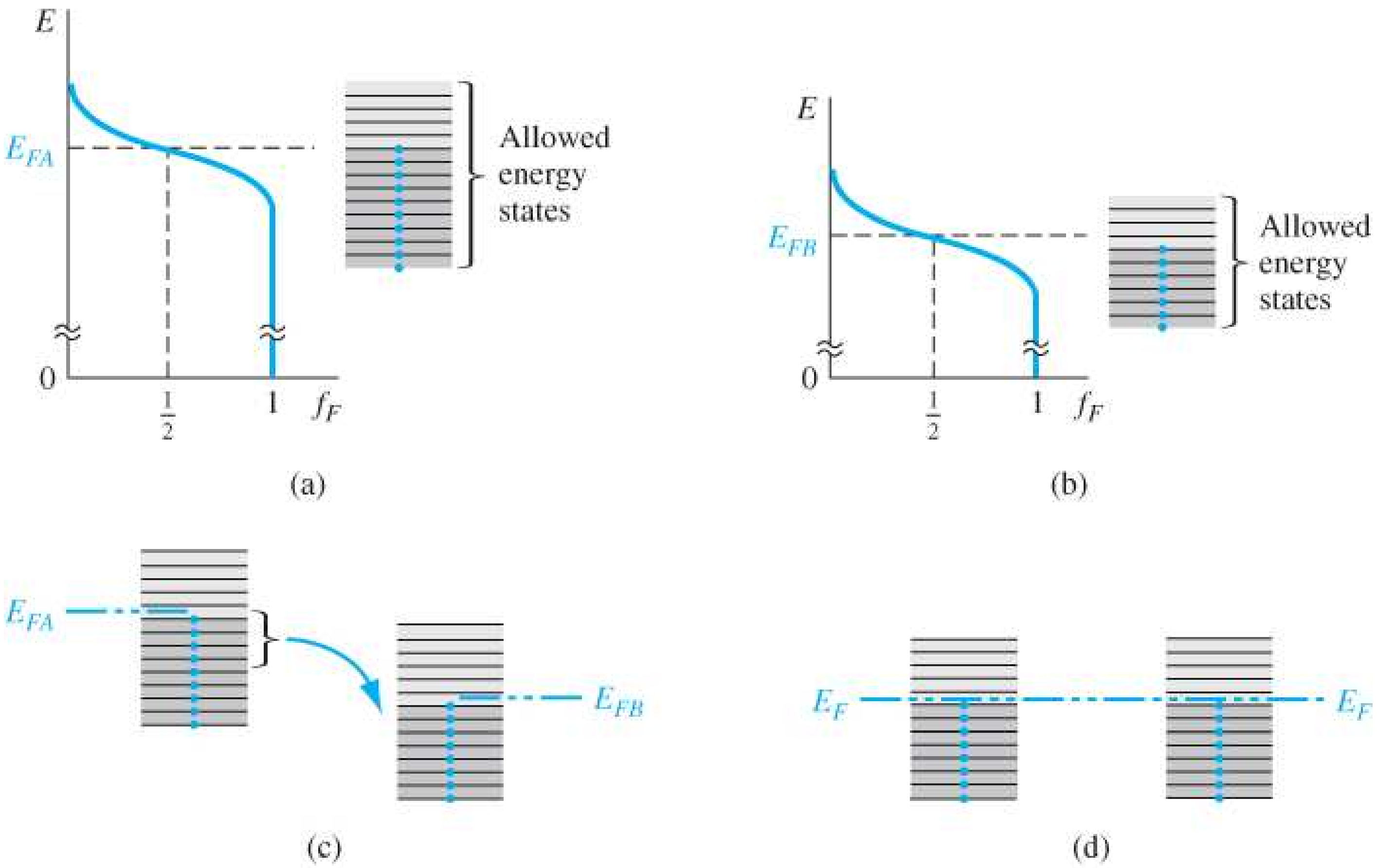


Figure 4.20 | The Fermi energy of (a) material A in thermal equilibrium, (b) material B in thermal equilibrium, (c) materials A and B at the instant they are placed in contact, and (d) materials A and B in contact at thermal equilibrium.

Important terms

Intrinsic semiconductor; A pure semiconductor material with no impurity atoms and no lattice defects in the crystal

Extrinsic semiconductor; A semiconductor in which controlled amounts of donors and/or acceptors have been added so that the electron and hole concentrations change from the intrinsic carrier concentration and a preponderance of either electron (n-type) or hole (p-type) is created.

Acceptor atoms; Impurity atoms added to a semiconductor to create a p-type material

Donor atoms; Impurity atoms added to a semiconductor to create n-type material

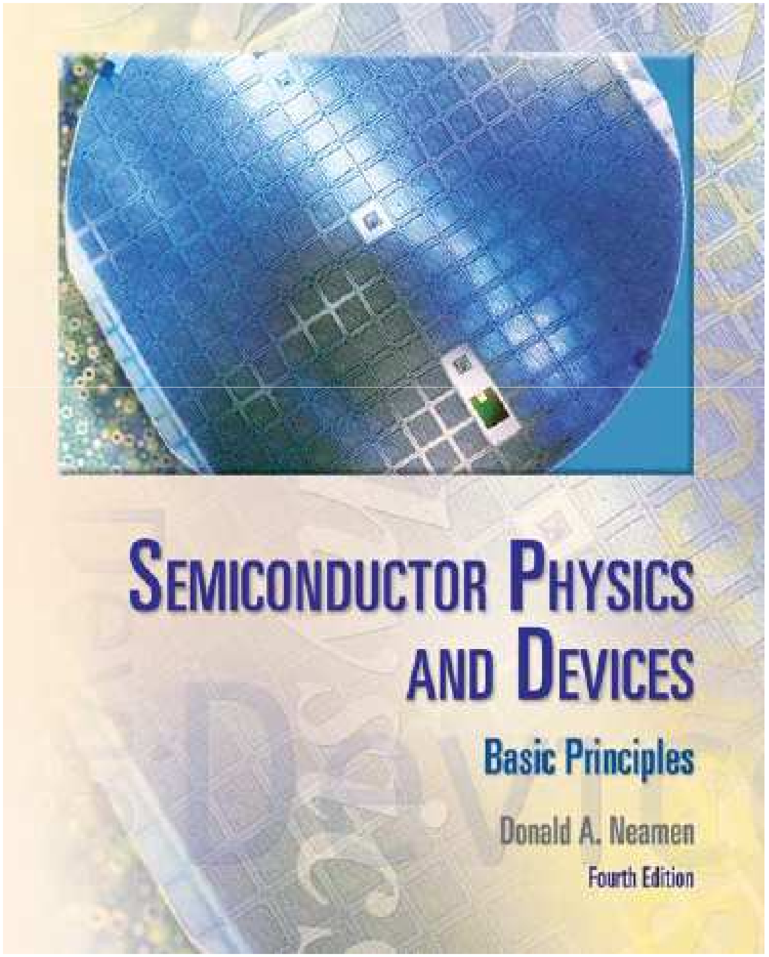
Complete ionization; The condition when all donor atoms are positively charged by giving up their donor electrons and all acceptor atoms are negatively charged by accepting electrons

Freeze-out; The condition that occurs in a semiconductor when the temperature is lowered and the donors and acceptors become neutrally charged. The electron and hole concentrations become very small

Fundamental relationship

$$n_o p_o = n_i^2$$

Reference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