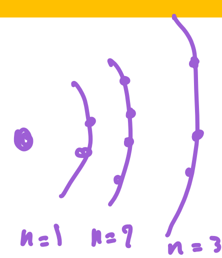
Electronics
&
Semiconductors

from chem

Si
14

needs another element of Si



if I have an isol. and a cond.

this doesn't happen here

what's special about it?

جار g → charges from orbit to surface

Energy goes from one level to another

if it couldn't

diff. between two levels → big gap → e^- can't go from one to another

what if the levels overlap? conducter

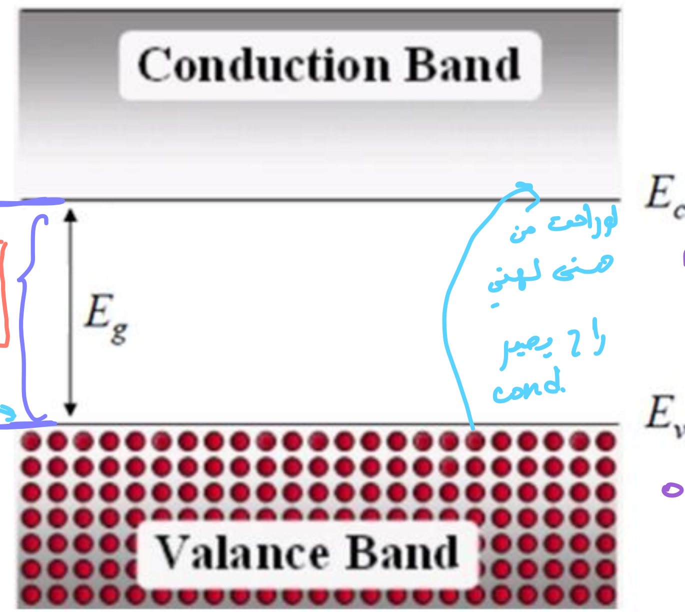
Classification of Solids and Energy Bands

In solid-state physics:

The valence band and conduction band are the bands that determine the electrical conductivity of the solid.

each level has a Volt. value

if E_g is really big → isol.
otherwise it could start conducting



لوراحت لفوق راح يصير
فيه connection

عند ال orbit

there are so many levels here

In non-metals:

The valence band is the highest range of electron energies in which electrons are normally present at absolute zero temperature, while the conduction band is the lowest range of vacant electronic states.

semi [illegible] → but if we dope it, it'll have high charge to conduct

Classification of Solids and Energy Bands

Eg is the called the bandgap energy of the solid. It is measured in electron-volt (e.v).

unit

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{joules.}$$

for energy inside a material

Eg is called also the forbidden band because electrons are not allowed to be that energy level.

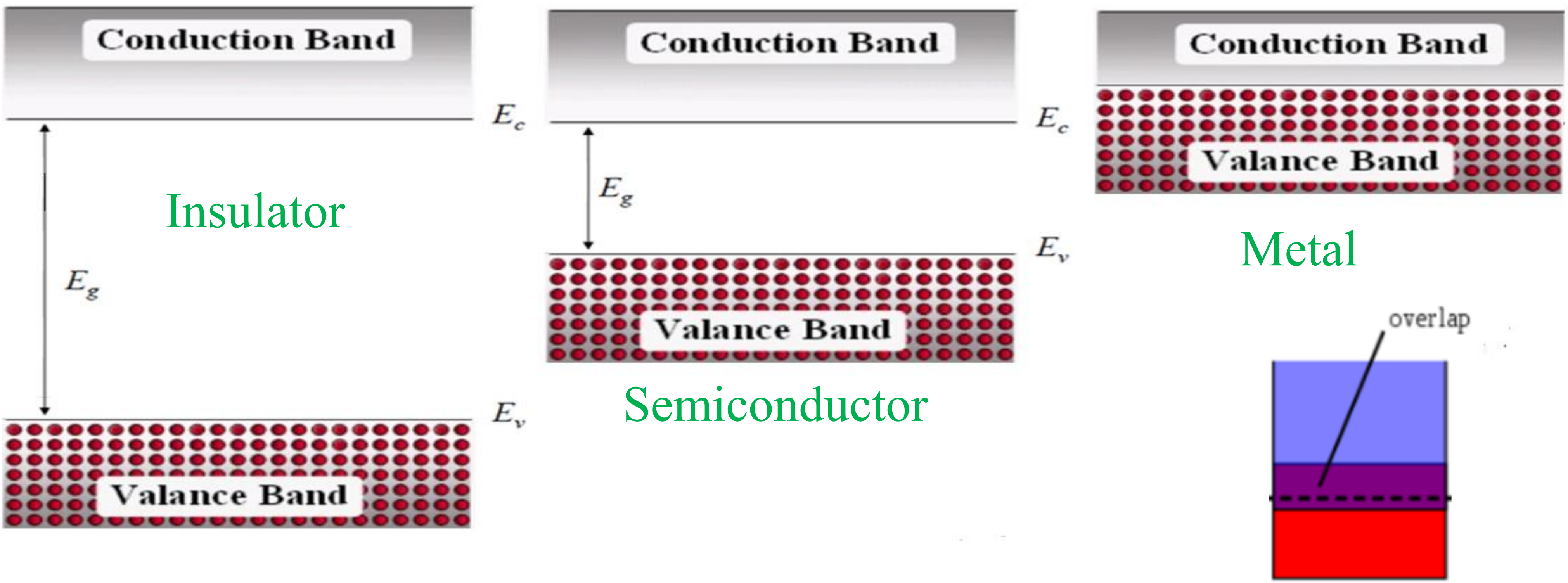
Eg is the energy separation of the conduction and valence band.

we can define whether the material is iso. or cond. based on the gap

The solid are classified as Insulator or Semiconductor or Metal according to Eg

Classification of Solids and Energy Bands

and could overlap in the case of a perfect cond.



Classification of Solids and Energy Bands

Isolators has Eg range of 3 to 6 (eV), are insulators because and at room temperature, essentially no free electrons exist in the conduction band.

In contrast, materials that contain free electrons at room temperature are conductors.

In a *semiconductor,* the bandgap energy is on the order of 1 eV.

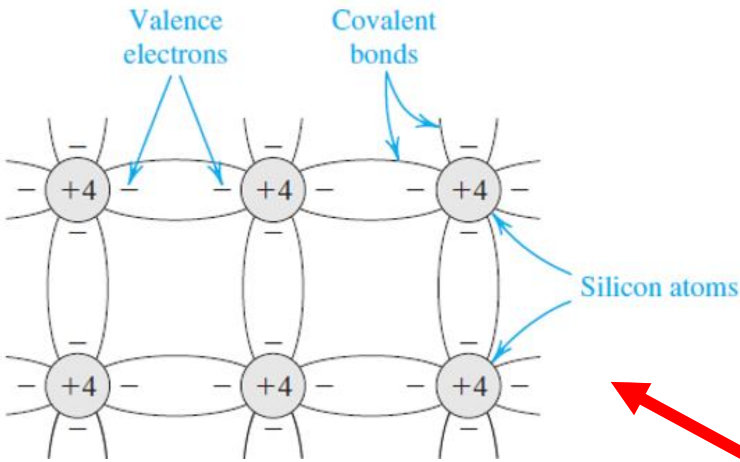
Semiconductor **Material**	***Eg*** **(eV)**
Silicon (Si)	1.1
Gallium arsenide (GaAs)	1.4
Germanium (Ge)	0.66

constants

Intrinsic Semiconductors

ideal case, no impurities   when do we have this?
at room temp.

Intrinsic Semiconductor means No impurities or defects

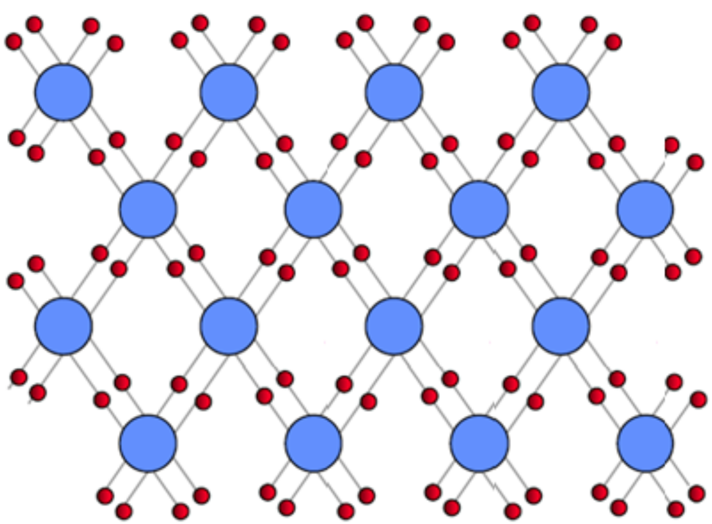


No charge carriers at T= 0 °K

$$n = p = 0\ /cm^3$$

n # of electron/cm³

p # of holes/cm³

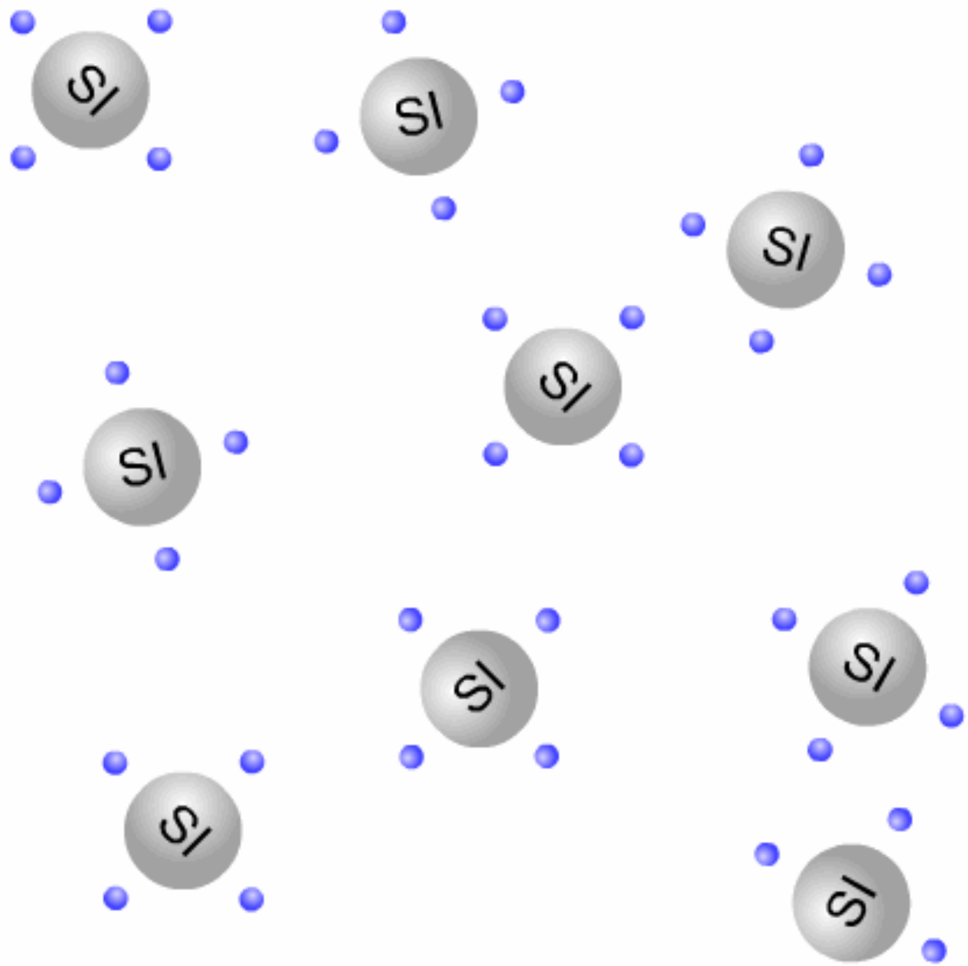


Si Atom

Shared electron covalent bonds

No free charge carriers

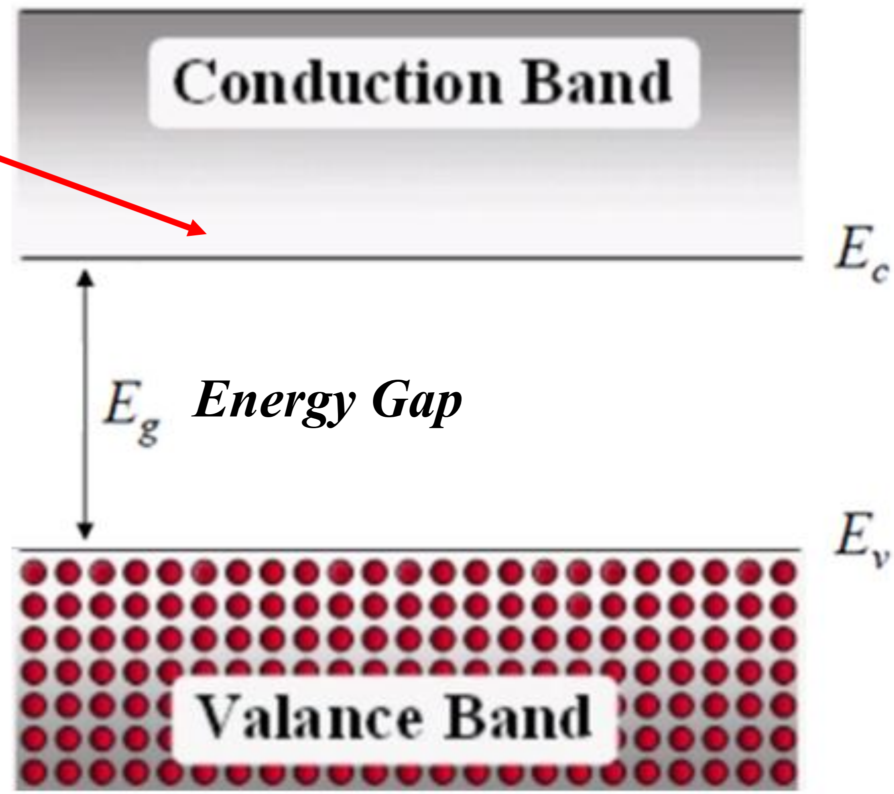
Intrinsic Semiconductors



Intrinsic Semiconductors

At *T= 0 ºK* *No free charge carriers*

Empty States (No Carriers)



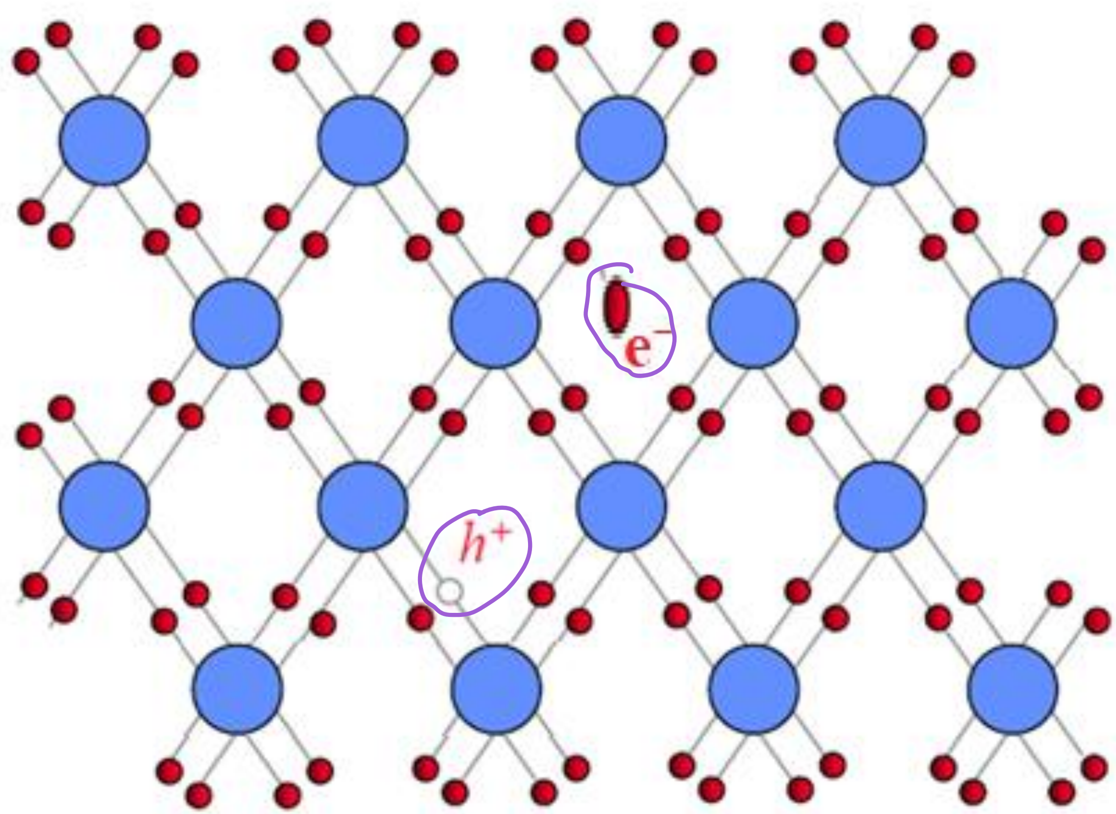
Filled States

Current can only flow when there are allow carrier movement

only happens in two cases:
I add charge
or it moves from $E_v \rightarrow E_g$

Intrinsic Semiconductors

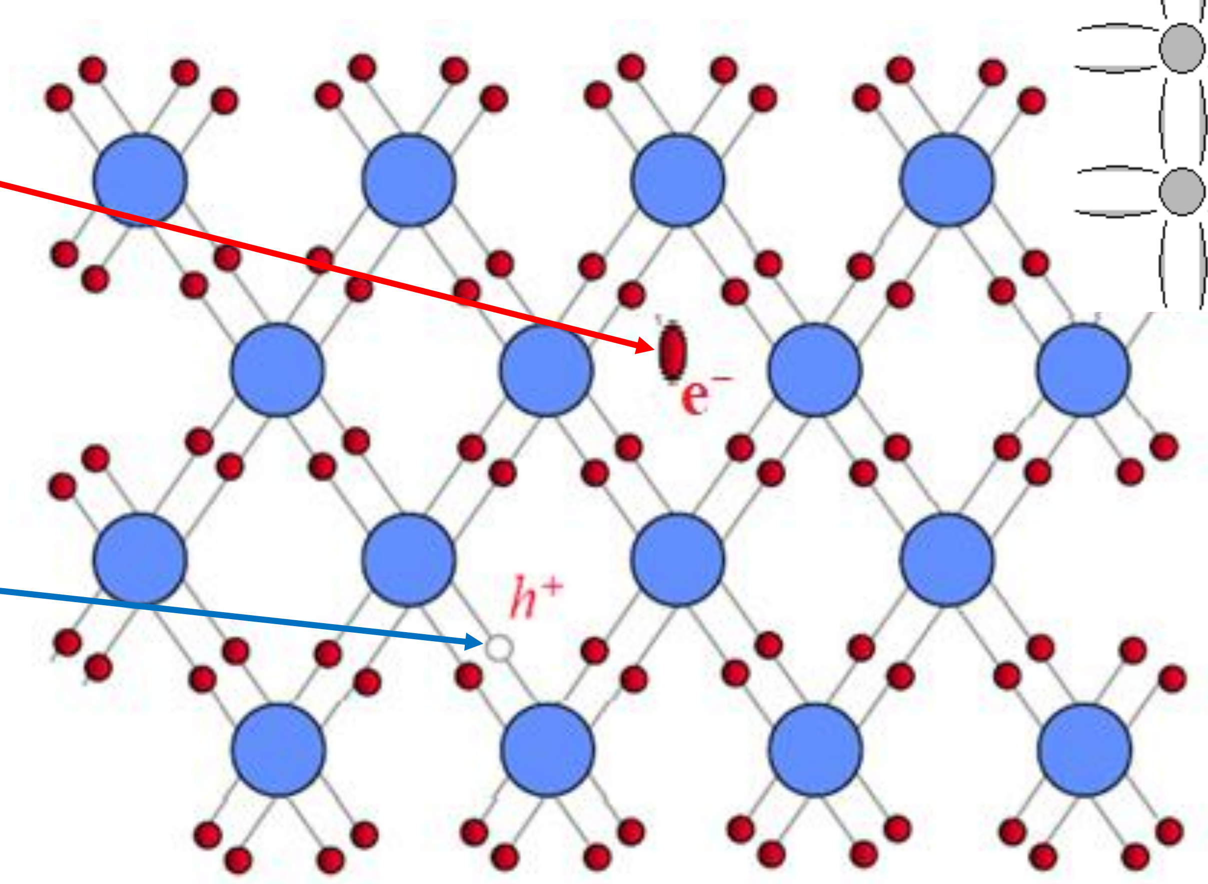
As temperature increases, Generation and Recombination of free E-H carriers will occur

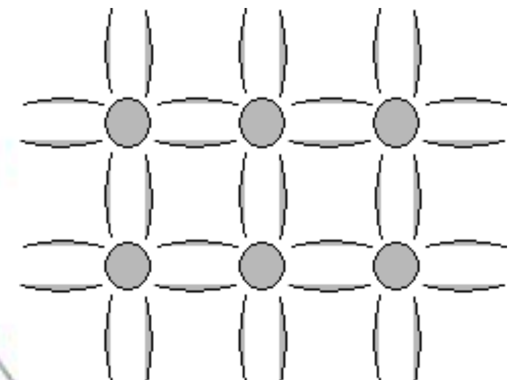


Intrinsic Semiconductors

As temperature increases, Generation and Recombination of free E-H carriers will occur

Free Electron (Carriers)





Vacant State in Valence Band

$\boxed{n_o = p_o}$

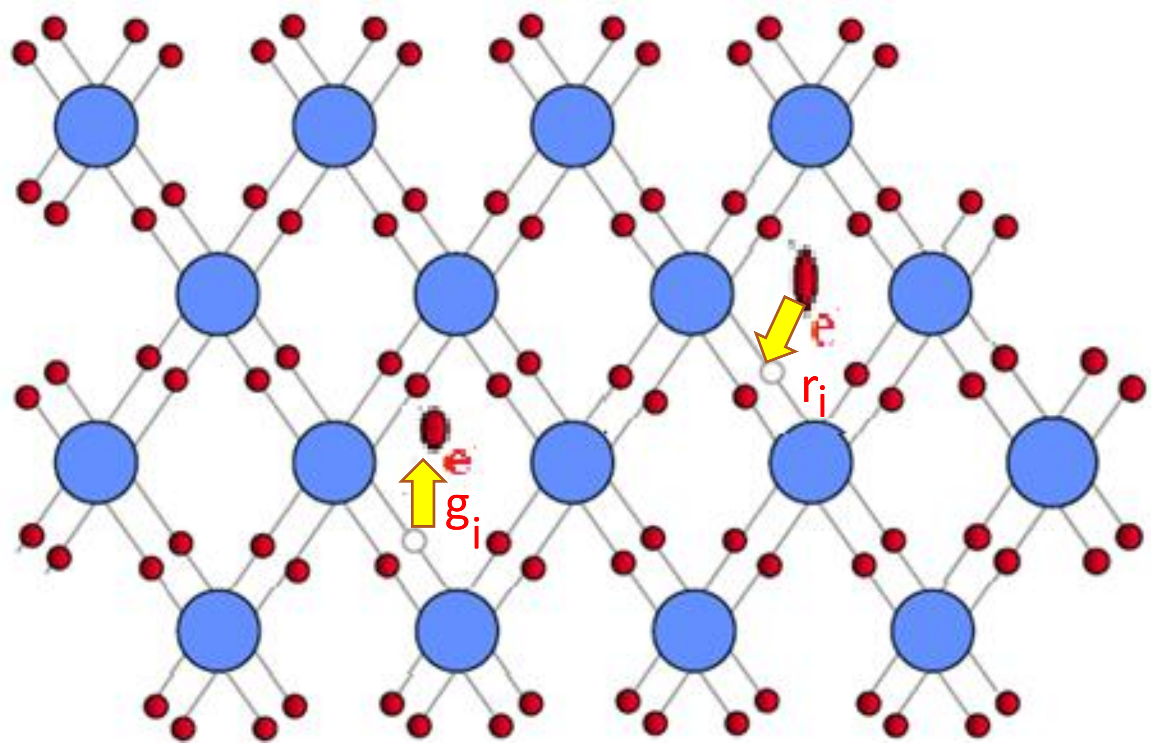
initially in the material before I ...?

Intrinsic Semiconductors

As temperature increases, Generation and Recombination of free carriers will occur

- **EHP generation= EHP recombination**

Generation rate g_i



Recombination rate r_i

rate of gen always = rate of recom.

$g_i(T) = r_i(T)$ Increases with temperature

Intrinsic Semiconductors

Band Structure at Room Temperature(300ºK)

Empty States (Electrons)

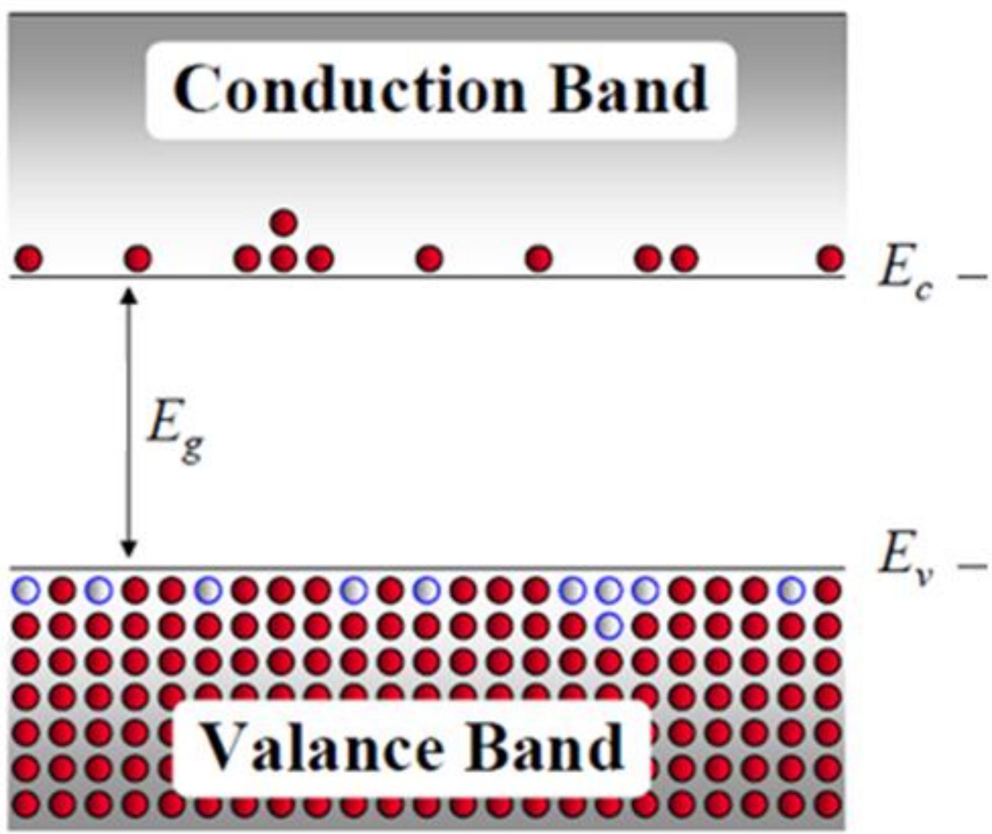
# of e⁻ here →

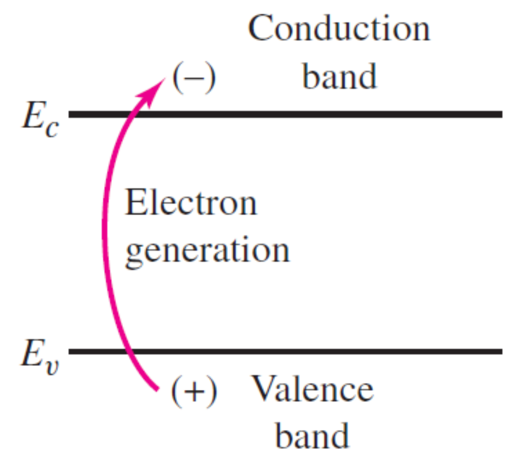
$n_0 = p_0$

=

# of holes here ←

Empty States (Holes)





Empty States in the valence band can be treated as Positively charged particles with positive mas called "holes"

Intrinsic Semiconductors

what does intrinsic mean?

At Room Temperature (300^{o}K)

- n_o= equilibrium concentration of electrons
- p_o= equilibrium concentration of holes
- $n_o = p_o = n_i = (1.5x\ 10^{10} cm^{-3}$ in Si at 300 ^{o}K)

  # of free e⁻
- n_i is called the intrinsic carrier concentration

$$n_o p_o = n_i^2 \text{ at any Temperature}$$

Intrinsic Semiconductors

- n_i = *intrinsic carrier concentration*

$$n_i = BT^{3/2}e^{\left(\frac{-E_g}{2kT}\right)}$$

k : Boltzamann's constant =8.6 x10^{-5} eV/K

Material	B (cm^{-3} K$^{-3/2}$)
Silicon (Si)	5.23×10^{15}
Gallium arsenide (GaAs)	2.10×10^{14}
Germanium (Ge)	1.66×10^{15}

Example 1

Calculate the intrinsic carrier concentration in silicon at $T = 300$ K.

Solution: For silicon at $T = 300$ K, we can write

* B → from what the material is

* const $K = 8.6 \times 10^{-5}$

* $E_g = 1.1$

$$n_i = B T^{\frac{3}{2}} e^{\left(\frac{-E_g}{2KT}\right)} = (5.23 \times 10^{15})(300)^{3/2} e^{\left(\frac{-1.1}{2(8.6 \times 10^{-5})(300)}\right)}$$

or

$$n_i = 1.5 \times 10^{10} / cm^3$$

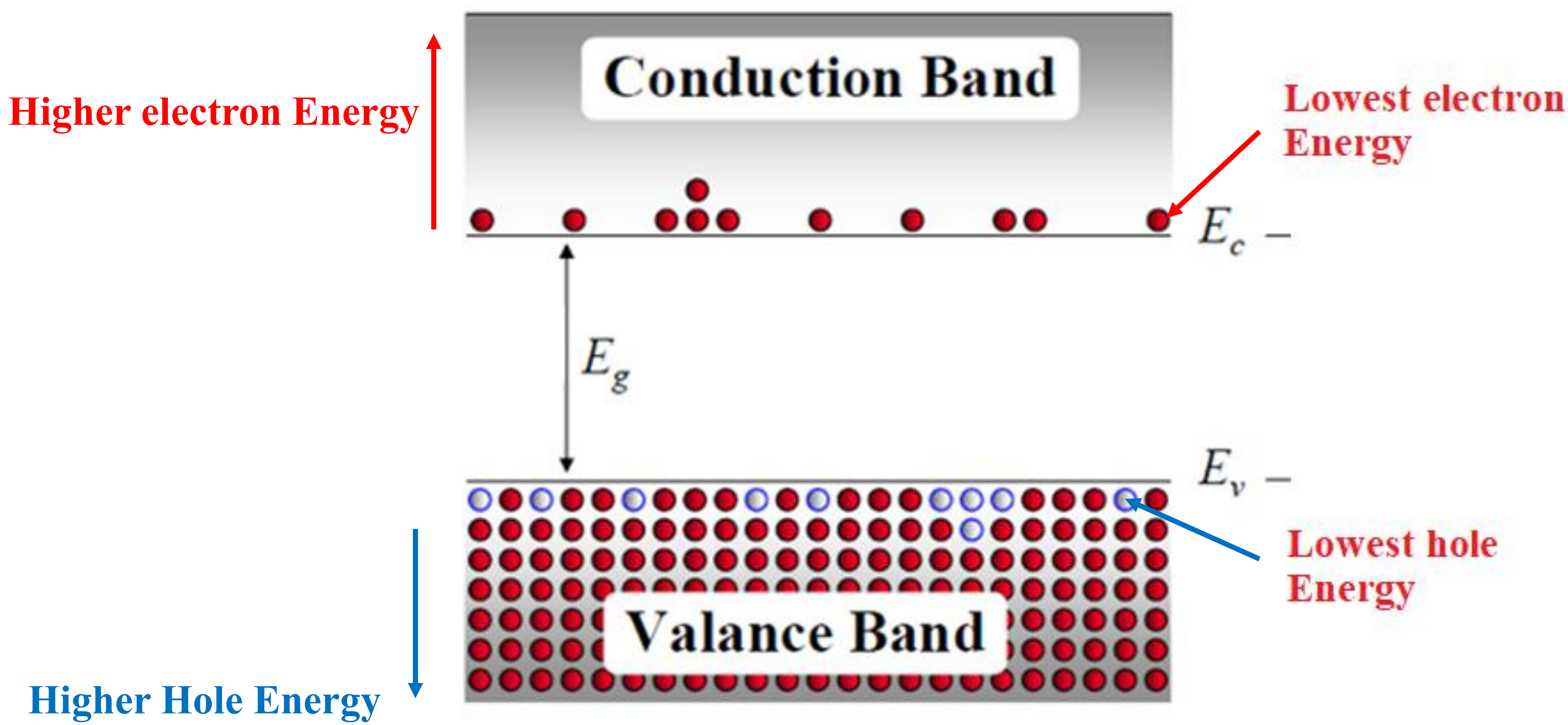
An intric. elec. concent. of $1.5 \times 10^{10} / cm^3$ may appear to be large. but it's relatively small compared to the concent. of Si atoms, which is $5 \times 10^{22} / cm^3$

Intrinsic Semiconductors

ext.
conduct.
بر وجه
بدون doping

Band Structure at Room Temperature(300ºK)

holes = concen.
بدون



Extrinsic Semiconductors

impur: الحين لو أنا حطيت

- ***Impurities introduced by doping***
- ***Doping allows the creation of extra carriers***

$$n_o \neq p_o \neq n_i$$

الأكثر على حسب الـ doping

إذا أبي n material لازم أحط elem. من 5 doner → راح تمير ⊖

- ***n-type material (electron carriers)***

Column V donor impurities Nd (P, As, Sb) $\quad n_o >> p_o\, ,\, n_i$

- ***p-type material (hole carriers)***

Column III acceptor impurities Na (B, Al, Ga, In) ??

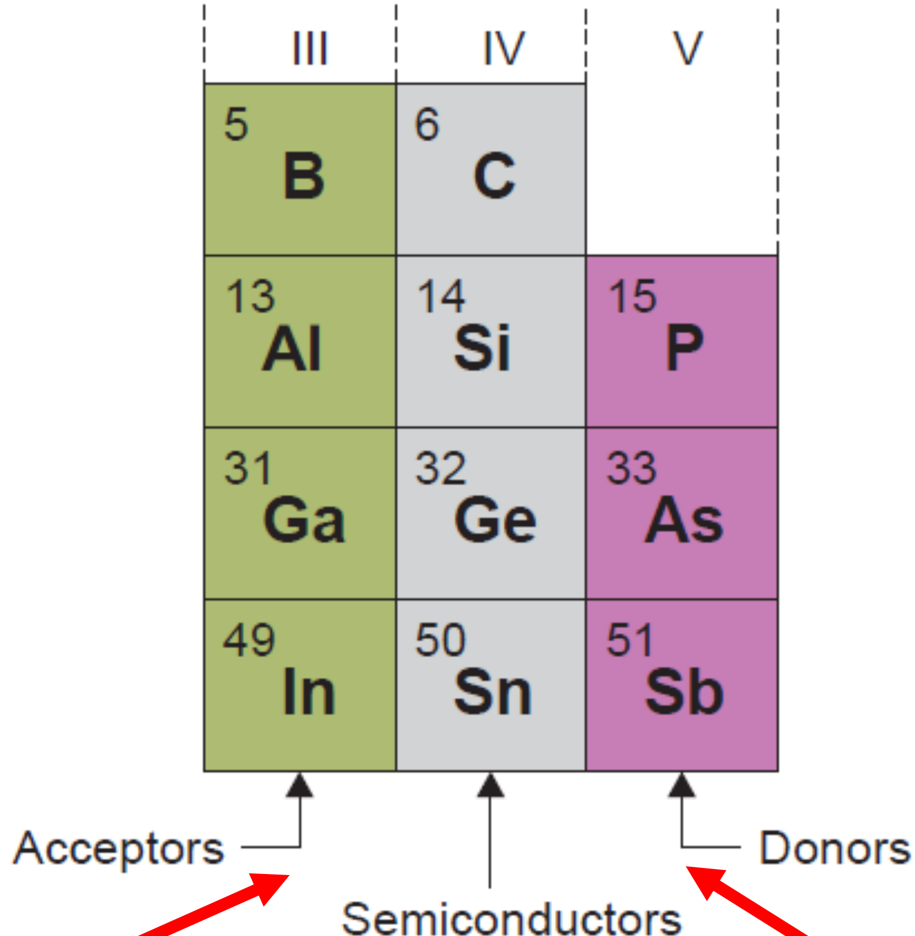
col. 3 من

$$p_o >> n_o\, ,\, n_i$$

Extrinsic Semiconductors

Impurities

really imp. listen!!



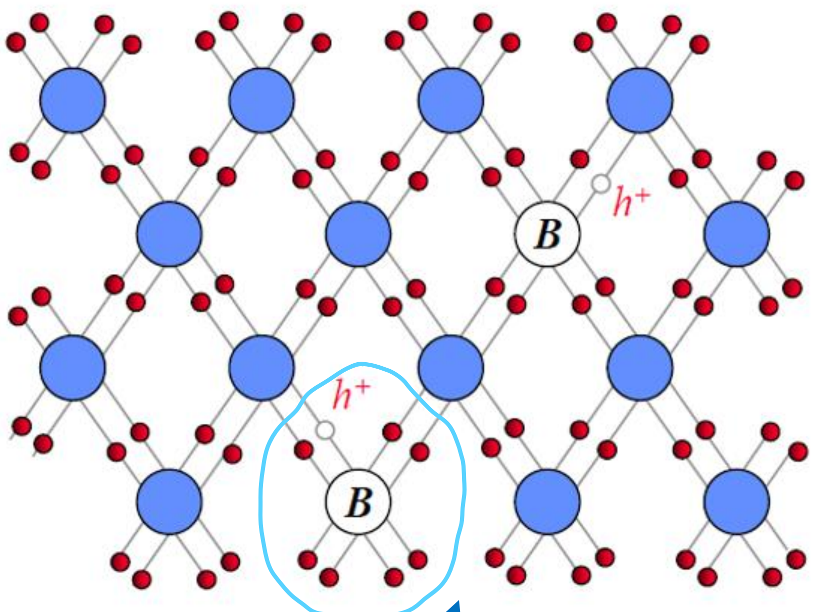
Na P-Type

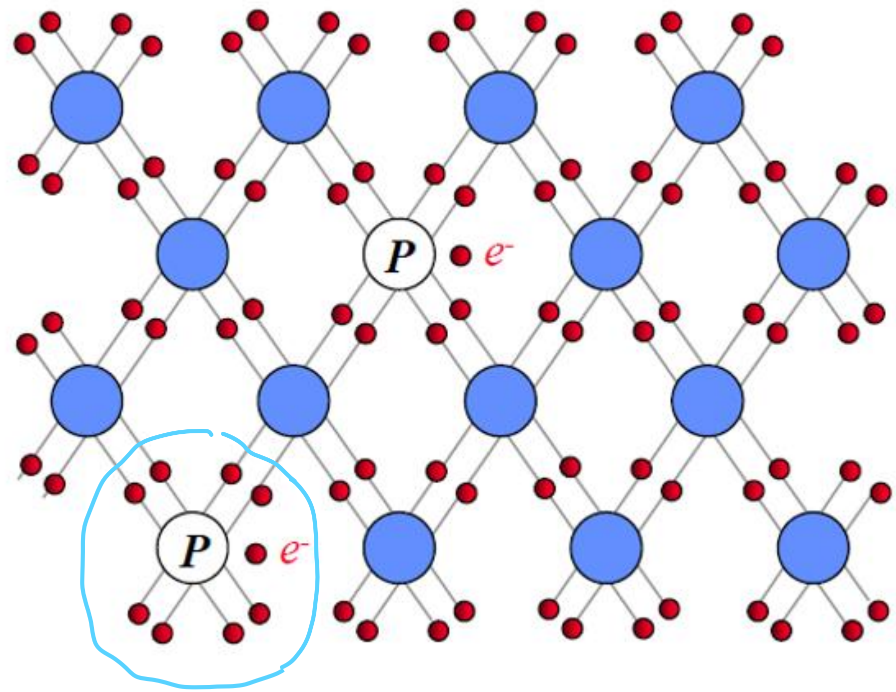
Nd N-Type

Extrinsic semiconductors

Na Acceptor

Nd Donor



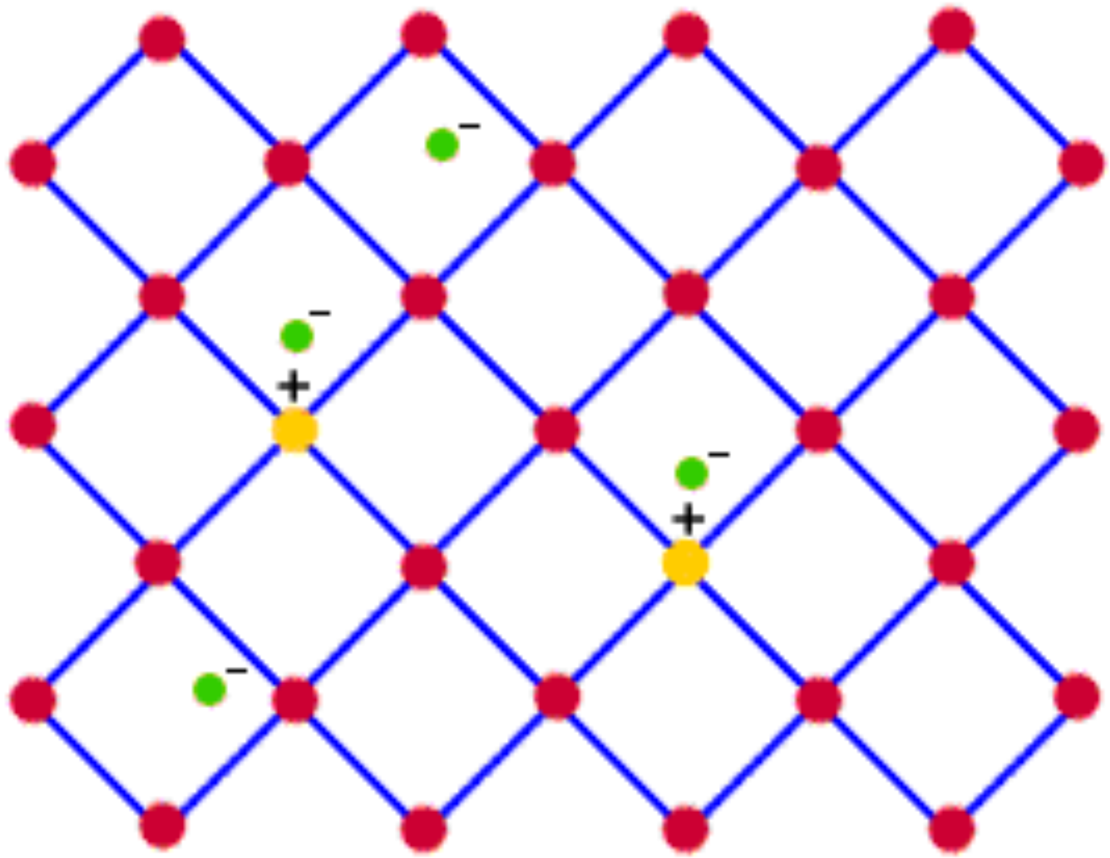


p-Type

n-Type

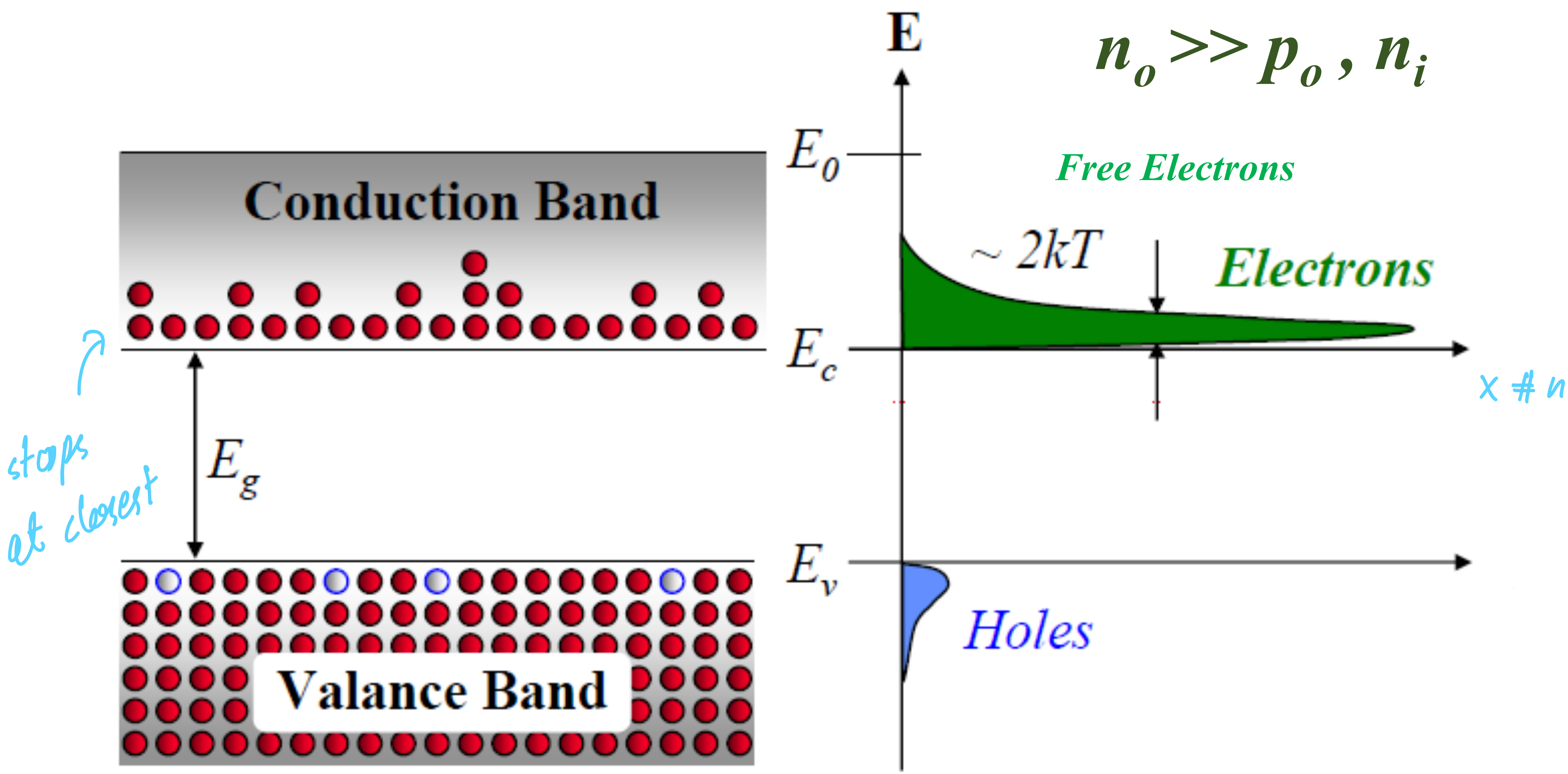
n-type Semiconductor

فيه اختلاف بال energy
gap

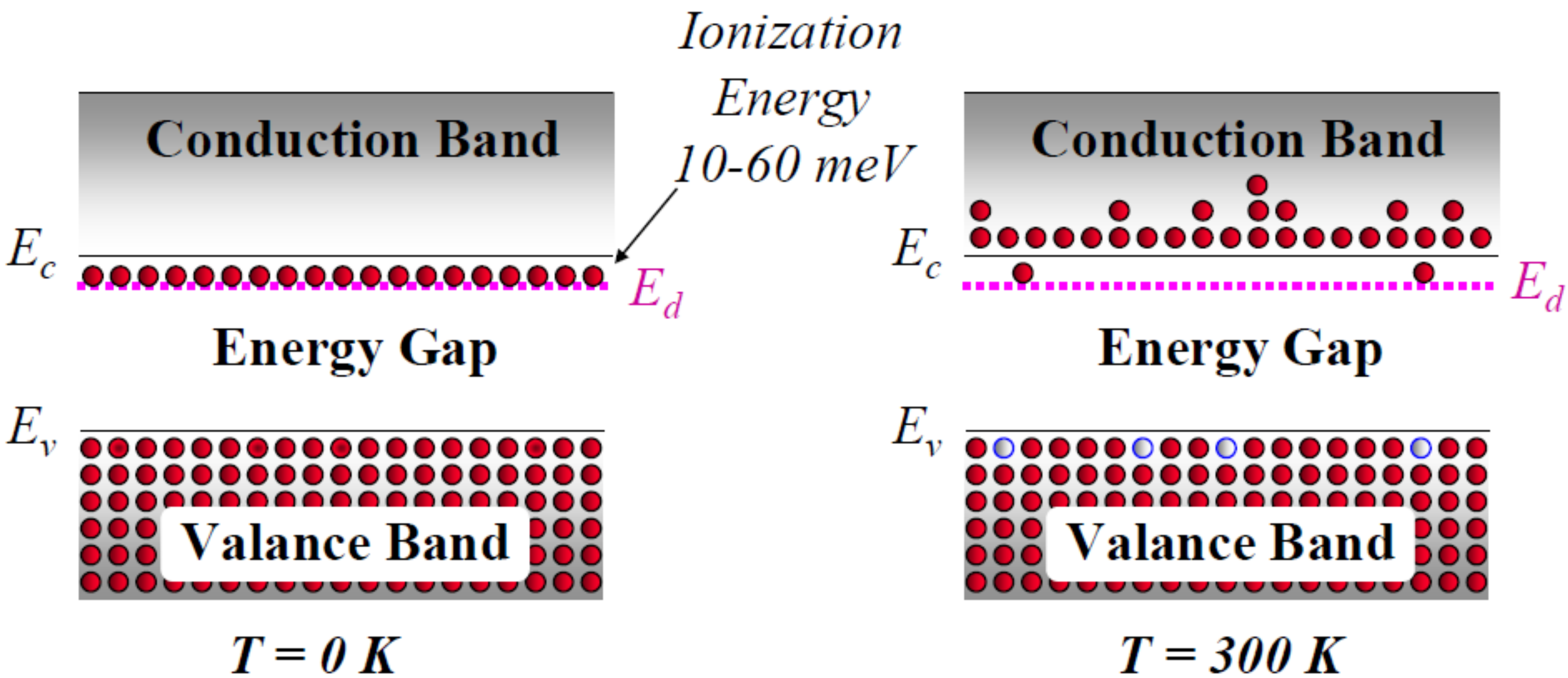


n-Type Semiconductors

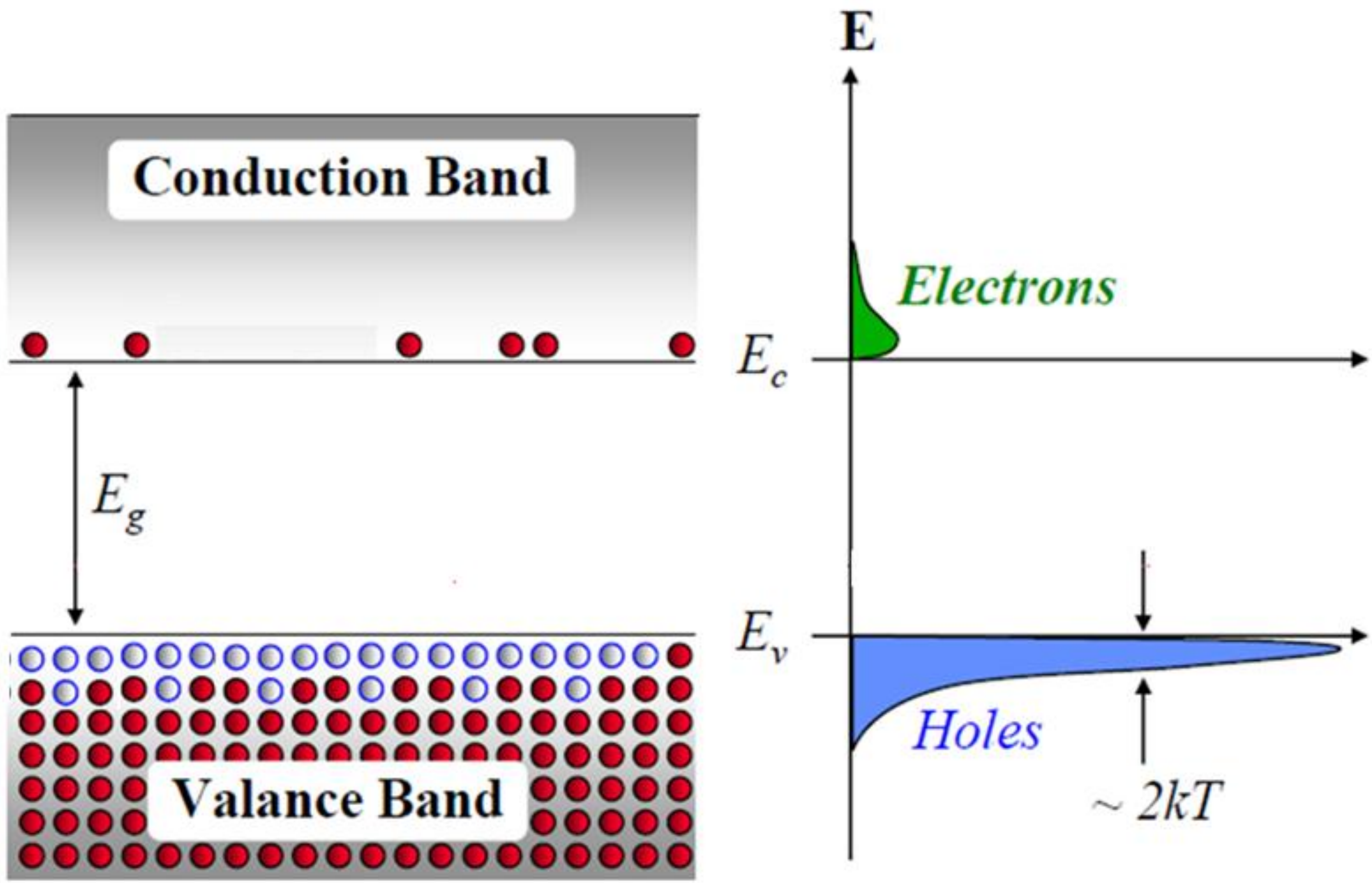
$$n_o >> p_o\ ,\ n_i$$



n-Type Semiconductors

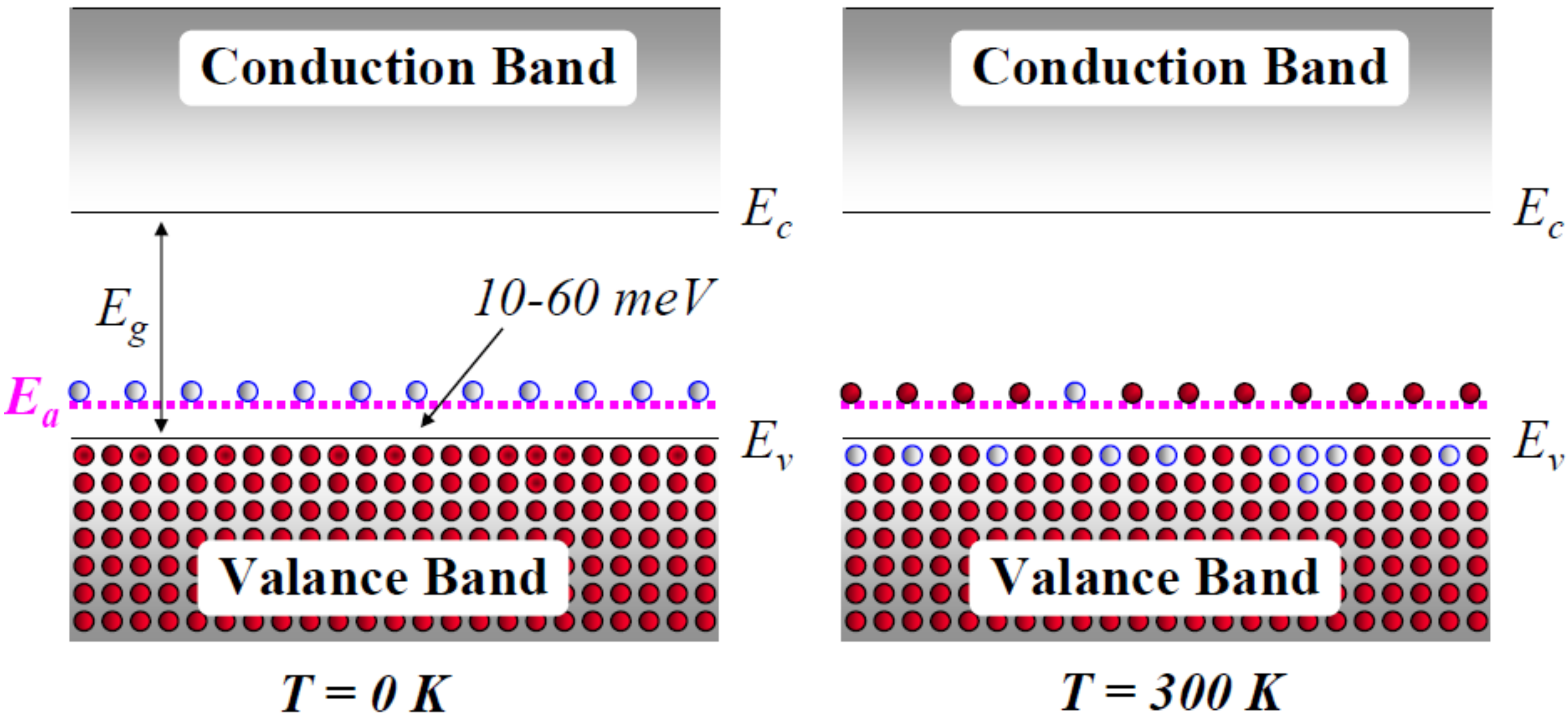


p-Type Semiconductors



$$p_o >> n_o , n_i$$

p-Type Concentration



Extrinsic Semiconductors

n-type

If the donor concentration N_d is much larger than the intrinsic concentration, we can approximate

$\boxed{np = n_i^2}$

N_d

$$n_o \cong N_d \qquad \text{Then,} \qquad p_o = \frac{n_i^2}{N_d}$$

if we know the majority we'll be able to find the minority

If the acceptor concentration N_a is much larger than the intrinsic concentration, we can approximate

$$p_o \cong N_a \qquad \text{Then,} \qquad n_o = \frac{n_i^2}{N_a}$$

Example 2

Calculate the thermal equilibrium electron and hole concentrations.

Consider silicon at $T = 300$ K doped with phosphorus at a concentration of $N_d = 10^{16}\ \text{cm}^{-3}$. $n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$.

Solution: since $N_d >> n_i$ the elec conc is

$n_0 \cong N_d = 10^{16}/\text{cm}$

$n = N_d >> n_i$

$p = \dfrac{n_i^2}{N_d}$

$= 2.25 \times 10^4/\text{cm}$

In an $\boxed{\text{n-type}}$ semiconductor, electrons are called the **majority carrier** because they far outnumber the holes, which are termed the **minority carrier.**

Example 3

Calculate the thermal equilibrium electron and hole concentrations.

Consider silicon at $T = 300$ K doped with boron at a concentration of $N_a = 5 \times 10^{16}$ cm^{-3}.

Solution: Since $N_a \gg n_i$, the hole concentration is

$$p_o \cong N_a = 5 \times 10^{16} /cm$$

and the elec. conc. is

$$n_o = \frac{n_i^2}{N_a} = 4.5 \times 10^{3} /cm^3$$

Compensated Semiconductor

A compensated semiconductor is one that contains both donor and acceptor impurity atoms in the same region.
We classify the compensated semiconductors as

P in the same
B ?

1- An *n*-type compensated semiconductor occurs when $Nd > Na$

2- A *p*-type compensated semiconductor occurs when $Na > Nd$

3. If $Na = Nd$, we get completely compensated semiconductor that has the characteristics of an intrinsic material

semicond.

n-Type Compensated Semiconductor

In thermal equilibrium, a semiconductor crystal is electrically neutral when

$$n_o + N_a^- = p_o + N_d^+$$

$$n_o + (N_a - p_a) = p_o + (N_d - n_d)$$

Assuming complete ionization $(p_a = n_d = 0)$

$$n_o + N_a = p_o + N_d$$

$$\boxed{n_o + N_a = \frac{n_i^2}{n_o} + N_d \quad with \quad p_o = \frac{n_i^2}{n_o}}$$

n-Type If only N_d Set $N_a=0$

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

صغيرة تنلغي

??

p-Type Compensated Semiconductor

In thermal equilibrium, a semiconductor crystal is electrically neutral

$$n_o + N_a^- = p_o + N_d^+$$

$$n_o + (N_a - p_a) = p_o + (N_d - n_d)$$

Assuming complete ionization $(p_a = n_d = 0)$

$$n_o + N_a = p_o + N_d$$

$$\frac{n_i^2}{p_o} + N_a = p_o + N_d \quad with \quad n_o = \frac{n_i^2}{p_o}$$

$n = \frac{n_i^2}{p}$

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

p-Type If only N_a Set $N_d = 0$

Example 4

Objective: Determine the thermal-equilibrium electron and hole concentrati in silicon at $T = 300$ K for given doping concentrations. (*a*) Let $N_d = 10^{16}$ cm^{-3} a $N_a = 0$. (*b*) Let $N_d = 5 \times 10^{15}$ cm^{-3} and $N_a = 2 \times 10^{15}$ cm^{-3}.

Recall that $n_i = 1.5 \times 10^{10}$ cm^{-3} in silicon at $T = 300$ K.

■ **Solution**

(a) the maj. carr. elec. conc. is

$$n_o = \frac{10^{16}}{2} \sqrt{\left(\frac{10^{16}}{2}\right)^2 + (1.5 \times 10^{10})^2} \cong 10^{16}/cm^3$$

The min. carrier hole conc. is found to be

$$p_o = \frac{n_i^2}{n_o} = \left(\frac{1.5 \times 10^{10}}{2}\right)^2 + (1.5 \times 10^{10})^2 \cong 3 \times 10^{15}/cm^3$$

$$p_o = 7.5 \times 10^4/cm^3$$

Example 4

Example 5

Objective: Calculate the thermal-equilibrium electron and hole concentrations in a compensated p-type semiconductor.

Consider a silicon semiconductor at $T = 300$ K in which $N_a = 10^{16}$ cm^{-3} and $N_d = 3 \times 10^{15}$ cm^{-3}. Assume $n_i = 1.5 \times 10^{10}$ cm^{-3}.

$N_a > N_d \rightarrow p$ type

major. $\rightarrow p$

■ **Solution**

$p_o \simeq 7 \times 10^{15} / cm^3$

$$n_o = \frac{n_i^2}{p_o} = \frac{(1.5 \times 10^{10})^2}{7 \times 10^{15}} = 3.21 \times 10^4 / cm^3$$

Example 5