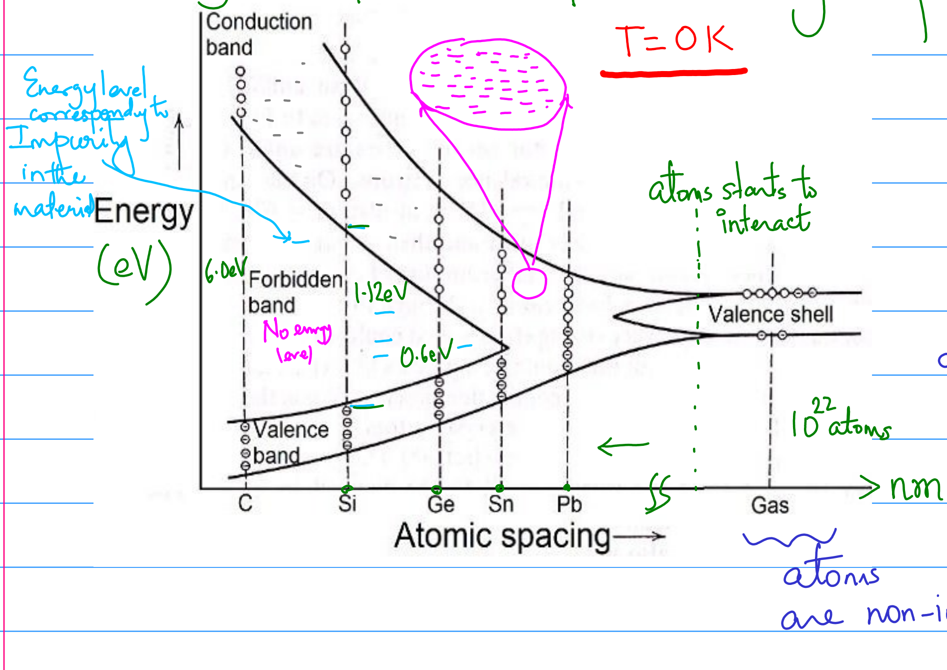
21. 09. 2023

Charge-Carriers density in Semiconductors

Band diagram of the solids of Carbon group (gr. 14) elements :



$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta}$$

α, β are the parameters.

For Silicon :

- Lets assume it to be 100% pure.

Condition (i) : Temperature T = 0K

at T = 0K ; thermal energy $= k_B T \approx 0$

$\Rightarrow$ all valance electrons remain in the valance band. That is,

Conduction Band is empty with the electrons.

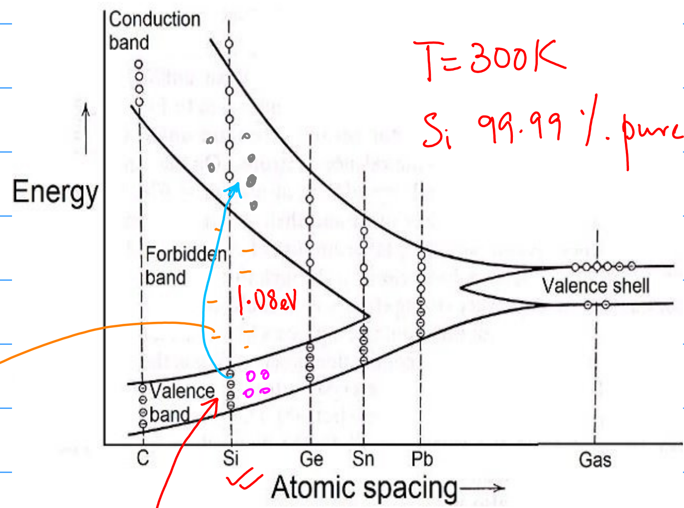
$\boxed{\text{ie, Intrinsically, No "Free" charge-carriers.}}$

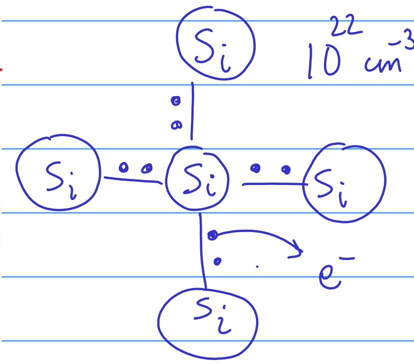
$\Rightarrow$ Intrinsic carrier-density at T=0 is "zero".

Condition (ii) $T = 300K$; we have 99.99% pure Silicon.

Thermal Energy $= k_B T \approx 25\,meV$

defect states





Valance electrons are receiving 25 meV of energy.

at this given condition;

roughly $\sim 10^{10}\,cm^{-3}$ electrons from the Valance band cross the forbidden band (Energy gap) and populate into the conduction band.

Compare this population w.r.t # silicon atoms

$10^{10}\,cm^{-3}$ $\qquad$ $10^{22}\,cm^{-3}$

$\Rightarrow$ Out of one trillion silicon atoms, only one silicon atom got the chance to release its valance electron to the conduction band.

Intrinsically, there are $\sim 10^{10}$ "FREE" electrons at 300K.

n = electron density (cm^{-3})

p = hole (vacancy) density (cm^{-3})

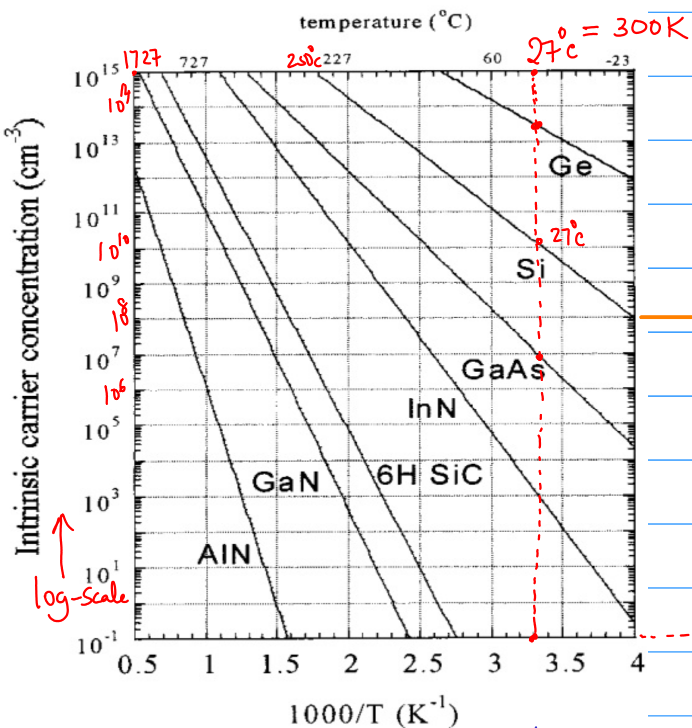
$$\boxed{n = p = n_i = 10^{10}\ cm^{-3}}$$

Practical values:

$n_i(\text{silicon}) = 1.5 \times 10^{10}\ cm^{-3}$

$n_i(\text{Germanium}) = 2.4 \times 10^{13}\ cm^{-3}$ at 300K

$n_i(\text{GaAs}) = 1.8 \times 10^{6}\ cm^{-3}$



For Silicon,

$T = -23°c$

$n_i = 10^{8}\ cm^{-3}$

$T = 250°c$

$n_i = 10^{15}\ cm^{-3}$

In silicon,

$\Rightarrow$ Raising the temperature by a factor of 10; raises the

the n_i by $10^5\ cm^{-3}$ (five orders of magnitude)

On earth, even we are at the place with lowest / highest temperature, the variation in intrinsic carrier density of silicon to not much

ie, it varies b/w $\underbrace{10^9\ cm^{-3} \text{ to } 10^{11}\ cm^{-3}}$.

As compared to the "free" carrier density in conductors ($\simeq 10^{22}\ cm^{-3}$), these are negligible.

Therefore,

$\Rightarrow$ Intrinsically, the semiconductors are insulators.

For practical devices using semiconductor, the density of intrinsic carriers is not sufficient.

$\Rightarrow$ You need to look for the condn, wherein more "free" charge-carriers can be created.

$\Rightarrow$ Needs to tune the carrier-density Extrinsically.

Ques: Why do we need to tune the carrier-density?

$$\sigma_e = e\mu n$$

Conductivity: σ_e

electronic charge (1.6×10^{-19} C): e

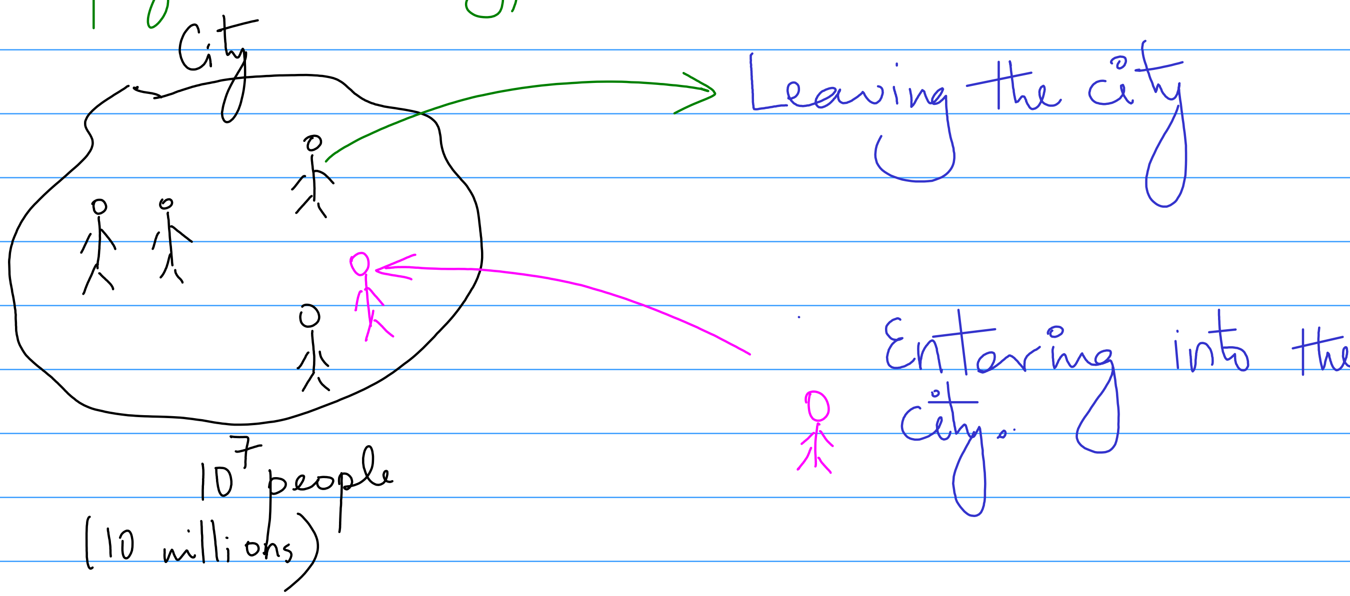
charge-carrier mobility: μ

Charge-carrier density (cm^{-3}): n

if we control the electronic density (n) by some extrinsic mean, we can control the conductivity.

Extrinsic Mean $\longrightarrow$ DOPING

Doping: An Analogy

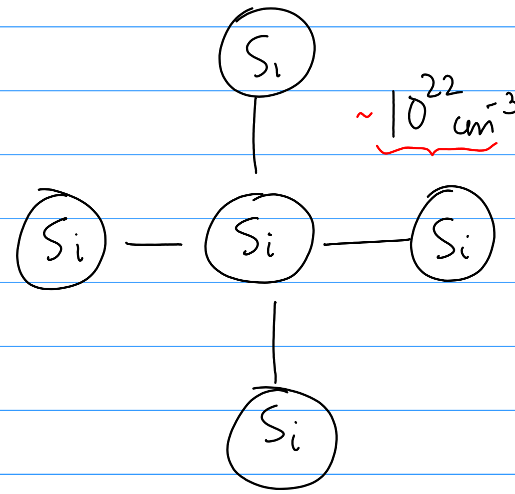


Effectively, out of a population of 10 million people, replacing one person with another will not make any effect on the demography of the city.

Doping of Silicon:

Intrinsic Silicon:

atomic density $\sim 10^{22}\ cm^{-3}$

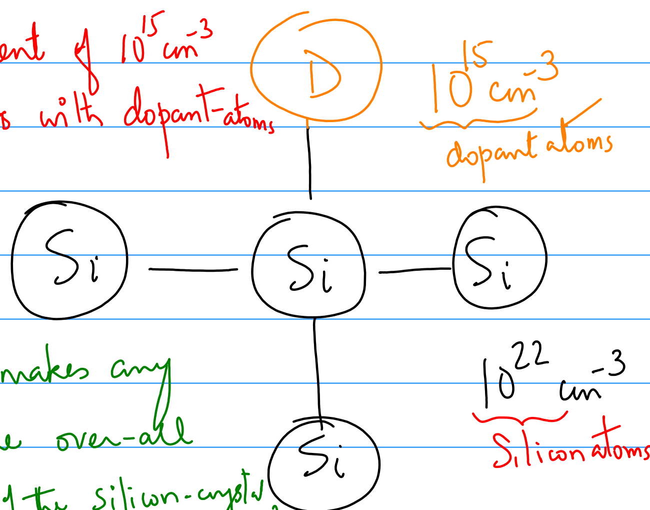


Doping of Silicon:

Atomic density $= 10^{22}\ cm^{-3}$

Dopant density : $10^{15}\ cm^{-3}$

Replacement of $10^{15}\ cm^{-3}$ Silicon atoms with dopant-atoms



Ques: Will this process of doping makes any change in the over-all properties of the silicon-crystal?

$\boxed{\text{Out of } 10^{7} \text{ Silicon atoms only one Silicon atom is replaced with the Dopant-atom}}$

As a result, one cannot see any change in the mechanical properties of the Silicon.

However, the electronic properties changes. How?

Lets see dopant is a "donor". (Which can donate electrons)

Si atomic density $= 5 \times 10^{22}\ cm^{-3}$

Donor density $= 1 \times 10^{15}\ cm^{-3}$

$\Rightarrow$ Out of 5×10^{7} Silicon atoms cm^{-3}; 1 silicon atom is being replaced with the donor-atom.

$\Rightarrow$ The donor is 20 parts per billion (ppb)

Silicon atoms of 1 billion population $\rightarrow$ 20 atoms are the extrinsic one (donor-atom)

Our focus is the electronic effect:

Add $10^{10} + 10^{15}\ cm^{-3}$
$= 10^{15}\ cm^{-3}$

$$\sigma = e \mu n$$

Intrinsic Conductivity $\sigma_i = e \mu n_i$

$\left\{ n = p = n_i = 10^{10}\ cm^{-3} \right\}$

Extrinsic conductivity (due to doping) $\sigma_{ex} = e \mu n_D$

n_D = Dopant density cm^{-3}
$= 10^{15}\ cm^{-3}$

Ratio of conductivities $= \dfrac{\sigma_{ex}}{\sigma_i} = \dfrac{\cancel{e\mu}\, n_D}{\cancel{e\mu}\, n_i} = \dfrac{10^{15}\,cm^{-3}}{10^{10}\,cm^{-3}} = 10^5$

$$\boxed{\sigma_{ex.} = 10^5\, \sigma_i}$$

$\Rightarrow$ Conductivity of the Silicon enhances by five Order of magnitude!

Analogy : Wallet is having Rs. 100.

if it is enhanced with five order of magnitude

Rs $100 \cdot 10^5$ = Rs 10^7 = Rs 10 million.

= Rs 1 Crore

Two kinds of dopants :

1) Donors : Releasing electrons $\equiv$ n-type semiconductors

2) Acceptors : Accepting electrons (Releasing holes) $\equiv$ p-type semiconductors

Donors $\rightarrow$ Pentavalent elements P, As, Sb (Antimony) - - - -

Acceptors – Trivalent elements B, Al, Ga, In . . .

$\Rightarrow$ What would be the distribution of "FREE" charge carriers in CB & VB.?