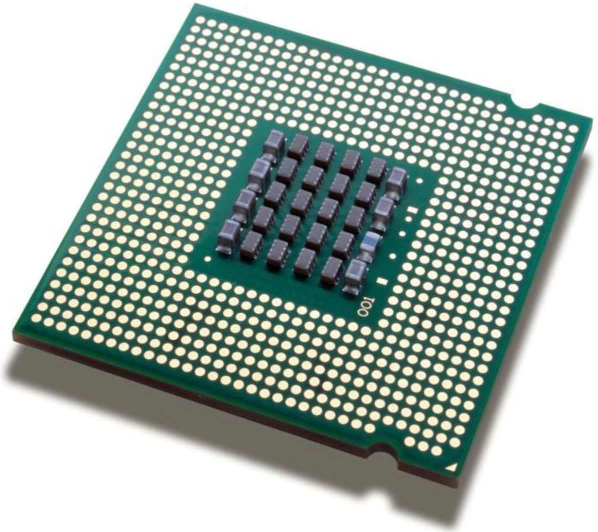
# UNIT IV

## Semiconductor Physics

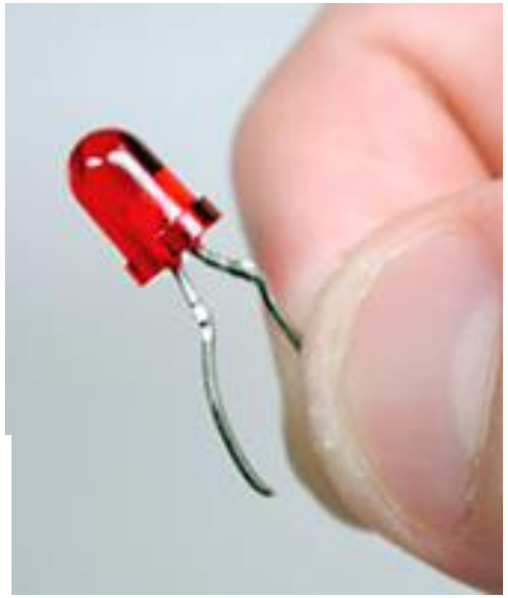
# What is a Semiconductor?



Microprocessors


Transistors


Capacitors



LED

# Electronic Materials

- ✓ The goal of electronic materials is to generate and control the flow of an electrical current.

- ✓ Electronic materials include:

  - ❑ Conductors: have low resistance which allows electrical current flow
  - ❑ Insulators: have high resistance which suppresses electrical current flow
  - ❑ Semiconductors: can allow or suppress electrical current flow

# Conductors

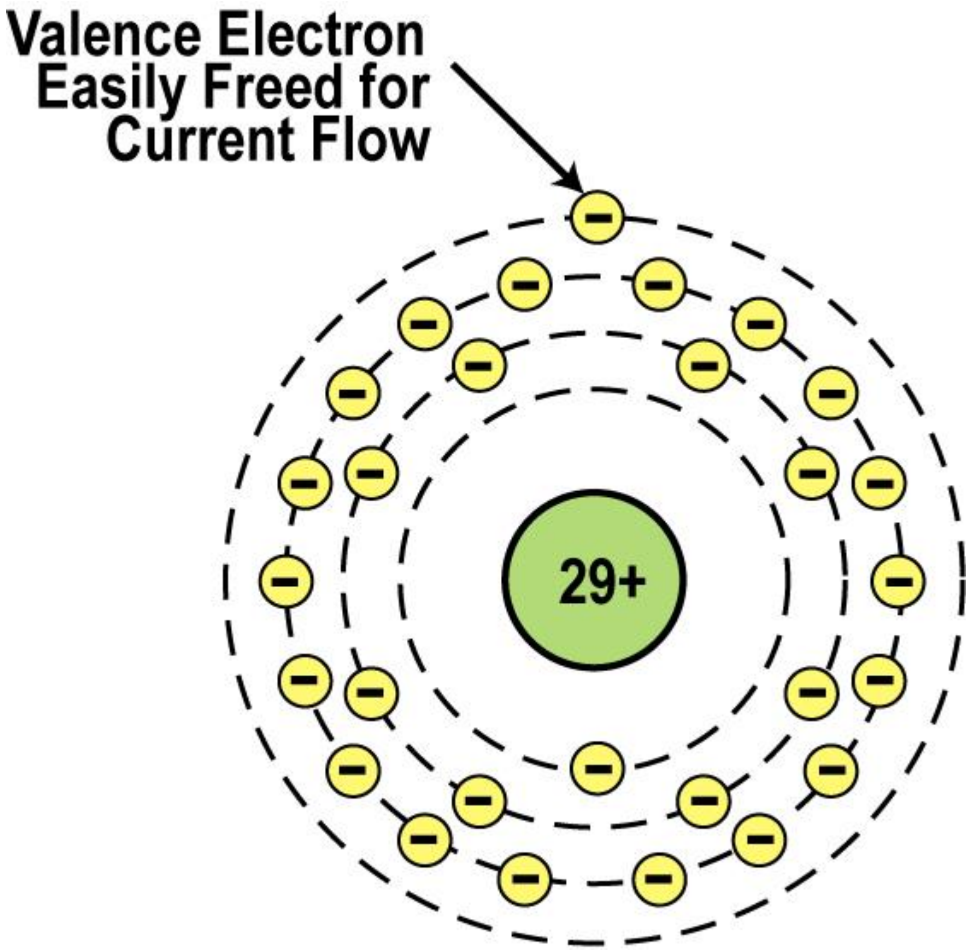
- ✓Good conductors have low resistance so electrons flow through them with ease.
- ✓**Best** element conductors include: Copper, silver, gold, aluminum, & nickel
- ✓Alloys are also good conductors: Brass & steel
- ✓Good conductors can also be liquid: Salt water

# Conductor Atomic Structure

- ✓ The atomic structure of good conductors usually includes only <u>one electron in their outer shell</u>.

  - ✓ It is called a valence electron.

  - ✓ It is easily striped from the atom, producing current flow.




Copper Atom

# Insulators

- ✓ Insulators have a high resistance so current does not flow in them.
- ✓ Good insulators include: Glass, ceramic, plastics, & wood
- ✓ Most insulators are compounds of several elements.
- ✓ The atoms are tightly bound to one another so electrons are difficult to strip away for current flow.

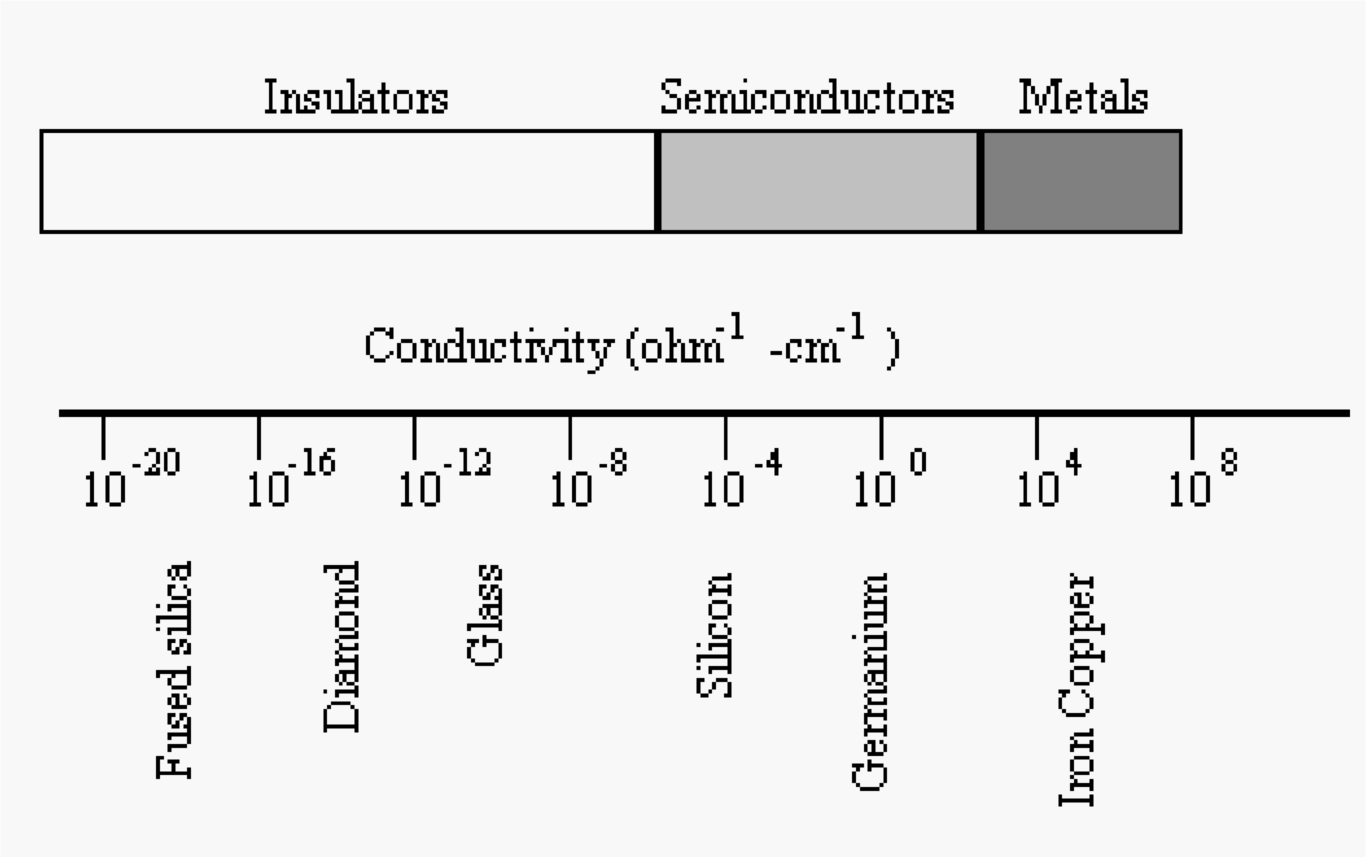
# Semiconductors

- ✓ Semiconductors are materials that essentially can be conditioned to act as good conductors, or good insulators, or any thing in between.

- ✓ Common elements such as **carbon, silicon**, and **germanium** are semiconductors.

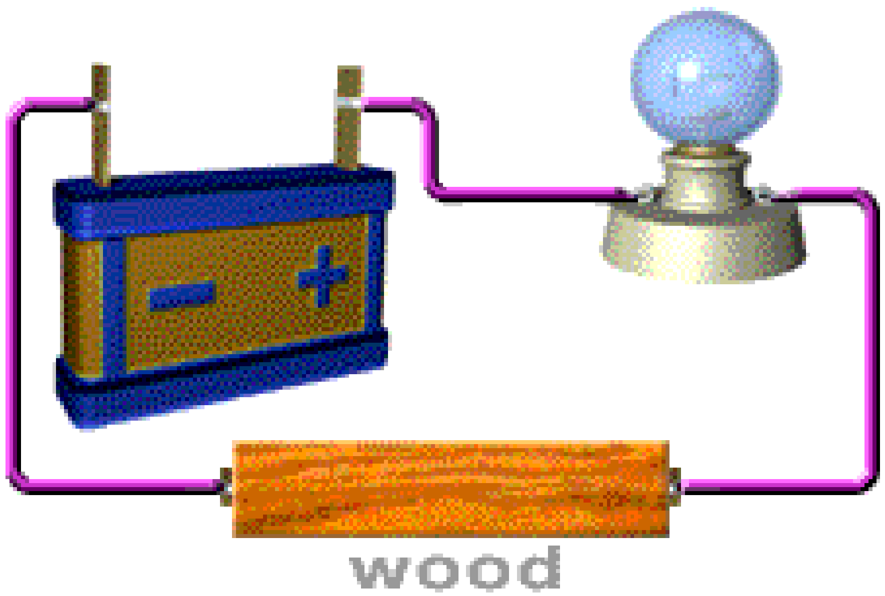
- ✓ Silicon is the best and most widely used semiconductor.

# Range of conduciveness




***The semiconductors fall somewhere midway between conductors and insulators.***

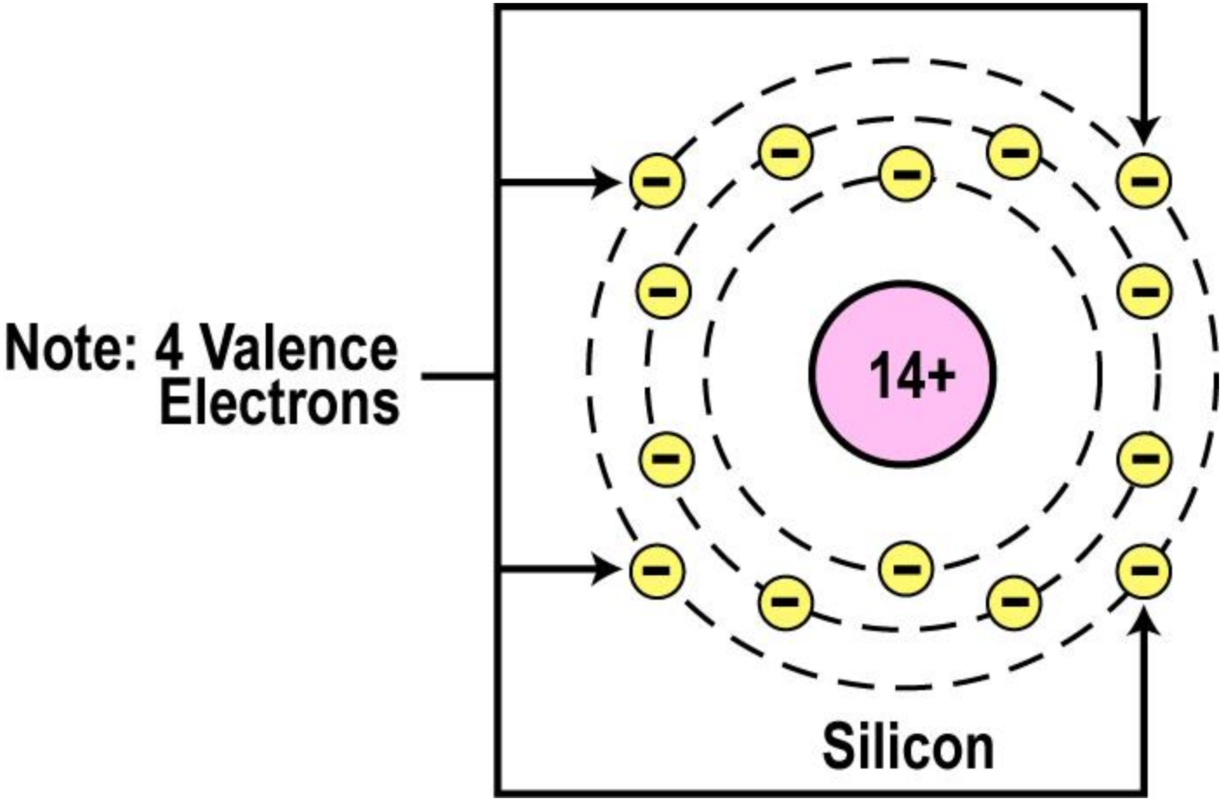
# Range of conduciveness



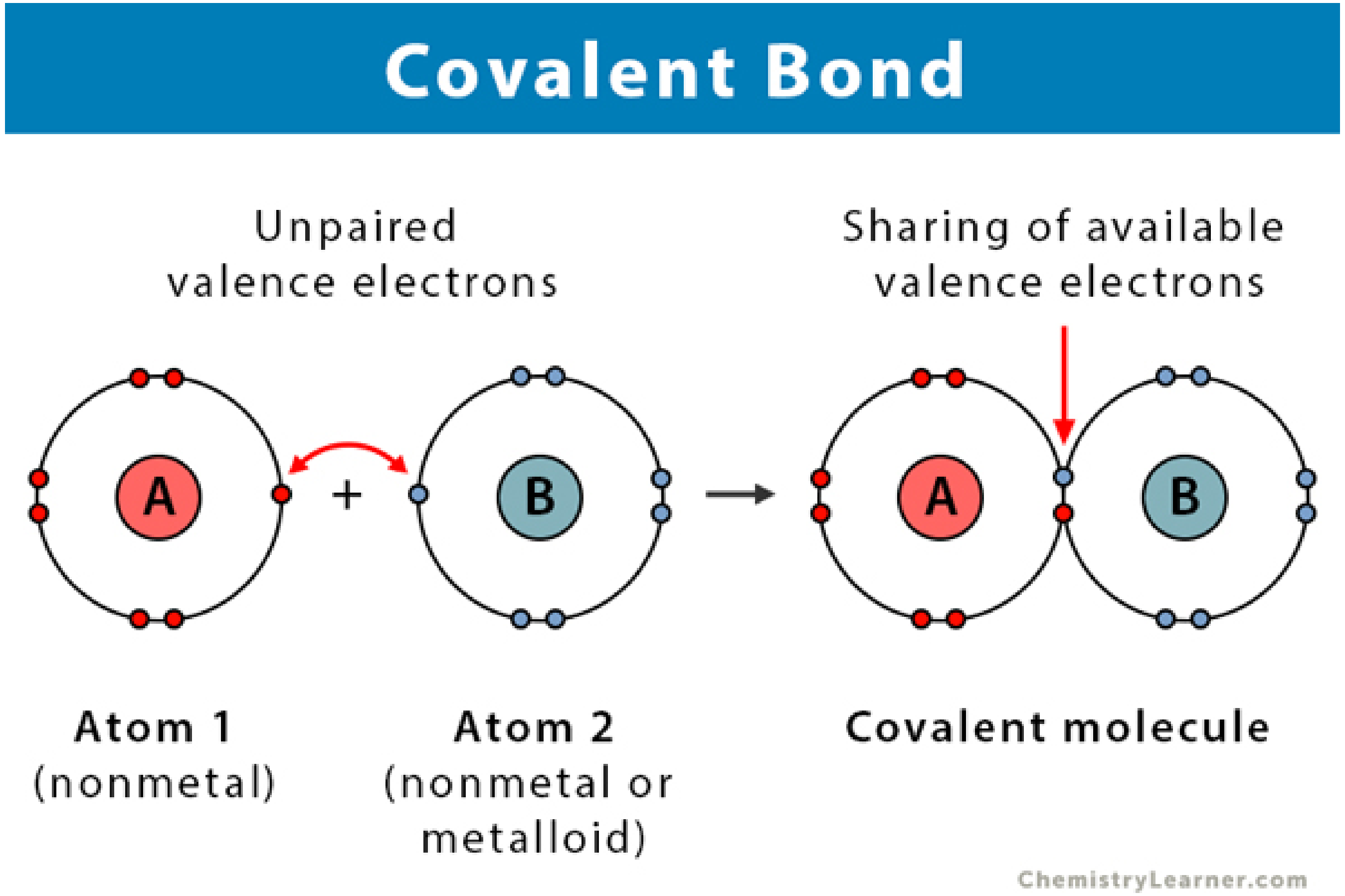

***Semiconductors have special electronic properties which allow them to be insulating or conducting depending on their composition.***

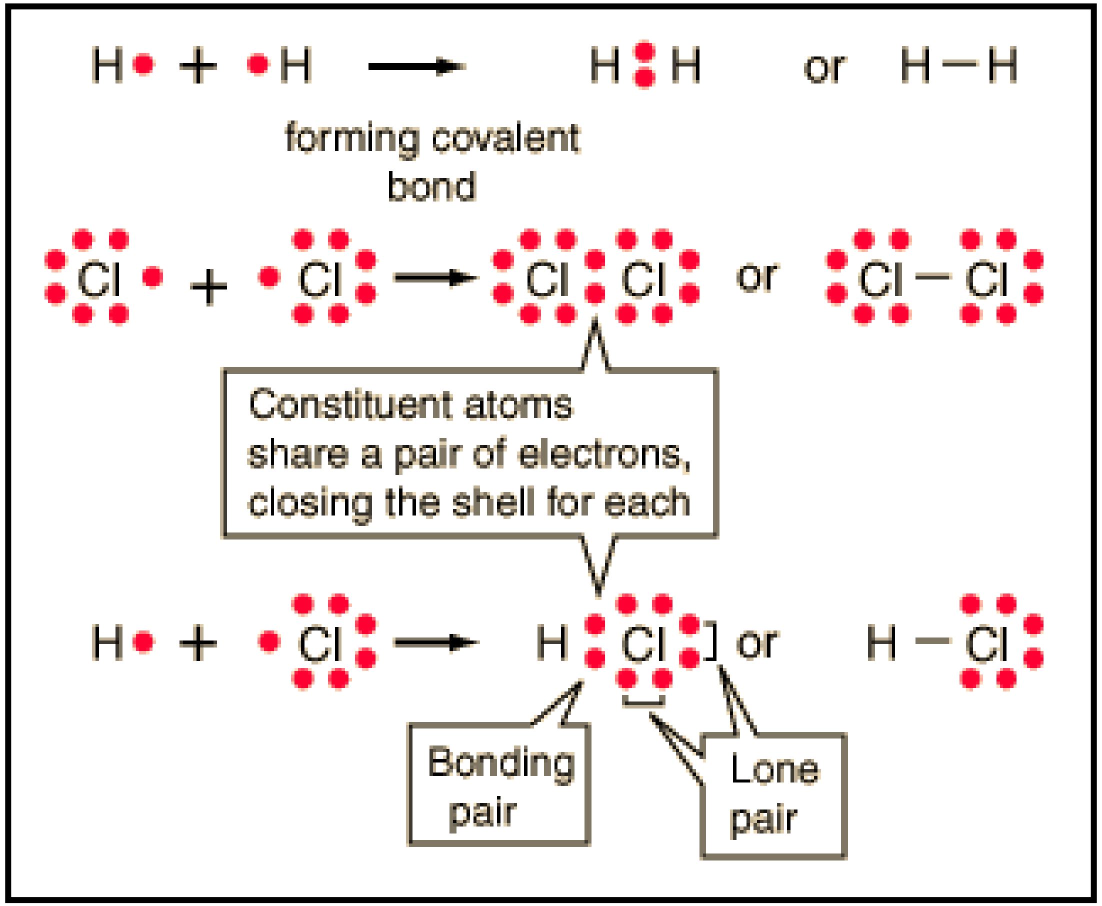
## Semiconductor Valence Orbit

- The main characteristic of a semiconductor element is that it has **four electrons** in its outer or valence orbit.



# Covalent Bonds



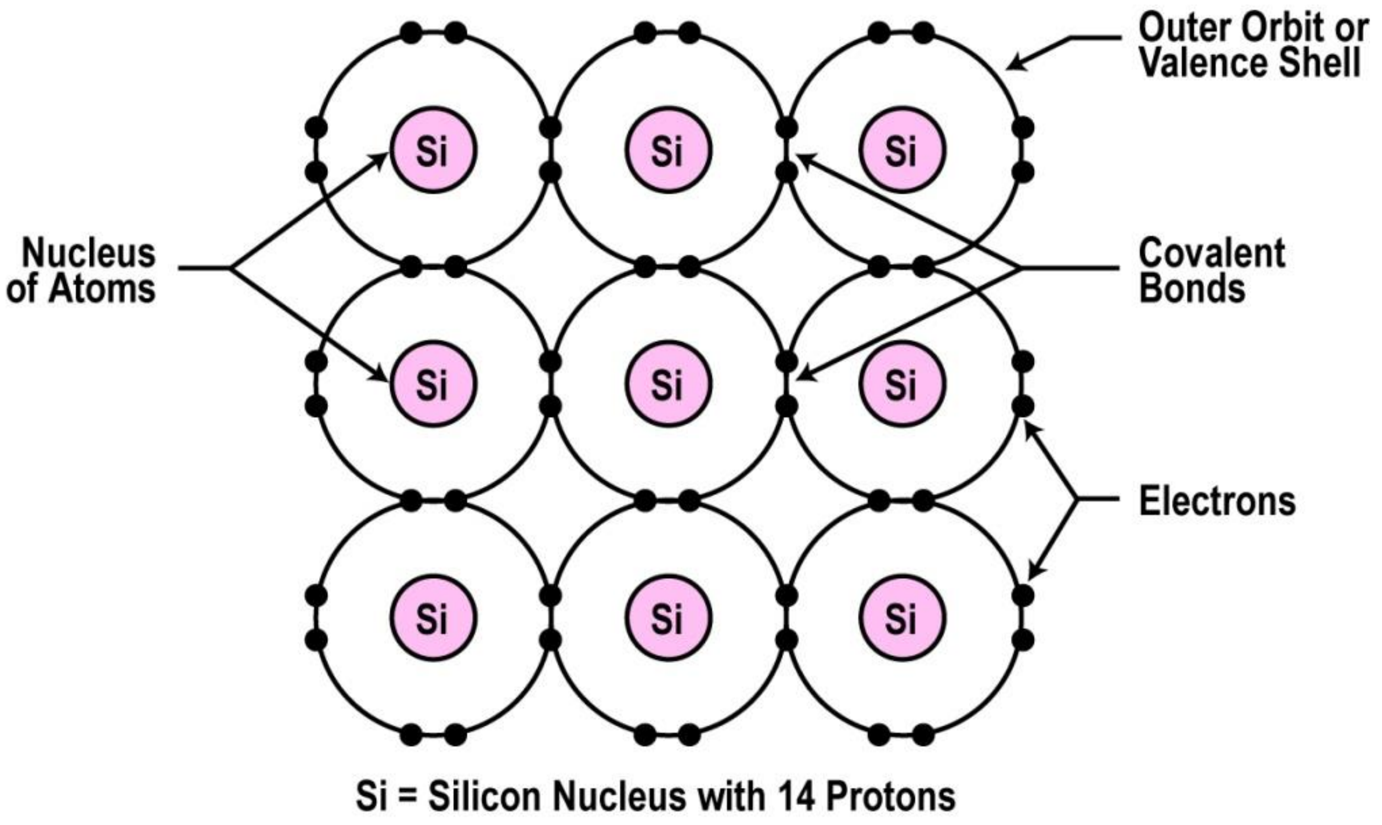



# Crystal Lattice Structure

- ✓ The unique capability of semiconductor atoms is their ability to link together to form a physical structure called a crystal lattice.

- ✓ The atoms link together with one another sharing their outer electrons.

- ✓ These links are called covalent bonds.




**2D Crystal Lattice Structure**

# Covalent Solids

Ge, Si, diamond

- 3D collection of atoms bound by shared valence electrons
- difficult to deform because bonds are directional
- high melting points (b/c diff to deform)
- no free electrons → poor electrical conductors
- most solids adsorb photons in visible → opaque

# Classification of semiconductors

## Intrinsic semiconductor

Semiconductors which are chemically pure, meaning free of impurities, are called **Intrinsic Semiconductors** or Undoped Semiconductor

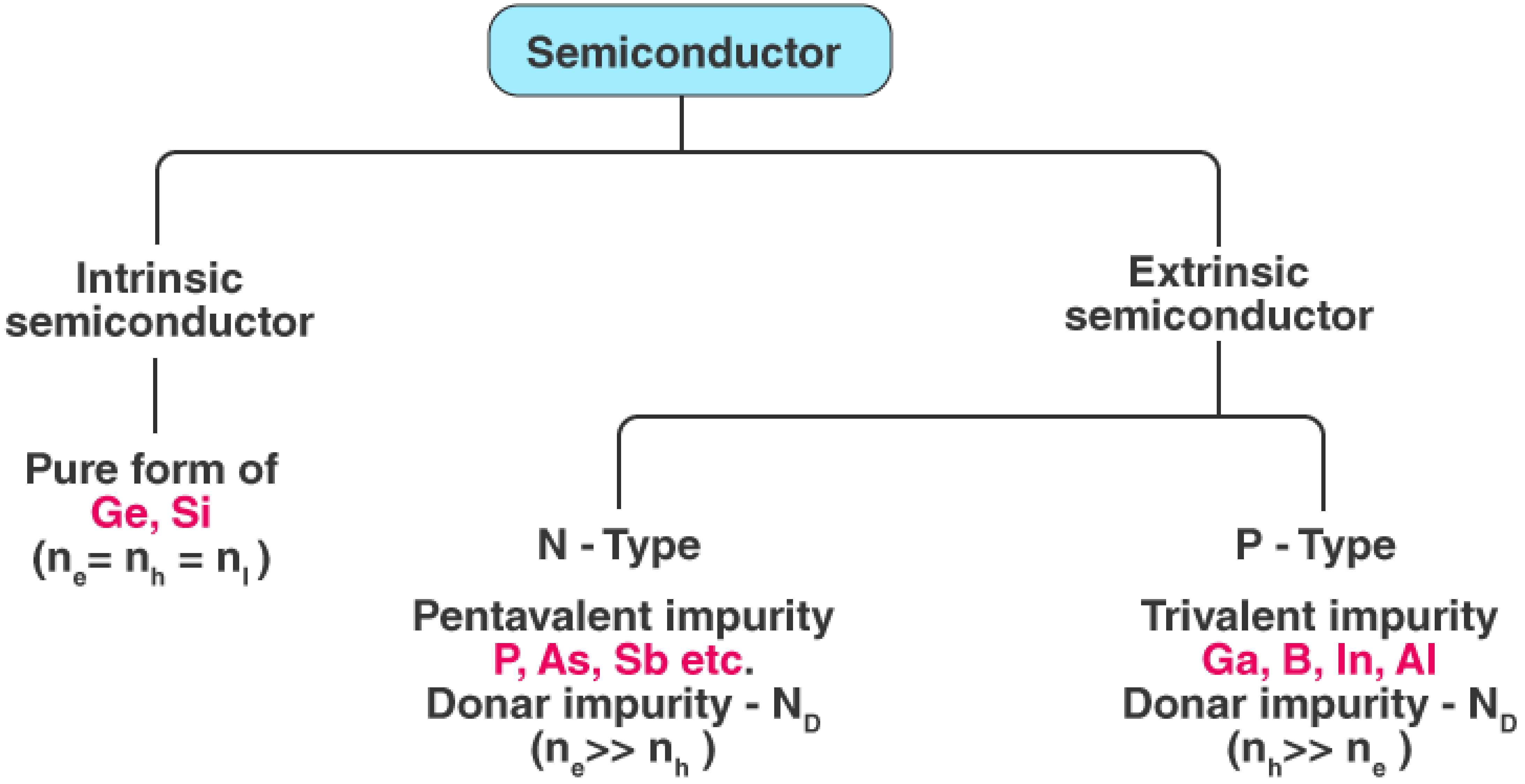
Example : Si and Ge

## Extrinsic semi conductor

Semiconductors which are doped with impurities are called **extrinsic Semiconductors** or doped Semiconductor

Example : Si and Ge doped with As, Ga etc.

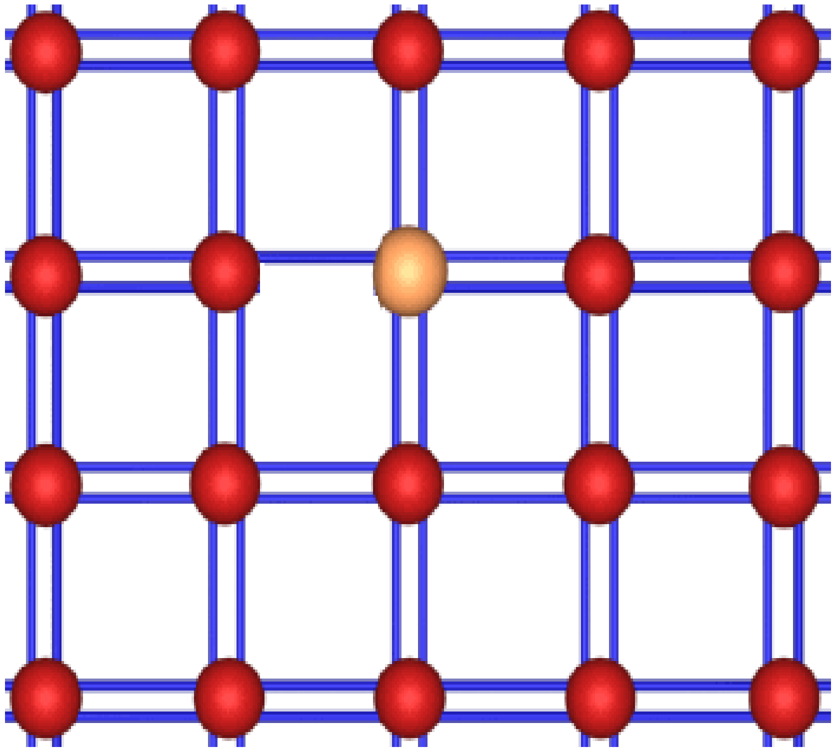
| S.No | Intrinsic Semiconductor | Extrinsic Semiconductor |
|---|---|---|
| 1. | Semiconductor in a pure form is called intrinsic semiconductor. | Semiconductor which are doped with impurity is called extrinsic semiconductor |
| 2. | Here the change carriers are produced only due to thermal agitation. | Here the change carriers are produced due to impurities and may also be produced due to thermal agitation. |
| 3. | They have low electrical conductivity. | They have high electrical conductivity. |
| 4. | They have low operating temperature. | They have high operating temperature. |
| 5. | At 0K, Fermi level exactly lies between conduction band and valence band. | At 0K, Fermi level exactly lies closer to conduction band in "n" type semiconductor and lies near valence band in "p" type semiconductor. |
| | **Examples:** Si,Ge,etc. | **Examples:** Si and Ge doped with Al, In,P,As etc |


Semiconductor
Intrinsic semiconductor
Pure form of
Ge, Si
$(n_e = n_h = n_i)$
Extrinsic semiconductor
N - Type
Pentavalent impurity
P, As, Sb etc.
Donar impurity - $N_D$
$(n_e >> n_h)$
P - Type
Trivalent impurity
Ga, B, In, Al
Donar impurity - $N_D$
$(n_h >> n_e)$

# Doping

- To make the semiconductor conduct electricity, other atoms called impurities must be added.
- "Impurities" are different elements.
- This process is called doping.

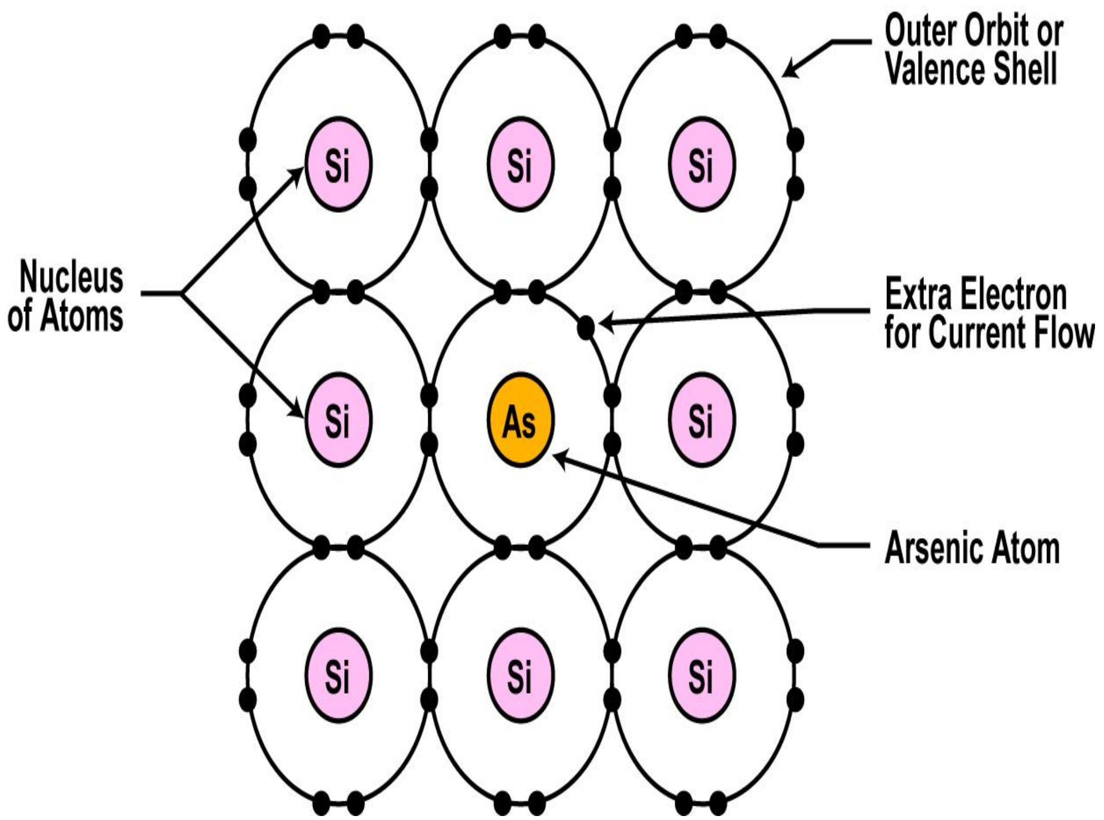
Doping can be done by adding trivalent impurities (Al) and pentavalent impurities (P)



***Doping (adding an impurity) can produce 2 types of semi-conductors depending upon the element added.***

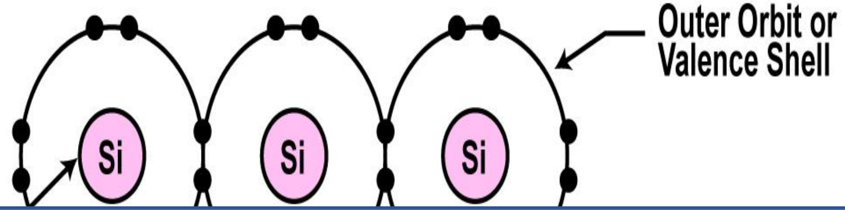
# Pentavalent doping :

- An impurity, or element like arsenic, has 5 valence electrons.
- Adding arsenic (doping) will allow four of the arsenic valence electrons to bond with the neighboring silicon atoms.
- The one electron left over for each arsenic atom becomes available to conduct current flow.



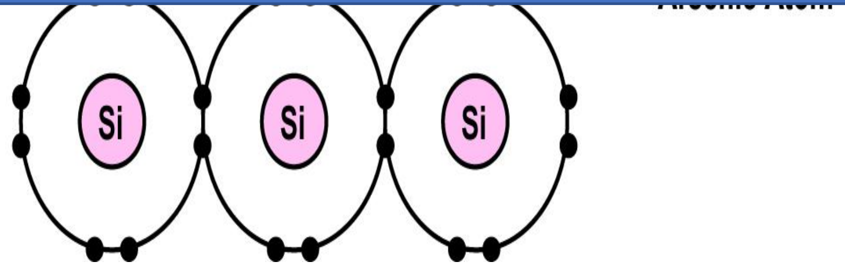
# Pentavalent doping :

- An impurity, or element like arsenic, has 5 valence electrons.




**Intrinsic semiconductor + Pentavalent impurity = N-type semiconductor**

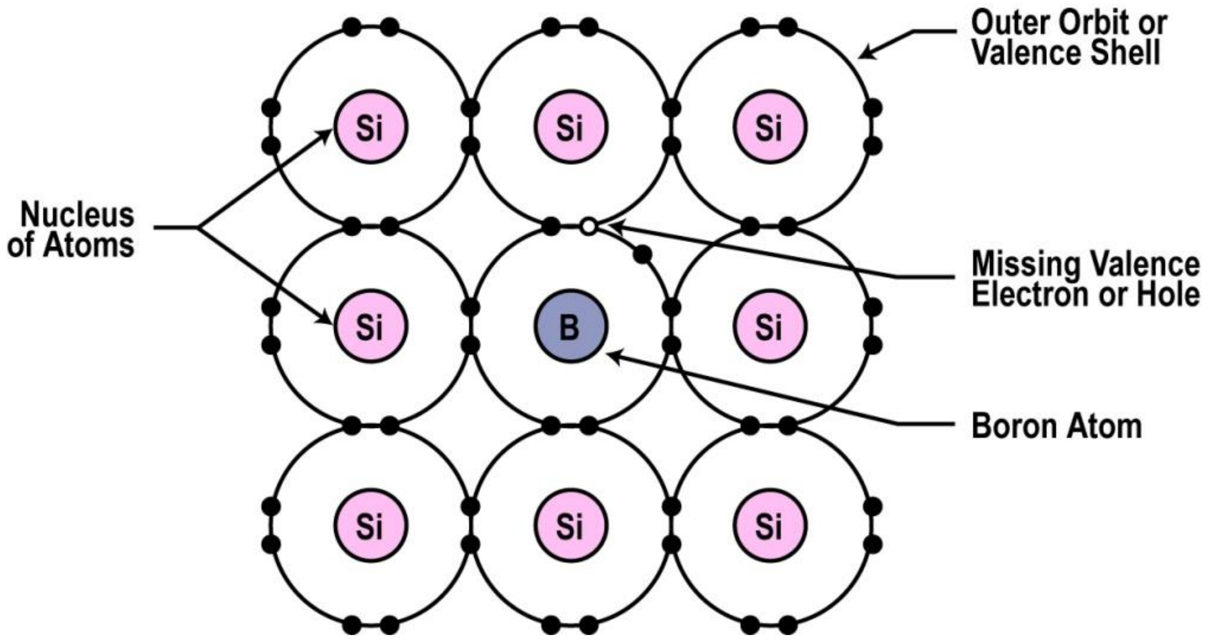
**Majority carriers : Electrons**




- The one electron left over for each arsenic atom becomes available to conduct current flow.

# Trivalent doping :

- You can also dope a semiconductor material with an atom such as boron that has only 3 valence electrons.
- The 3 electrons in the outer orbit do form covalent bonds with its neighboring semiconductor atoms as before. But one electron is missing from the bond.
- This place where a fourth electron should be is referred to as a hole.
- The hole assumes a positive charge so it can attract electrons from some other source.
- Holes become a type of current carrier like the electron to support current flow.



# Trivalent doping :

- You can also dope a semiconductor material with an atom such as boron that has only 3 valence electrons.

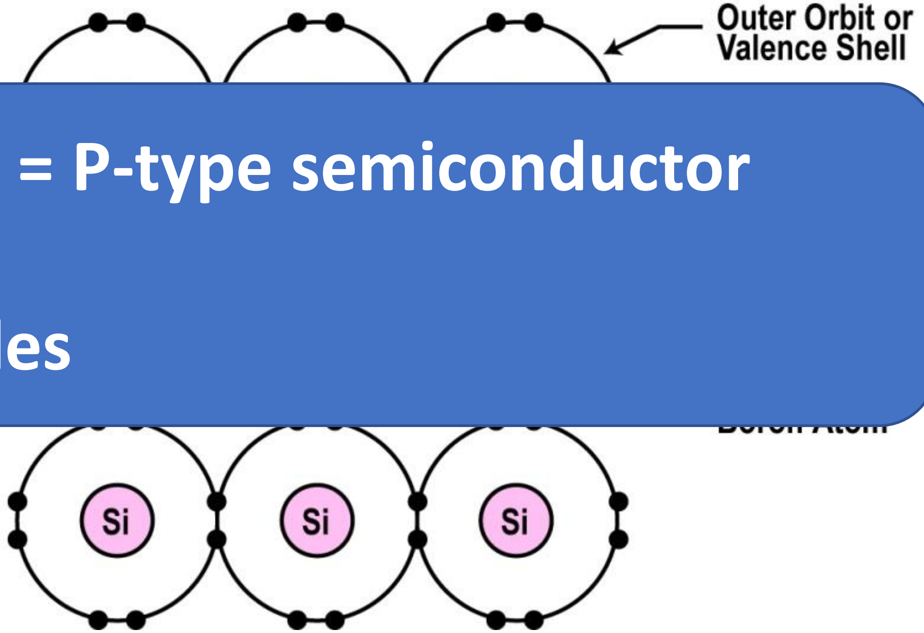
- The 3 electrons in the outer orbit do form covalent bonds with its neighboring

**Intrinsic semiconductor + Trivalent impurity = P-type semiconductor**

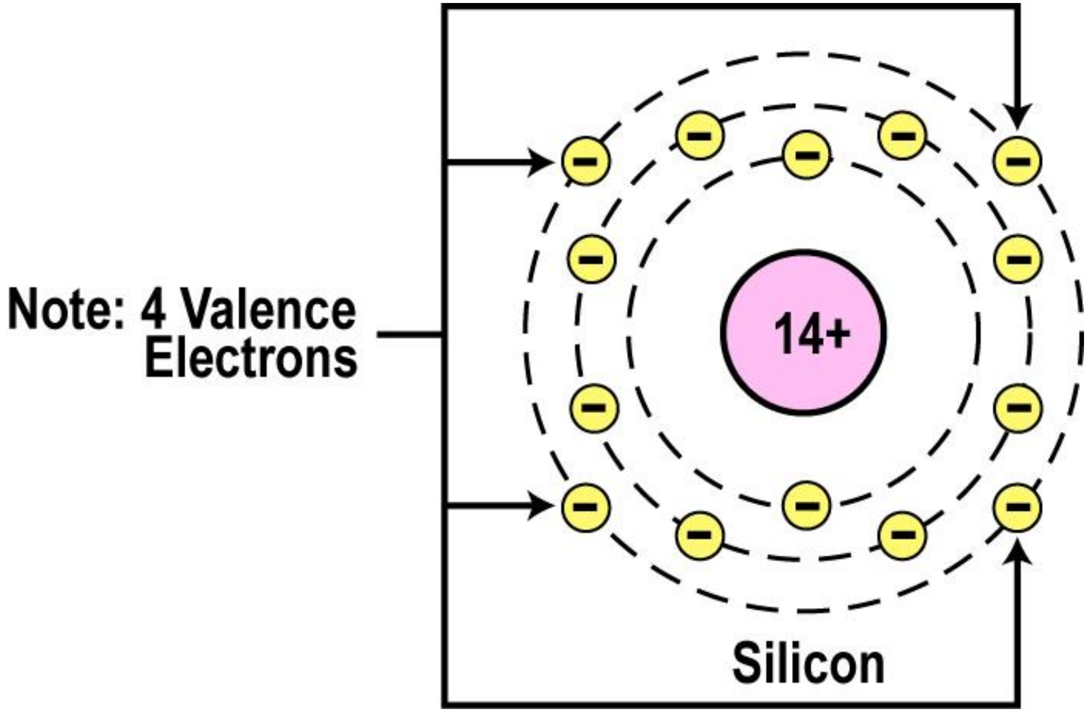
**Majority carriers : Holes**

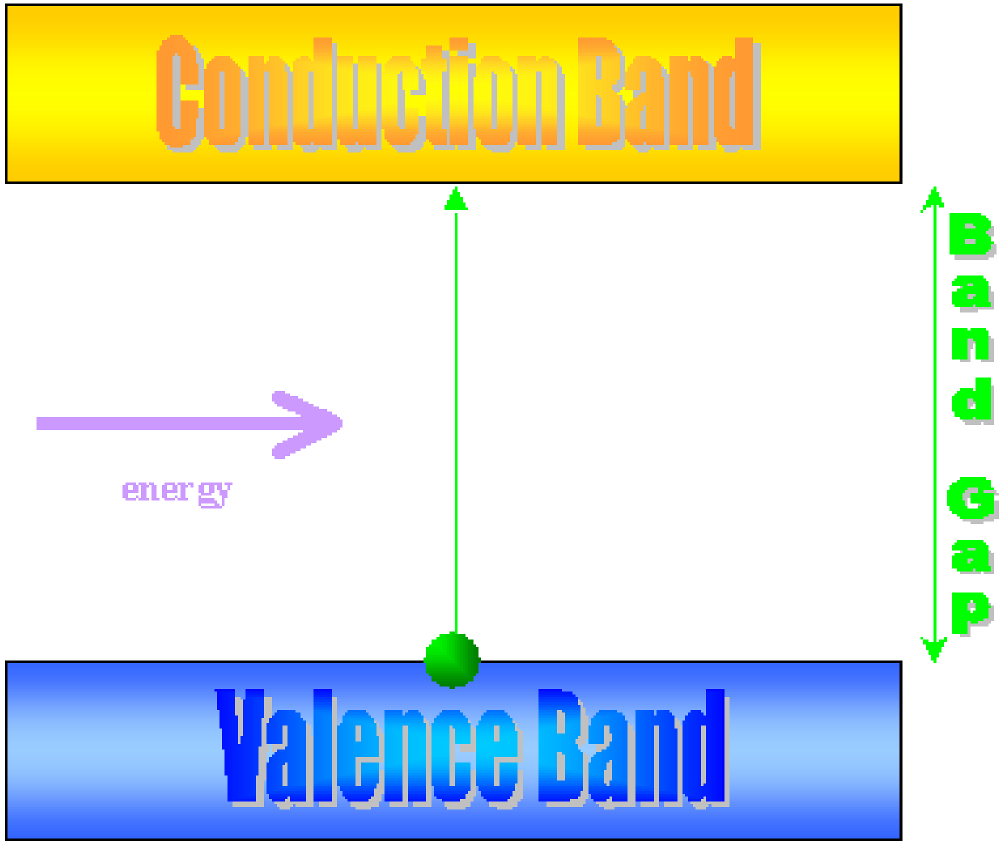
- The hole assumes a positive charge so it can attract electrons from some other source.

- Holes become a type of current carrier like the electron to support current flow.

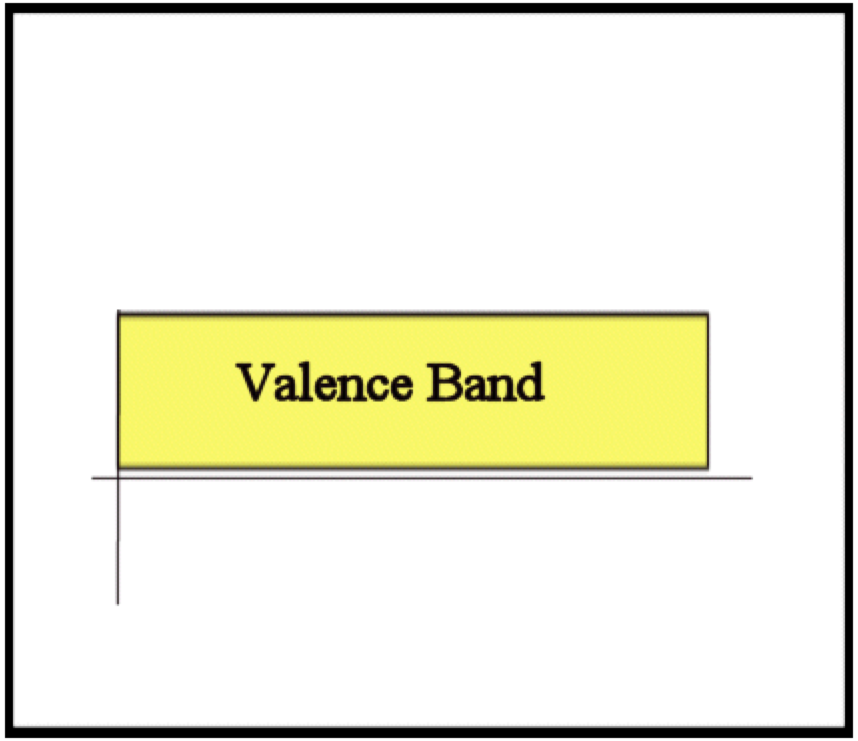


# Scientific Principle of Conduction



# Valence Band



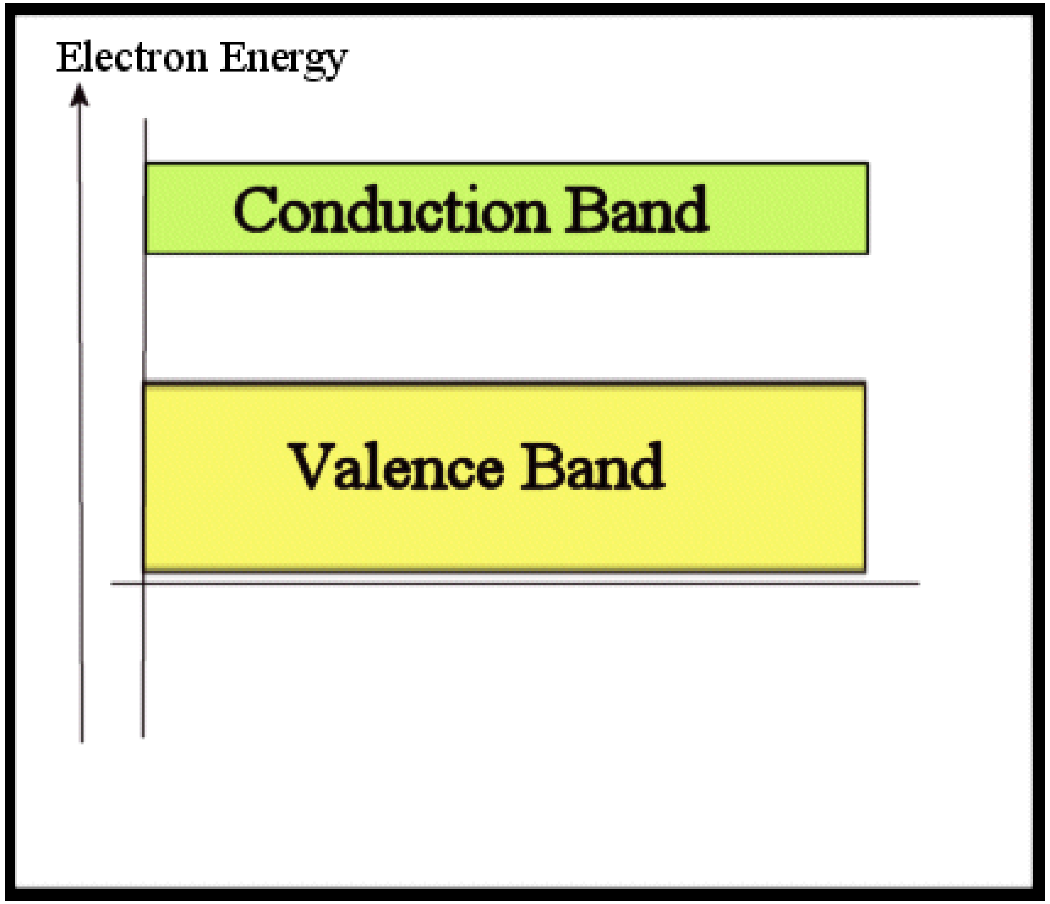

***The highest occupied energy band is called the valence band.***

***Most electrons remain bound to the atoms in this band.***

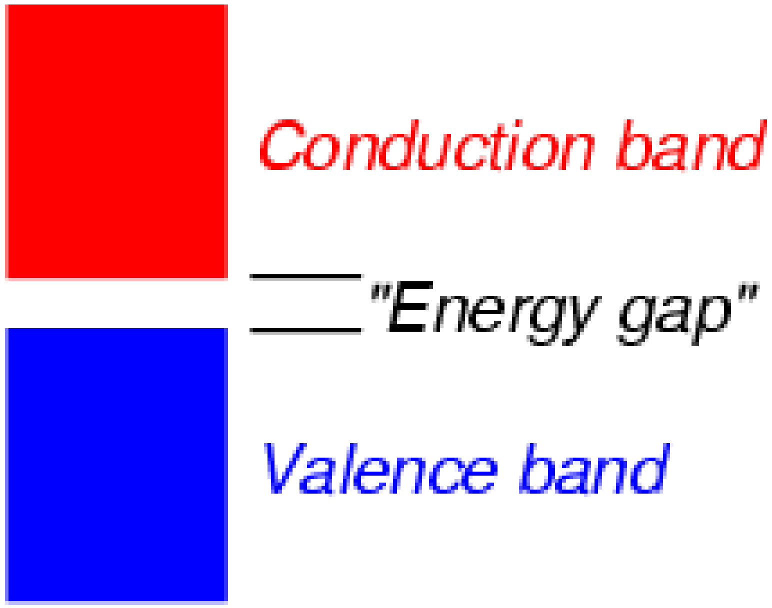
# Conduction Band

***The conduction band is the band of orbitals that are high in energy and are generally empty.***

***It is the band that accepts the electrons from the valence band.***



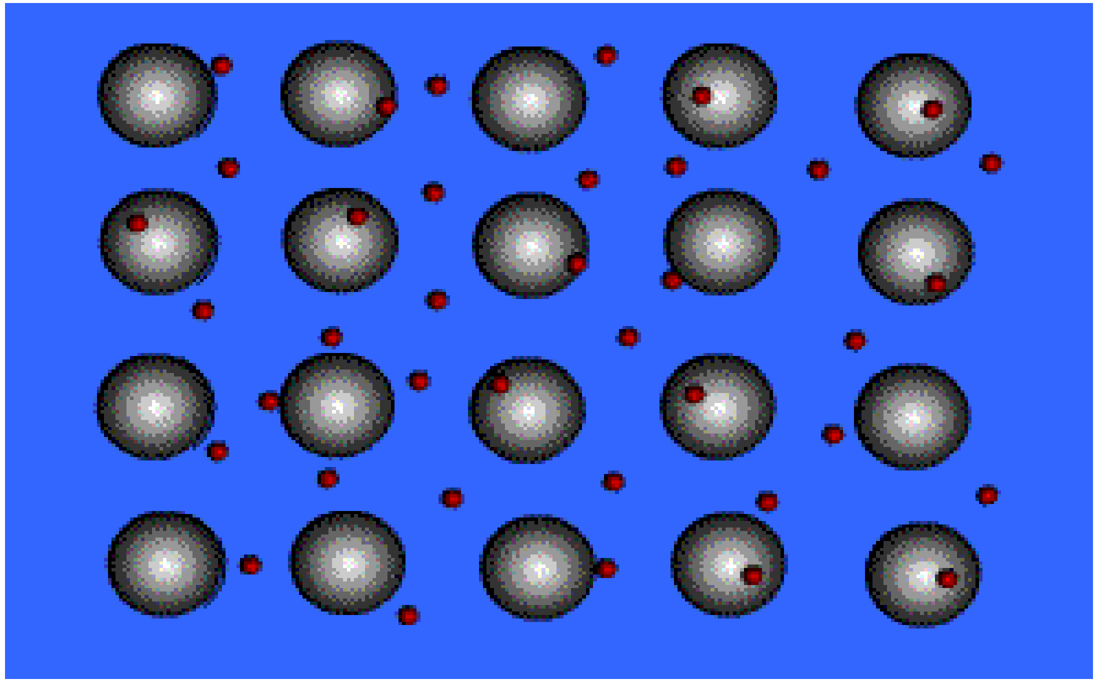
# Energy Gap




***The "leap" required for electrons from the Valence Band to enter the Conduction Band.***

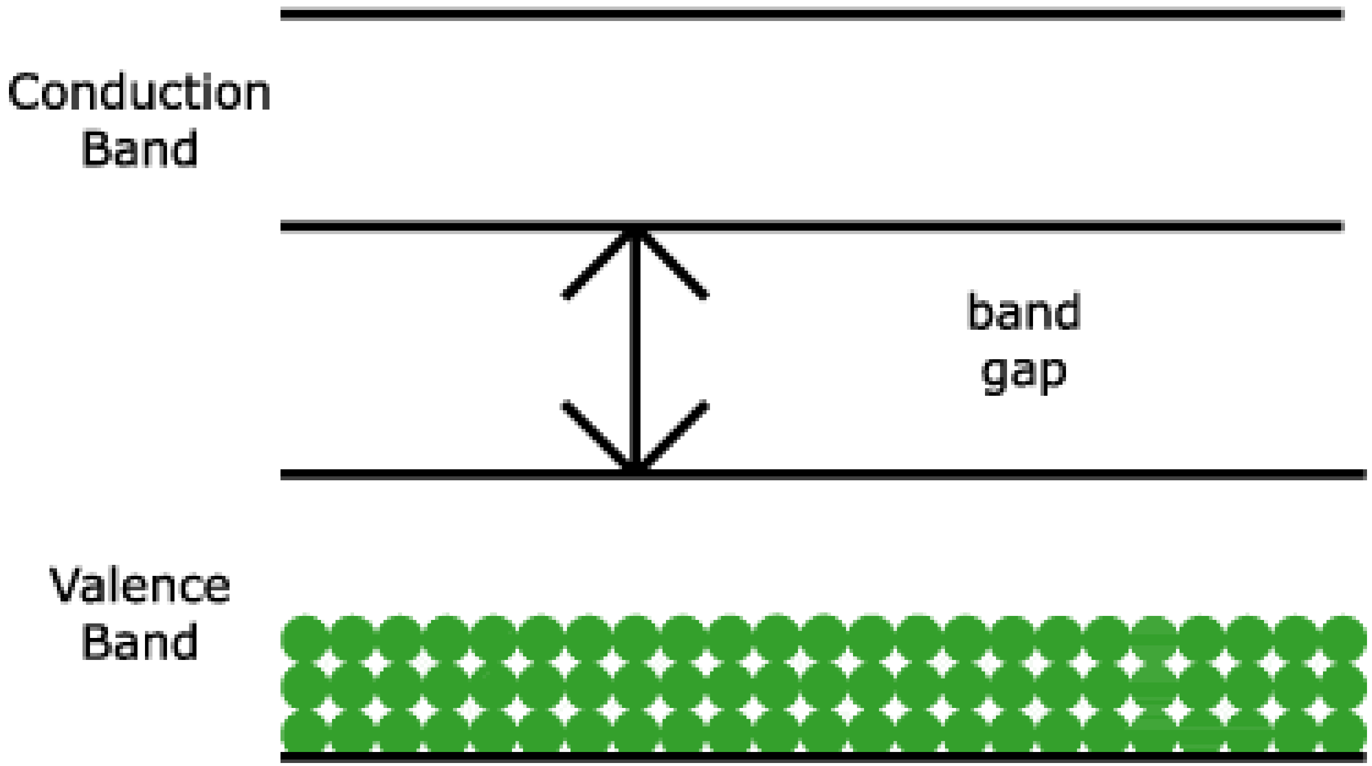

Conduction Band
Band Gap
Valence Band
LongIslandExchange.com

# Conductors



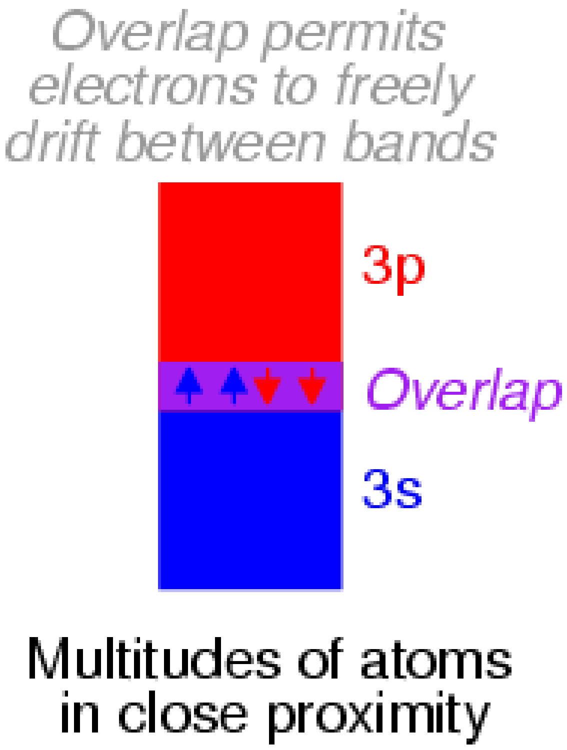
***In a conductor, electrons can move freely among these orbitals within an energy band as long as the orbitals are not completely occupied.***

# Conductors



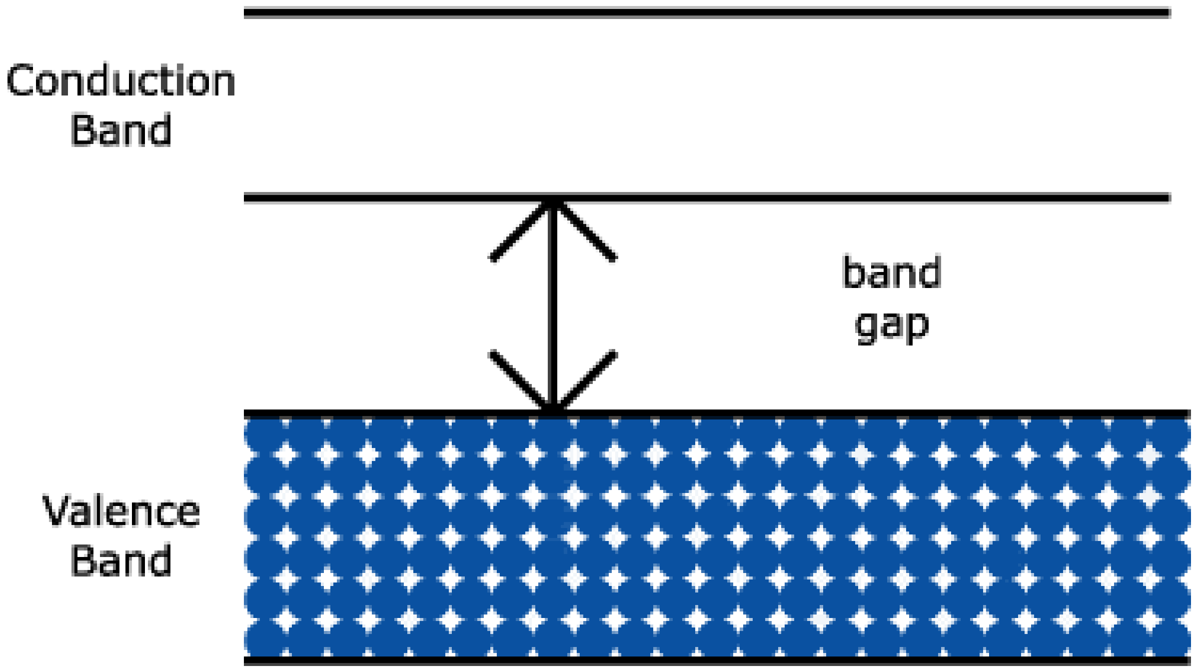

***In conductors, the valence band is empty.***

# Conductors



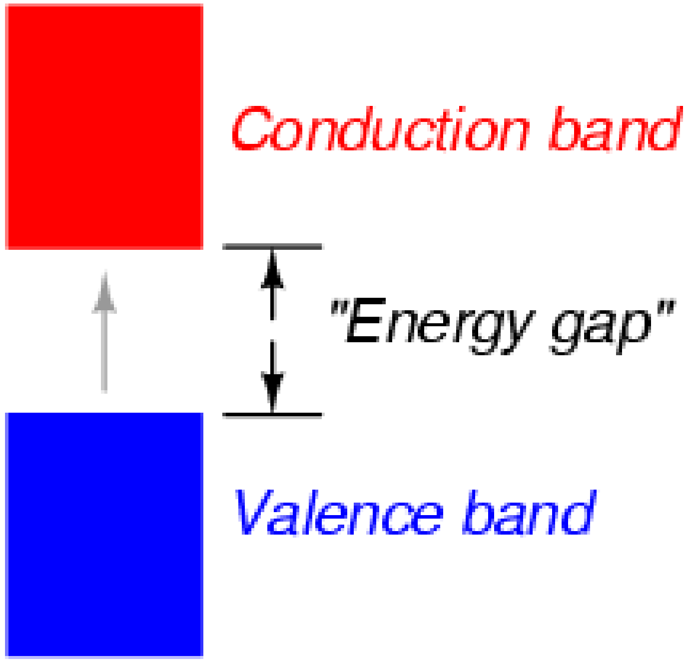

***Also in conductors, the energy gap is nonexistent or relatively small.***

# Insulators



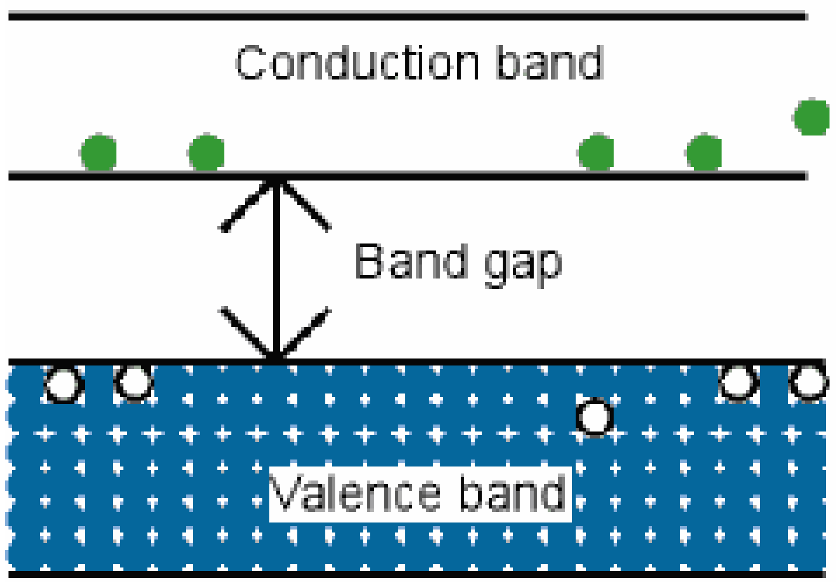

***In insulators, the valence band is full.***

# Insulators



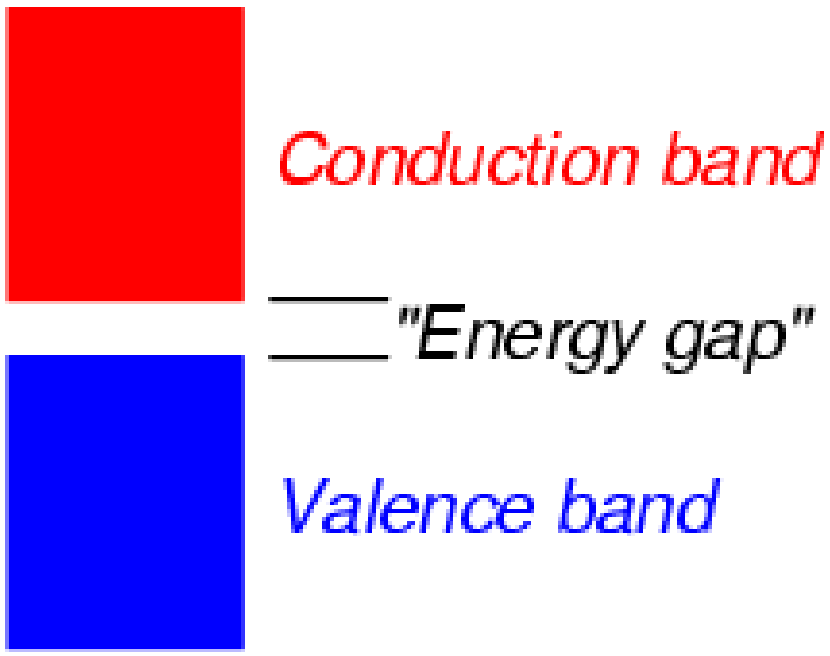

***Also in insulators, the energy gap is relatively large.***

# Semiconductors



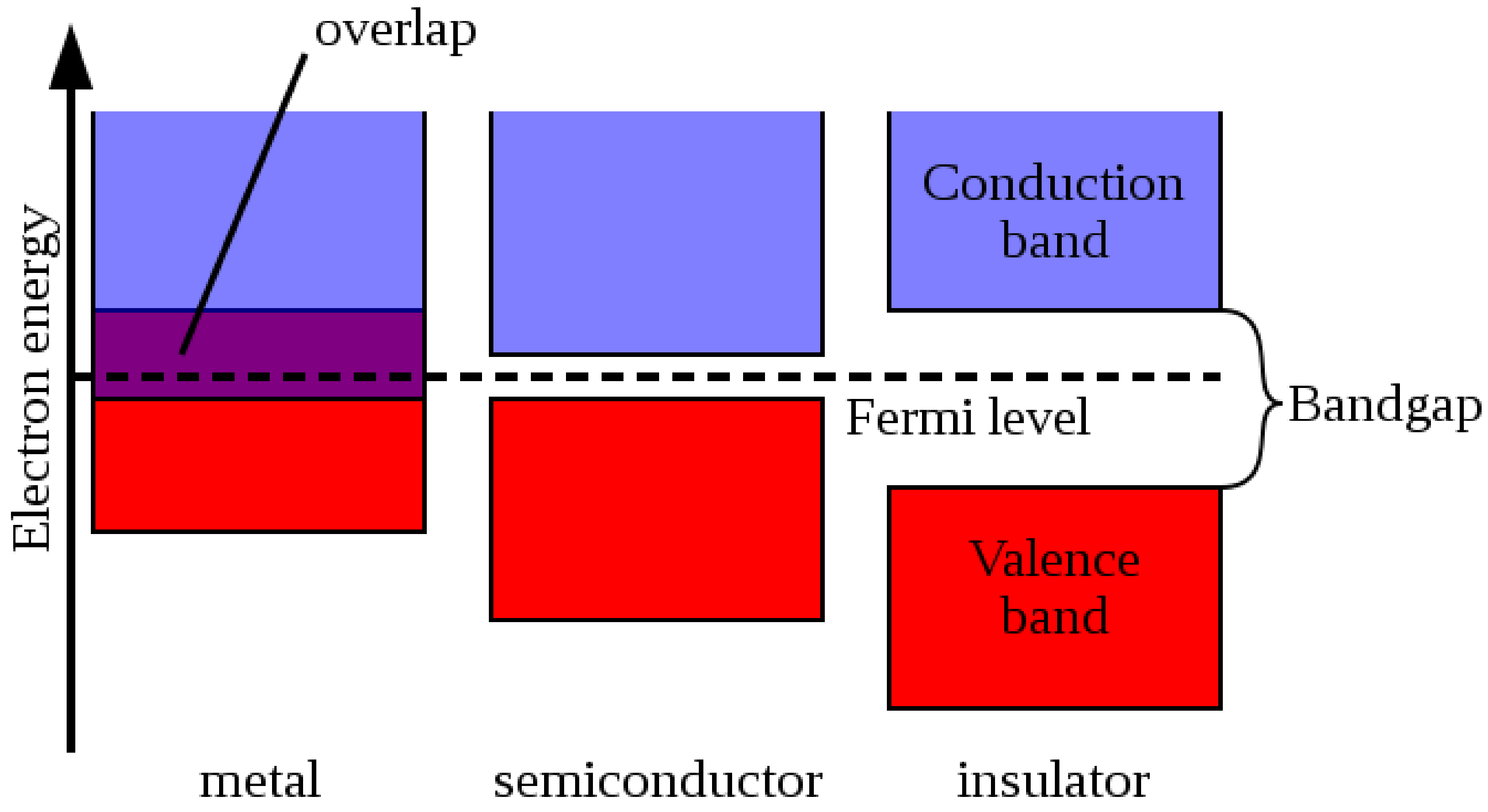

***In semiconductors, the valence band is full but the energy gap is intermediate.***

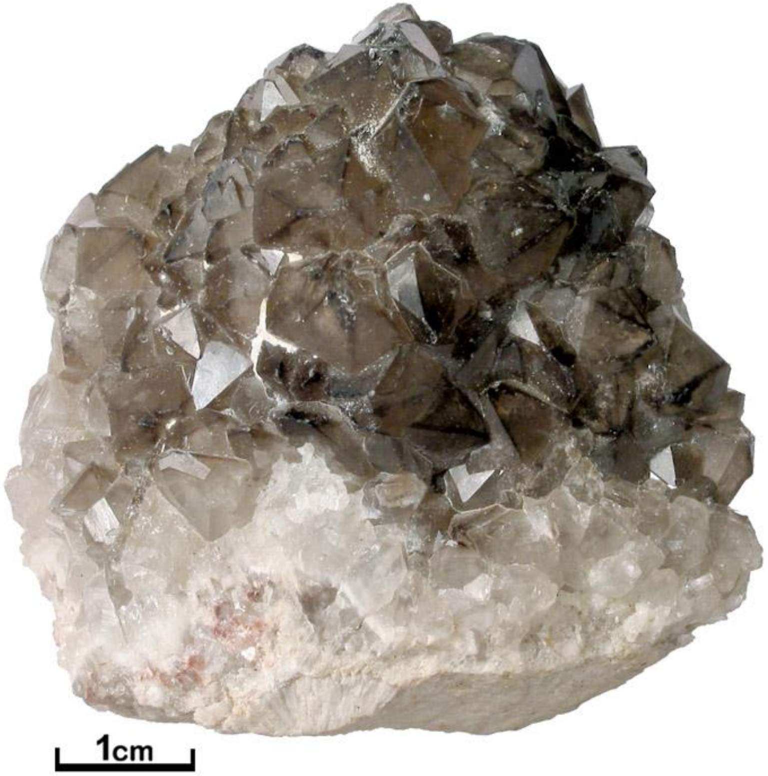
# Semiconductors




***Only a small leap is required for an electron to enter the Conduction Band.***

# Band Diagrams

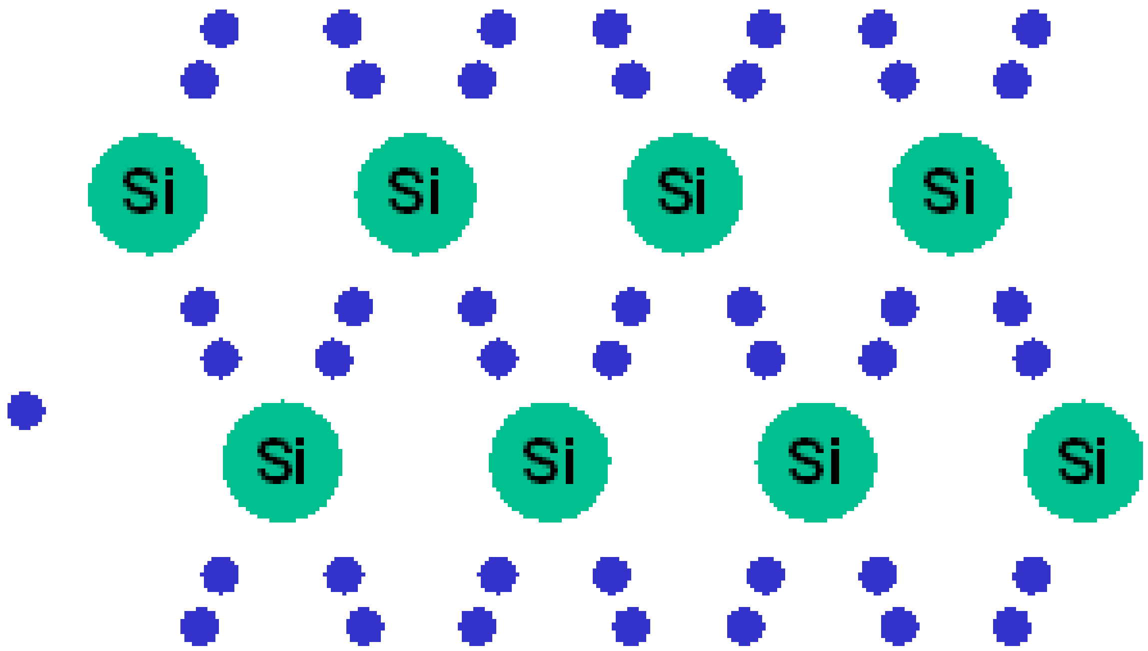


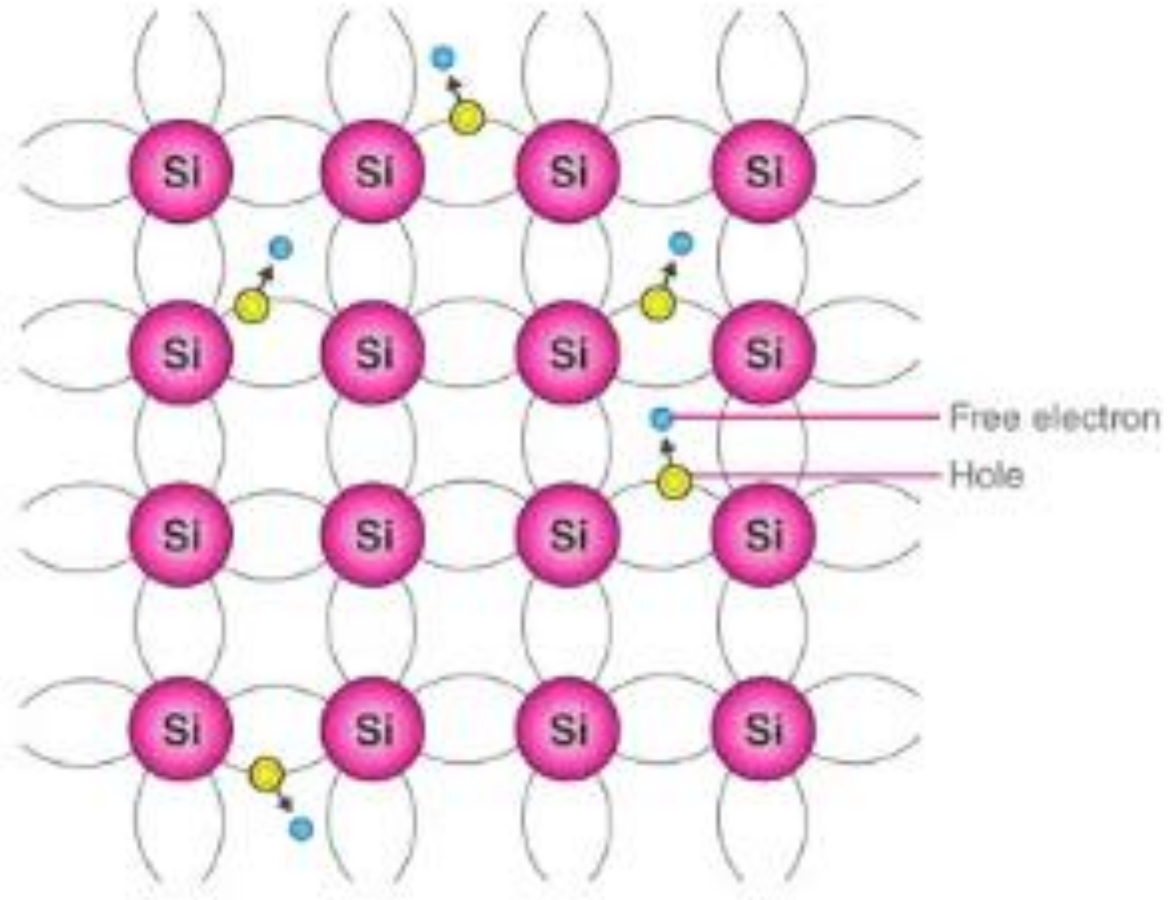



***Silicon is a very common element, the main element in sand & quartz.***

# Intrinsic Silicon

**The semiconductor is said to be intrinsic if it is not contaminated with impurity atoms.**

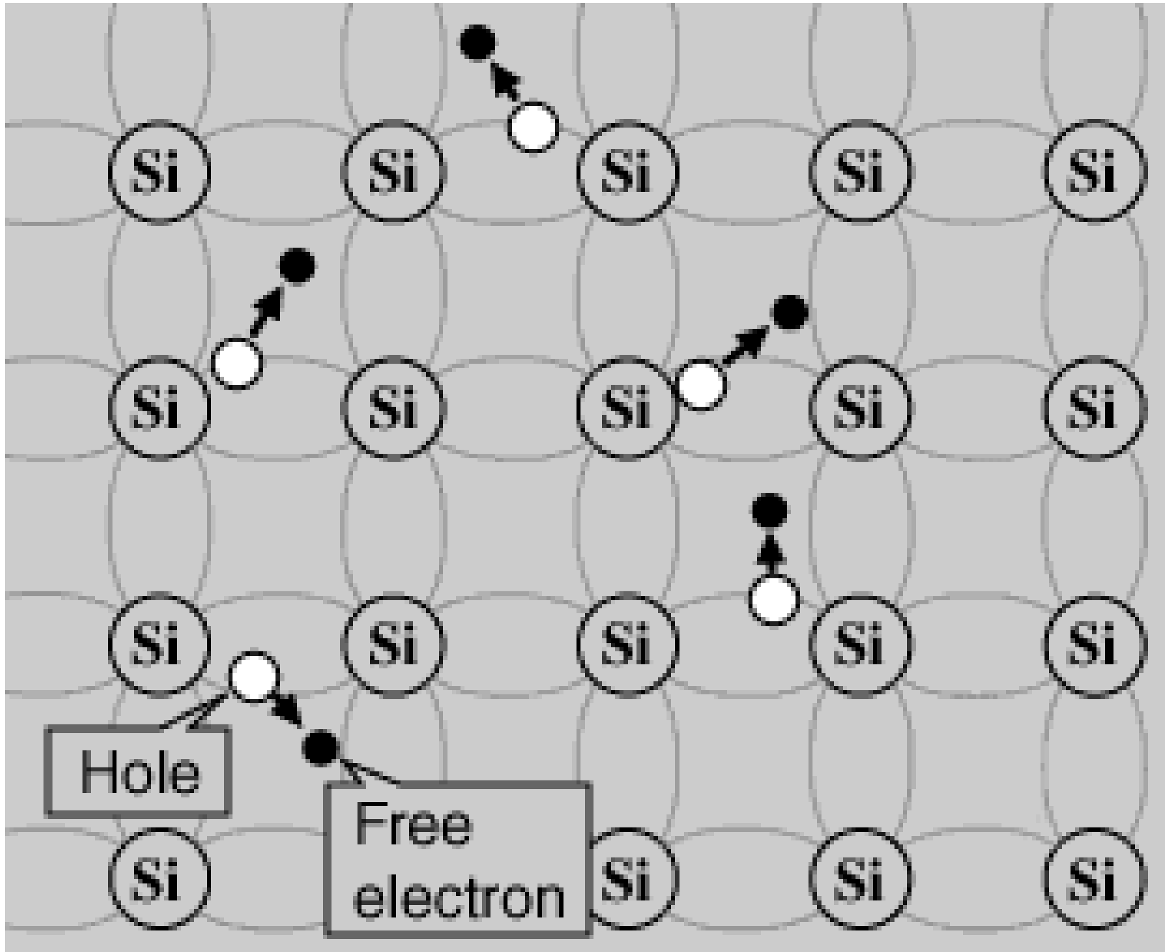



***At any temperature above absolute zero temperature, there is a finite probability that an electron in the lattice will be knocked loose from its position.***

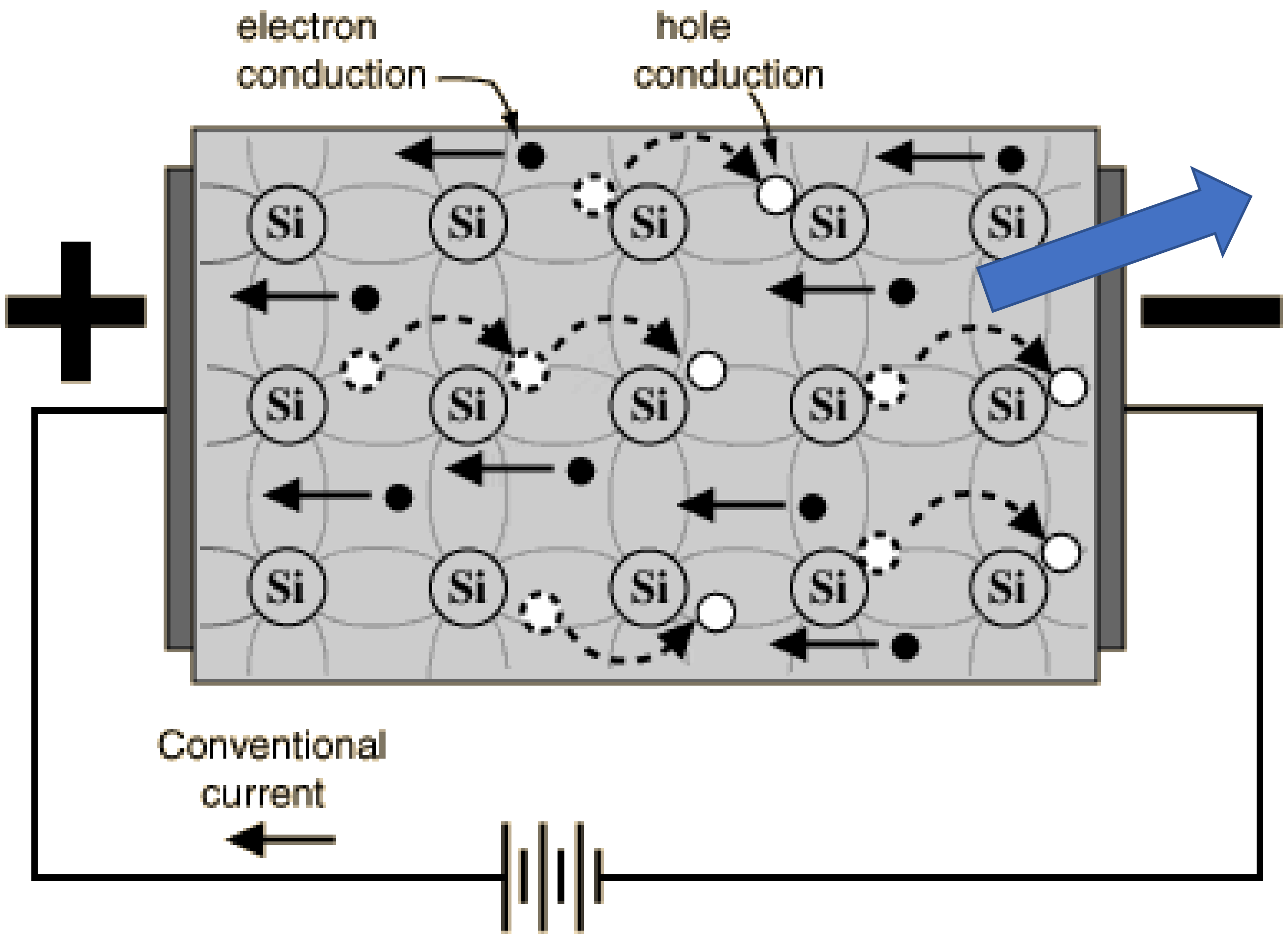
**Number of electrons = Number of holes**

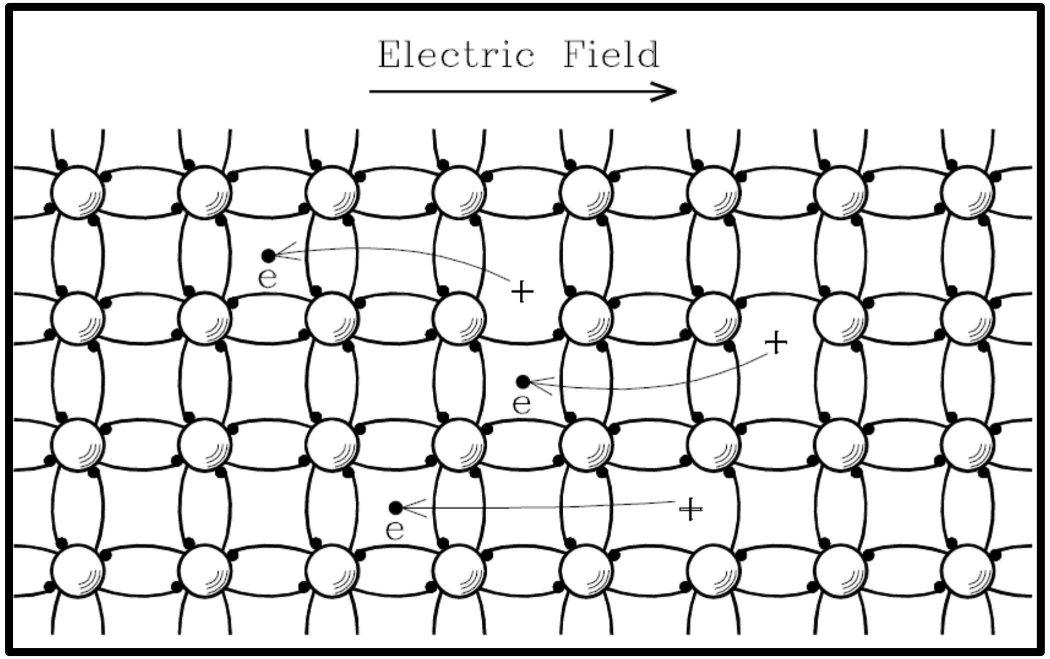
# Conduction mechanism in intrinsic semiconductor




***The electron in the lattice knocked loose from its position leaves behind an electron deficiency called a "hole".***

# Conduction mechanism in intrinsic semiconductor



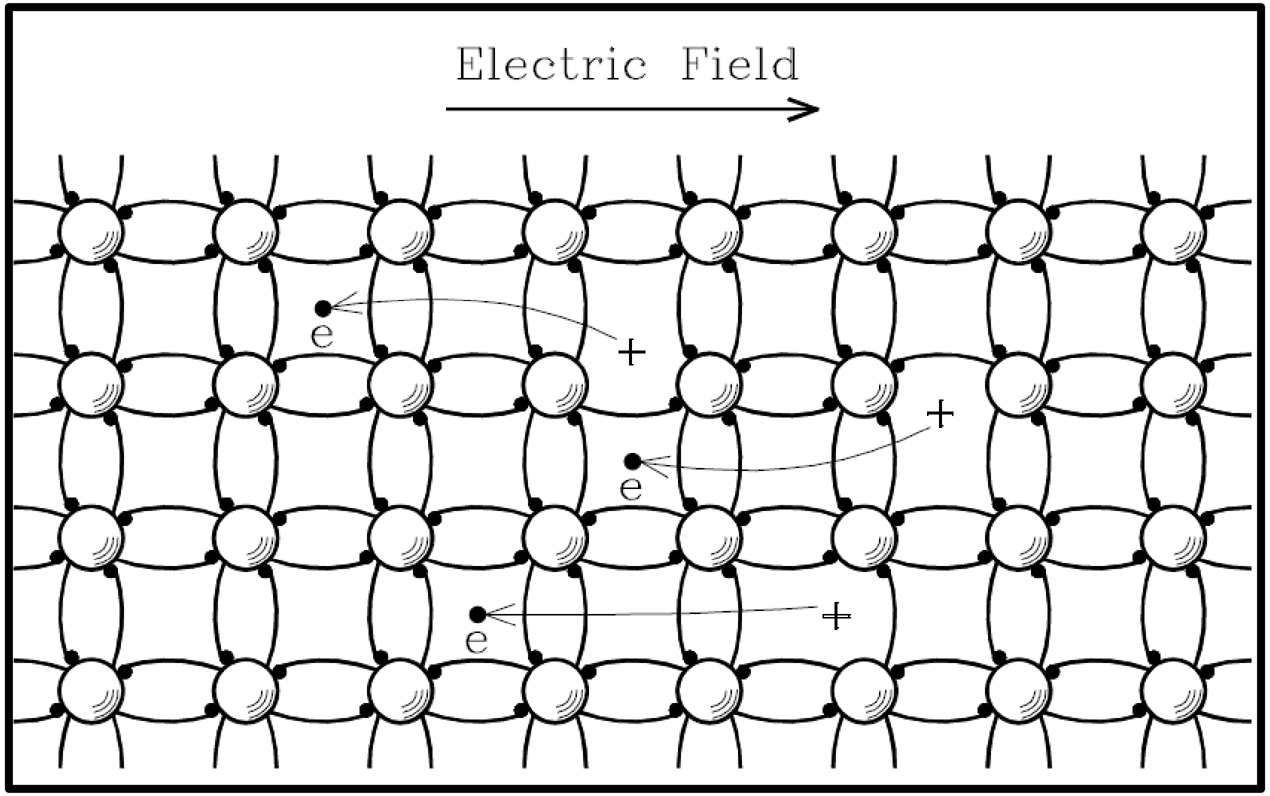

***If a voltage is applied, then both the electron and the hole can contribute to a small current flow.***

# Conduction mechanism in intrinsic semiconductor

## (Generation and recombination)

**In intrinsic semiconductor, The mean lifetime of electrons = mean lifetime of holes, Thus, they recombine each other,**

At any temperature, a stable state is reached when the creation rate of hole-electron pairs is equal to the recombination rate.



# Intrinsic carrier concentration in semiconductors

$$n_i = N_s \exp\left(-\frac{E_g}{2k_B T}\right)$$

T is the absolute temperature in Kelvin; it is assumed that $k_B T \leq E_g/5$

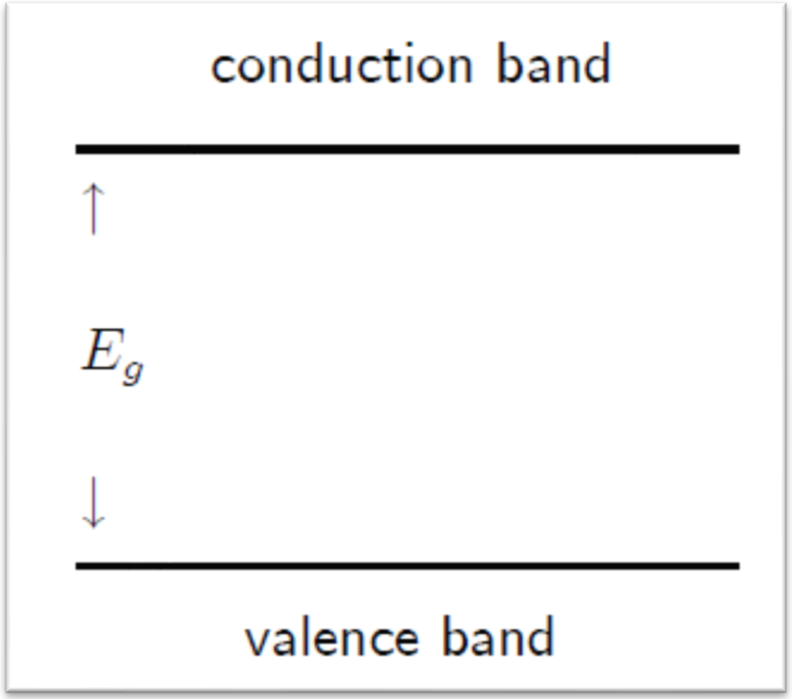
$n_i$ is the intrinsic carrier concentration, i.e., the number of electrons in the conduction band (and also the number of holes in the valence band) per unit volume in a semiconductor that is completely free of impurities and defects

$N_s$ is the number per unit volume of effectively available states; its precise value depends on the material, but it is of order $10^{19} cm^{-3}$ at room temperature and increases with temperature

$E_g$ is the energy gap (between the bottom of the conduction band and the top of the valence band)

$k_B$ is Boltzmann's constant, $k_B$ = 1:381 x $10^{-23}$ Joules/Kelvin

# Intrinsic carrier concentration in semiconductors

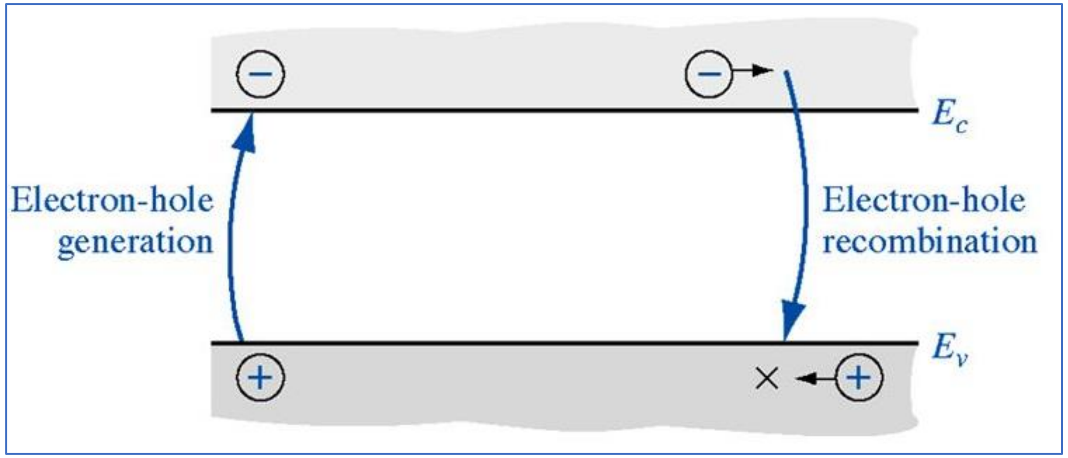



The probability of exciting an electron from the top of the " valence band to the bottom of the conduction band is Eg

proportional to the Boltzmann factor **$\exp(-\frac{E_g}{k_B T})$**

This process leaves behind a hole in the valence band and is called electron-hole pair creation.

At thermal equilibrium, the creation of electron-hole pairs is balanced by their recombination.




If n is the concentration of conduction-band electrons and p the concentration of valence band holes,

$$np = K \exp\left(-\frac{E_g}{k_B T}\right)$$

# Electron –hole concentrations

- ✓ A vacancy is left when a covalent bond is broken.
- ✓ The vacancy is called a hole.
- ✓ A hole moves when the vacancy is filled by an electron from a nearby broken bond (hole current).
- ✓ The electron density is $n$ ($n_i$ for intrinsic material), Hole density is represented by $p$.
- ✓ For intrinsic silicon, $n = n_i = p$.
- ✓ The product of electron and hole concentrations is $\boldsymbol{pn = n_i^2}$.
- ✓ The $pn$ product above holds when a semiconductor is in thermal equilibrium (not with an external voltage applied).

## Intrinsic carrier concentration in semiconductors

- ✓The density of carriers in a semiconductor as a function of temperature and material properties is:

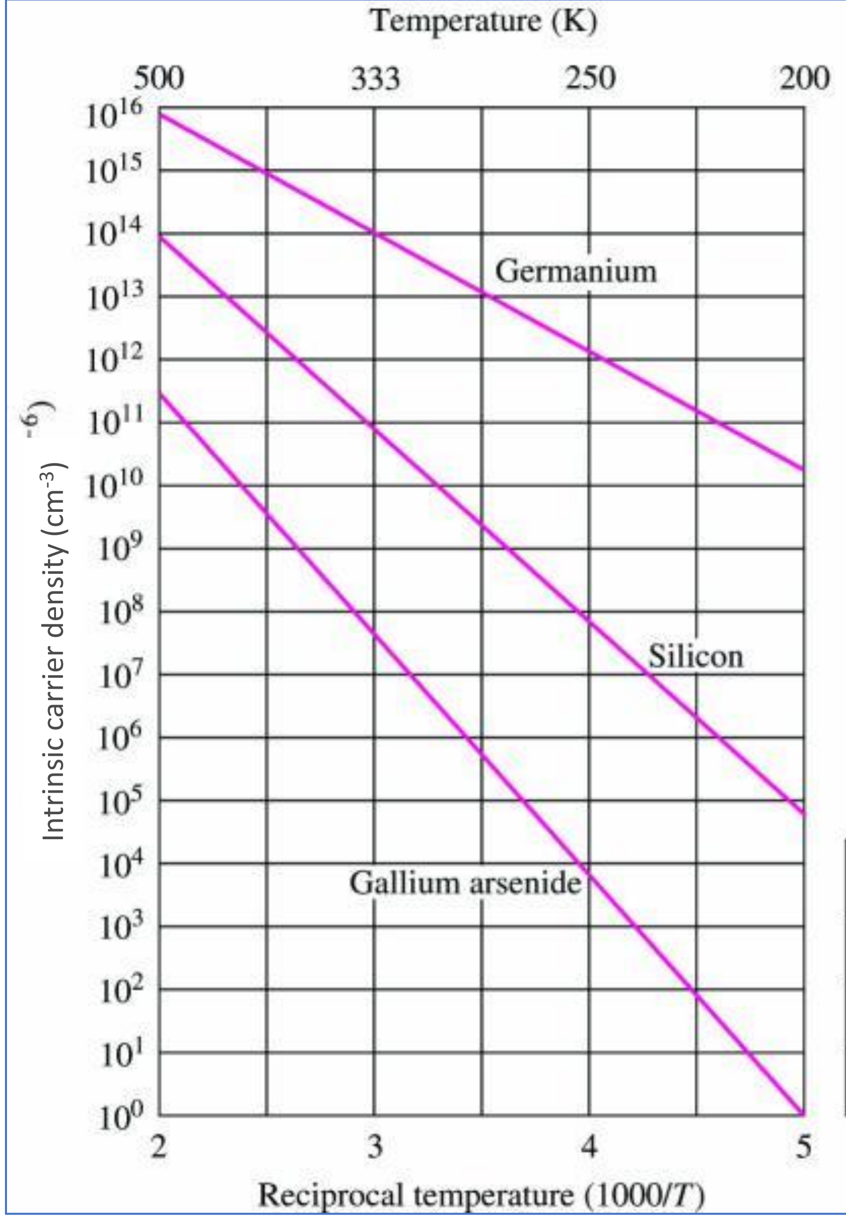
$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) \quad \text{cm}^{-6}$$

- ✓$E_G$ = semiconductor bandgap energy in eV (electron volts)
- ✓ $k$ = Boltzmann's constant, $8.62 \times 10^{-5}$ eV/K
- ✓ $T$ = absolute termperature, K
- ✓ $B$ = material-dependent parameter, $1.08 \times 10^{31}$ $K^{-3}$ $cm^{-6}$ for Si

- ✓Bandgap energy is the minimum energy needed to free an electron by breaking a covalent bond in the semiconductor crystal.

# Intrinsic carrier concentration Vs Temperature in semiconductors

- ✓ Electron density is $n$ (electrons/cm$^3$) and for intrinsic material $n = n_i$.
- ✓ Intrinsic refers to properties of pure materials.
- ✓ $n_i \approx 10^{10}$ cm$^{-3}$ for Si
- ✓ The density of silicon atoms is $n_a \approx 5\text{x}10^{22}$ cm$^{-3}$
- ✓ Thus at a room temperature one bond per about $10^{13}$ is broken




| | B (K$^{-3}$ · cm$^{-6}$) | $E_G$ (eV) |
|---|---|---|
| Si | $1.08 \times 10^{31}$ | 1.12 |
| Ge | $2.31 \times 10^{30}$ | 0.66 |
| GaAs | $1.27 \times 10^{29}$ | 1.42 |

# Electric current in intrinsic semiconductor

The total current in the semiconductor is equal to **Electron current + Hole current**

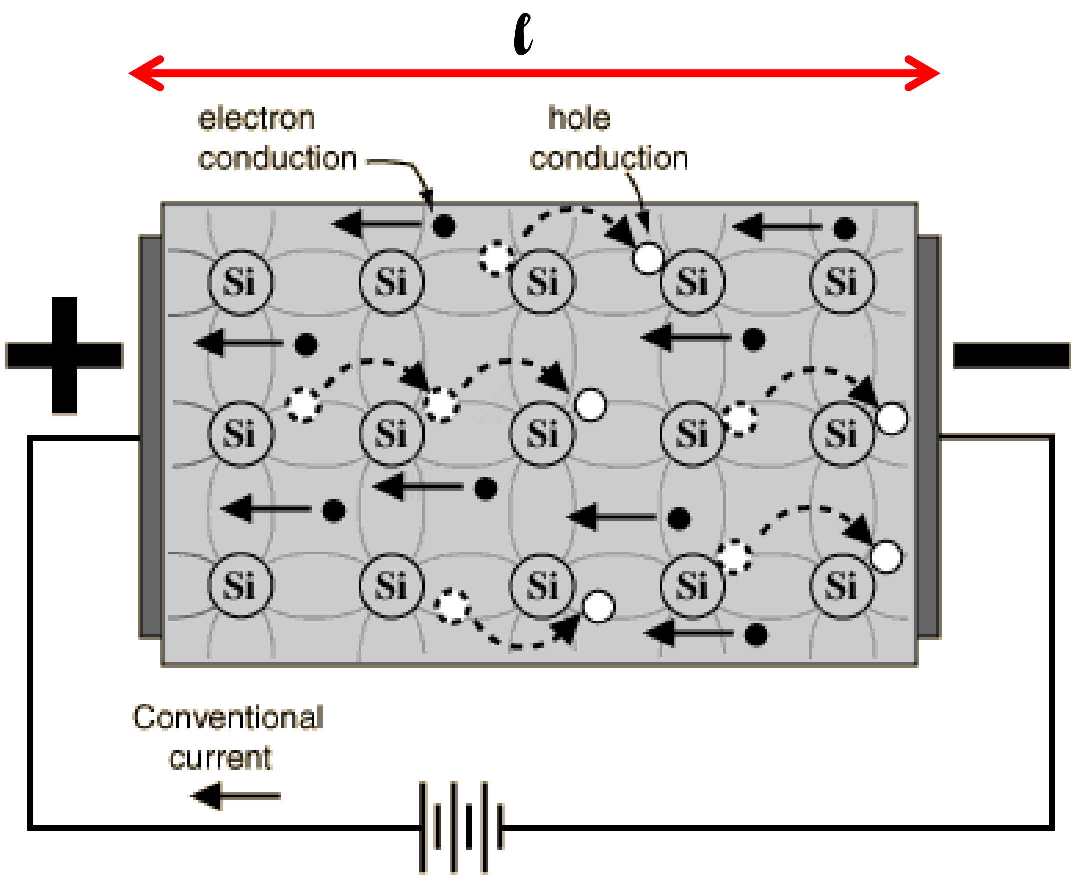
$$I = I_e + I_h$$

**Area of semiconductor : A**

**Length of the semiconductor : $\ell$**

**Electric field across the semiconductor** $E = \dfrac{V}{l}$

**Number density of holes = $n_h$**




**Charge in the semiconductor due to holes (q) = $n_h$ X Volume of S.C X Charge on a hole**

$$q = n_h A l\, e$$

$$Hole\ current\ (Ih) = \frac{q}{t} = \frac{n_h A l\, e}{t} = n_h A e\, vh$$

## Electric current in intrinsic semiconductor

Charge in the semiconductor due to holes (q) = $n_h$ X Volume of S.C X Charge on a hole

$$q = n_h Al\, e$$

$$\text{Hole current } (Ih) = \frac{q}{t} = \frac{n_h Al\, e}{t} = n_h Ae\, vh$$

Charge in the semiconductor due to electrons (q) = $n_e$ X Volume of S.C X Charge on a hole

$$q = n_e Al\, e$$

$$\text{Electron current } (Ie) = \frac{q}{t} = \frac{n_e Al\, e}{t} = n_e Ae\, ve$$

$$\text{Total current } (I) = I_h + I_e = Ae\,(n_h v_h + n_e v_e)$$

*Electric current in conductors or metals is due to **electrons only***

*Electric current in semiconductors is due to **electrons + holes***

## Electric conductivity of Semiconductor (resistivity and mobility)

*We know that the resistance offered to the flow of electric current*

$$R = \rho \frac{l}{A}$$

$$\frac{V}{I} = \rho \frac{l}{A} \qquad (ohm's\ law\ V = IR)$$

$$\frac{V}{l} = \rho \frac{I}{A} \qquad (since\ we\ know\ I)$$

$$E = \rho \frac{Ae\,(n_h v_h + n_e v_e)}{A} = \rho e\,(n_h v_h + n_e v_e)$$

$$\frac{1}{\rho} = \frac{e\,(n_h v_h + n_e v_e)}{E} = e\,(n_h \frac{v_h}{E} + n_e \frac{v_e}{E})$$

# Electric conductivity of Semiconductor

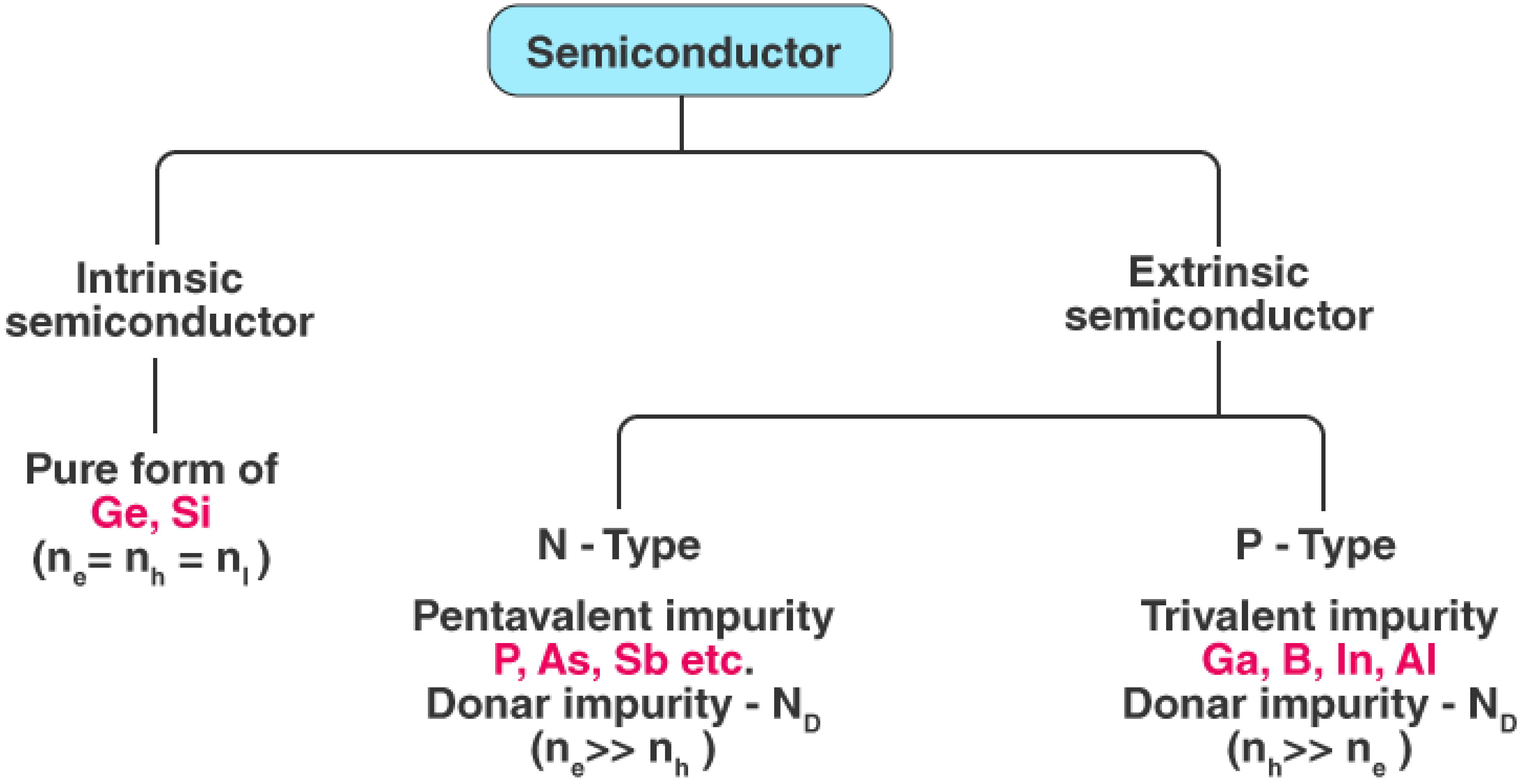
$$\frac{1}{\rho} = \frac{e\ (n_h v_h + n_e v_e)}{E} = e\ (n_h \frac{v_h}{E} + n_e \frac{v_e}{E})$$

*Where* $\frac{v_h}{E} = \mu_h$ *(mobility of holes ) and* $\frac{v_e}{E} = \mu_e$ *(mobility of electrons)*

$$\frac{1}{\rho} = e\ (n_h \mu_h + n_e \mu_e)$$

***Thus the conductivity of the semiconductor***

$$\sigma = \frac{1}{\rho} = e\ (n_h \mu_h + n_e \mu_e)$$

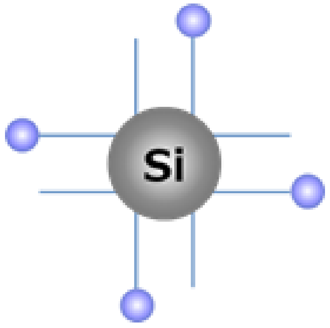


Semiconductor
Intrinsic semiconductor
Pure form of
Ge, Si
$(n_e = n_h = n_i)$
Extrinsic semiconductor
N - Type
Pentavalent impurity
P, As, Sb etc.
Donar impurity - $N_D$
$(n_e >> n_h)$
P - Type
Trivalent impurity
Ga, B, In, Al
Donar impurity - $N_D$
$(n_h >> n_e)$

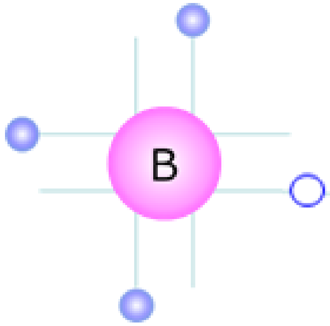
# P-type Semiconductor

## Intrinsic semiconductor + trivalent impurity

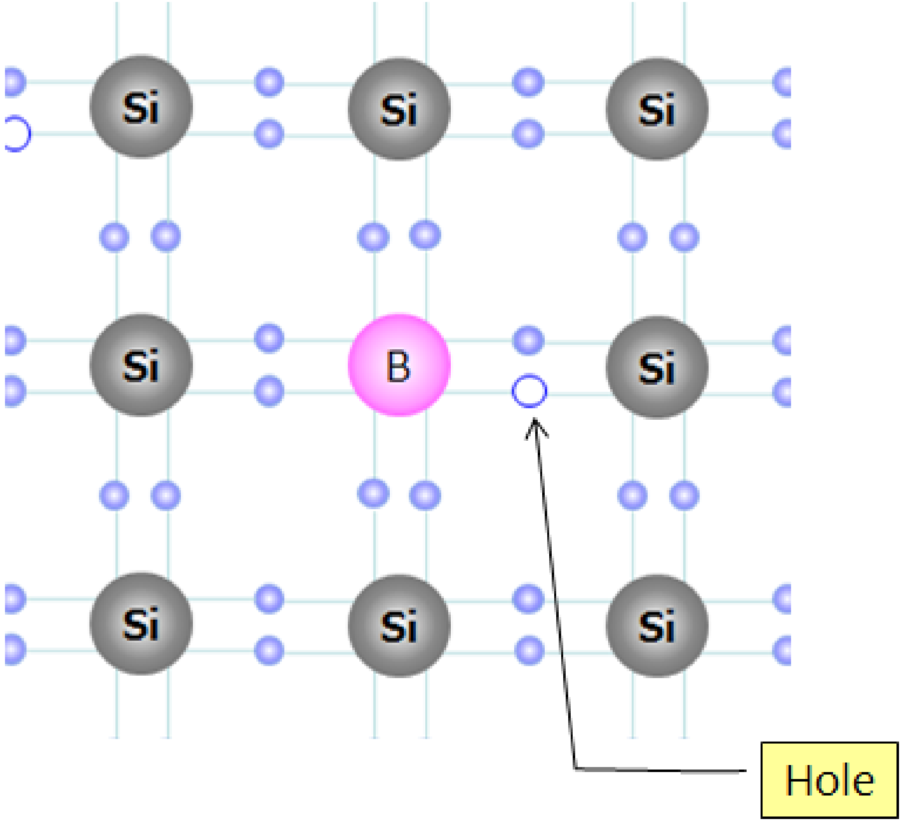
Silicon (Si): Four valence electrons




Boron (B): Three valence electrons




Adding boron to pure silicon crystal results in lack of an electron. And it becomes a hole.

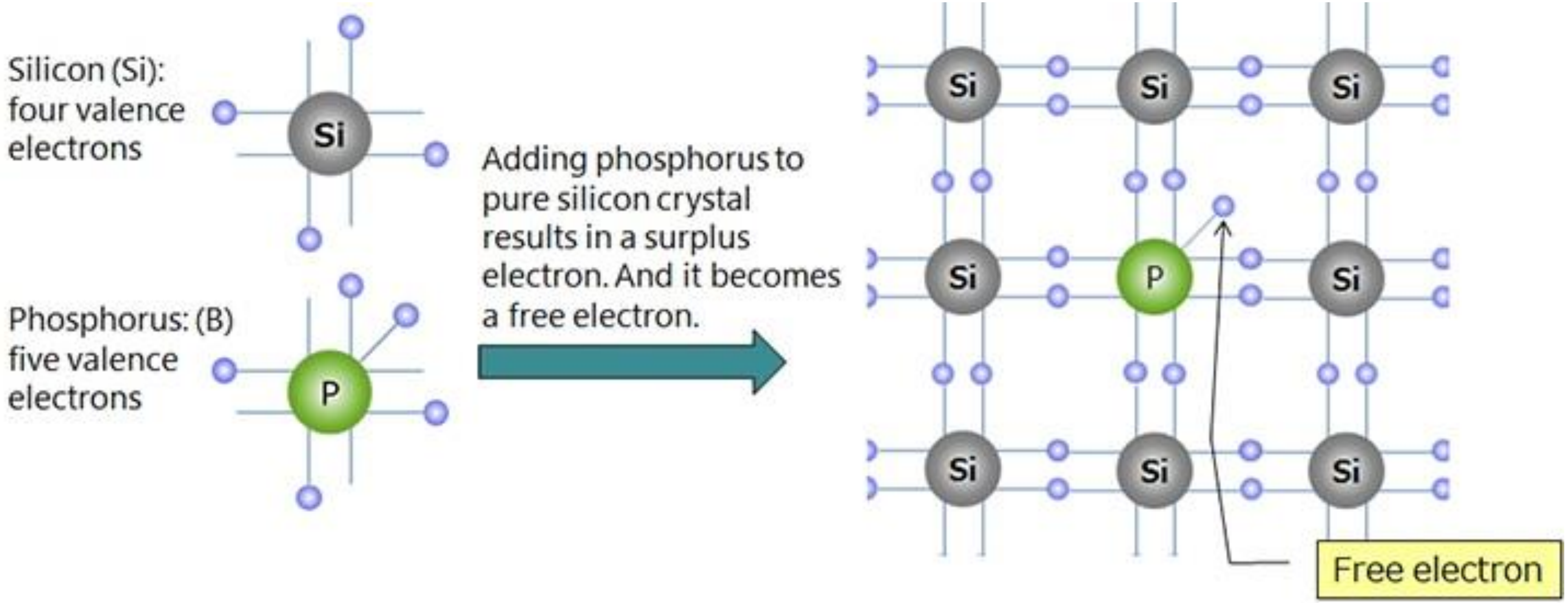



**Majority carriers : HOLES**

**Minority carriers: Electrons**

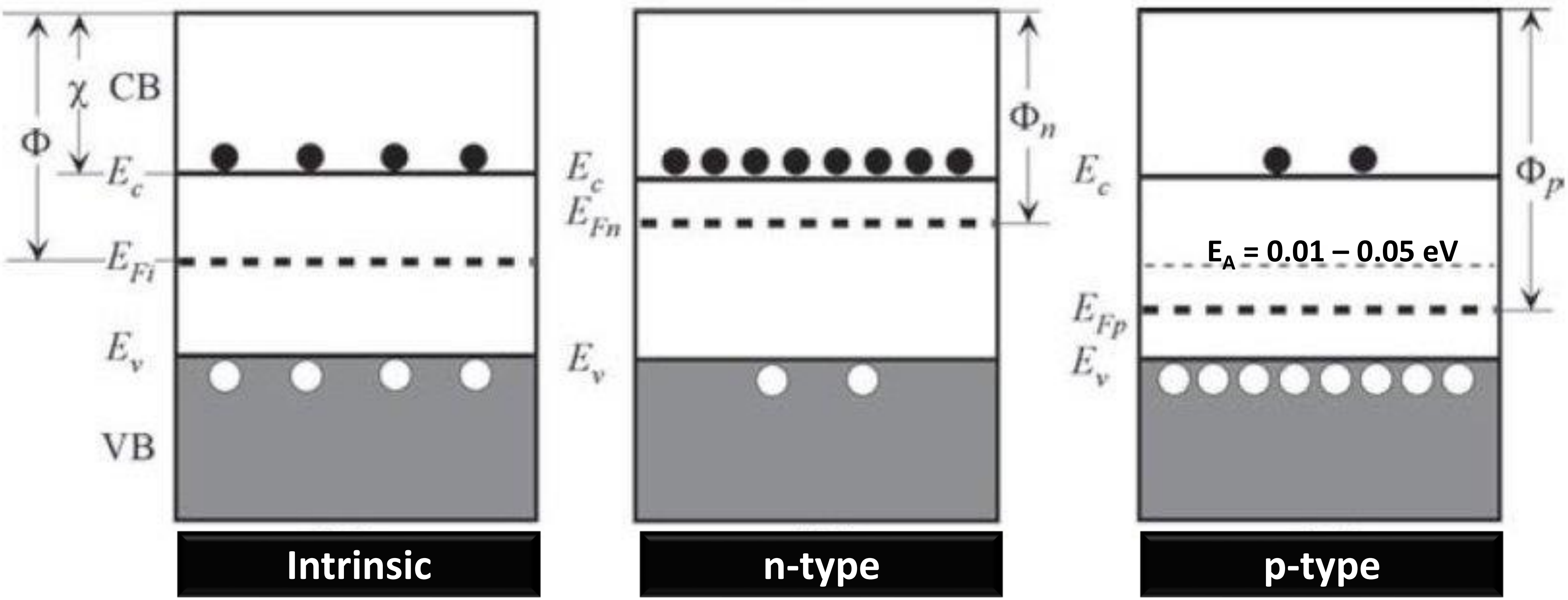
# n-type Semiconductor

## Intrinsic semiconductor + pentavalent impurity

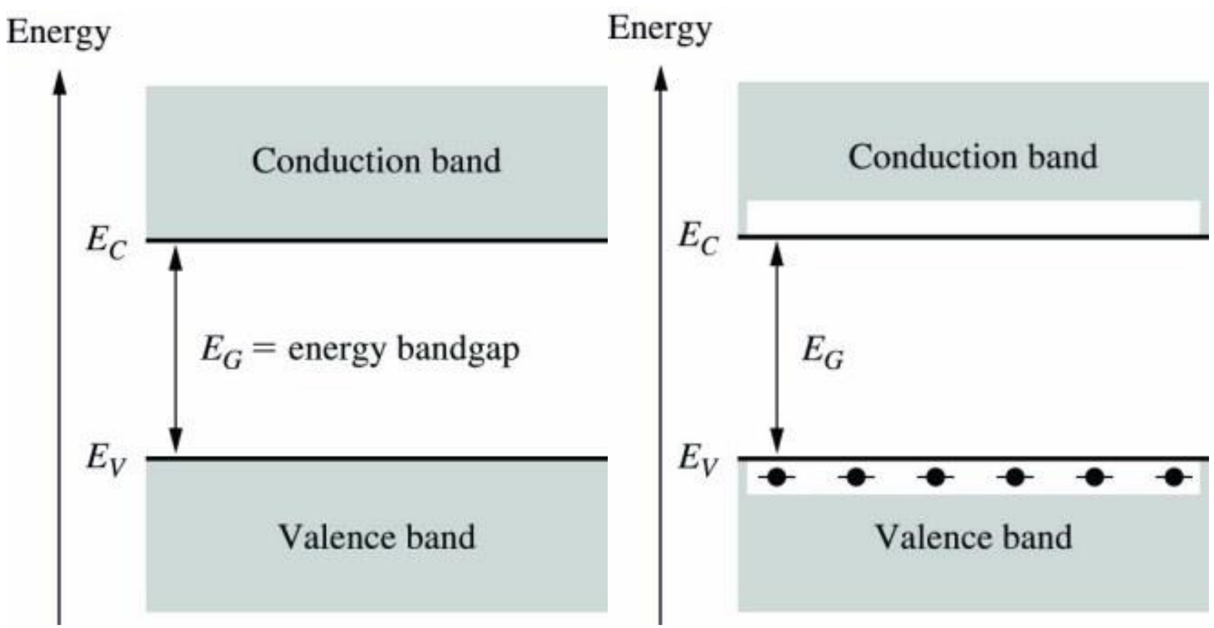



**Majority carriers : ELECTRONS**
**Minority carriers: Holes**

# Energy band diagrams of semiconductors



# Energy band diagrams of semiconductors

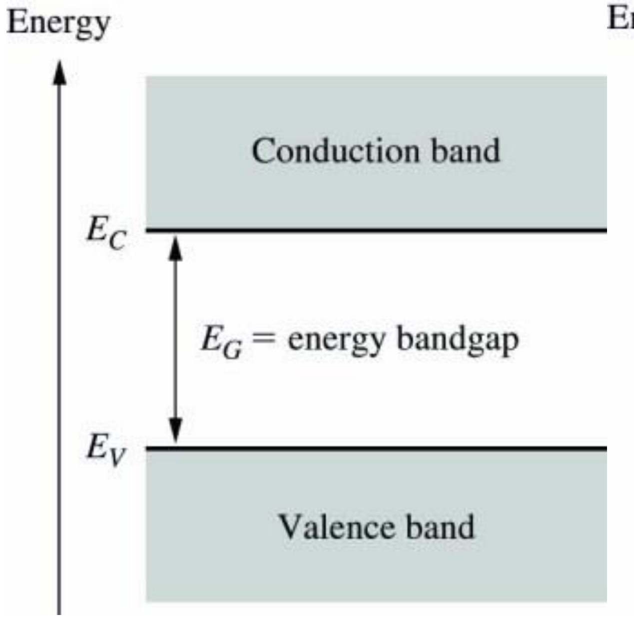



Semiconductor energy band model. $E_C$ and $E_V$ are energy levels at the edge of the conduction and valence bands.

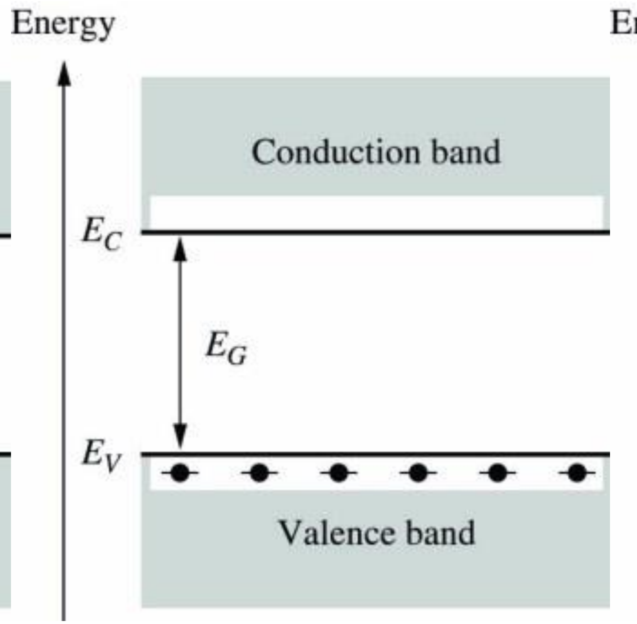
Electron participating in a covalent bond is in a lower energy state in the valence band. This diagram represents 0 K.

What happens as temperature increases?

# Energy band diagrams of semiconductors




Semiconductor energy band model. $E_C$ and $E_V$ are energy levels at the edge of the conduction and valence bands.

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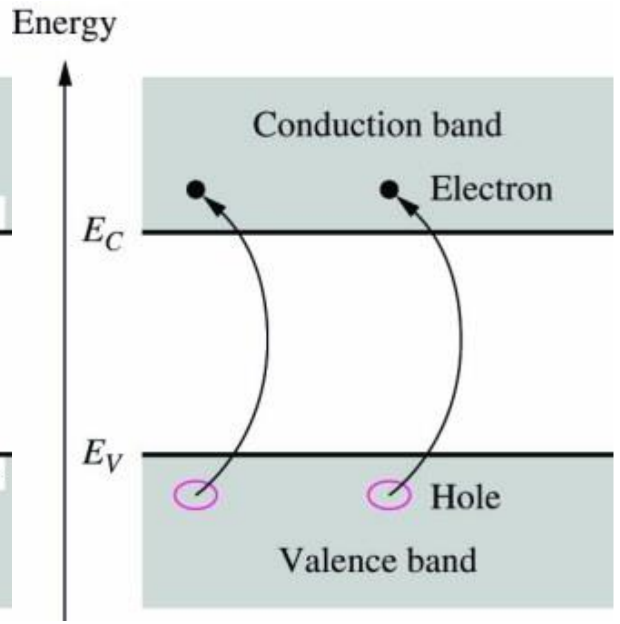
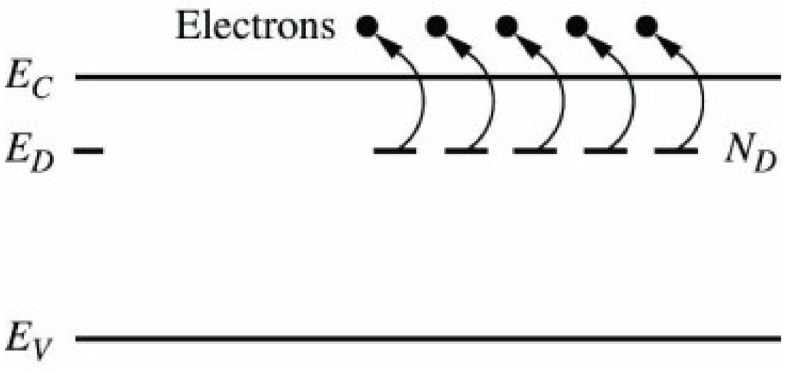
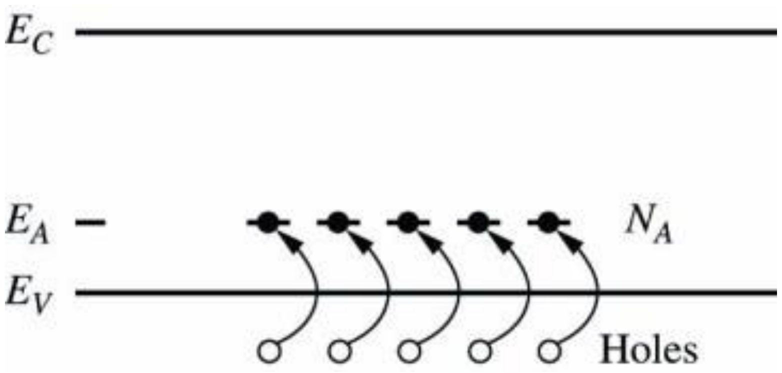



Thermal energy breaks covalent bonds and moves the electrons up into the conduction band.

# Energy band diagrams of doped semiconductors




Semiconductor with donor or n-type dopants. The donor atoms have free electrons with energy $E_D$. Since $E_D$ is close to $E_C$, (about 0.045 eV for phosphorous), it is easy for electrons in an n-type material to move up into the conduction band and create negative charge carriers.

Semiconductor with acceptor or p-type dopants. The aaacceptor atoms have unfilled covalent bonds with energy state $E_A$. Since $E_A$ is close to $E_V$, (about 0.044 eV for boron), it is easy for electrons in the valence band to move up into the acceptor sites and complete covalent bond pairs, and create holes – positive charge carriers.

# Drift current Vs Diffusion current

## Drift current

Drift current is defined as the current constituted due to the combined movement of electrons and holes in a semiconductor by applying external electric field

$$\text{Total current } (I) = I_h + I_e = Ae\,(n_h v_h + n_e v_e)$$

$$\text{Current density } (J) = \frac{I}{A} = e\,(n_h v_h + n_e v_e)$$

*Or*

$$\text{Current density } (J) = \frac{I}{A} = e\,(n_h \mu_h E + n_e \mu_e E) = \sigma E$$

$$J = \sigma E$$

*Concentration of charge carriers*

# Drift current Vs Diffusion current

## Diffusion current

**The diffusion current can be defined as the flow of charge carriers within a semiconductor travels from a higher concentration region to a lower concentration region.**

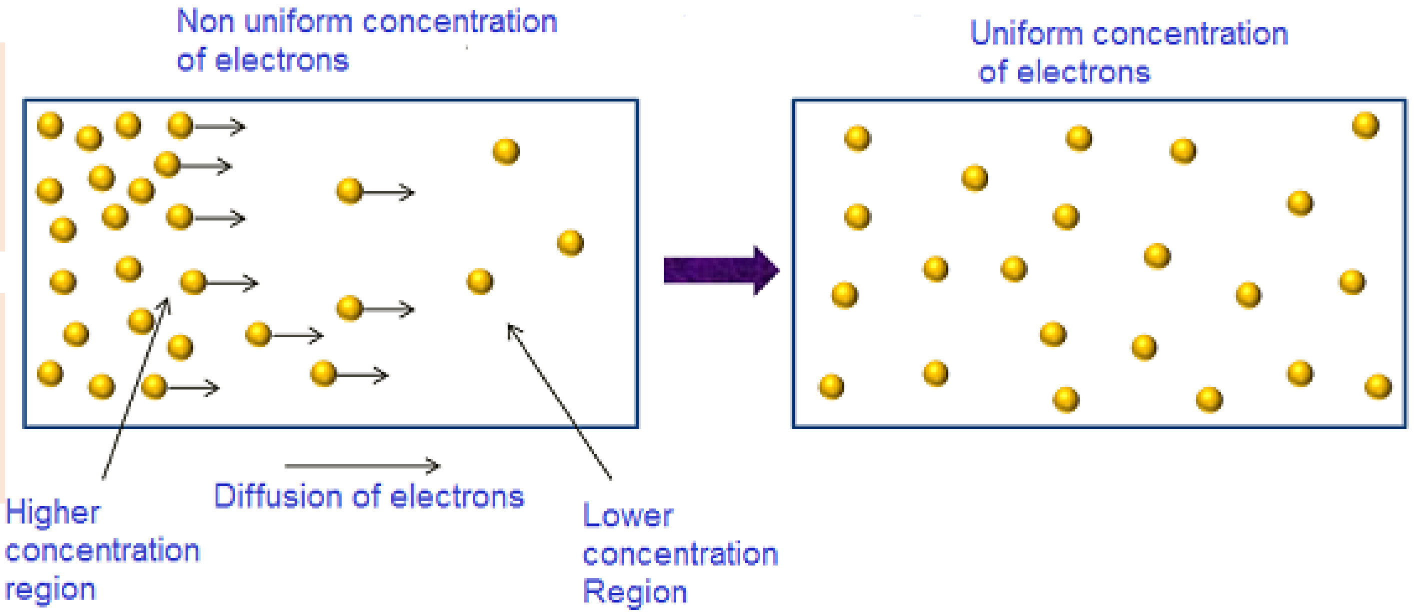
A higher concentration region is nothing but where the number of electrons present in the semiconductor. Similarly, a lower concentration region is where the less number of electrons present in the semiconductor. The process of diffusion mainly occurs when a semiconductor is doped non-uniformly.

Diffusion current due to electrons

$$J_n = q\,Dn\,\frac{dn}{dx}\ \text{A/cm}^2$$

Diffusion current due to holes

$$J_h = -q\,Dh\,\frac{dn}{dx}\ \text{A/cm}^2$$



# Drift current Vs Diffusion current

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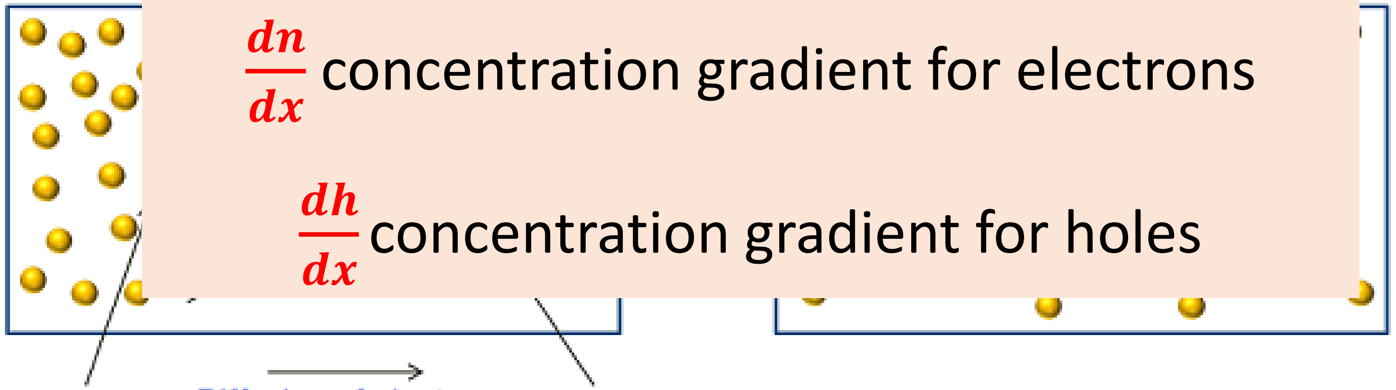
Diffusion current density due to electrons

$$J_n = q\,Dn\,\frac{dn}{dx}\ \text{A/cm}^2$$

Where D = diffusion coefficient

$\frac{dn}{dx}$ concentration gradient for electrons

$\frac{dh}{dx}$ concentration gradient for holes



Diffusion current density due to holes

$$J_h = -q\,Dh\,\frac{dh}{dx}\ \text{A/cm}^2$$

**Total current = Drift current + Diffusion current**