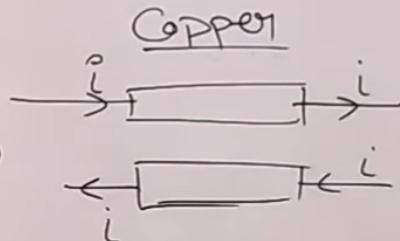


Semiconductor

Intro.

Semiconductors: Semiconductors are those materials which have conductivity between Conductors (Silver, Copper, etc) and Insulators (glass, diamond)

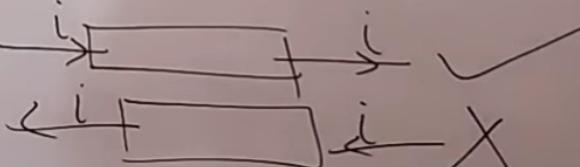


Q) why Semiconductors are important?

Ans: Semiconductors have two important properties

- ① Can control the number of charge carriers
↓
Conductivity can be controlled. (electrons & holes)

- ② Can give Unidirectional Current.



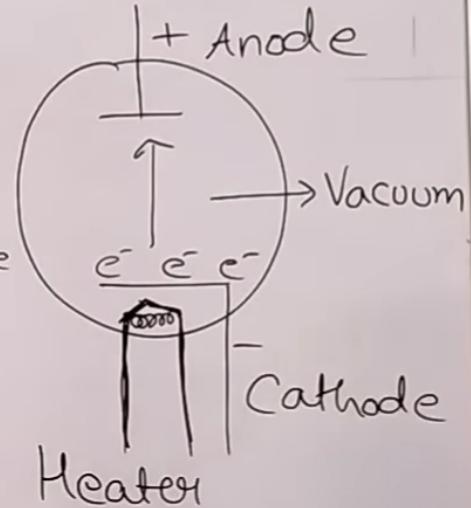
Before the discovery of Semiconductors, these operations were performed by vacuum tubes.

number of e^- can be controlled by
⇒ varying voltage between Anode & Cathode

⇒ e^- can flow only in one direction

Cathode to Anode ⇒ Valves

⇒ Vacuum is created because
 e^- can collide with air molecules & loose it's energy



So in 1930s, some SOLID STATE SEMICONDUCTORS were discovered in which the charge carriers (electrons & holes) can be varied with small intensity of heat, light, voltage.

- Advantages:
- ① Small in Size
 - ② No heating required
No Vacuum required
 - ③ Low Power
 - ④ Low Voltage
 - ⑤ Long life
 - ⑥ High reliability.

Eg of Semiconductors:

Elemental Semiconductors: Silicon & Germanium
Si Ge

Compound Semiconductors: GaAs, InP, etc
(Inorganic)

Anthracene, Polyaniline, etc
(Organic)



24:29 / 29:07



MaterialResistivity (ρ)Conductivity (σ)

$$\sigma = \frac{1}{\rho}$$

① Conductors

$$10^{-2} - 10^{-8} \Omega m$$

$$10^2 - 10^8 Sm^{-1}$$

② Semiconductors

$$10^{-5} - 10^6 \Omega m$$

$$10^5 - 10^{-6} Sm^{-1}$$

③ Insulators

$$10^{11} - 10^{19} \Omega m$$

$$10^{-11} - 10^{-19} Sm^{-1}$$

Band Theory

Energy Bands in Crystal:

C
Si
Ge

In an isolated atom, the energy of an e^- depends upon the orbit it is revolving in.

(Bohr's theory)



$$-0.85\text{eV} \quad n=4$$

$$-1.51\text{eV} \quad n=3$$

$$-3.4\text{eV} \quad e^- \quad n=2$$

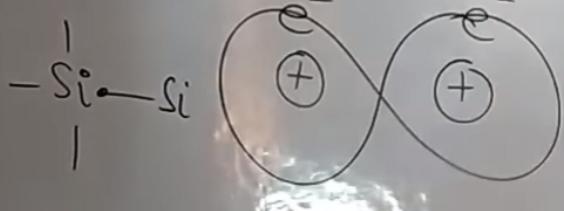
$$-13.6\text{eV} \quad e^- \quad n=1 \quad (\text{H-atom})$$

In Isolated Atom,

discrete energy levels

are present (like straight lines)

In a crystal \Rightarrow Atoms come close ($2\text{ to }3\text{ \AA}$) & the electrons have some new interactions:



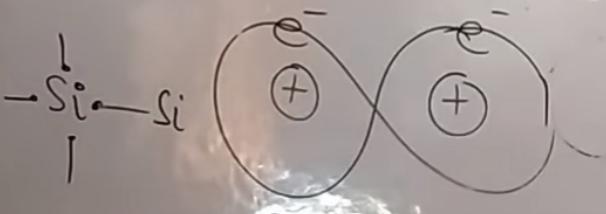
(i) with electrons of neighbouring atoms

(ii) with nucleus, " "

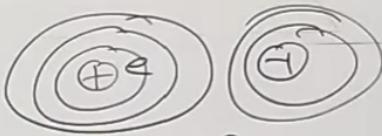
→ In a crystal each atom has a UNIQUE position hence each electron has UNIQUE position & hence each electron has UNIQUE interactions Hence each electron will have Different Energy level even when they belong to same subshell of isolated atom. Their energies are slightly greater or smaller than their original energies in Isolated state.

In a crystal ⇒ Atoms come close ($2\text{ to }3\text{ \AA}$) & the electrons have some new interactions:

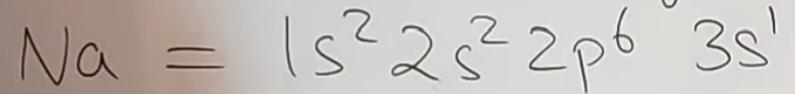
- (i) with electrons of neighbouring atoms
- (ii) with nucleus, " "



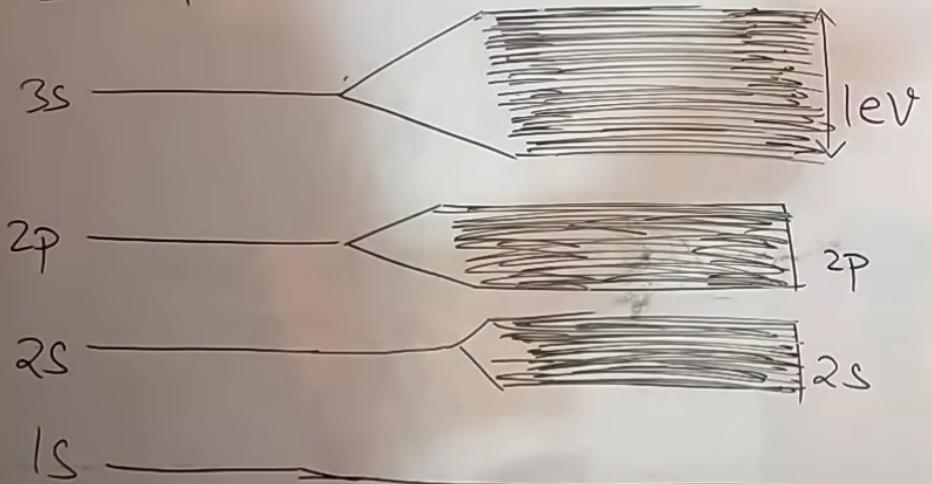
Let us take example of Sodium (Na)



Suppose we have 1 mole of Sodium atoms = 6×10^{23} atoms



$$Z = 11$$



diff btw two consecutive
energy levels $\approx 10^{-23} \text{ eV}$

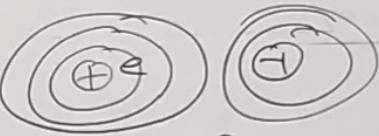
$\approx 10^{23}$ energy lines

Placed very close to
each other which
appears as a
Continuous Energy
Band.

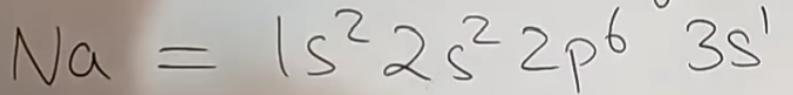
The inner e^- nearly
remain unaffected by
neighboring atoms

Isolated state \Rightarrow Crystal

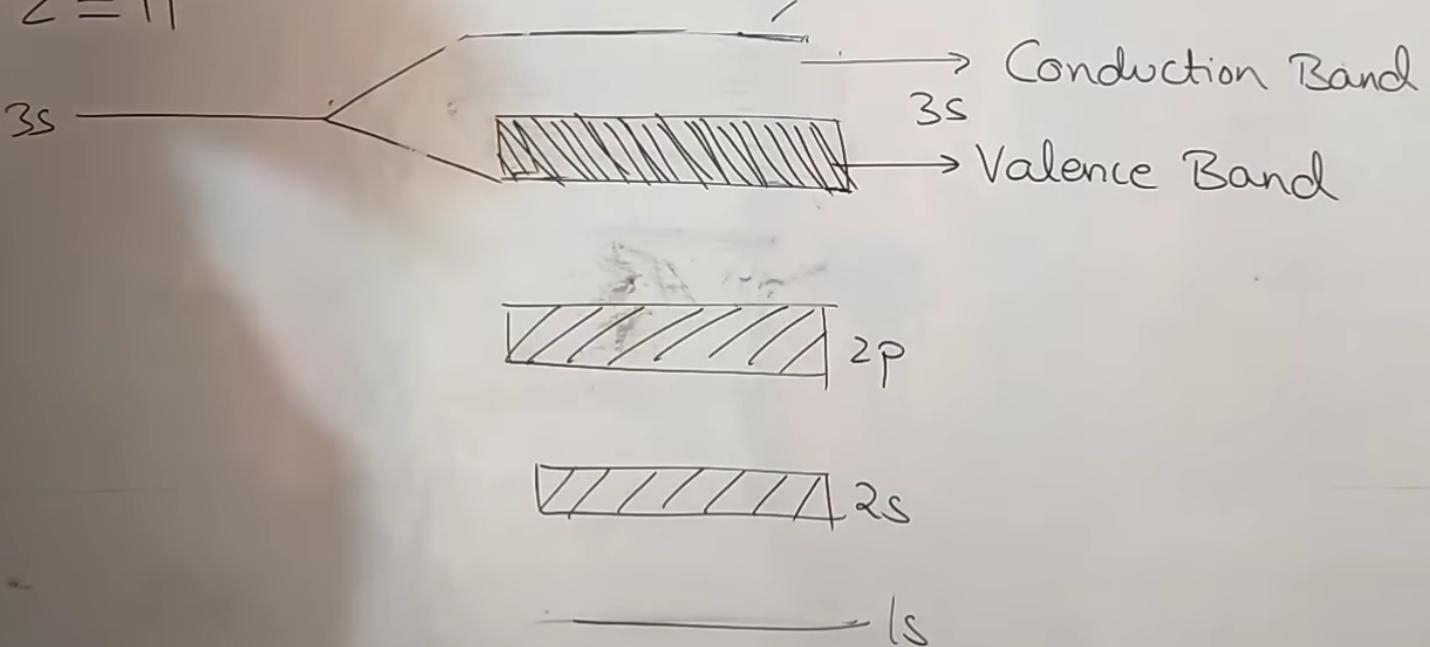
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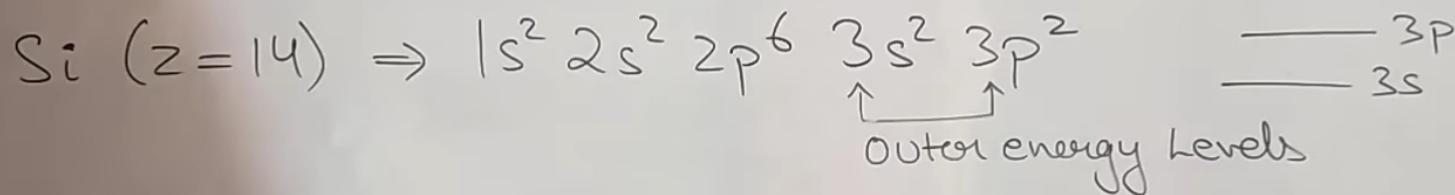
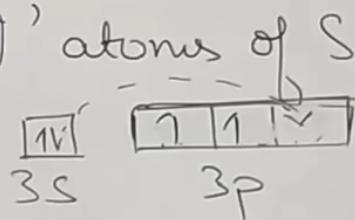


$$Z = 11$$



eg of Silicon or Germanium (Semiconductors)

we have a crystal of Si containing 'N' atoms of Si
(N is of the order of 10^{23} - 10^{24})



No of e^- in outer orbit of each Si atom = 4

Total No. of e^- in outer orbit = $4N$

No of outer energy levels (available) in each Si atom = 8 ($2s+6p$)

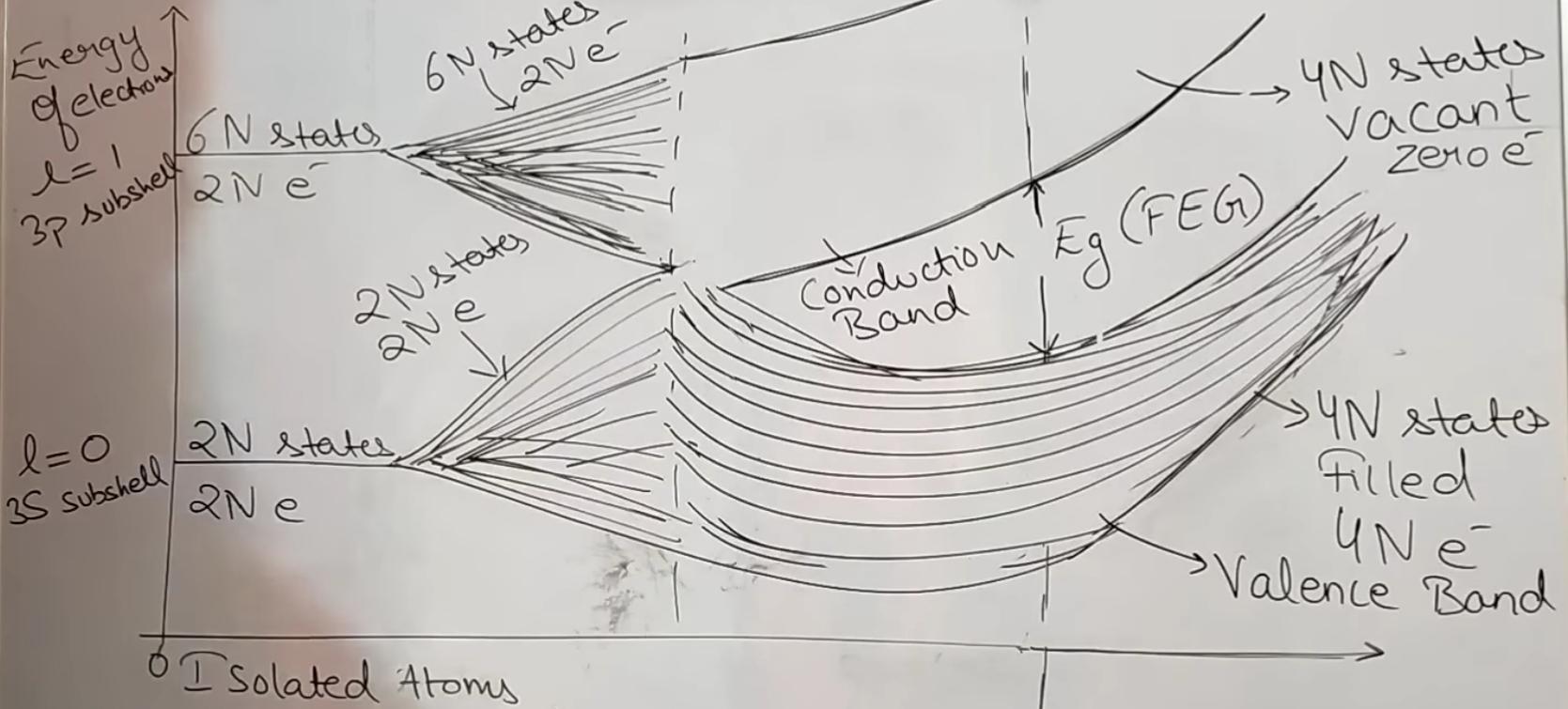
No. of outer " " " in crystal = $8N$

Out of available $8N$ energy levels

$4N$ are filled with e^- & $4N$ are vacant at zero Kelvin

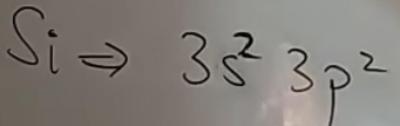
$$2Ns + 2Np \times$$

$$(2Ns + 6Np)$$



$\gamma \rightarrow$ atomic space

$$QY =$$



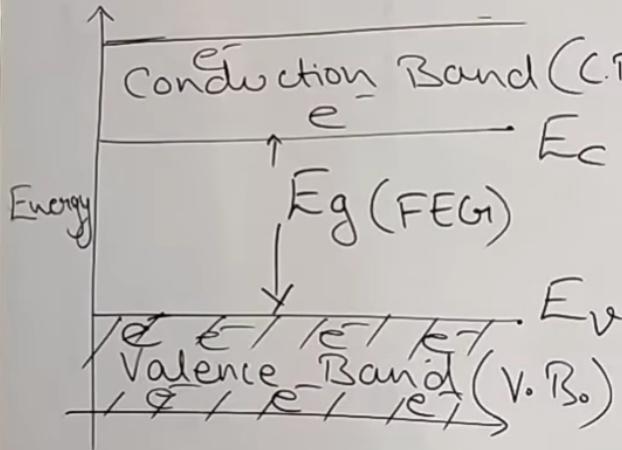
11	111
3s	3p

At zero Kelvin

Crystal

$$\gamma = \gamma_0$$





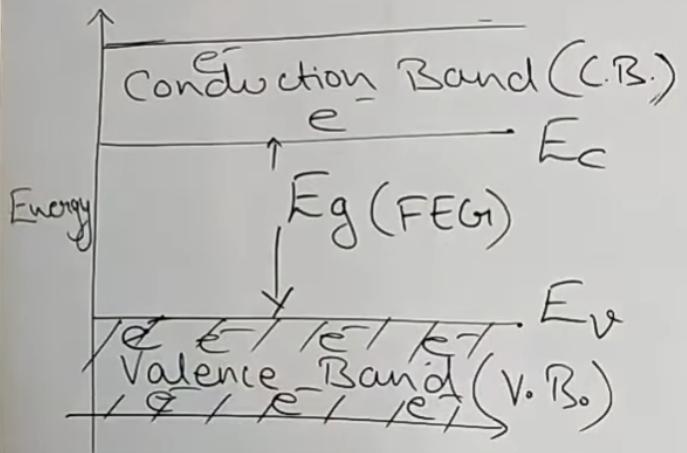
Valence Band: (V. B.)

- i) Range of energies possessed by valence electrons in a crystal.
- ii) It contains valence electrons
- iii) These V. B. electrons Do NOT participate in electrical conductivity.

Conduction Band :

- iv) C.-B. electrons are responsible for electrical conductivity

- i) The band above valence band is called Conduction Band
- ii) Range of energies possessed by free electrons in a crystal
- iii) Electrons may or may not exist here



E_g or ΔE_g or FEG.

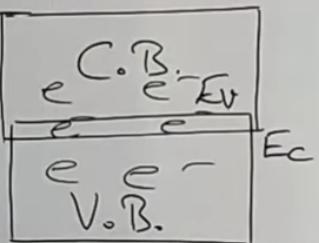
Forbidden Energy Gap:

$$E_g = E_c - E_v$$

$$E_g = (C.B.)_{\min} - (V.B.)_{\max}$$

electrons in V.B. may gain energy & JUMPS to C.B. The electrons can not be found in the region between V.B. & C.B. Some energy levels in between V.B. & C.B. are forbidden (restricted, prohibited) for electrons. These energy levels are together known as FEG.

Conductors (Metals)



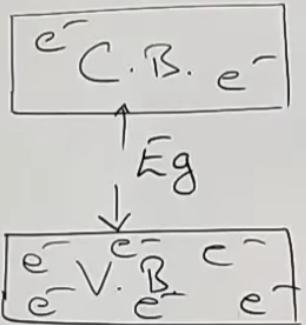
V.B. & C.B.

overlaps

$$E_g \approx 0 \text{ eV}$$

e^- readily jumps
to C.B. from V.B.
& conducts electricity

Semi-Conductors



$$E_g < 3 \text{ eV}$$

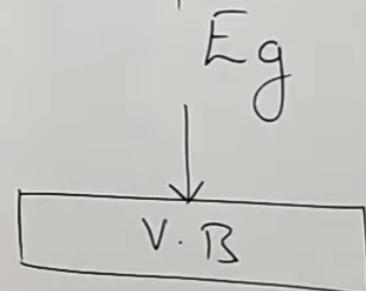
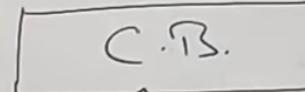
for example

$$\text{Si } E_g \approx 1.1 \text{ eV}$$

$$\text{Ge } E_g \approx 0.74 \text{ eV}$$

e^- on absorbing heat from surrounding (even at Room Temperature) jumps from V.B. to C.B.

Insulators



$$E_g > 3 \text{ eV}$$

for example

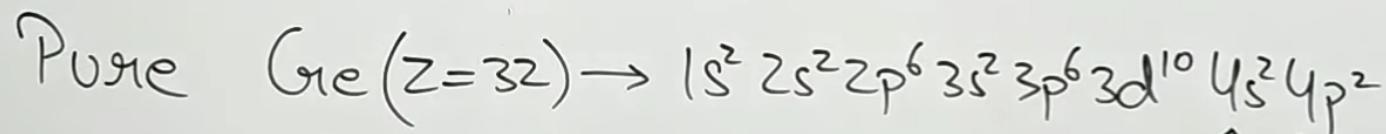
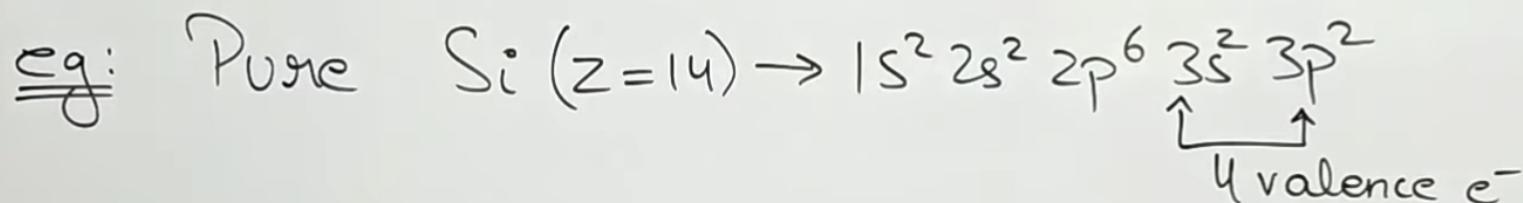
$$\text{Diamond: } E_g \approx 6 \text{ eV}$$

It has to be heated at high temp to excite V.B. electrons to C.B.

Intrinsic Semicons

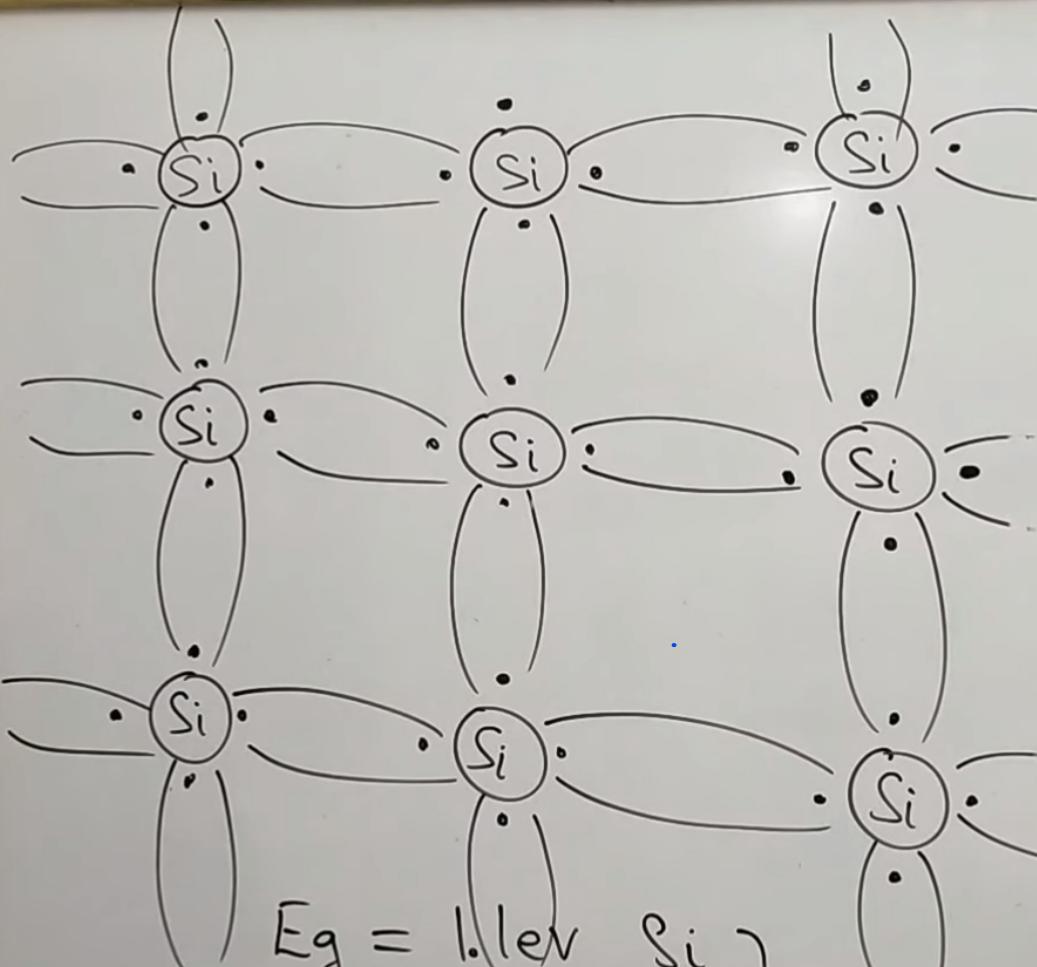
Intrinsic Semiconductors

→ Inborn | Natural | Pure | without any impurity | Basic



⇒ Both have 4 valence electrons

⇒ All 4 valence electrons are involved in
Covalent Bond formation in Si or Ge crystal



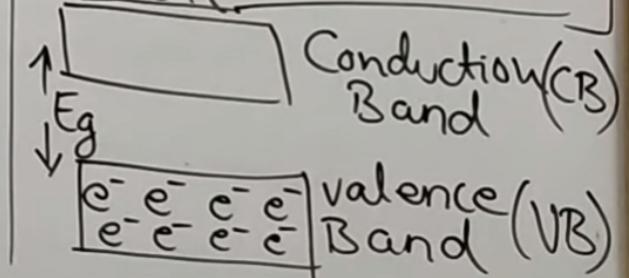
$$E_g = \text{I.lev Si}$$

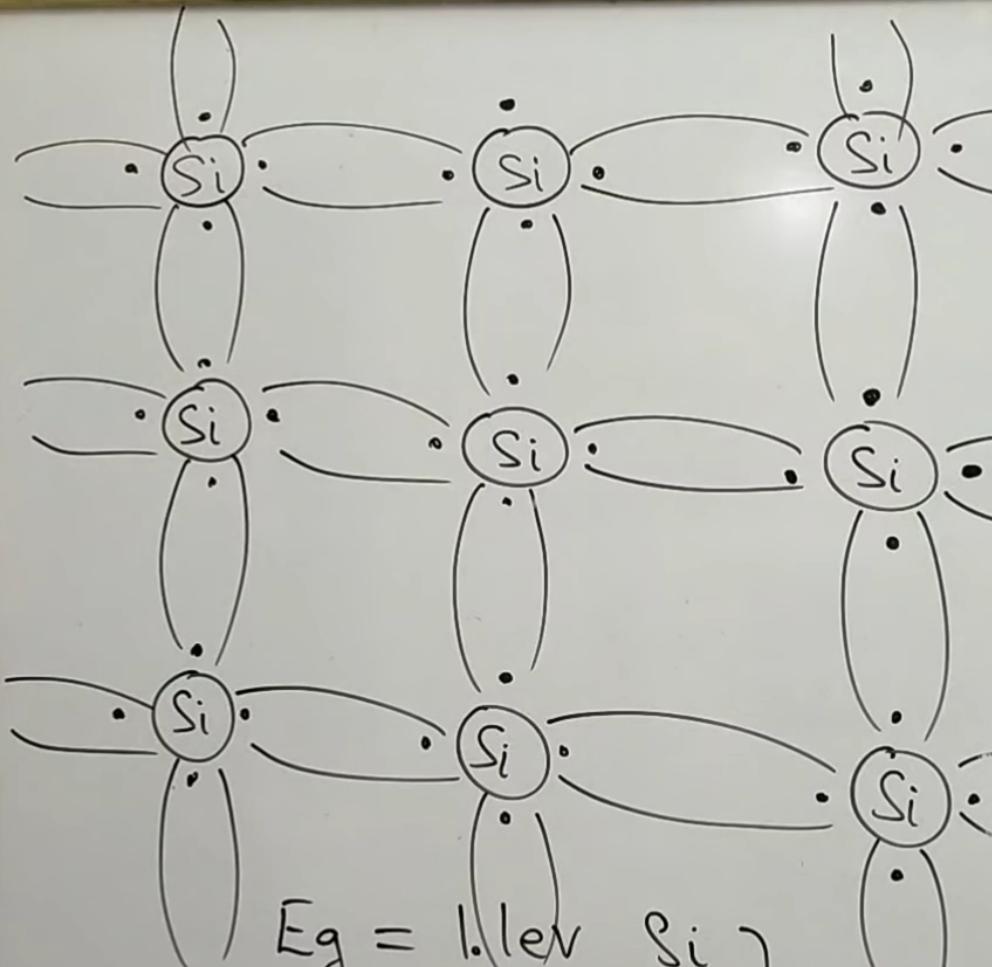
$$E_g = 0.72\text{eV Ge}$$

Pure

① At Absolute Zero Temperature (0K) there are NO FREE electrons. As all the valence e^- are involved in Covalent Bond.

A Semiconductor will behave like an Insulator at 0K



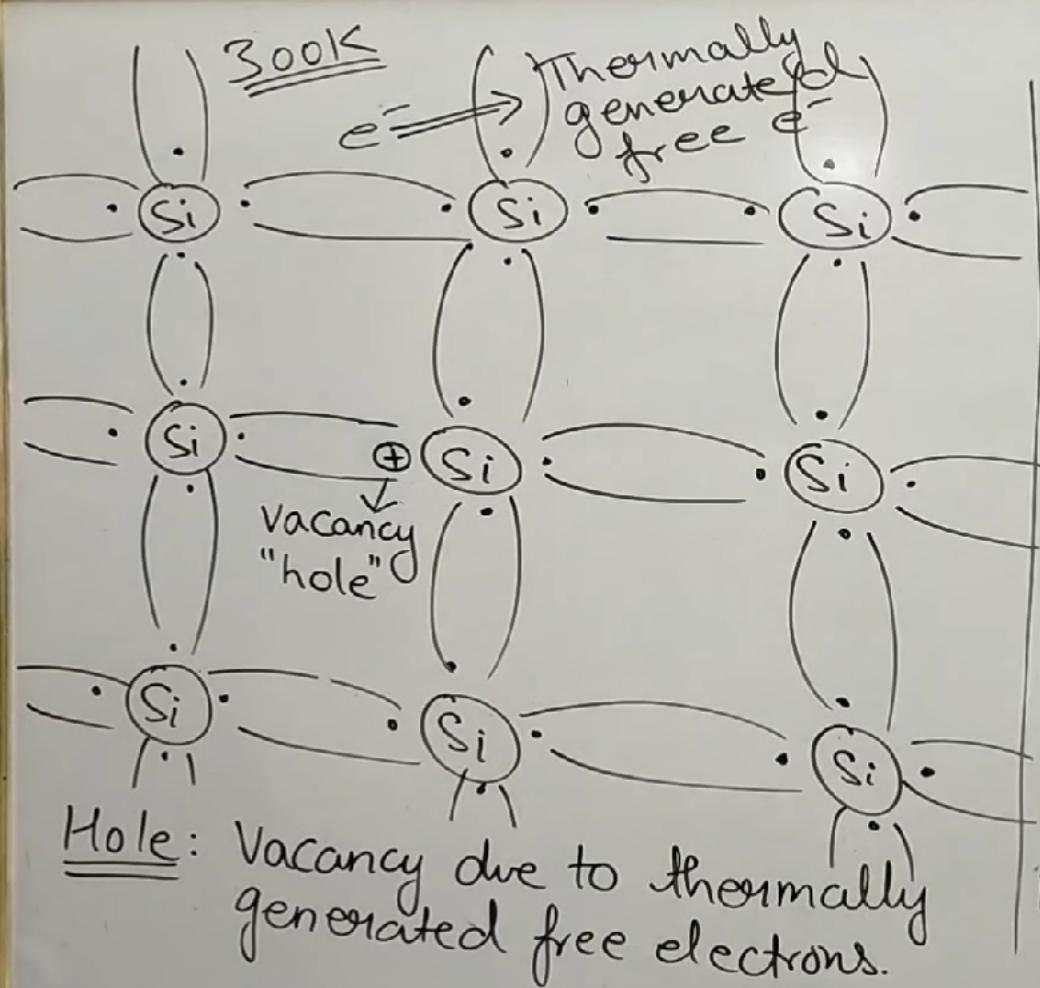


$$E_g = 1.1 \text{ eV Si} \\ E_g = 0.72 \text{ eV Ge}$$

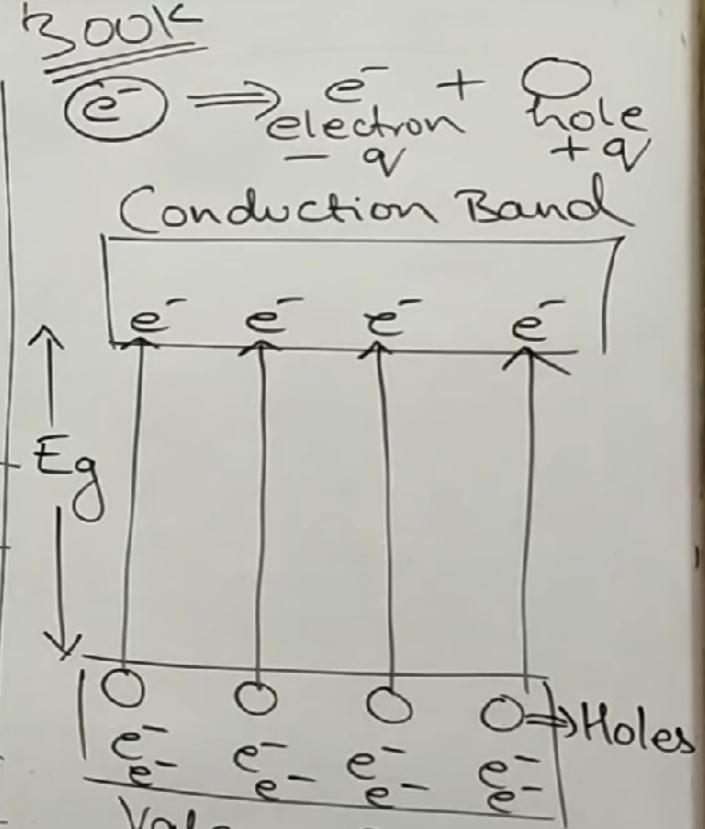
} Pure

② On Increasing Temperature, more & more thermal energy is available. Some Covalent Bonds may break & some free e^- are generated.

At 300K (27°C)
Room Temperature
1 Covalent Bond breaks
in 10^{29} atoms.



Hole: Vacancy due to thermally generated free electrons.



Holes are +ve charged.

Recombination of thermally generated free e^- & holes takes place at all Temperature.

③ Number of thermally generated free e^- (n_e)
is equal to number of holes (n_h) for Intrinsic
Semiconductor

$$n_e = n_h = n_i$$

(number per unit volume)

$n_i \rightarrow$ intrinsic Concentration

At Room Temp 300K (27°C)

$$n_i = 2.4 \times 10^{19} / m^3 \text{ for Ge}$$

$$n_i = 1.5 \times 10^{16} / m^3 \text{ for Si}$$

| intrinsic charge carrier
density

$$n_i \propto e^{-E_g / kT}$$

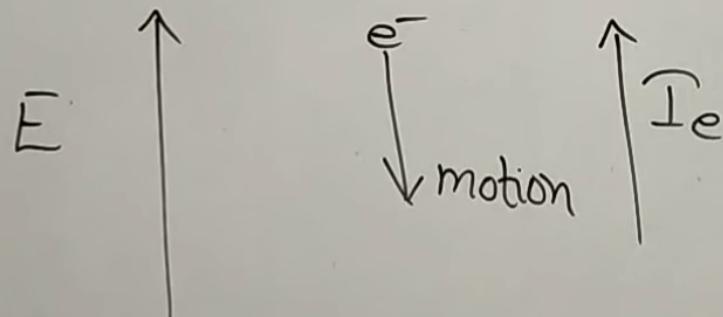
Boltzmann Constant
Temp in Kelvin
Energy Gap

④ Current in Semiconductors is due to

a) Thermally generated free e^-

b) holes

a) thermally generated free $e^- \Rightarrow$ Current due to it
 I_e



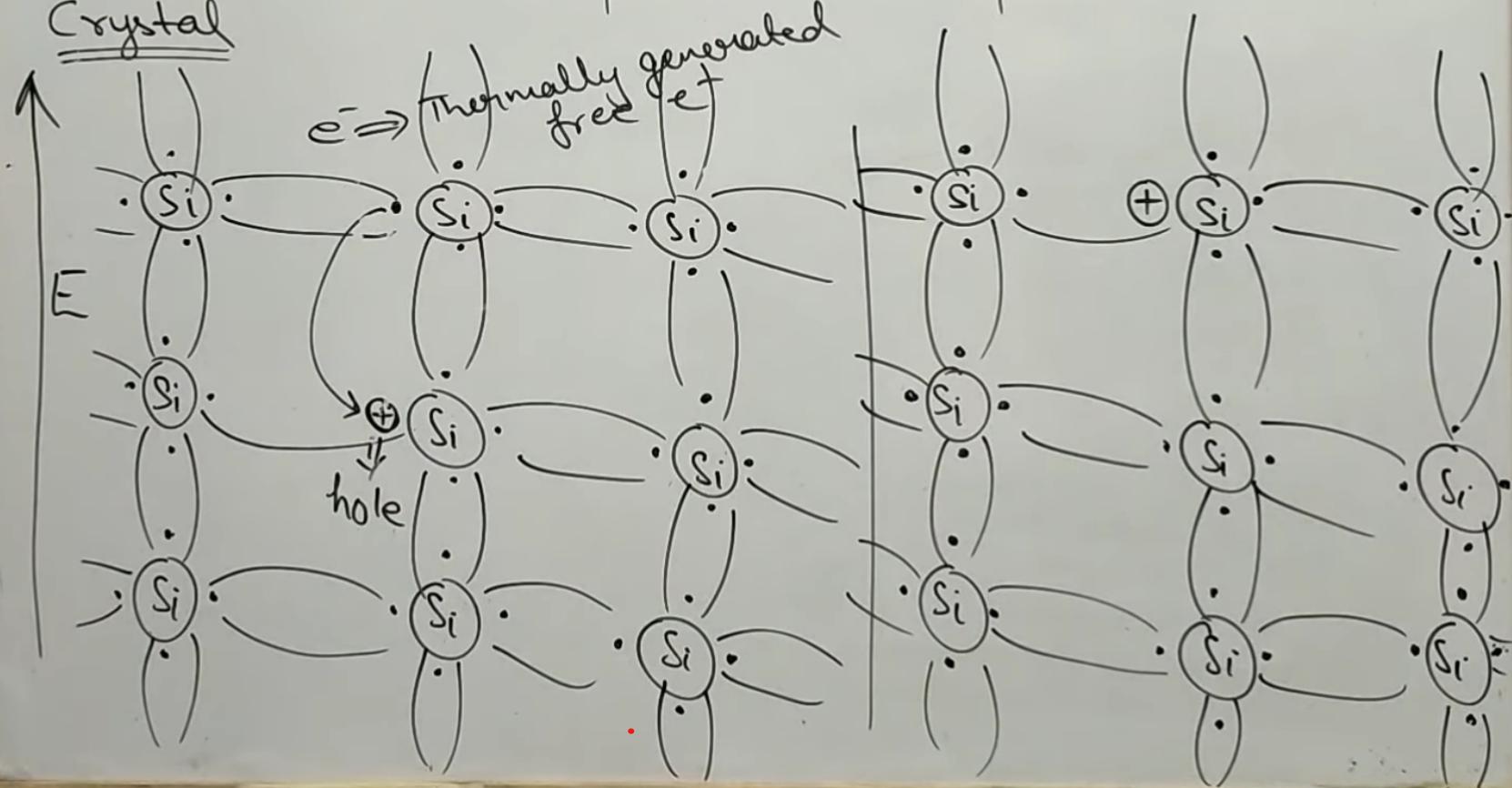
b) holes \Rightarrow current due to it I_h

$$\begin{matrix} -ve & \longleftrightarrow & +ve \\ I & & I \end{matrix}$$

Holes [apparently] move in direction of Applied Electric field.

$$\begin{matrix} E & \uparrow & + & \uparrow & I_h & \uparrow & E \\ & & & & | & & \\ & & & & I_h & & \\ & & & & \uparrow & & \\ & & & & e^- & \uparrow & I_e \\ & & & & | & & \\ & & & & e^- & & \end{matrix}$$

Crystal



Lifetime - The amount of time from the creation and disappearance of electron is called Lifetime of Free electron.

Recombination - Recombination is the merging of a hole & a free electron
=> Recombination releases energy in form of heat, Light, or radiation

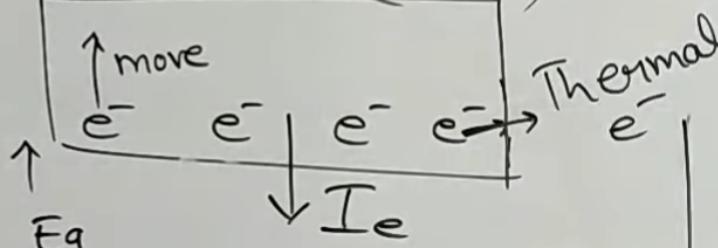
★ Why Recombination at Junction is a key focus :-

=> Intensity :- The rate of recombination is the highest at the junction rather than n or p-type region.

=> Efficiency (for LEDs) :- In LEDs, The material is specifically engineered so that most of the recombination happens in a specific "active layer" at the junction to ensure light can easily escape the structure without being re-absorbed by the surrounding material.

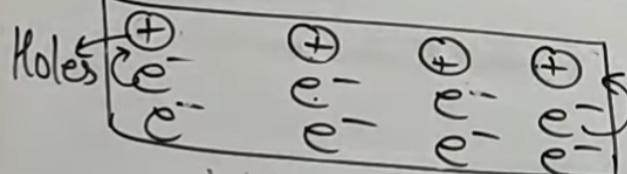
Energy Band.

Conduction (Band)



Eg

Mobility of holes
is less than that
of free electrons



Valence Band
(VB)

$$I_{\text{net}} = I_e + I_h$$

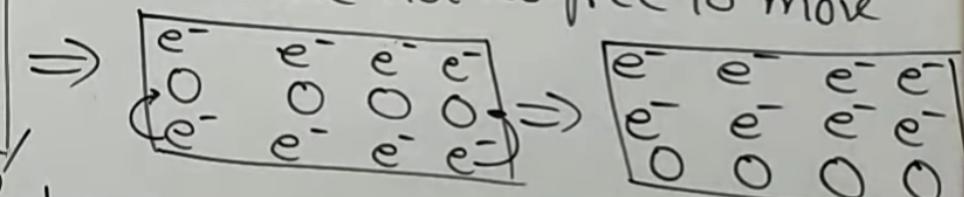
In Intrinsic Semiconductors

$$n_e = n_h = n_i$$

$$I_e > I_h$$

I_e is due to electrons in CB
which are free to move

I_h is due to electrons in VB
which are not so free to move



$$I_h \downarrow \quad i = V_d / \rho \cdot A$$

Extrinsic Semicons

Extrinsic Semiconductors \rightarrow n-type & p-type

- ① The electrical conductivity of Intrinsic (pure) semiconductors increases with Temperature. Even on reaching Room Temperature (27°C) its conductivity is very poor.
- ② The addition of Certain impurities can increase the conductivity of intrinsic (natural) semiconductors.

Extrinsic Semiconductors \rightarrow n-type & p-type

③ Very small amount (in parts per million ppm) of impurity atoms can increase conductivity of intrinsic semiconductors many times.

(1 atom of impurity in 10^8 pure atoms of Ge increases conductivity of pure Ge 16 times)

The Semiconductor thus obtained is called
Extrinsic Semiconductors.

Extrinsic Semiconductors \rightarrow n-type & p-type

④ The process of addition of impurities (intentionally) is called 'Doping'.

The impurity atom is called 'Dopant'.

The impure semiconductor thus formed is called 'Doped Semiconductor'.

Doping can be done in many ways :-

- i) Heating Pure Semiconductor in atmosphere of impurity atoms so that impurity atoms diffuse in pure crystal
- ii) Bombarding pure Crystal with ions of impurity atom

Extrinsic Semiconductors \rightarrow n-type & p-type

⑤ Extrinsic Semiconductor can be of two types based on the type of impurity atom:-

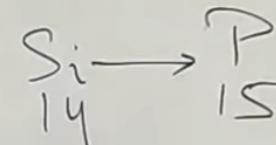
i) n-type Semiconductor: Pentavalent impurity atom

(Phosphorous (P), Antimony (Sb), Arsenic (As))

ii) p-type Semiconductor: Trivalent impurity atom

(Boron (B), Aluminium (Al), Indium (In))

n-type Semiconductors

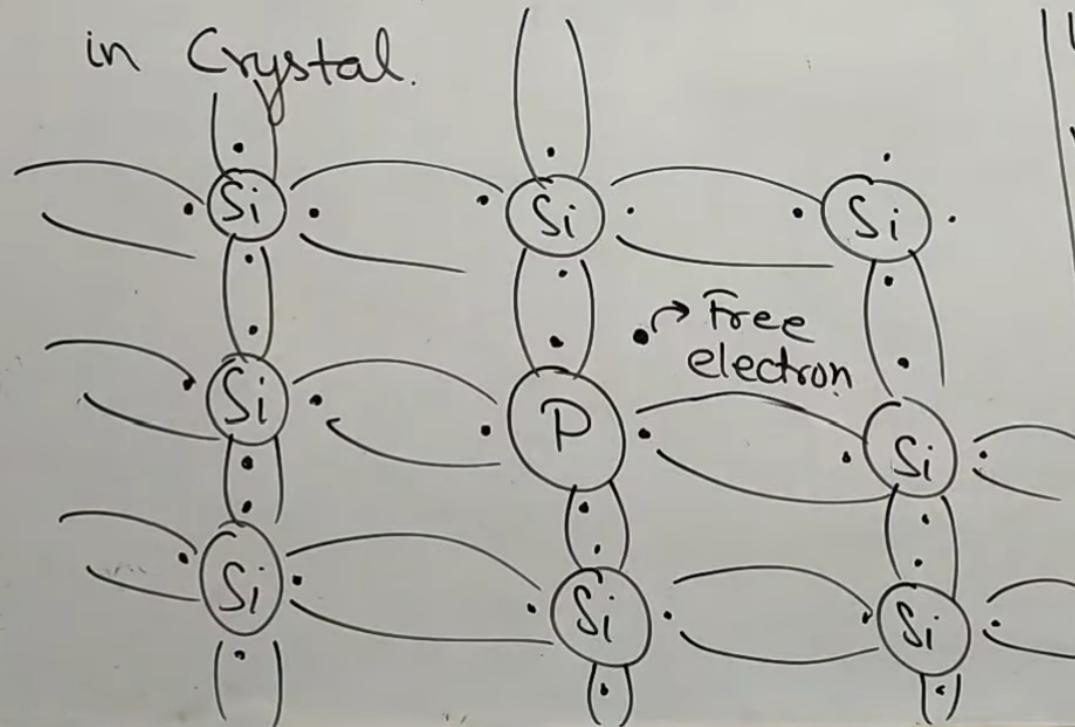


2,8,4 2,8,5

① Pentavalent impurity atoms

(P, Sb, As) replaces pure Si (or Ge) atoms

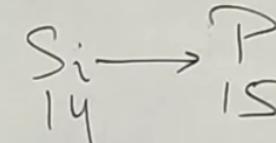
in crystal.



4 out of 5
Valence e^- of P
forms Covalent
Bonds with neighbor
using Si atoms.

But the fifth e^-
is nearly free.

n-type Semiconductors

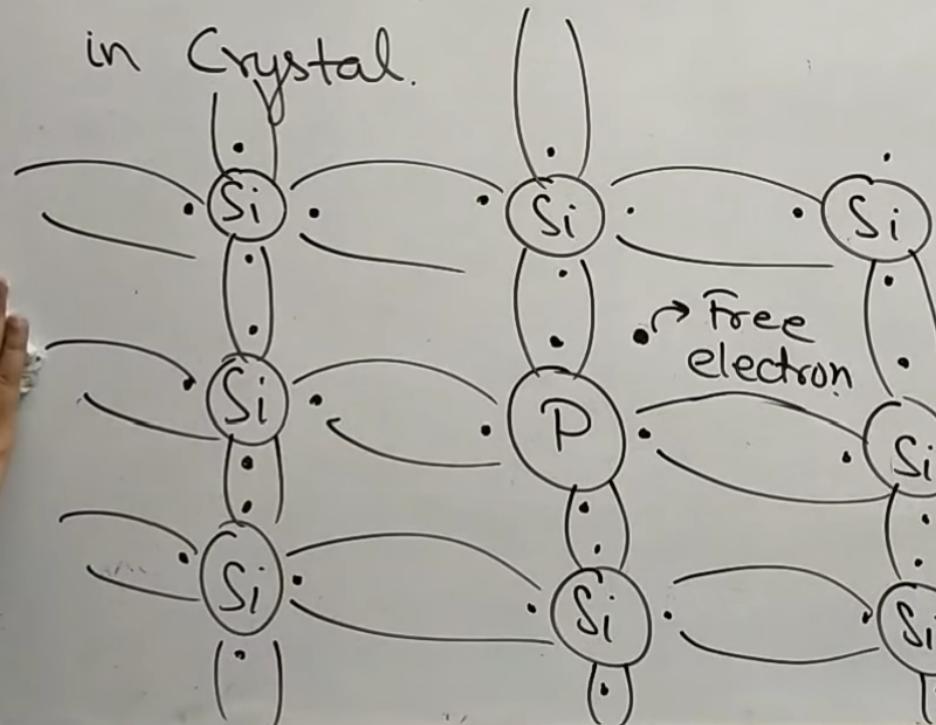


2,8,4 2,8,5

① Pentavalent impurity atoms

(P, Sb, As) replaces pure Si (or Ge) atoms

in crystal.



The ionisation energy required to free fifth valence e^- is very low
(0.06eV in Ge, 0.05eV in Si)
Contrary to that required in p-type semiconductors

n-type Semiconductors

- ③ The energy required to free fifth valence e^- can be obtained at room temperature so this electron is set free & it goes to Conduction Band & is available for electrical conduction.
- ④ Pentavalent impurity donates one electron per atom. & hence they are called "Donor impurity"

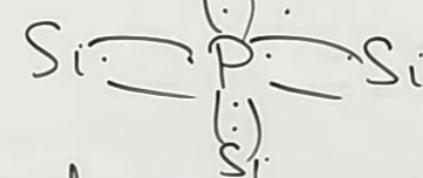
n-type Semiconductors



- ⑤ The conductivity increases with doping.

More doping \Rightarrow More Donor impurity \Rightarrow $\text{Si} \cdot \text{Si} \cdot \text{Si} \cdot \text{Si} \cdot$

More free electrons.



Conductivity of n-type do not depend on Temperature

- ⑥ Note that some free electrons are also generated thermally due to breaking of few covalent Bonds. An equal number of holes are also generated

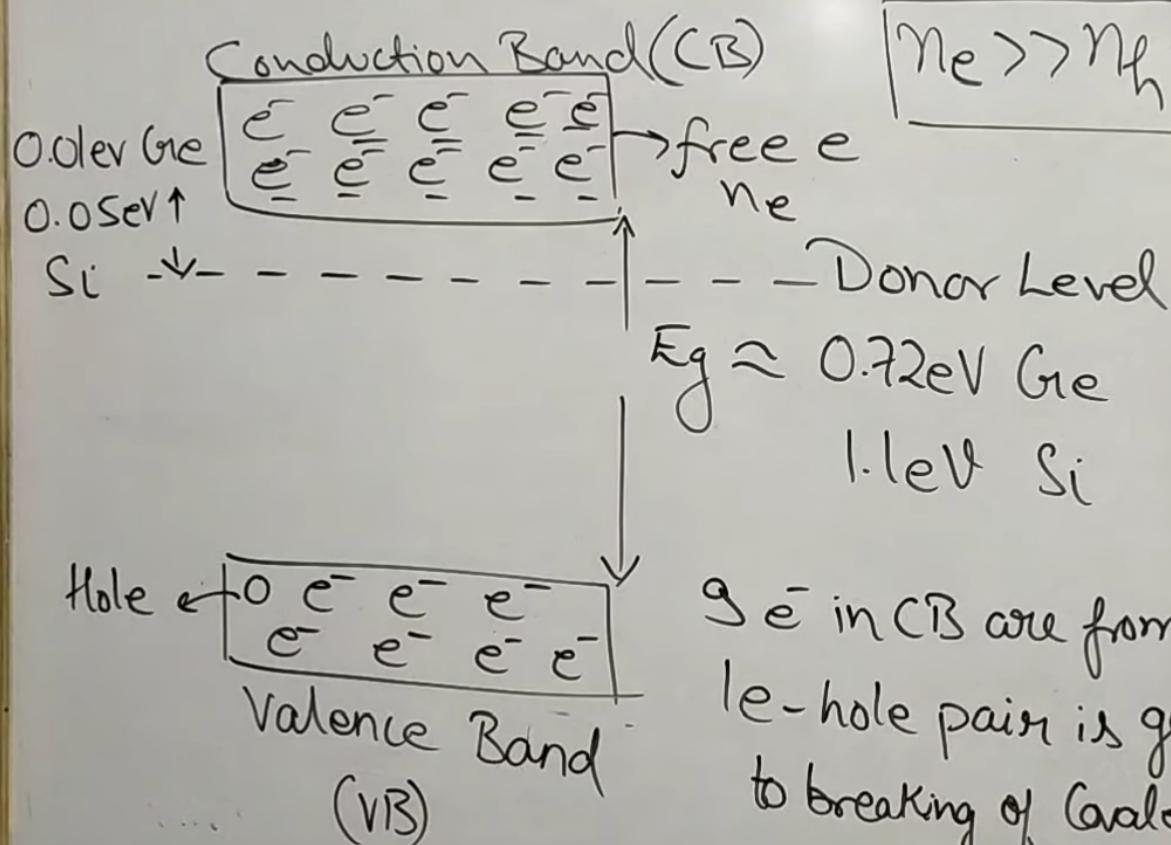
n-type Semiconductors ($n_e \gg n_h$)

⑥ n_e (no. of e^- /volume) — P —
 n_h (no. of holes/volume) — T —

n_e → 30% due to Pentavalent impurity atoms
10% due to breaking of Covalent Bonds

n_h → due to breaking of Covalent Bonds

Energy Band for n-type:



electrons are
Majority charge
carriers.

holes are
Minority charge
carriers

9 e^- in CB are from donor
1 e-hole pair is generated due
to breaking of Covalent Bond

Energy Band for n-type:

⑦ n-type

→ negative type

$$n_e \gg n_h$$

electrons are
Majority charge
Carriers.

holes are
Minority charge
Carriers

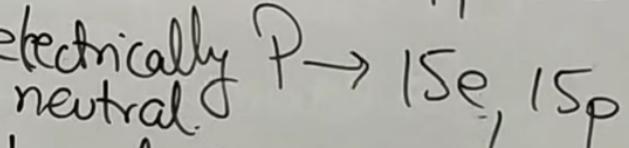
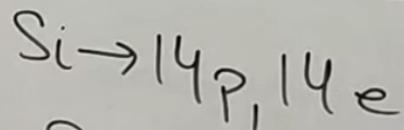
as negative charge carriers (electrons)

are Majority

⑧ n-type Semiconductors are electrically neutral

Pentavalent impurity brings one extra electron.

But it also brings one extra proton.

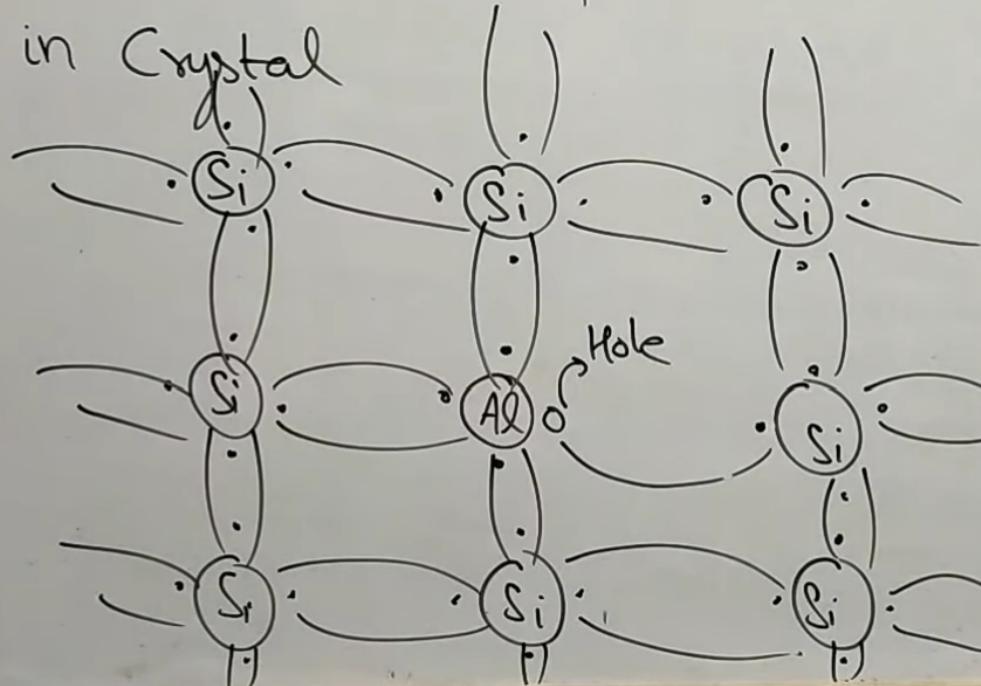


ii) P-type Semiconductors

① Trivalent impurity atoms: $2,8,3$ $2,8,4$

(B, Al, In) replaces atoms of pure Si (or Ge)

in Crystal



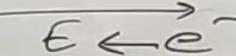
Al Si
13 14
↓ ↓

$1s^2 2s^2 2p^6 3s^2 3p^1$ 3 valence e⁻

3 valence e⁻ of Al forms 3 covalent bonds with neighboring Si atoms

A vacancy (Hole) is left at one site of trivalent impurity atom

ii) P-type Semiconductors



Al Si

13 14

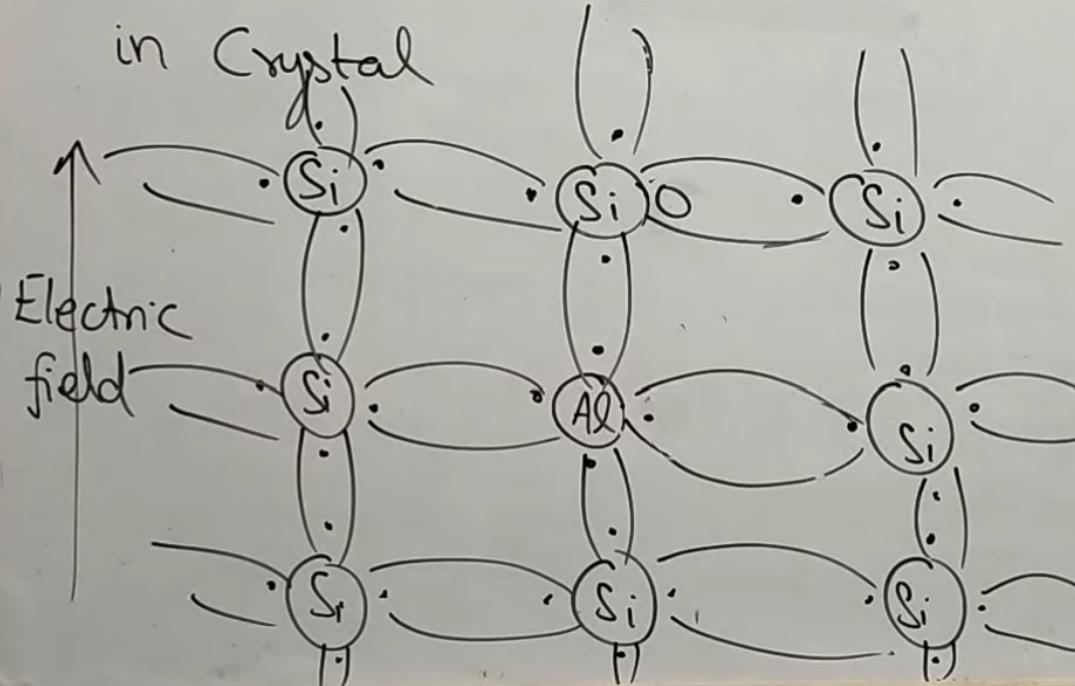
↓ ↓

2,8,3 2,8,4

$1s^2 2s^2 2p^6 3s^2 3p^1$ 3 valence e⁻

① Trivalent impurity atoms: $2,8,3$ $2,8,4$
 (B, Al, In) replaces atoms of pure Si (or Ge)

in Crystal



This requires
very small amount
of energy.

0.01eV Ge

0.05eV Si

ii) P-type Semiconductors

- ③ This energy is available at room temperature.
Hence large number of holes are available for
electrical conduction. (in Valence Band)
- ④ Trivalent impurity "Accepts" an electron from neighbouring atom & hence it is called "Acceptor impurity".
- ⑤ The electrical conductivity depends upon level of doping.
More doping \Rightarrow More Acceptor impurity \Rightarrow More holes
& is independent of Temperature.

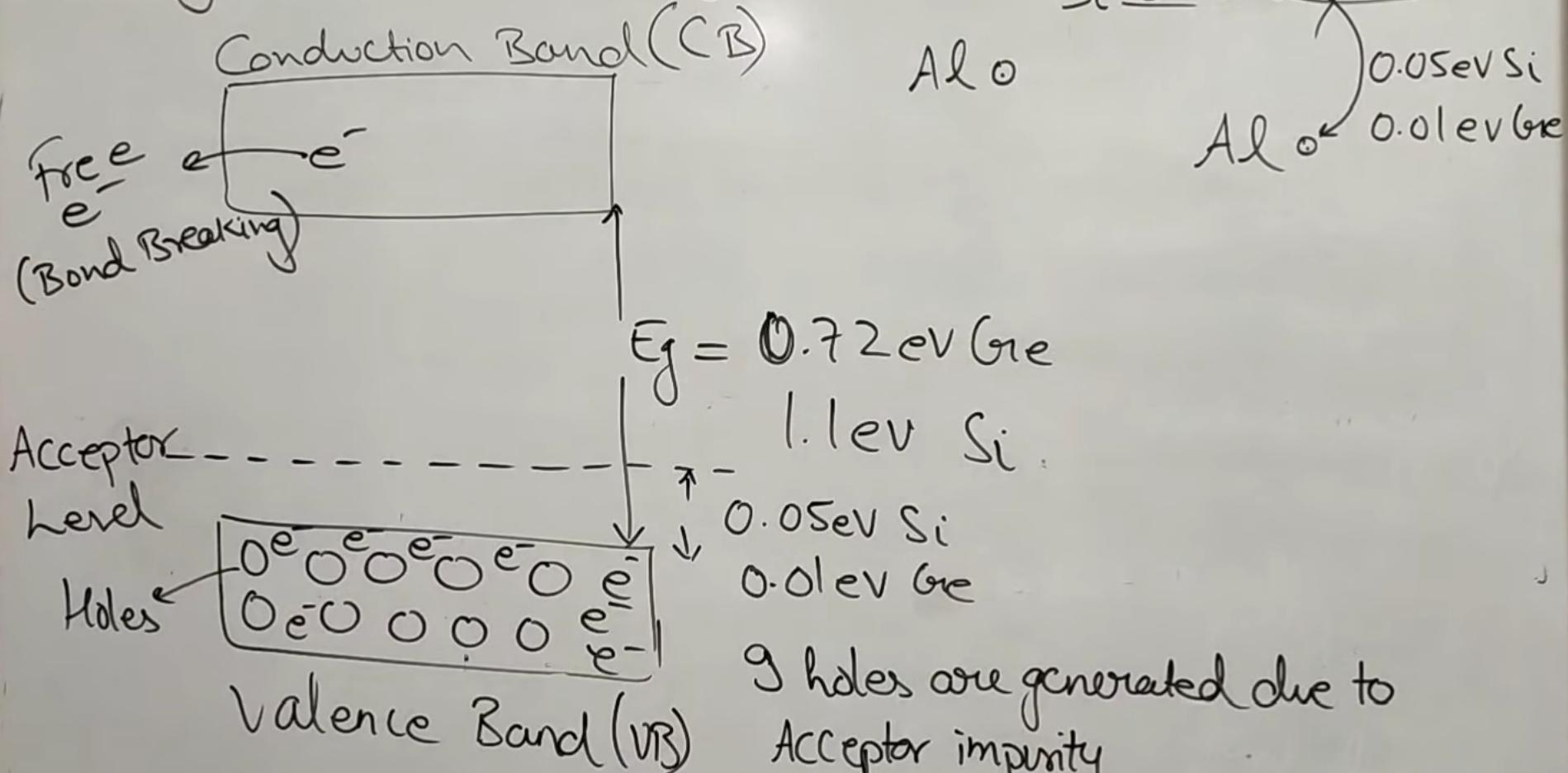
ii) P-type Semiconductors ($n_h >> n_e$) Si - Al : Si.
Si : (10)

- ⑥ Few covalent Bonds may break
which generates free electrons & equal number of holes

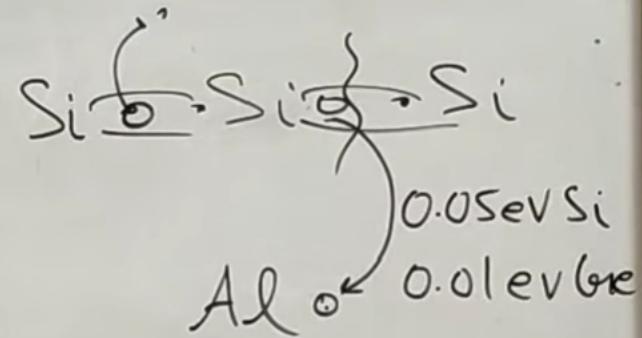
- ⑦ $n_h \rightarrow$
- 30% due to acceptor impurity (trivalent impurity)
 - 10% due to breaking of Covalent Bonds

$n_e \rightarrow$ due to breaking of Covalent Bonds.

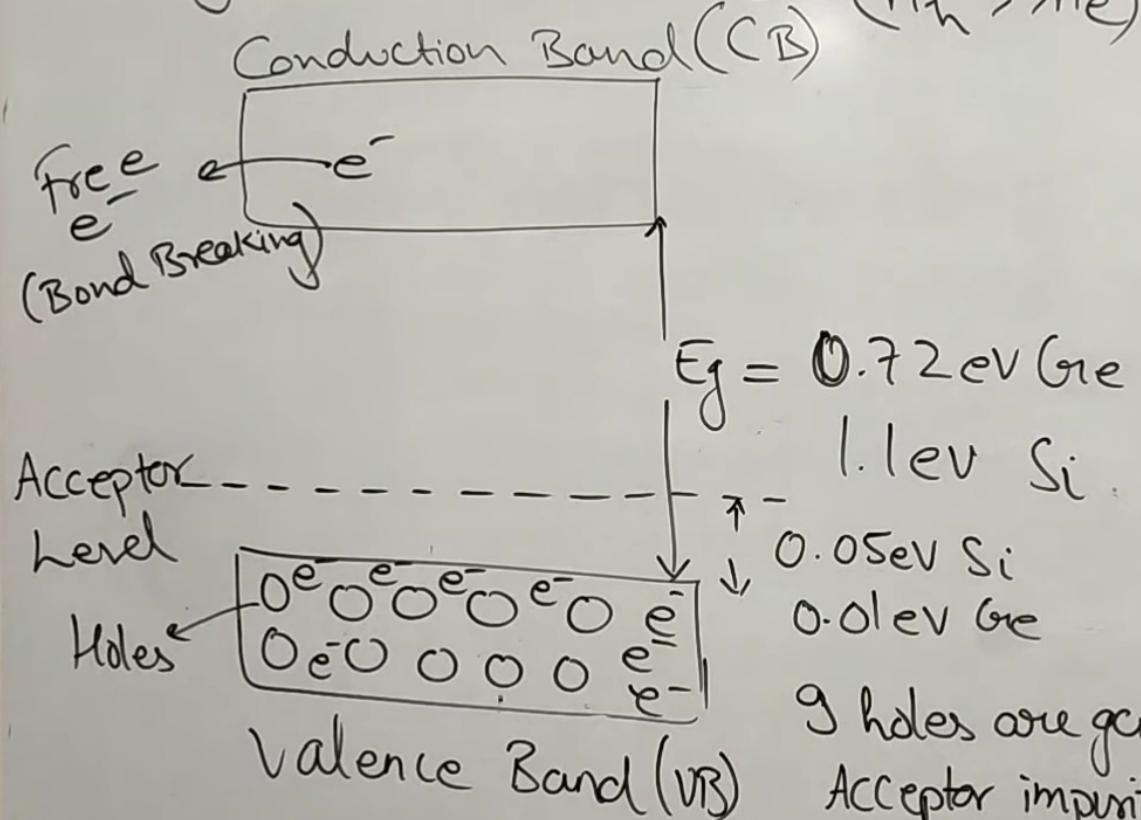
Energy Band for P-type: SiO



9 holes are generated due to
Acceptor impurity
i.e. - hole pair generated by
Breaking of bond.



Energy Band for P-type:



9 holes are generated due to
Acceptor impurity
i.e. hole pair generated by
Breaking of bond.

holes are
Majority charge
Carriers.

electrons are
Minority charge
Carriers.

Energy Band for P-type: ($n_h \gg n_e$)

P-type:

Positive-type

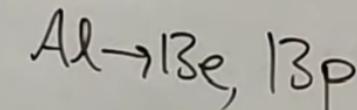
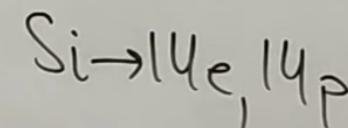
Majority charge carriers
(holes) which are +ve.

P-type Semiconductors are also neutral.

Trivalent impurity is short of one valence e^-
But it is also short of one proton (in its core)

$\textcircled{+}$
holes are
Majority charge
Carriers.

electrons are
Minority charge
Carriers.



n-type

① Pentavalent impurity

② One extra e^- in valence shell

③ Majority carriers $\rightarrow e^-$

④ Donor Level

$n_e \rightarrow$ no of free e^- / volume
(CB)

$n_h \rightarrow$ no of holes / volume
(VB)

$n_i \rightarrow$ intrinsic charge carrier / volume

P-type

Trivalent impurity

Short of one e^- in valence shell

Majority carrier \rightarrow holes

Acceptor Level

$$n_e n_h = n_i^2$$

Approximate & hypothetical