Semiconductors and Diodes

1. Semiconductors → Conductivity in between conductors & insulators.
   - → Valency = 4 (Four outer shell electrons).
     -ve charged particle.
   - (Simple) → Silicon (Si), Germanium (Ge), Carbon (C).
   - (Compound) → Gallium-Arsenide (Ga-As) III-V

e^-: Electrons

Silicon → Forms crystal matrix

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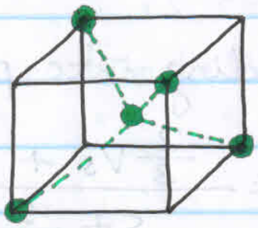
      |e⁻
e⁻— Si —e⁻
      |
      |e⁻
```

(2D)



(3D)

```
   |      |      |
— Si  =  Si  =  Si —
   ||     ||     ||
— Si  =  Si  =  Si —
   ||     ||     ||
— Si  =  Si  =  Si —
   |      |      |
```

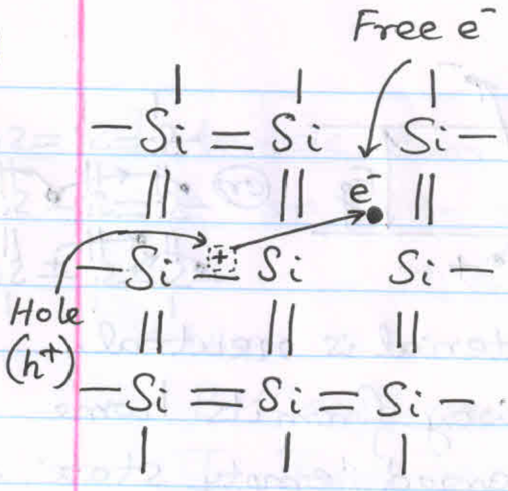
(2D with covalent bonds)
@ $T = 0\ K$ or $-273°C$

Si is an insulator

$T \uparrow \Rightarrow e^-$ energy $\uparrow$ (thermal energy) $\Rightarrow$ breaks co-valent bond

$\Rightarrow e^-$ moves freely (free e^-)

Min. energy to gain for becoming a free e^- is E_g or bandgap energy.

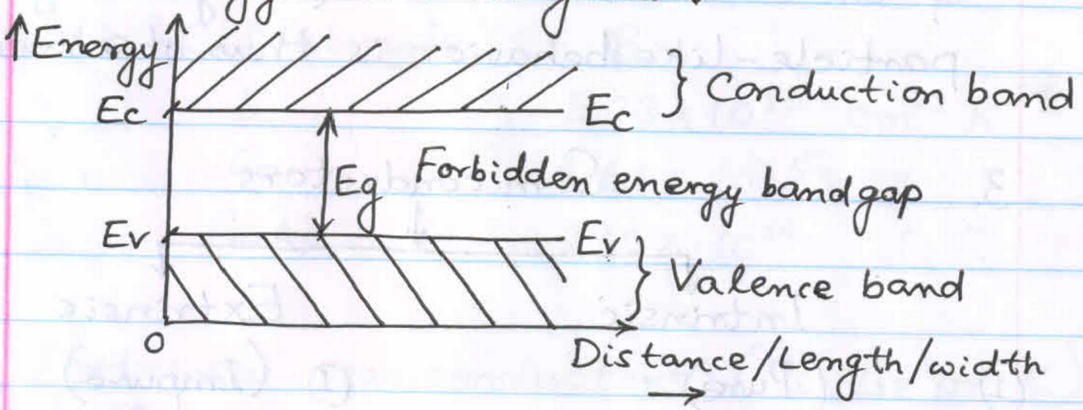


(at $T > 0K$)

e^- : $-$vely charged

h^+ : $+$vely charged or an absence of e^-

2. Energy band diagram:



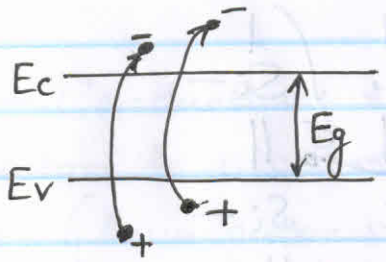
E_c: Min. energy of a conduction band
E_v: Max. energy of a valence band
E_g: Forbidden energy bandgap

Measured in electron-Volts (eV) (unit of energy)

$$1\ eV = 1.602 \times 10^{-19}\ \text{Joules}$$

Semiconductors	Eg	Group
Si	1.1 eV	IV
Ge	0.66 eV	IV
C	5.4 eV	IV
GaAs	1.43 eV	III-V

@ $T > 0K$,



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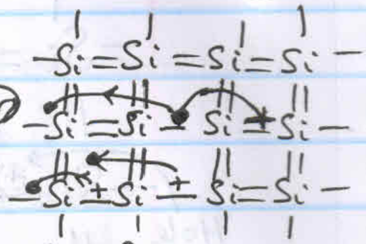


Net charge of a material is neutral. While an e^- moves away from its home position, a +ve ly charged 'empty state' is created at that position. This +vely charged location also moves, but in opposite direction of an e^-. A 'hole' or h^+ (+vely charged) particle-like behavior is thus observed.

3. Semiconductors

Intrinsic	Extrinsic
① (Pure)	① (Impure)
② Densities of e^- & h^+ are equal.	② Densities of e^- & h^+ are unequal.
③ Offers lower conductivity at a $T > 0K$	③ Higher conductivity at $T > 0K$
④ No sub-types	④ n- & p-types
⑤ Single crystal structure	⑤ Distorted crystal structure
⑥ Conductivity is more dependent on T	⑥ Less dependent on T
⑦ Used to create extrinsic material.	⑦ Used to create diodes & transistors.
⑧ Rarely used directly.	⑧ Always used directly.

Intrinsic carrier concentration (n_i) : Conc. of e^- or h^+ in an intrinsic semiconductors (S-C).

$$n_i = B \cdot T^{\frac{3}{2}} \cdot e^{\left(\frac{-E_g}{2kT}\right)}$$

where,

- B : Coefficient related to specific S-C material.
- T : Temp. in K.
- Eg : Bandgap energy
- k : Boltzmann's constant

S-C Materials	B
Si	5.23×10^{15} $cm^{-3} K^{-\frac{3}{2}}$
Ge	1.66×10^{15} " "
GaAs	2.10×10^{14} " "

Extrinsic semiconductors (Si, Ge or C).

↳ Created by adding group III or V materials

Trivalent impurities

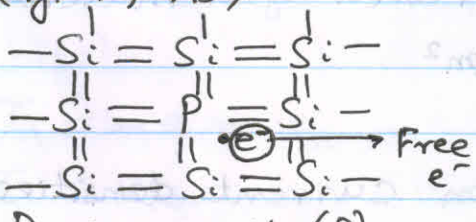
Pentavalent impurities.

Extrinsic S-C (Doped S-C)

n-type | p-type

n-type

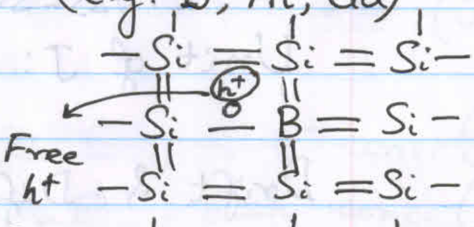
① Added group-V impurities (eg. P, As)



② Donor impurity (P)

p-type

① Added group III impurities. (e.g. B, Al, Ga)



② Acceptor impurity (B)

Relationship between e^- & h^+ concentration in a S-C at thermal equilibrium:

$$n_o . p_o = n_i^2$$

where, n_o = Thermal equilibrium conc. of e^-.
p_o = " " " " h^+.
n_i = Intrinsic carrier conc.

At T= 300K, each donor (Pentavalent (e.g. P) → n-type) atom donates free e^- to the S-C.

If, donor impurity conc. $(N_d) >> n_i \Rightarrow n_o \cong N_d$ (no. of e^-)
(n-type)

$\therefore p_o = \frac{n_i^2}{N_d}$ no. of h^+ (minority)

Also, at T=300K, each acceptor (Trivalent → p-type) atom accepts a valence e^-, creating a hole.

Acceptor conc. $N_a >> n_i \Rightarrow p_o \cong N_a$ (Majority carriers conc.)
(p-type)

$\therefore n_o = \frac{n_i^2}{N_a}$ minority

4. Drift & Diffusion: Basic processes to cause movement of e^- & h^+ in a S-C.

Lets, understand 'Current Density (J)' first.
J: Amount of current flowing per unit cross-section area of a material.
Unit of J: A/m^2

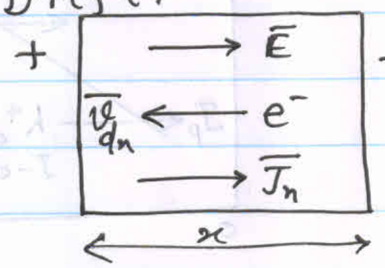
Drift & Diffusion current densities.

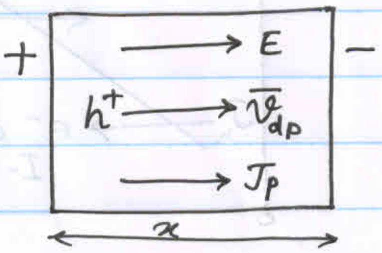
Diffusion current in a S-C is caused by diffusion of charge carriers (e^- or h^+) or concentration gradient inside the material (e.g. Si)

Drift current in a S-C is caused due to external force being extorted (e.g. by electric (E) field) for movement of e^- or h^+.

E-field: $\frac{\text{Volts}}{\text{Meter}}$ (S.I. unit)

Drift:





$v_{dn} = -\mu_n \cdot E$

$v_{dp} = +\mu_p \cdot E$

(Drift v_{dn} or v_{dp} velocity) Unit: cm/s

μ_n : Electron mobility ($cm^2/V\text{-}s$) $\cong 1350 \frac{cm^2}{V\text{-}s}$

μ_p : Hole mobility (") $\cong 480 \frac{cm^2}{V\text{-}s}$

(for low doped Si)

e^- drift produces drift current density (J_n) $\frac{A}{cm^2}$

h^+ " " " " (J_p) $\frac{A}{cm^2}$

$J_n = -q \cdot n \cdot v_{dn} = +q \cdot n \cdot \mu_n \cdot E$; $n = e^-$ conc. ($/cm^3$)

$J_p = +q \cdot p \cdot v_{dp} = -q \cdot p \cdot \mu_p \cdot E$; $p = h^+$ conc. ($/cm^3$)

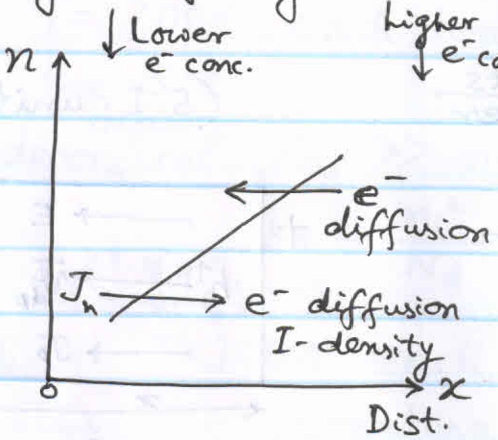
Conductivity (σ) $\left[\frac{1}{\Omega\text{-cm}}\right]$

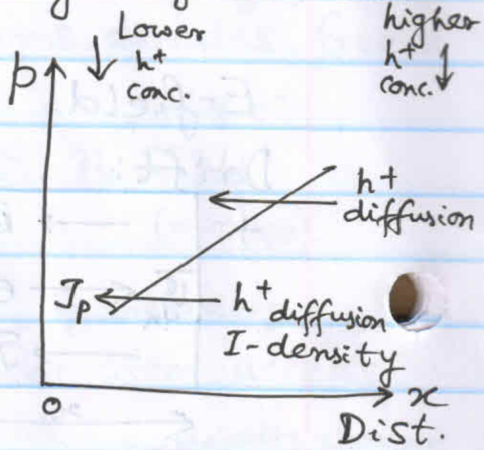
$$\sigma = q \cdot n \cdot \mu_n + q \cdot p \cdot \mu_p.$$

In n-type S-C : $n \gg p$

" p-type S-C : $p \gg n$

Diffusion: Causes flow of particles from a region of high conc. to a region of low conc.





$$J_n = q \cdot D_n \cdot \frac{dn}{dx}$$

$\frac{dn}{dx}$: Gradient of e^- conc.

D_n : e^- diffusion coefficient

$$J_p = -q \cdot D_p \cdot \frac{dp}{dx}$$

$\frac{dp}{dx}$: Gradient of h^+ conc.

D_p : h^+ diffusion coefficient

Excess carriers : e^- or h^+

e^-h^+ pairs are produced in a s-c while an external energy is applied (e.g. light).

$\therefore \quad n = n_0 + \delta_n$

$p = p_0 + \delta_p$ ← Excess carriers (only for a time)

↑ At thermal equilibrium (p_0)