Semiconductor Optoelectronics

Lecture 1: Semiconductor in Equilibrium

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Text book

Semiconductor Physics and Devices

Basic Principles

Third Edition

Donald A. Neamen

Chapter 4: Semiconductor in Equilibrium

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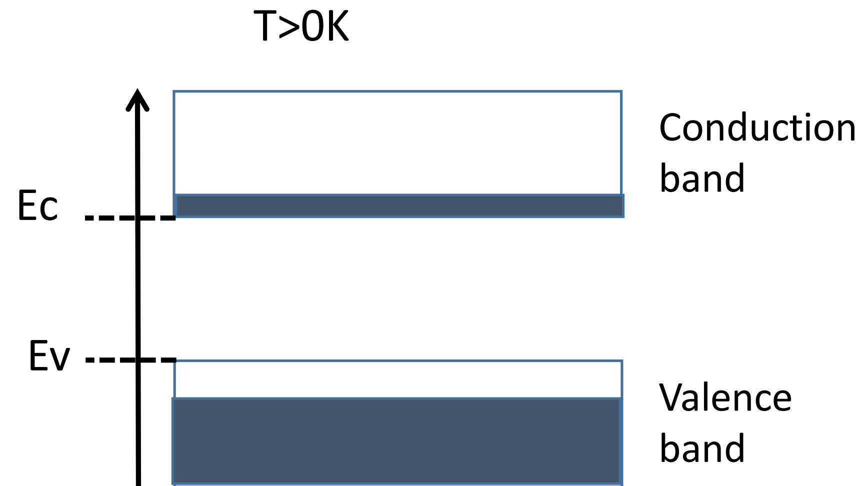
Chapter 4: Semiconductor in Equilibrium

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



carrier

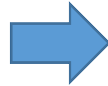
- Particles that can freely move and contribute to the current flow (conduction)

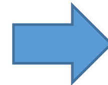
1. Electron in conduction band
2. Hole in valence band

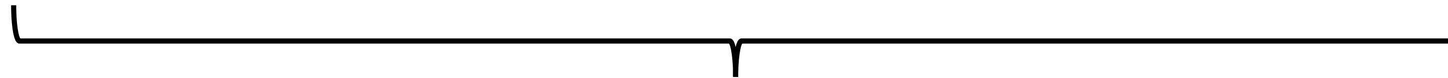
- **How to count number of carriers,n?**

Assumption; Pauli exclusion principle

If we know

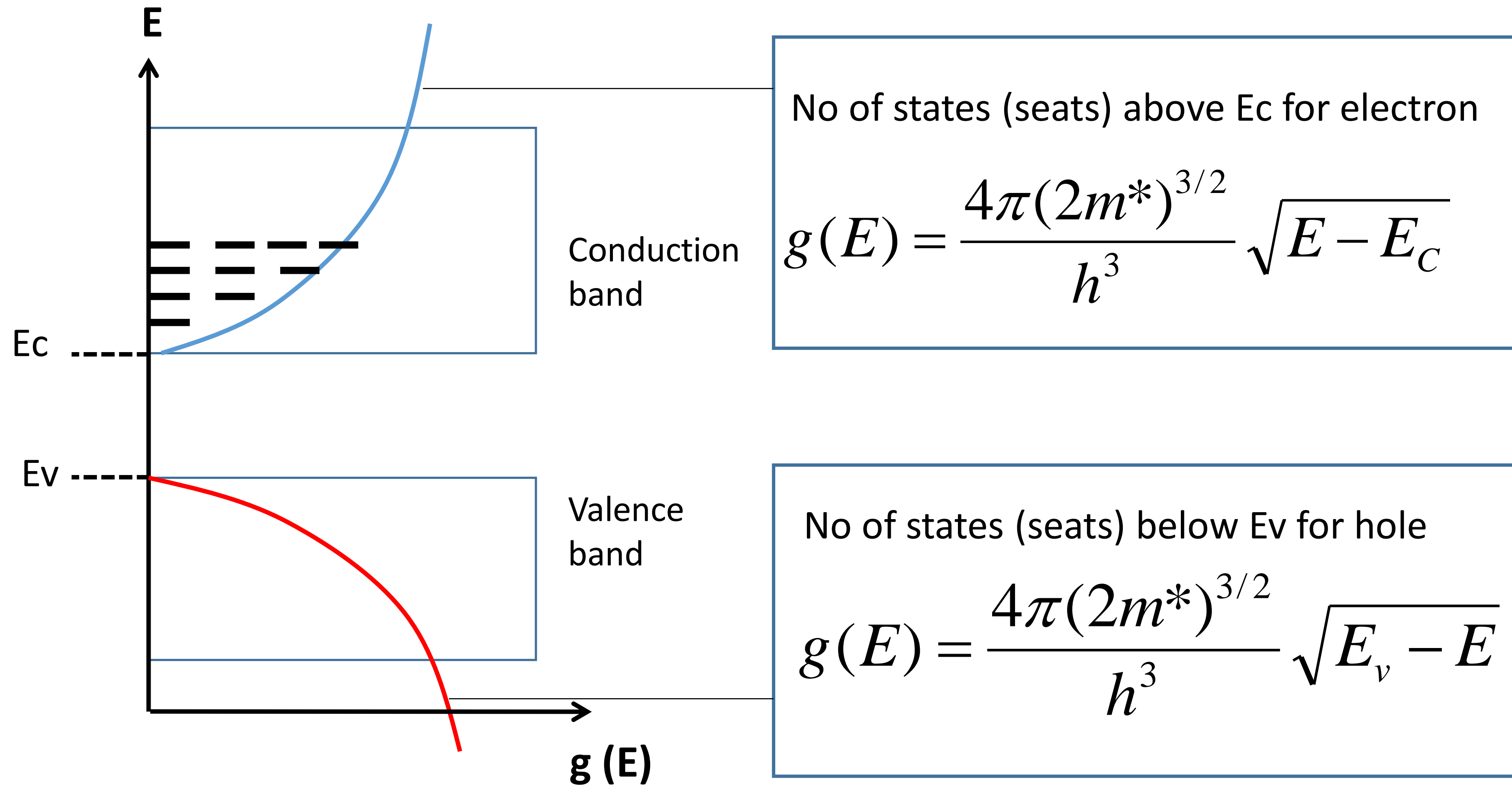
1. No. of energy states  Density of states (DOS)

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



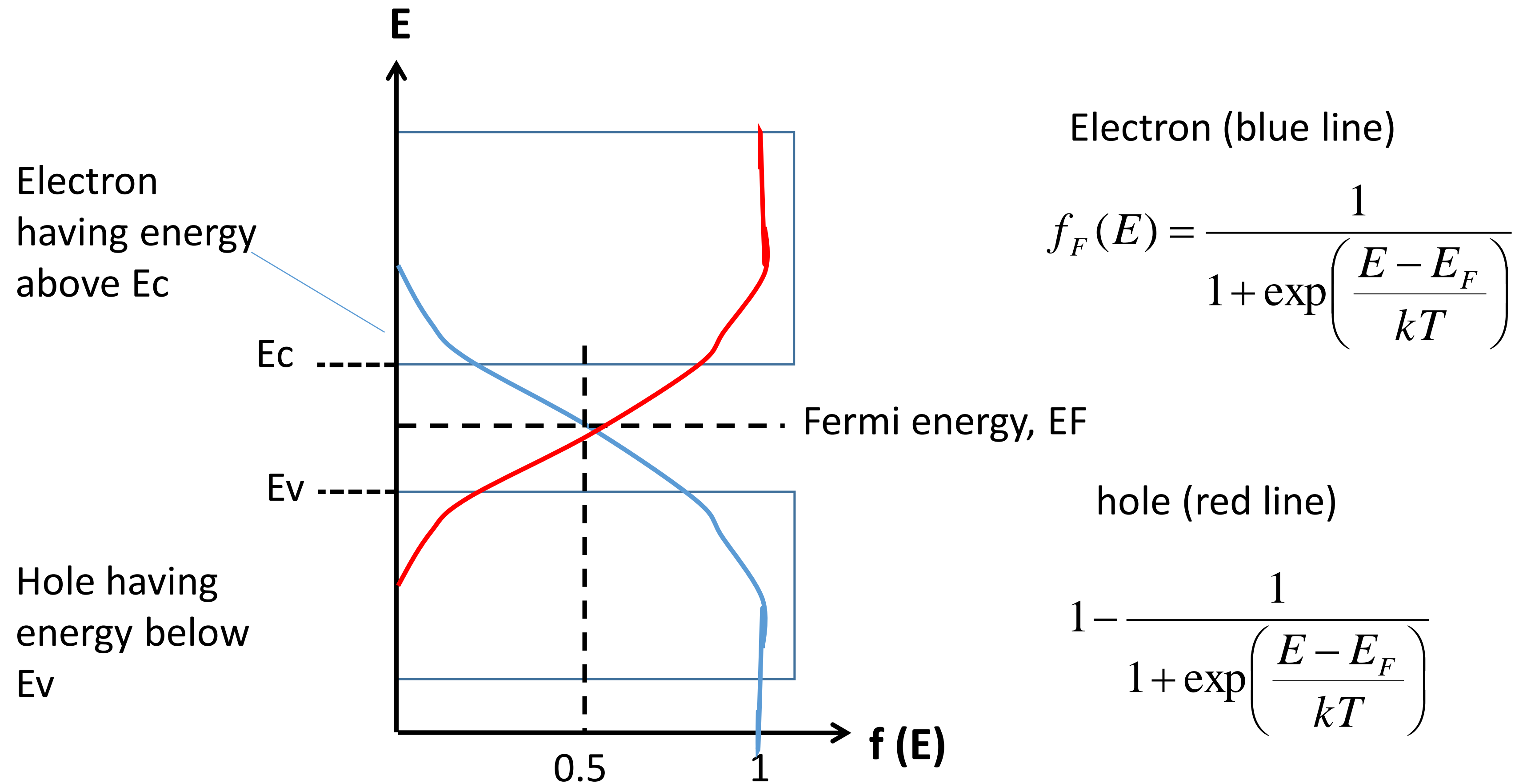
n = DOS x "Fermi-Dirac distribution function"

Density of state



Fermi-Dirac distribution

Probability of electron having certain energy

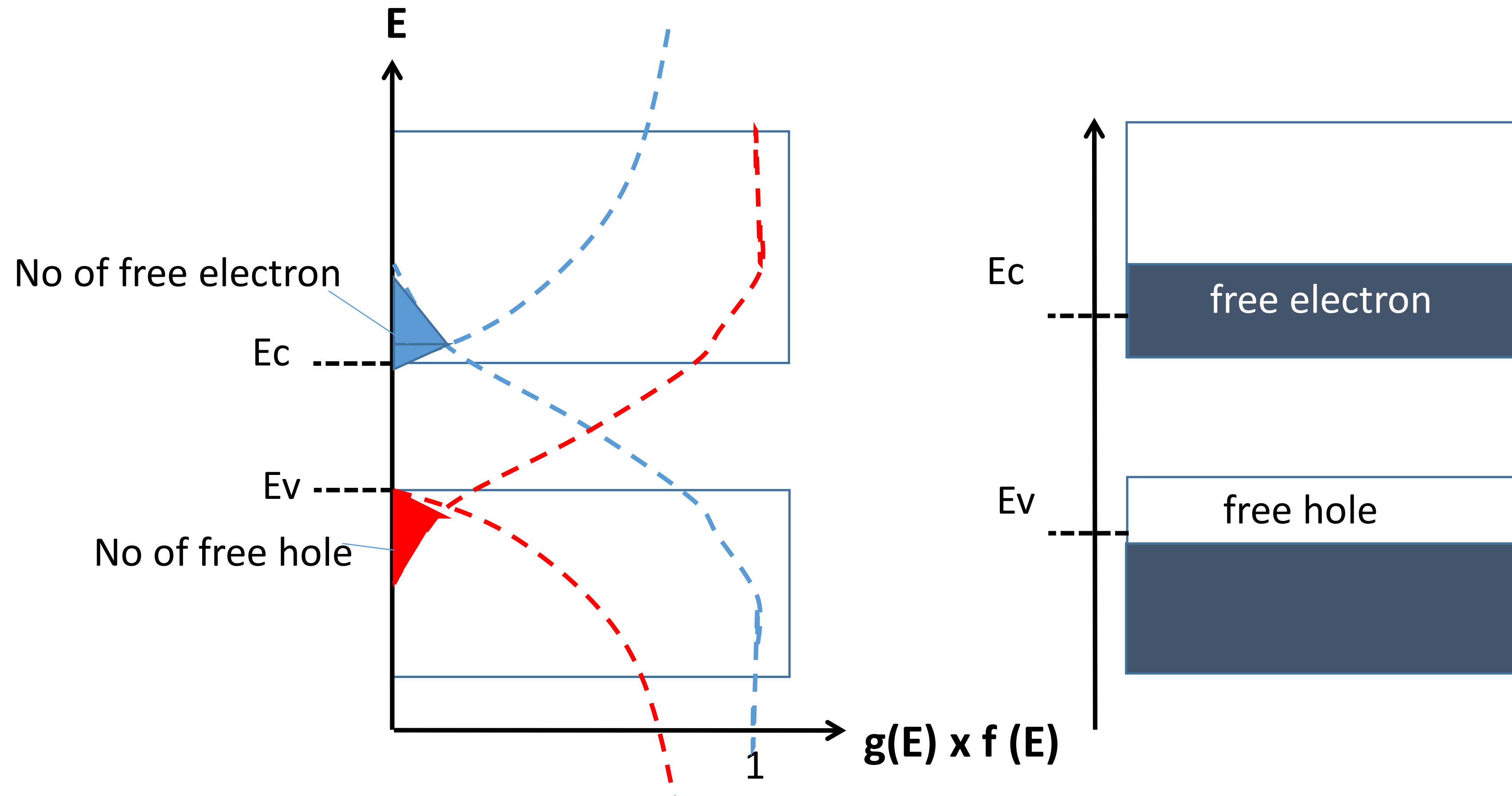


$$f_F(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}$$

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

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

No of carrier



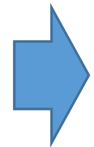
Thermal equilibrium concentration of electron, n_o

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

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

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

Boltzmann approximation



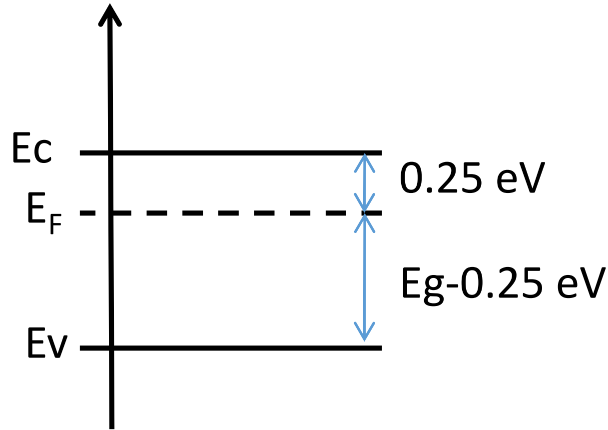
$$n_o = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \exp\left[\frac{-(E_C - E_F)}{kT}\right]$$

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

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 2.8×10^{19} cm^{-3}.



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

$$= 2.8 \times 10^{19} \cdot \exp\left[\frac{-(E_C - E_C + 0.25)}{0.0259}\right]$$

$$= 1.8 \times 10^{15}\, cm^{-3}$$

Hole concentration

Eg=1.12 eV

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

$$= 1.04 \times 10^{19} \cdot \exp\left[\frac{-(1.12 - 0.25)}{0.0259}\right]$$

$$= 2.68 \times 10^{4}\, cm^{-3}$$

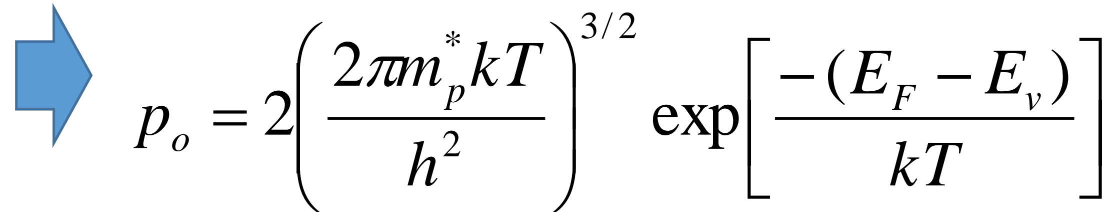
Thermal equilibrium concentration of hole, p_o

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

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

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

Boltzmann approximation



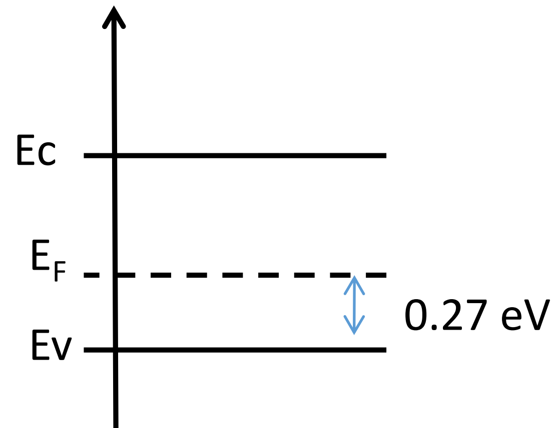
$$p_o = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

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

N_v; effective density of states function in valence band

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}.



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

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

- 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, $n<p$

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 conduction band, ni

Concentration of hole in in valence band, pi

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

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

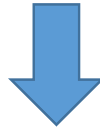
Independent of Fermi energy

Ex. 3; 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 Nc and Nv at 300 K are 4.7 x 1017 cm-3 and 7.0 x 1018 cm-3, respectively.

2. Intrinsic Fermi level position, E_{Fi}

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

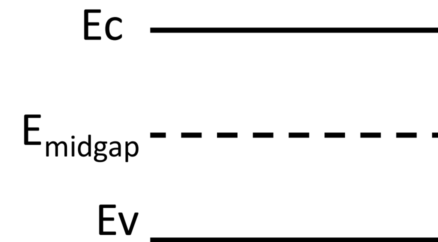
Intrinsic; n=p

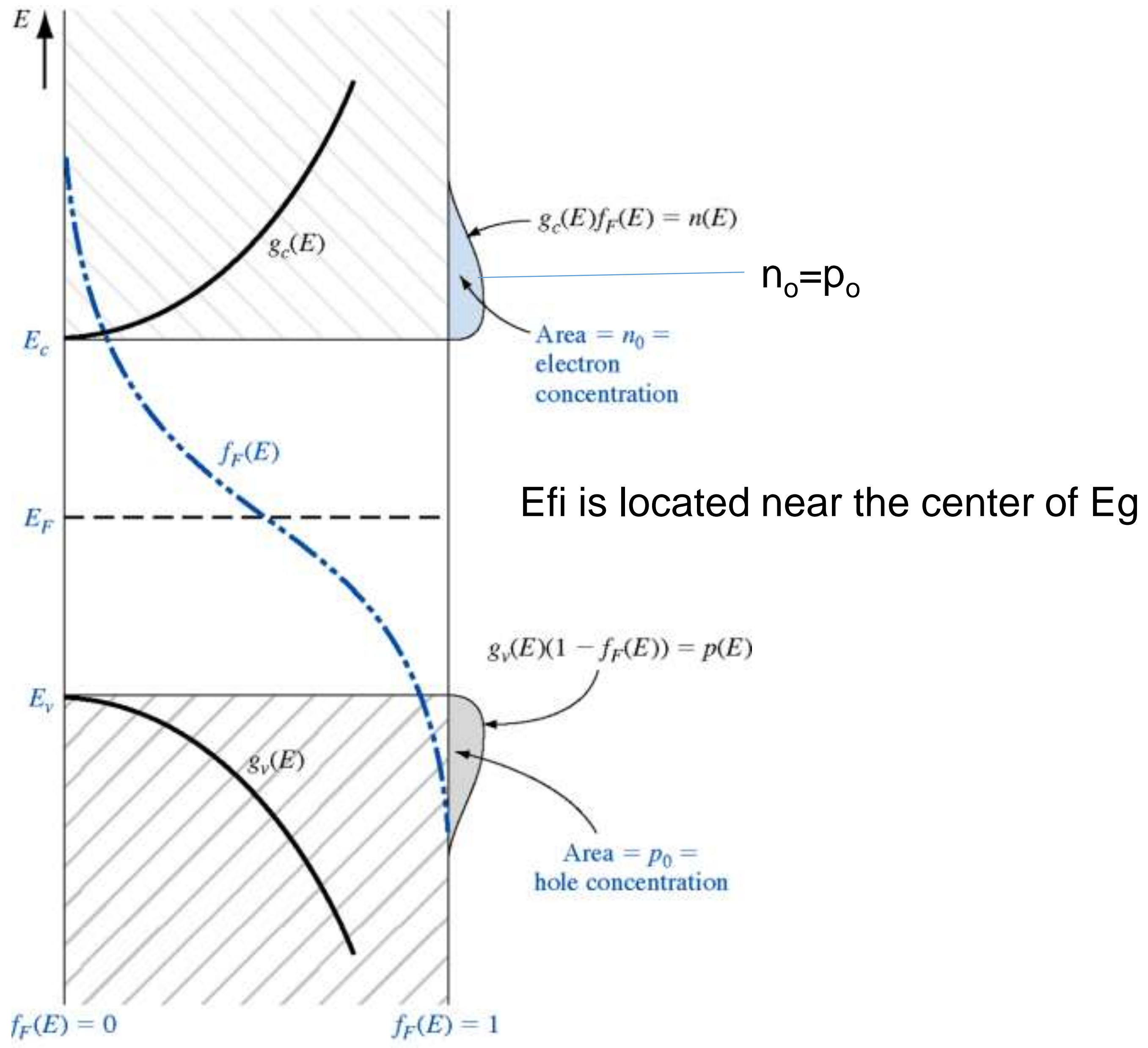


E_F is located near the center of the forbidden bandgap

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

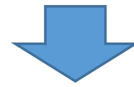
$$E_{Fi} = E_{midgap} + \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right)$$



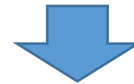

E
$g_c(E)f_F(E) = n(E)$
n_o=p_o
$g_c(E)$
Area = n_0 =
electron
concentration
E_c
$f_F(E)$
Efi is located near the center of Eg
E_F
$g_v(E)(1 - f_F(E)) = p(E)$
E_v
$g_v(E)$
Area = p_0 =
hole concentration
$f_F(E) = 0$
$f_F(E) = 1$
(a)

Dopant atoms and energy levels

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



Increase no. of carrier (either electron or hole)

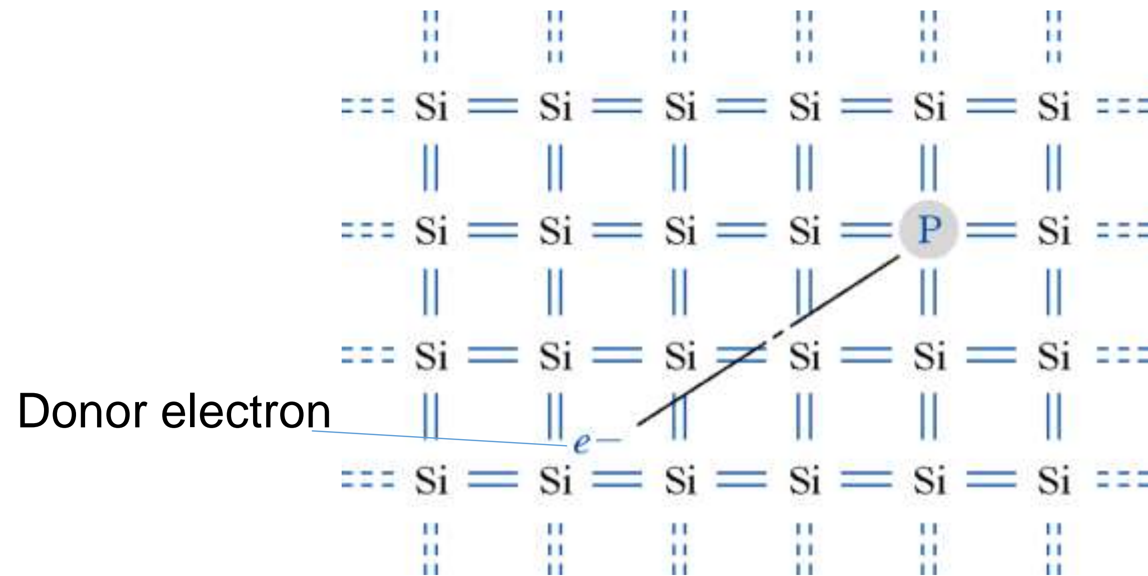


Alter the conductivity of semiconductor

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)

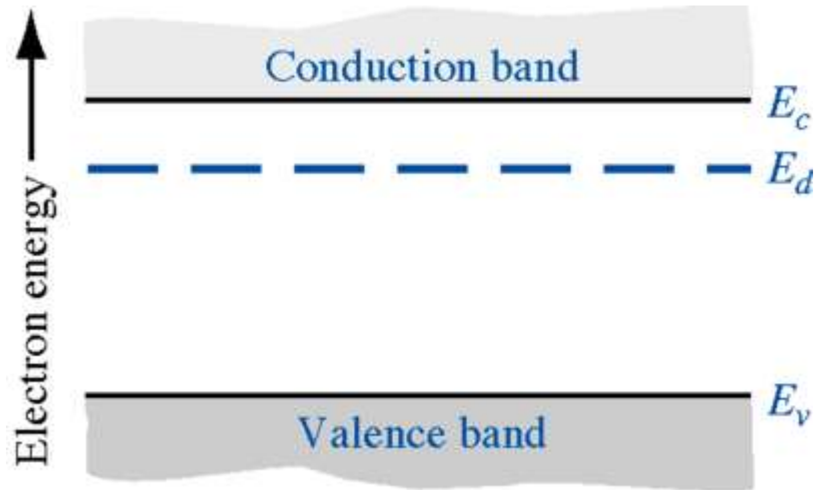
1. P as substitutional impurity (group V element; 5 valence electron)



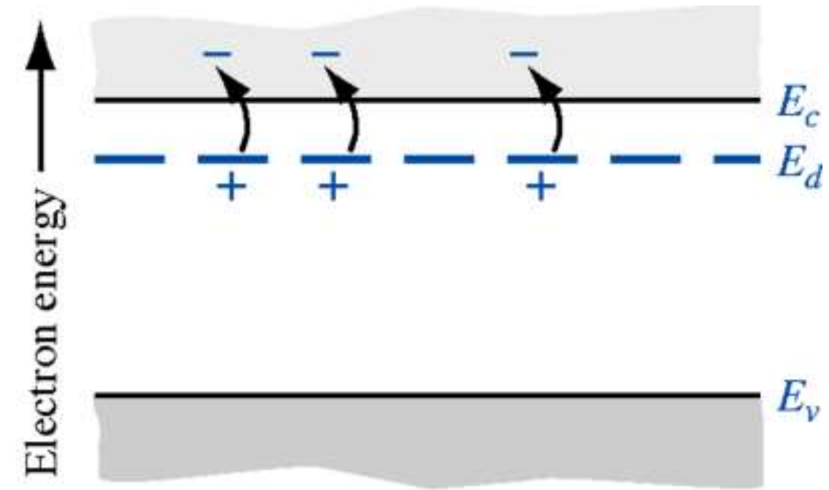
- In intrinsic Si, all 4 valence electrons contribute to covalent bonding.
- In Si doped with P, 4 valence electron of P contribute to covalent bonding and **1 electron loosely bound to P atom (Donor electron).**

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



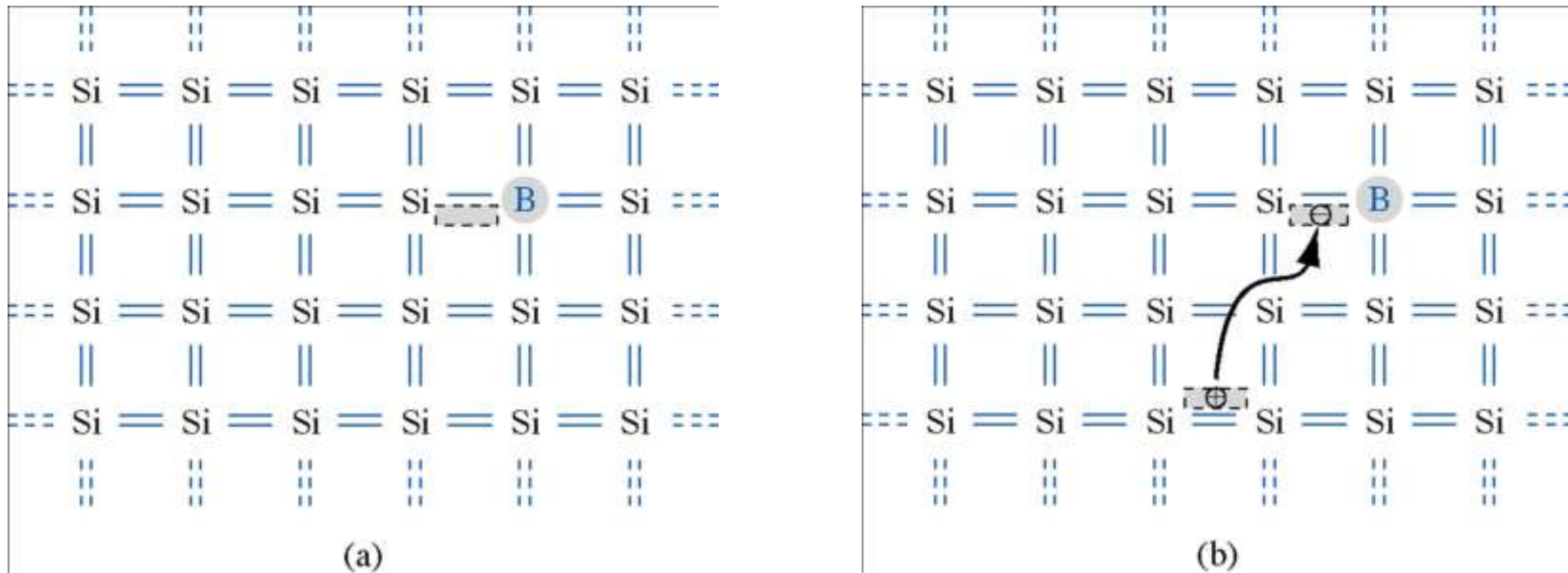
(a)



(b)

- 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)

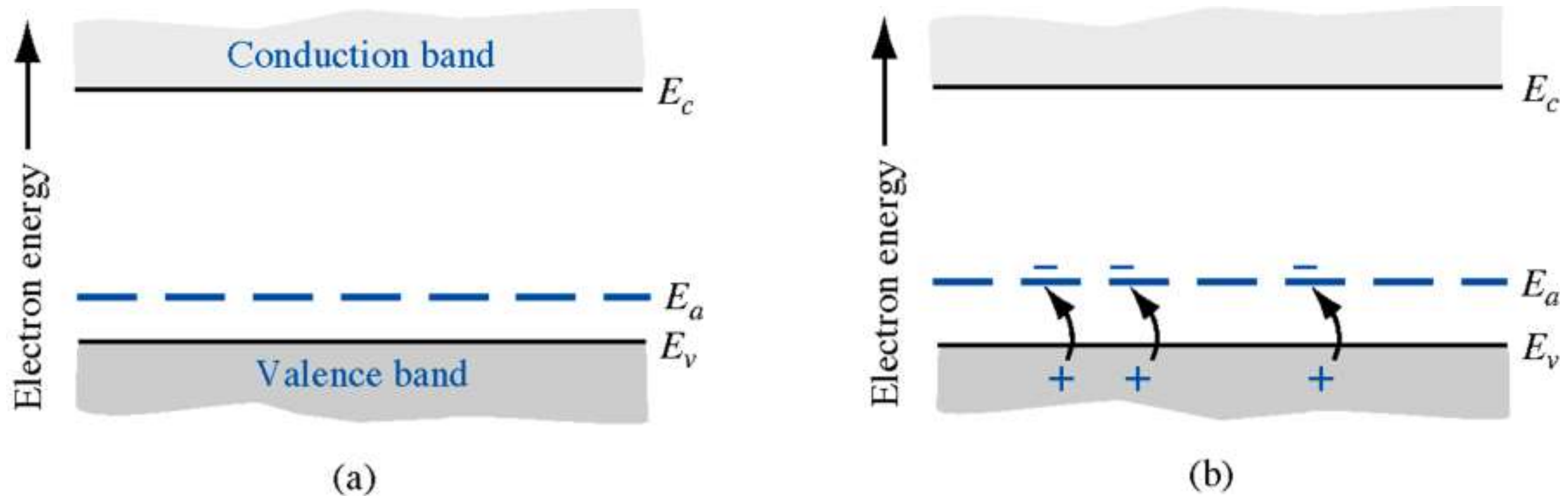
2. B as substitutional impurity (group III element; 3 valence electron)



- 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

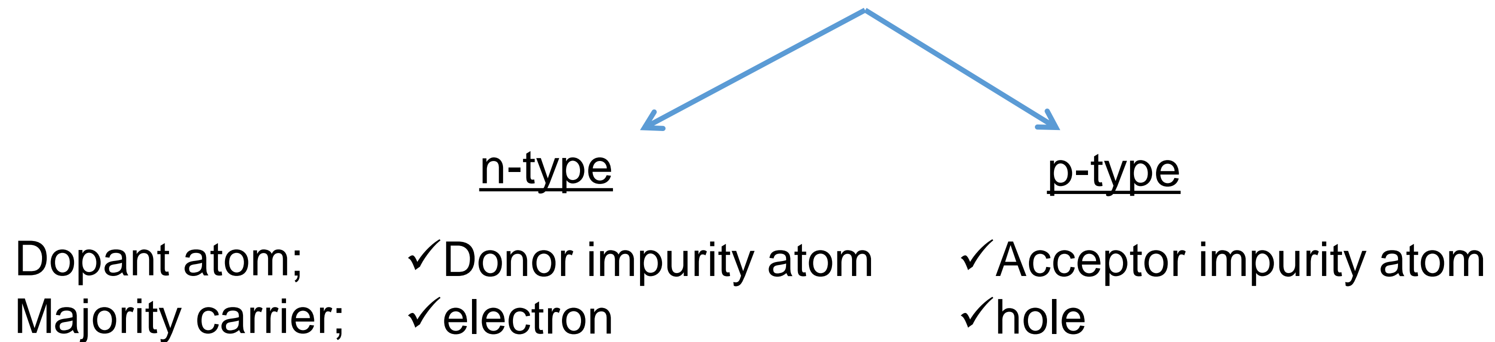
➢When electron from valence band elevate to Ea, hole and negatively charged B are created

➢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**

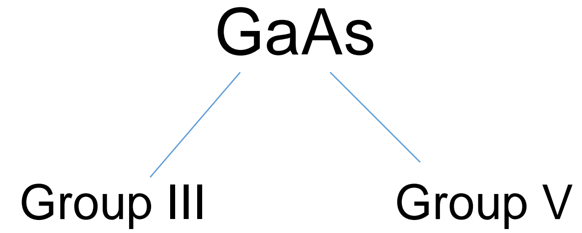
➢Semiconductor with dopant atoms; **extrinsic semiconductor**



Ionization Energy

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



Dopant atoms;

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

Semiconductor Optoelectronics

Lecture 2: Semiconductor in Equilibrium

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Chapter 4: Semiconductor in Equilibrium
Chapter 6: Nonequilibrium Excess Carriers in Semiconductors

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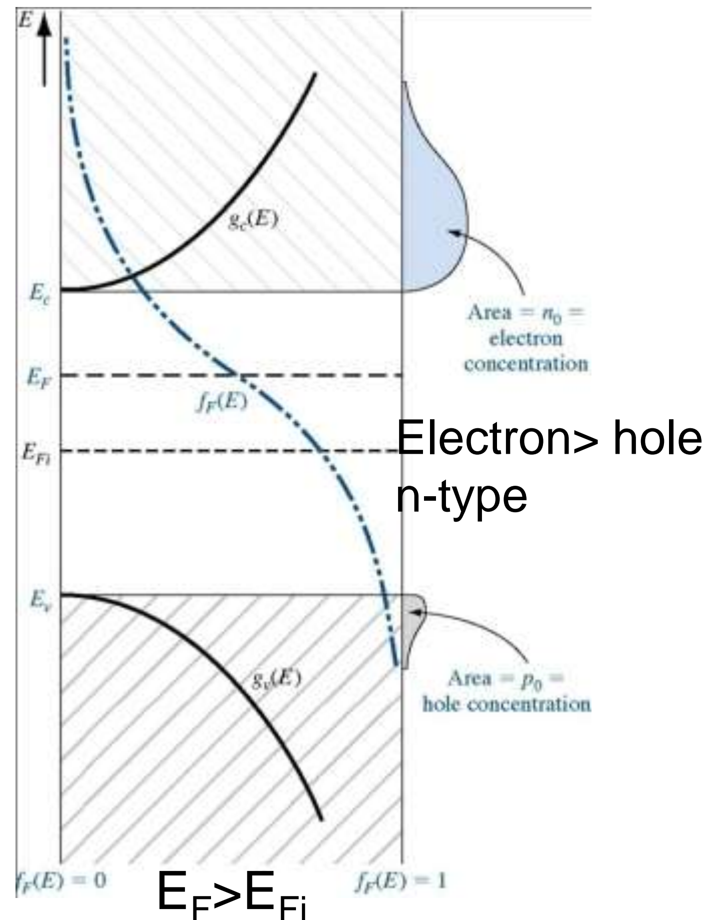
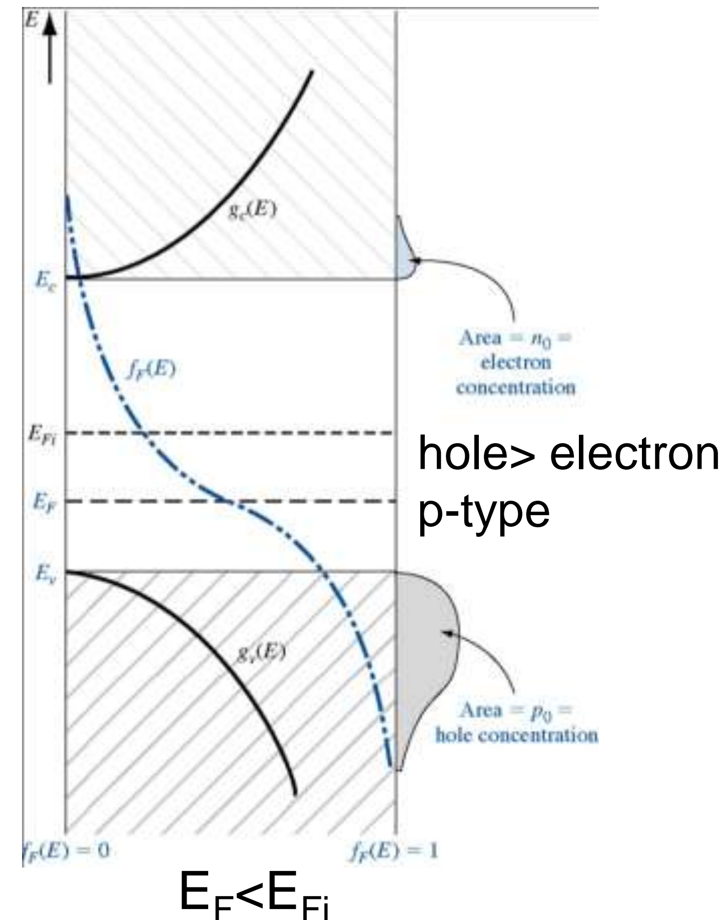
Carrier concentration of extrinsic semiconductor

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



$E_F > E_{Fi}$

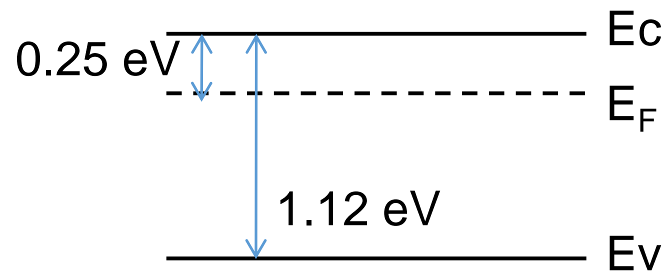


$E_F < E_{Fi}$

$$n_o = N_C \exp\left[\frac{-(E_C - E_F)}{kT}\right]$$ 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=2.8×10^{19}cm^{-3} and Nv=1.04×10^{19}cm^{-3}. Calculate n_o and p_o.

$$n_o = (2.8 \times 10^{19}) \exp\left(\frac{-0.25}{0.0259}\right) = 1.8 \times 10^{15}\, cm^{-3}$$

$$p_o = (1.04 \times 10^{19}) \exp\left(\frac{-(1.12 - 0.25)}{0.0259}\right) = 2.7 \times 10^{4}\, cm^{-3}$$

N-type Si

➢**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

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

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

$$= n_i^2$$

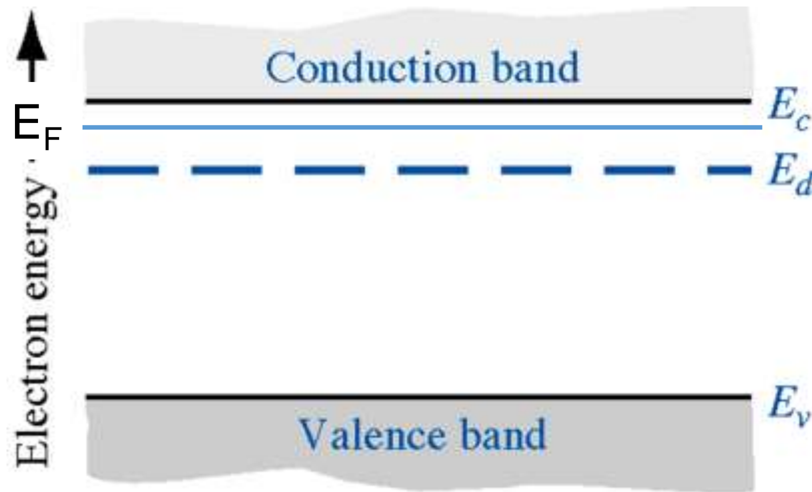
$$\boxed{n_o p_o = n_i^2}$$

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

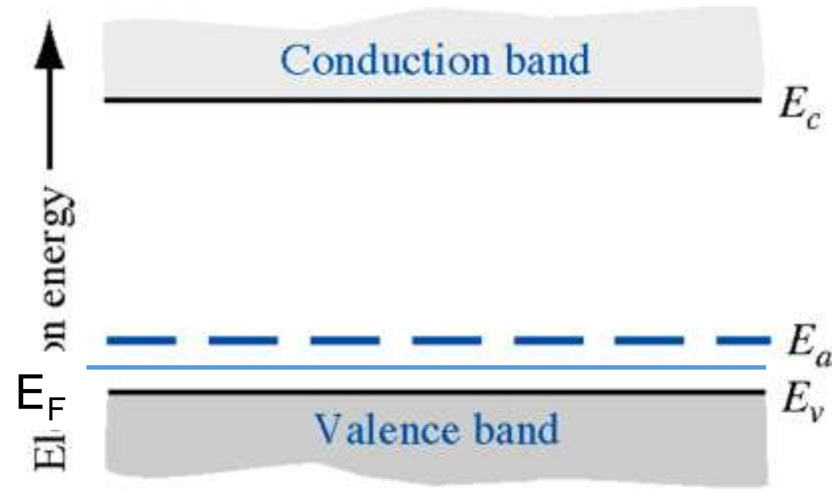
Degenerate and Non degenerate semiconductors

Small amount of dopant atoms (impurity atoms)

- ✓No interaction between dopant atoms
- ✓Discrete, noninteracting energy state.
- ✓E_F at the bandgap



donor

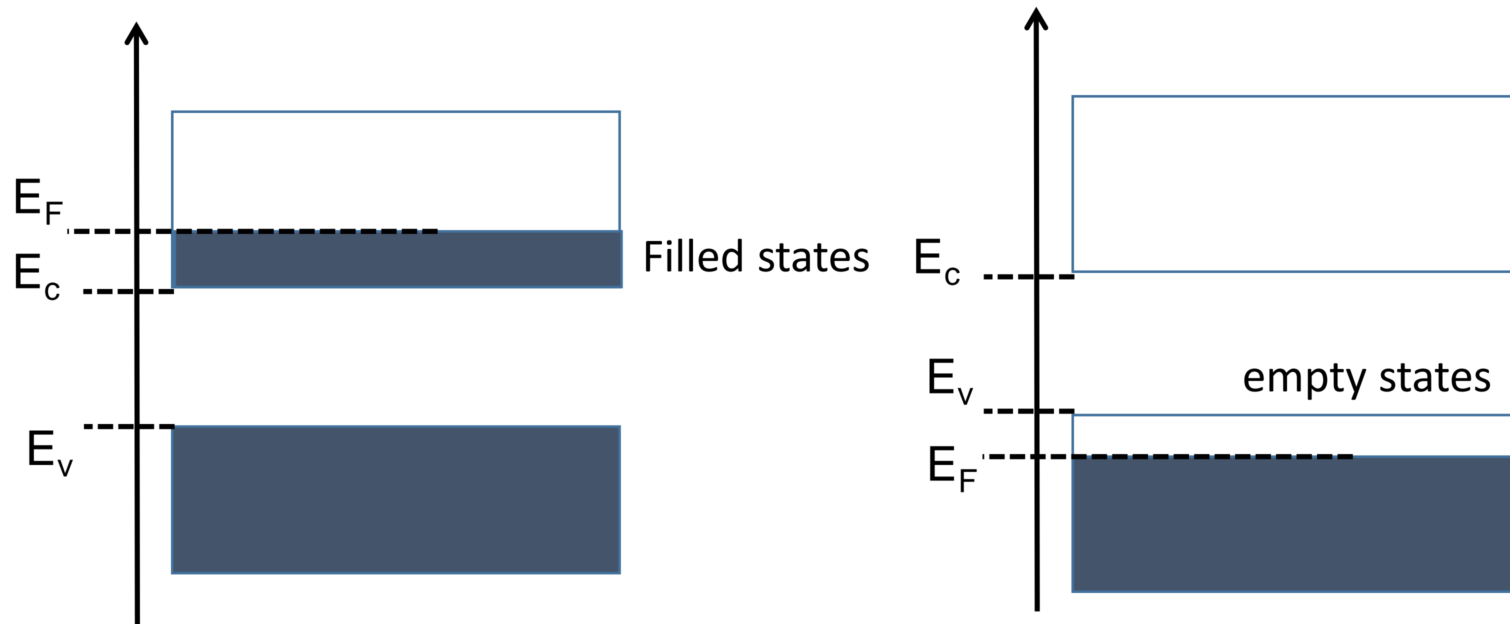


acceptor

Nondegenerate semiconductor

Large amount of dopant atoms (~effective density of states)

✓Dopant atoms interact with each other
✓Band of dopant states widens and overlap the allowed band (conduction @ valence band)
✓E_F lies within conduction @ valence band



Degenerate semiconductor

Position of Fermi Energy Level

As a function of **doping concentration** and **temperature**

Equations for position of Fermi level (n-type)

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

Compensated semiconductor, $n_o = N_d - N_a$

$$E_C - E_F = kT\ln\left(\frac{N_C}{N_d - N_a}\right)$$

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

Equations for position of Fermi level (p-type)

$$E_F - E_C = kT\ln\left(\frac{N_v}{p_o}\right)$$

Compensated semiconductor, $p_o = N_a - N_d$

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

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

Example;

Silicon at T=300 K contains an acceptor impurity concentration of $N_a=10^{16}$ cm^{-3}. Determine the concentration of donor impurity atoms that must be added so that the Silicon is n-type and Fermi energy is 0.20 eV below the conduction band edge.

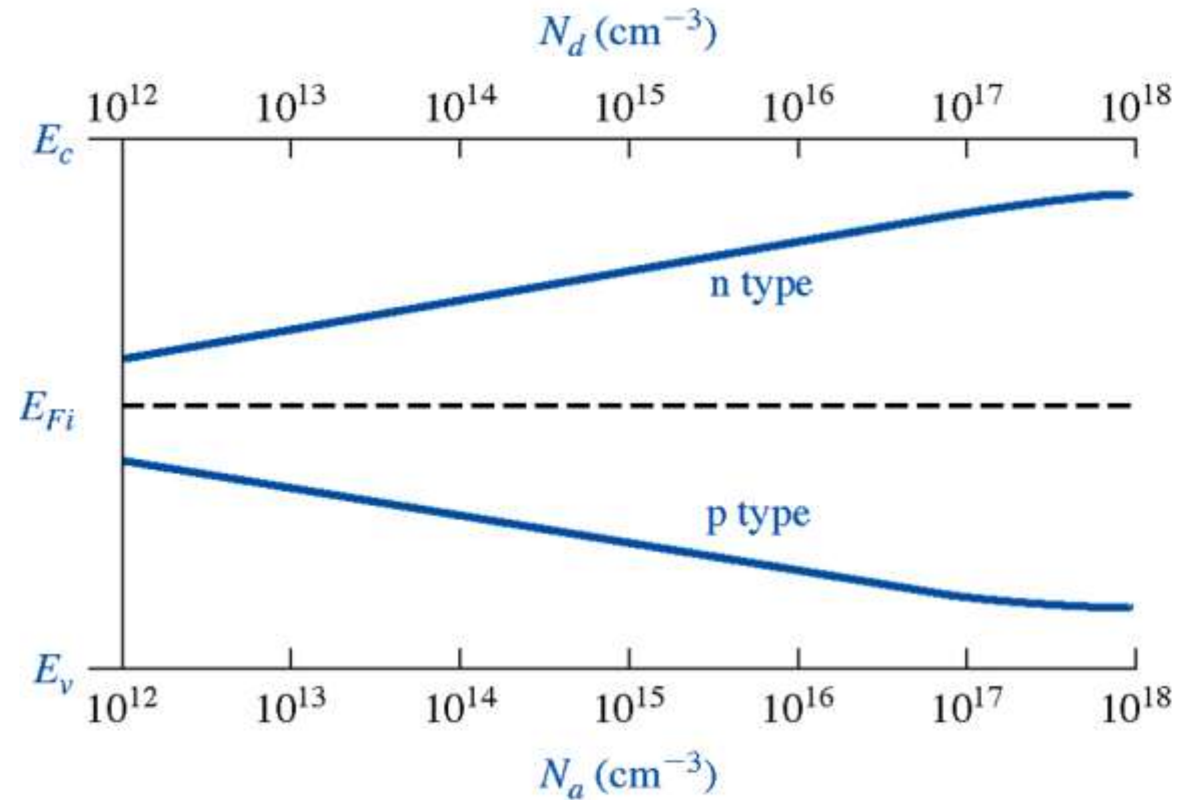
$$E_C - E_F = kT \ln\left(\frac{N_C}{N_d - N_a}\right)$$

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

$$= 2.8\times10^{19} \exp\left[\frac{-0.2}{0.0259}\right] = 1.24\times10^{16} cm^{-3}$$

$$N_d = 1.24\times10^{16} cm^{-3} + N_a = 2.24\times10^{16} cm^{-3}$$

Position of E_F as function of donor concentration (n-type) and acceptor concentration (p-type)



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

Nonequilibrium Excess Carriers in Semiconductors

In this chapter, we will discuss the behavior of nonequilibrium electron and hole concentrations as a functions of time and space coordinates

Excess electrons in the conduction band and excess holes in the valence band may exist in addition to the thermal-equilibrium concentrations if an external excitation is applied to the semiconductor.

Excess electrons and excess holes do not move independently of each other.

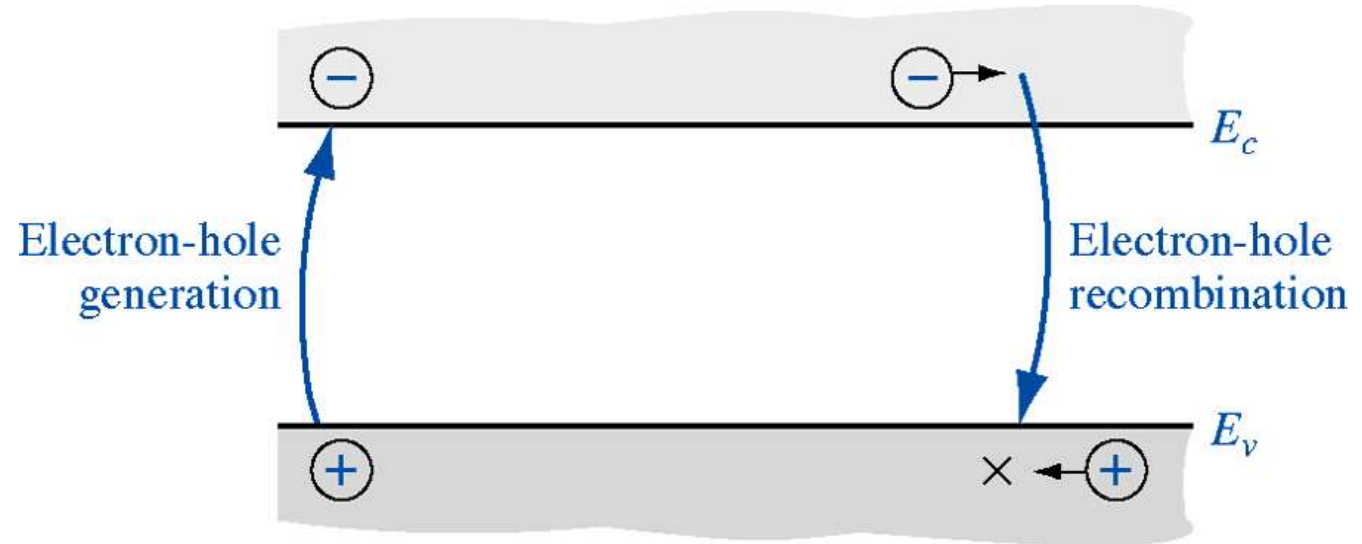
They diffuse, drift, and recombine with the same effective diffusion coefficient, drift mobility and life time.

This phenomenon is called ambipolar transport.

Carrier Generation & Recombination

- Generation is the process whereby electrons and holes are created.
- Recombination is the process whereby electrons and holes are annihilated.
- In thermal equilibrium we have electrons breaking out of covalent bonds due to the acquisition of enough thermal energy to hop from the valence to the conduction band. This creates both a free electron and a free hole (generation).
- For a specified period, there are free electrons that lose some of their thermal energy when they encounter a hole and fall back into covalent bond (recombination).

The Semiconductor in Equilibrium



Given that thermally generated free electrons and holes must come in pairs

$$G_{n0} = G_{p0}$$

and they will also recombine in pairs so

$$R_{n0} = R_{p0}$$

The Semiconductor in Equilibrium

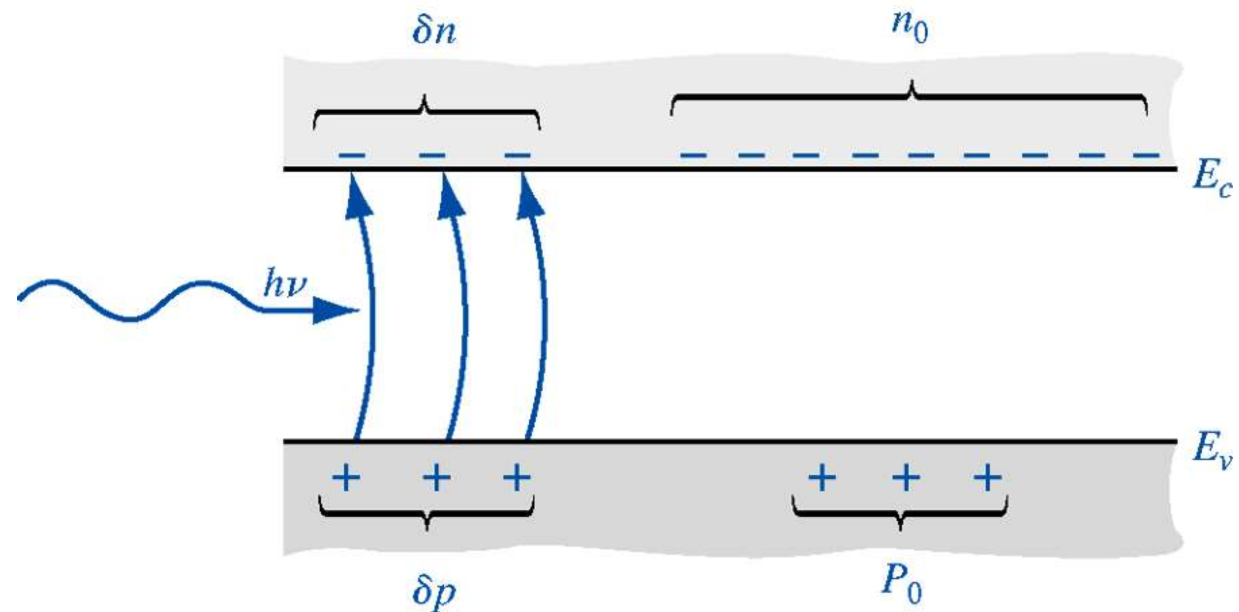
In thermal equilibrium the total number of free electrons and holes is constant so the rates at which they are being generated must be equal to the rates at which they are recombining.

$$G_{n0} = G_{p0} = R_{n0} = R_{p0}$$

Excess Carriers

- External events, such as incident photons, can disrupt this equilibrium though and create additional electron-hole pairs.
- These “excess” charge carriers would be generated at equal rates for electrons and holes, so

$$g_n' = g_p'$$



Excess Carriers

The *number* of actual excess electrons and holes though are δn and δp. Thus the total number of free electrons and holes in the semiconductor can now be written as:

$$n = n_0 + \delta n$$

$$p = p_0 + \delta p$$

Excess Carriers

The excess electrons and holes would also recombine in pairs so we can write:

$$R_n' = R_p'$$