Conductor : Supports a generous flow of charge when a voltage is applied across its terminal

Insulator : Material offers a very low level of Conductivity

Semiconductor: Conductivity level some what between extremes of an insulator and a conductor.

$\rho = \frac{R.A}{l}$ R : resistance A : Cross sec area

l : length

$\rho = R$, $A = 1$, $l = 1$ ρ : resistivity

Conductor	Semiconductor	Insulator
$\rho \simeq 10^{-6}\ \Omega\,cm$ (Copper)	$\rho \cong 50\ \Omega\,cm$ Ge $\cong 50 \times 10^{3}\ \Omega\,cm$ Si	$\rho \simeq 10^{12}\ \Omega\,cm$ (mica)

Si : More focus

Ge : Modest attention.

Both Si and Ge can be manufactured to a very high purity level.

1 part in 10 billion $1 : 10^{10}$

1 part impurity per million can change characteristics.

$\Rightarrow$ Doping.

Ge : 32 orbiting electron~~ics~~

Si : 14 Orbiting electrons

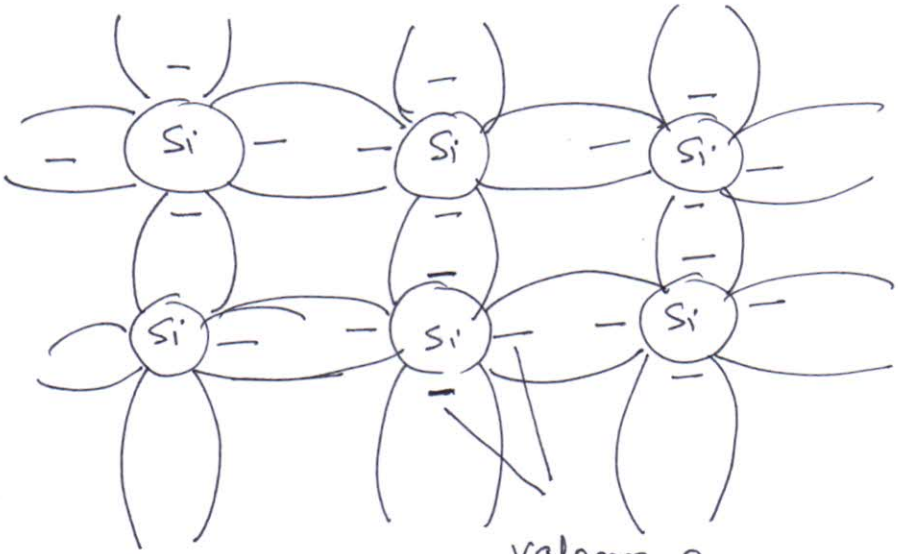
4 electrons in outermost (valance) shell.

Ionization potential : The energy required to remove any one of these 4 valance electrons is lower~~ed~~ than that of any electron

In pure Ge or Si Crystall, 4 valance electrons are bonded to 4 adjoining atoms.

Ge, Si : Tetravalent atoms.

Bonding of atoms by sharing ~~by~~ of electrons, is called covalent bonding.



valence electrons absorb sufficient kinetic energy from natural causes to breake the covalent bond and assume free state.

Natural causes : Light energy in the form of photon
thermal energy from surroundings.

Free ⇒ motion is sensitive to applied Electric field.

At room temp: approx 1.5×10^{10} free 'e' in one cc of intrinsic Si.

Intrinsic materials : carefully refined to reduce the impurities to a very low level — essentially as pure as can be made available.

Free electrons : intrinsic carriers

At room temp : Intrinsic Ge will have approx 2.5×10^{13} free carrier per cc.

No of Carriers : Ge : Si $> 10^3 : 1$

⇒ Ge is a better conductor at room temp

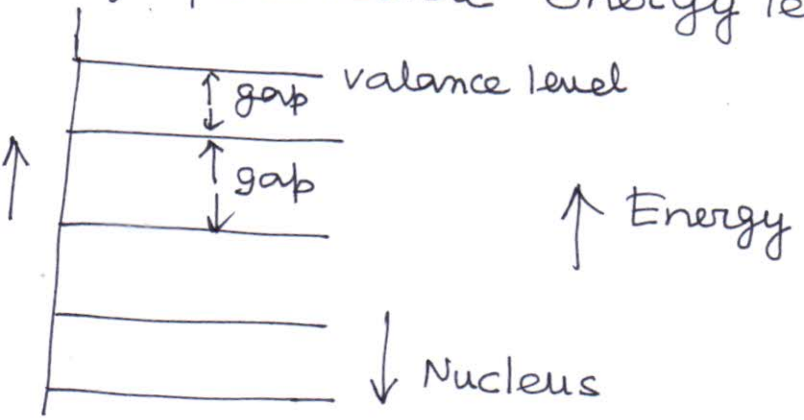
Resistivity Si : Ge $10^3 : 1$

- increase in temp of a Semiconductor can result in a substantial increase in the number of free electrons in a material.
- Increase in conductivity ⇒ lower resistance level.

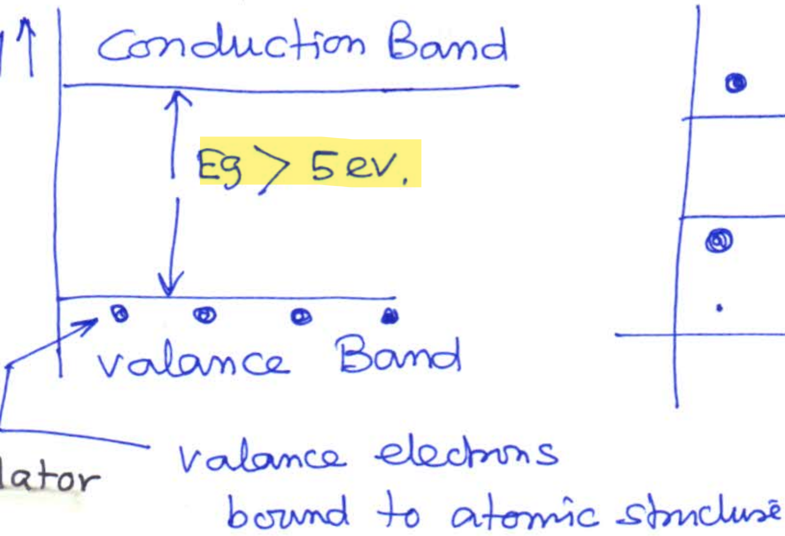
..., Ge, (semiconductor) materials show a reduction in resistance with increase in temperature ⇒ negative temp coefficient.

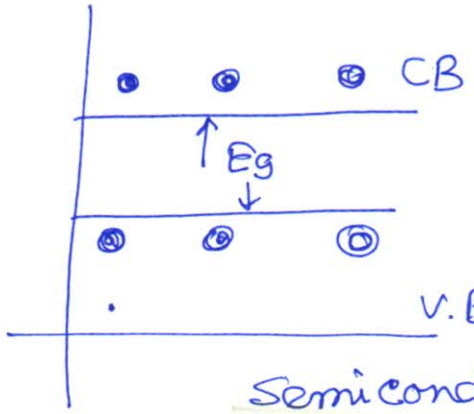
Energy Levels

Discrete energy levels associated with each electron. Each material will have its own set of permissible energy levels for electrons



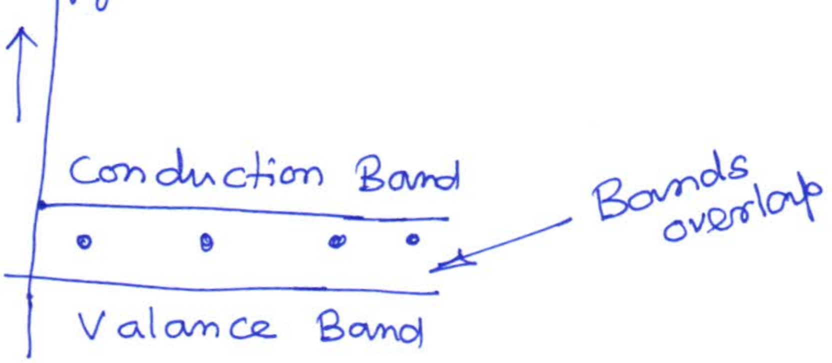
- More distant electron from nucleus, higher the energy state.
- Any electron which left parent atom has a higher energy state than any electron in atomic structure.





Semiconductor

$E_g = 1.1$ ev Si
$= 0.67$ ev Ge
$= 1.41$ ev GaAs



Conductor.

Ionization : Mechanism whereby an electron can absorb sufficient energy to break away from atomic structure and move to CB.

Energy is measured in eV,

$1\,eV = 1.6 \times 10^{-19}\,C \cdot 1\,V = 1.6 \times 10^{-19}\,J.$

At $0^\circ K$ all valance e^- are locked with energy level associated with V.B.

At room temp $300^\circ K$ or ~~25~~ $27^\circ C$, a large no. of e move to CB crossing the Energy gap E_g.

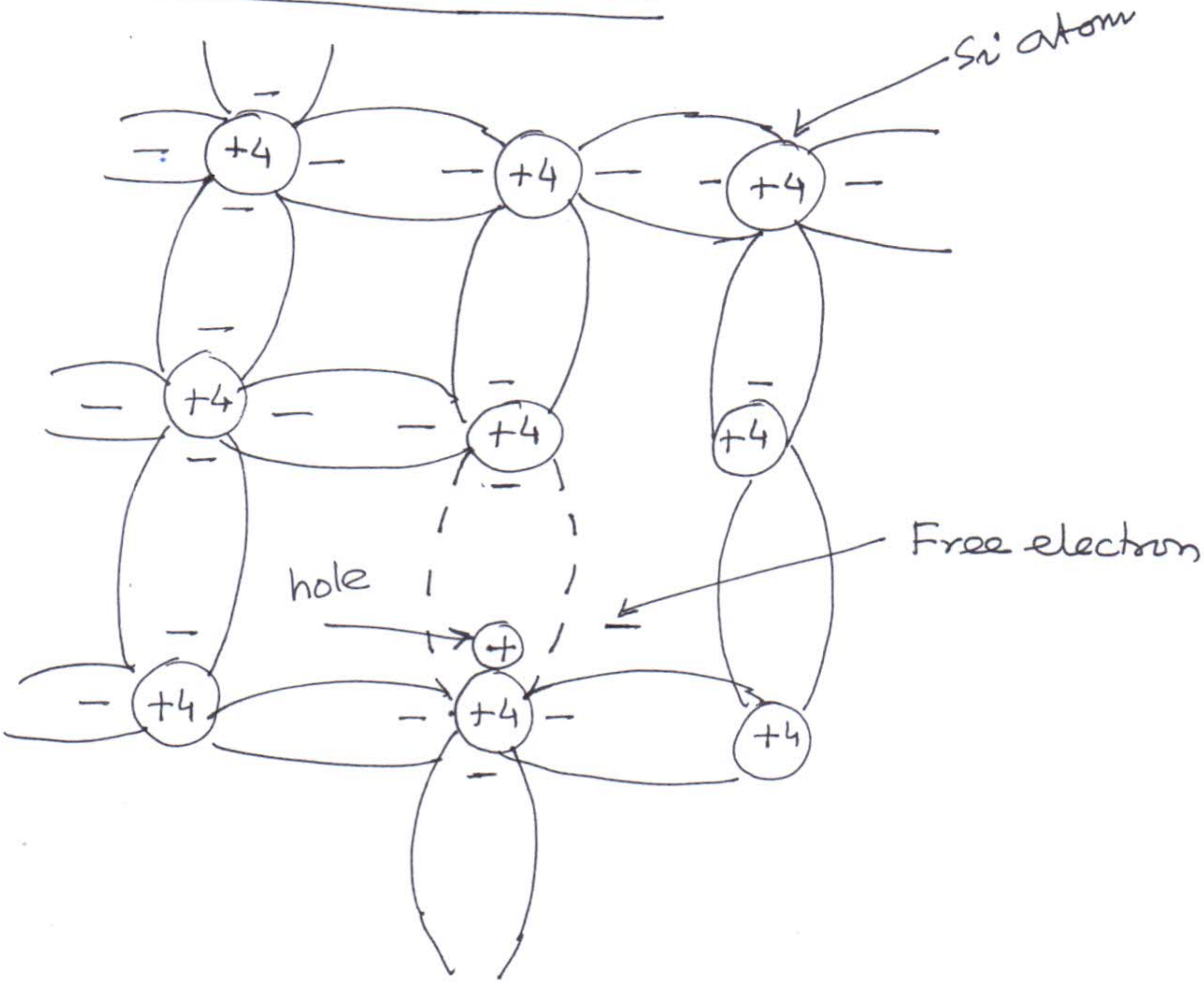
Si : E_g 1.1 eV, Ge : 0.67 eV

Lower E_g of Ge ⇒ increased number of carriers compared to Si. at room temp.

Insulator has energy gap $E_g = 5\,eV$ or more
limits no. of electrons in CB at room temp.

Conductor has electrons in CB even at 0K
At room temp more than enough free carriers
⇒ heavy flow of charge or ct.

Intrinsic Material



Thermal generation ⇒ free electrons and holes in equal numbers ⇒ equal concentrations.

Some free moving electrons may fill some holes

⇒ recombination results in disappearance of e and h.

Recombination rate ∝ no. of free e and h
depends on generation rate.

Generation rate depends on temp.

Thermal Equilibrium Recombination rate = generation rate recombination rate = generation rate

Conc. of free electron: n

Conc of holes : p

Intrensic conc : n_i

n_i : no. of free electrons and holes in a unit vol (cc) of intrinsic Si at a given temp.

$$\boxed{n = p = n_i}$$

$$\boxed{n_i = A_0 T^{3/2} e^{-E_g/2kT}}$$

A_0 : material dependent parameter,

for Si : $7.3 \times 10^{15}\ cm^{-3}\ K^{-3/2}$

E_g : 1.12 eV for Si, k : boltzman const

$k = 8.62 \times 10^{-5}$ eV/K

Further, $\boxed{np = n_i^2}$

for Si at room temp $n_i \simeq 1.5 \times 10^{10}$/cc.

This relationship extends to doped Si as well.

Ex: Calculate intrinsic carrier density n_i for Si at $T = 50K$ and $350K$

(Ans) 9.6×10^{-39}/cc , 4.15×10^{11}/cc

Ex: Calculate n_i for Si at room temp $T = 300K$

$n_i = 1.5 \times 10^{10}$ carrier/cc.

n_i for Si at $T = 300K$

$$n_i = A_0 T^{+3/2} e^{-E_g/2kT}$$

$$= 7.3\times10^{15} (300)^{3/2} \cdot e^{-1.12/2\times 8.62\times10^{-5}\times 300}$$

$$= 1.5\times10^{10} \text{ carriers/cc.}$$

Although it seems to be very large.

Si has 5×10^{22} atoms/cc.

Thus only one in about 5×10^{12} atoms is ionized and contributing a free electron and hole.

Extrinsic Semiconductor / Doped

Intrinsic Si : equal conc. of free e and h generated by thermal generation.

small conc. to conduct appreciable ct at room temp.

Doping ⇒ Process of changing carrier conc. in a semiconductor substantially and in a precisely controlled manner. (1 part in 10 million)

Introducing impurity atoms into Si crystal in sufficient numbers to substantially increase the conc. of either free e or holes with little or no change in crystalline structure.

- To increase conc. of free e, n, Si is doped with an element with a valancy of 5 such as phosphorus.
  The resulting doped Si is said to be 'n' type

- To increase conc. of holes, p, Si is doped with an element having a valance of 3 such as Boron, resulting doped Si is 'p' type

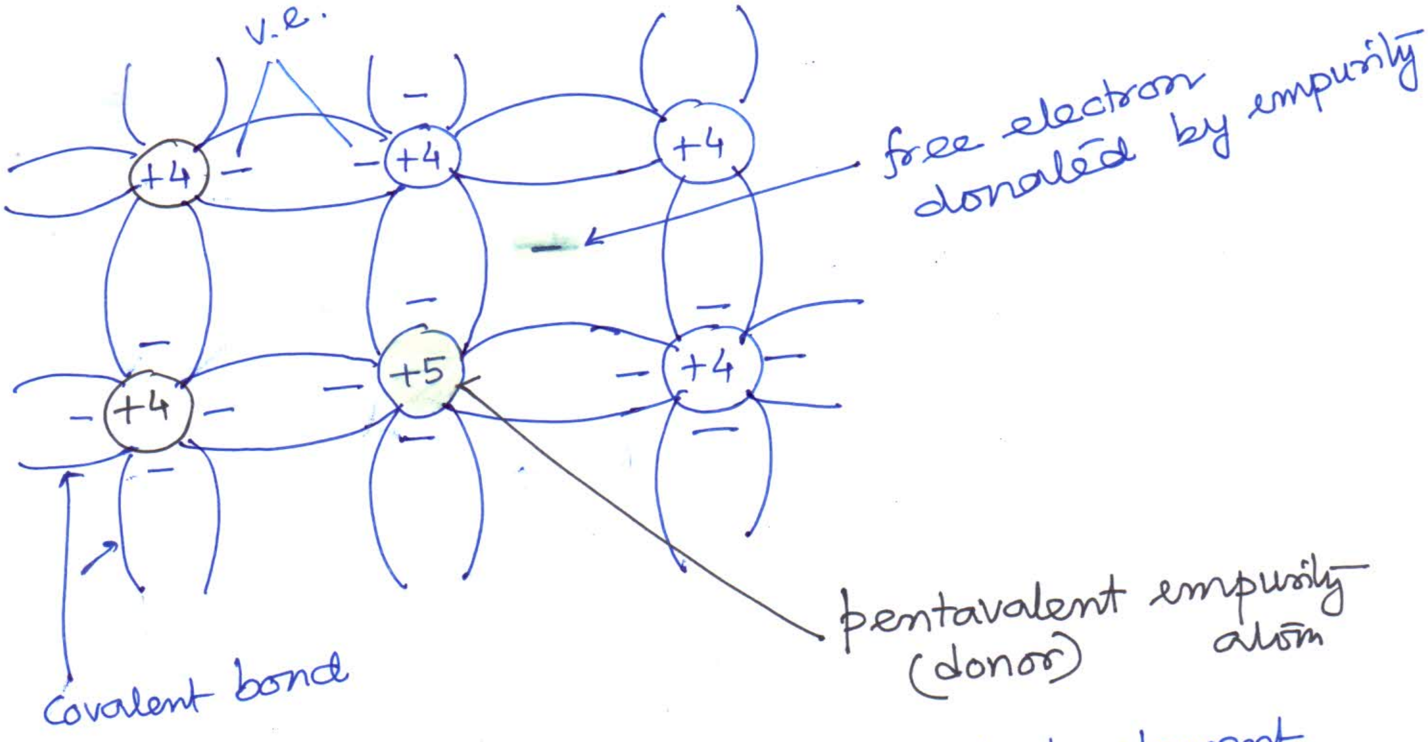


Fig: Si Crystal doped by Pentavalent element

Each dopant atom donates a free electron and thus called a donor.

The doped semiconductor becomes 'n' type.

Pentavalent - Sb, As, phosphorus

Each phosphorus atom donates a free 'é'
to Si crystal. phosphorus is donor

Positive charge associated with phosphorus is
bound charge that does not move through crystal.

Conc. of Donor N_D $\qquad N_D \gg n_i$

Conc. of free electrons in n-type Si

$$\boxed{n_n \approx N_D}$$

n_n determined by doping conc.
not by temperature.

Hole conc (p_n) depends on temp, as all holes
in the n-type Si are generated by thermal ionization

Under thermal equilibrium

$$\boxed{p_n n_n = n_i^2}$$

$$\boxed{p_n \cong \frac{n_i^2}{N_D}}$$

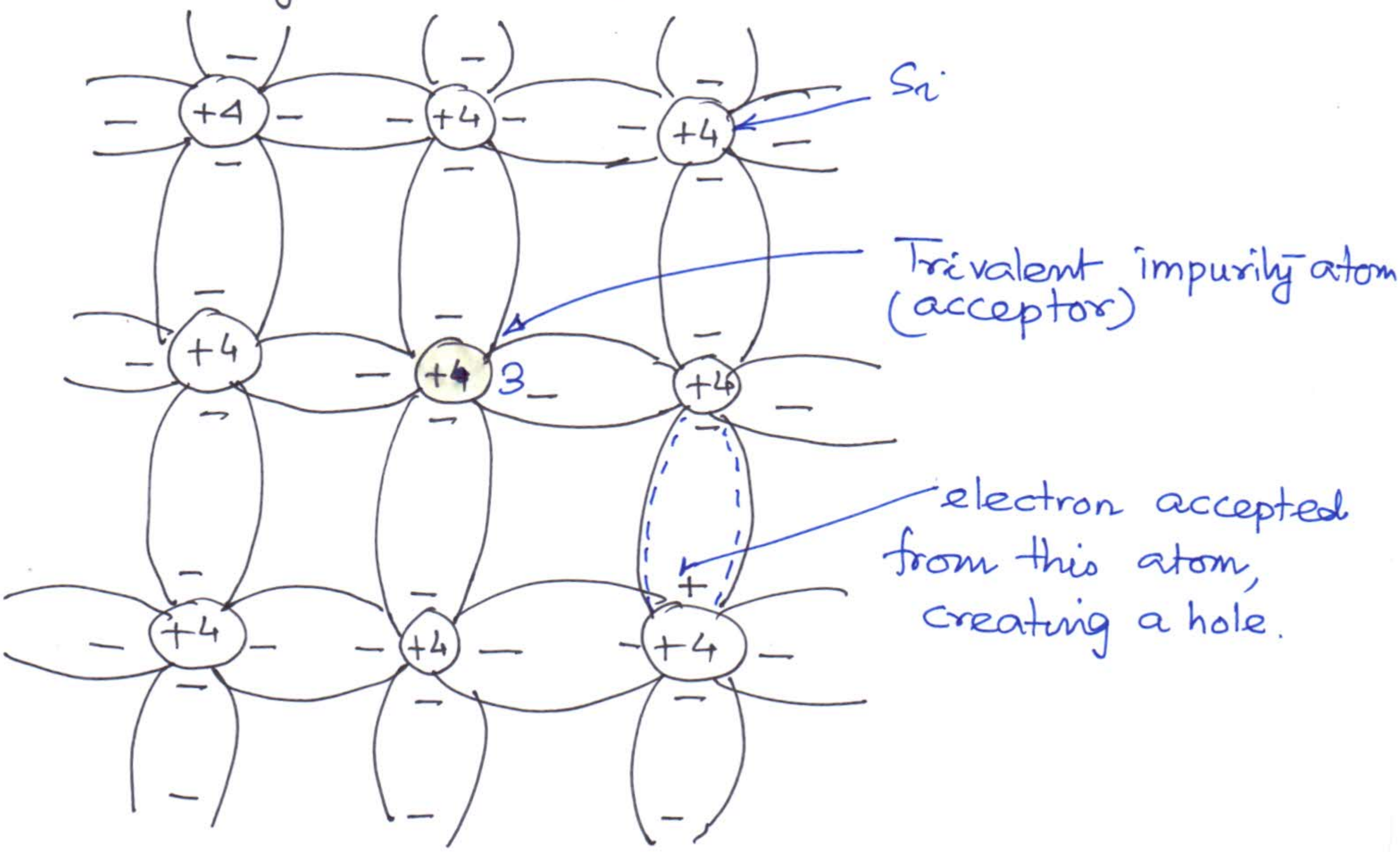
Thus p_n will have the same dependency on temp as that of n_i^2. (n_i^2)

In n-type Si, conc. of free electrons n_n
is much larger than holes (p_n).
e- are majority Carrier
h - are minority charge carrier.

Now consider p-Si where holes are majority charge carriers,

A trivalent (Boron) is used.

Si crystal is doped with boron atom.



Each Boron has 03 electrons in outer shell, accepts an electron from neighboring atom, forming covalent bond.

Hole in a neighboring atom and a bound -ve charge at the acceptor Boron atom.

N_A : acceptor conc. $N_A \gg n_i$

$p_p \simeq N_A$ for p type Si

Holes : majority carrier, Electrons : minority carrier

$$p_p n_p = n_i^2$$

$$n_p \simeq \frac{n_i^2}{N_A}$$

Conc. of minority electrons will have same temp dependence as that of n_i^2.

Ex: Consider an n type Si for which $N_D = 10^{17}/cc$ Find e and h conc at $T = 300\,K$

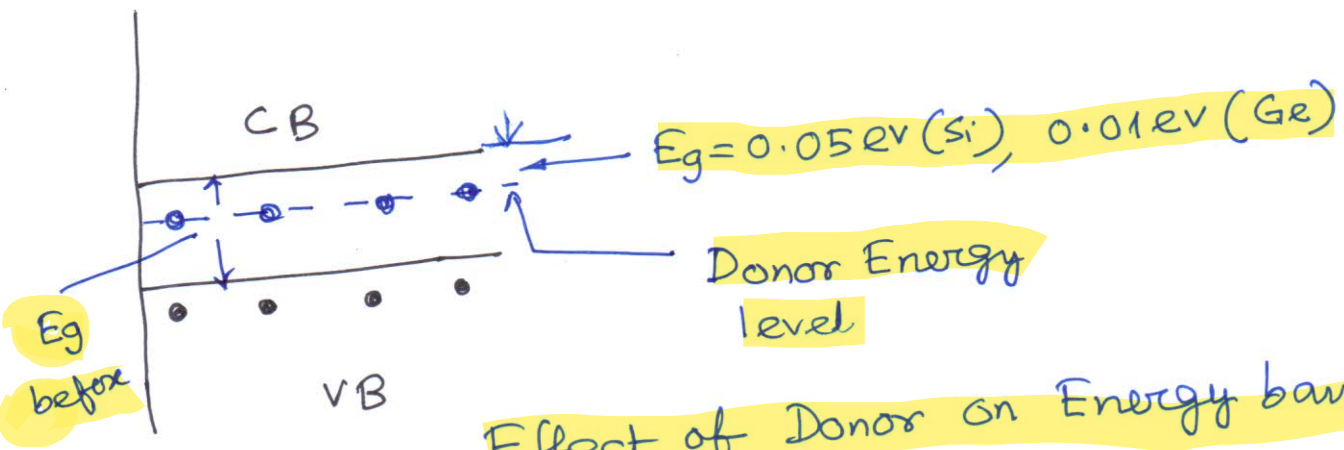
$n_n \simeq N_D = 10^{17}$ at $T = 300$

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

$$p_n \simeq \frac{n_i^2}{N_D}$$

$$\simeq \frac{(1.5 \times 10^{10})^2}{10^{17}} = 2.25 \times 10^3/cm^3$$

$n_n \gg n_i$ and n_n is vastly higher than p_n.



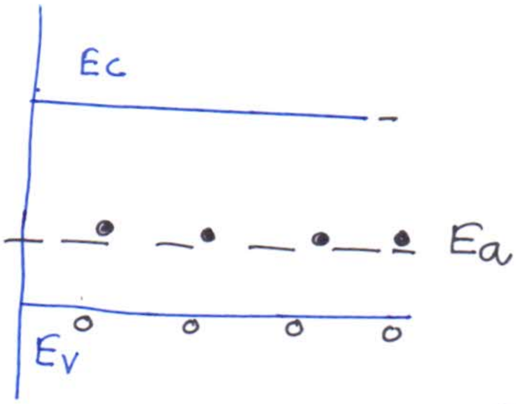
Effect of Donor on Energy band structure

Si : 1 free e for 10^{12} atom

Ge : 1 free e for 10^9 atom

The addition of donor impurities contributes electron energy levels high in the semiconductor band gap so that electrons can be easily excited into the conduction band. This shifts the effective Fermi level to a point about halfway between the donor levels and the conduction band.

If our dosage level is 1 in 10 million (10^7), the ratio $\frac{10^{12}}{10^7} = 10^5$ indicates carrier conc has increased by ratio of $10^5 : 1$

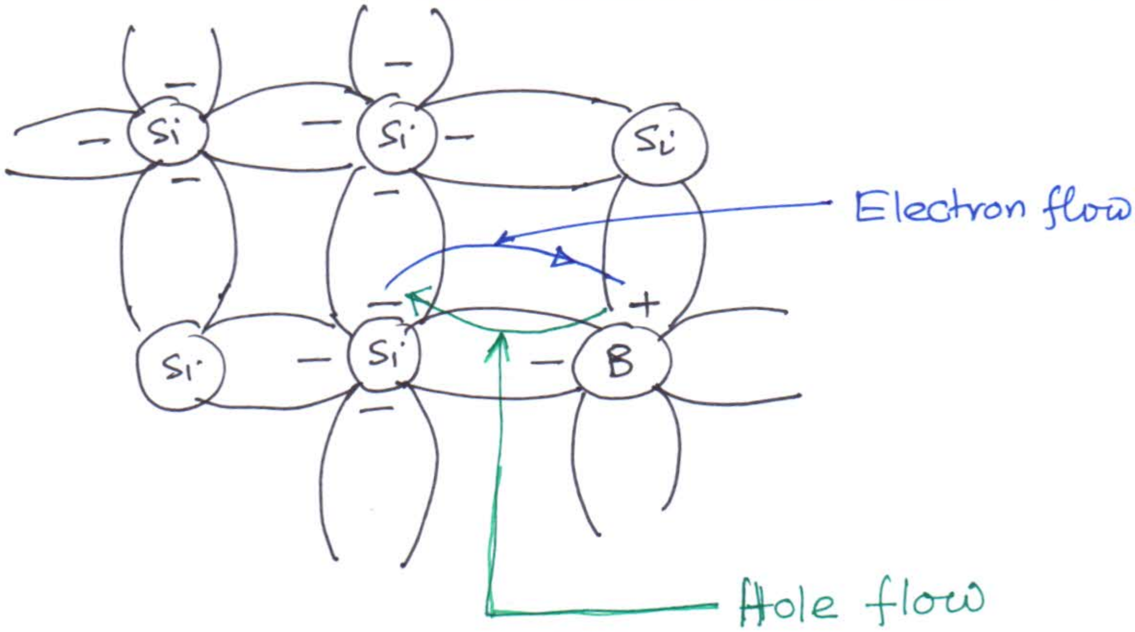


Energy band diagram for acceptor

The addition of acceptor impurities contributes hole levels low in the semiconductor band gap so that electrons can be easily excited from the valence band into these levels, leaving mobile holes in the valence band. This shifts the effective Fermi level to a point about halfway between the acceptor levels and the valence band.

Electron Flow vs Hole Flow

El



Majority and Minority Carriers

In an n type material, no. of holes ≈ intrinsic level.

No. of electrons ≫ No. of holes.

e — majority carrier   h ⟶ minority carrier.

p-type material, h ⟶ majority carrier
e ⟶ minority carrier.