Semiconductors and Diodes

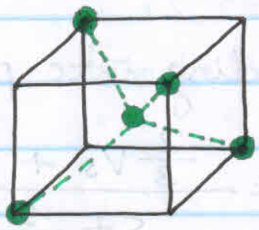
1. Semiconductors → Conductivity in between conductors & insulators.
   - → Valency = 4 (Four outer shell electrons).
     -ve charged particle.
   - (Simple) → Silicon (Si), Germanium (Ge), Carbon (C).
   - (Compound) → Gallium-Arsenide (Ga-As) III-V

e^- : Electrons

Silicon → Forms crystal matrix

$$\begin{array}{ccc} & |e^- & \\ e^- - & Si & - e^- \\ & |e^- & \end{array}$$

(2D)



(3D)

$$\begin{array}{c} | \quad\; | \quad\; | \\ -Si=Si=Si- \\ \| \quad \| \quad \| \\ -Si=Si=Si- \\ \| \quad \| \quad \| \\ -Si=Si=Si- \\ | \quad\; | \quad\; | \end{array}$$

(2D with covalent bonds)

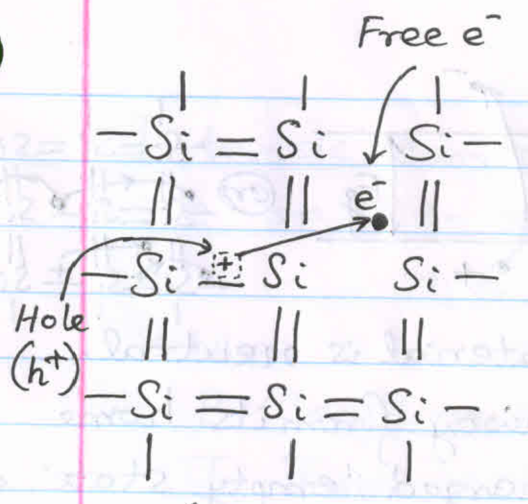
@ $T = 0\ K$ or $-273°C$

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.

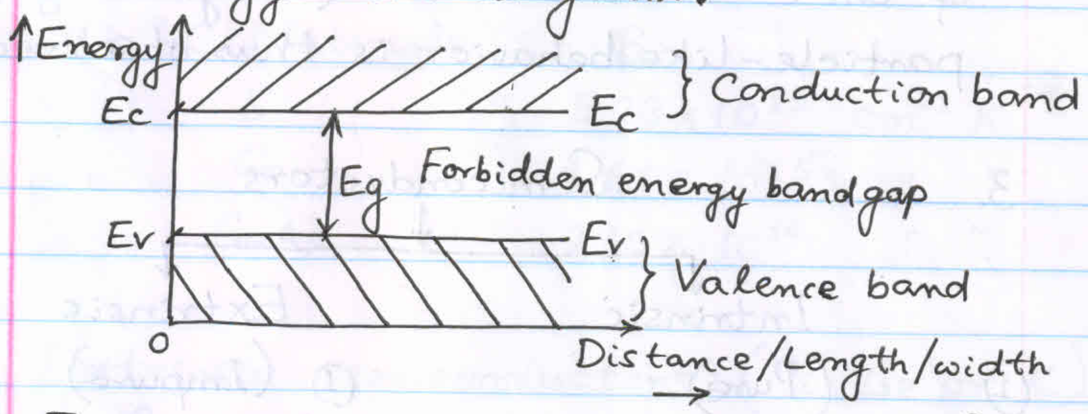


(at $T > 0K$)

e^- : −vely charged

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

2. Energy band diagram:



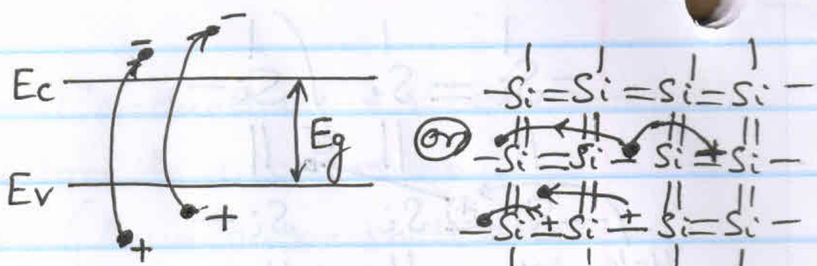
E_c: Min. energy of a conduction band
E_v: Max. energy of a valence band
E_g: Forbidden energy bandgap

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

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

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

@ $T > 0K$,



Net charge of a material is neutral. While an e^- moves away from its home position, a +vely 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).

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

where,

B: Coefficient related to specific S-C material.

T: Temp. in K.

Eg: Bandgap energy

k: Boltzmann's constant $(86 \times 10^{-6}\ eV/^{\circ}K)$

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

Extrinsic semiconductors (Si, Ge or C).

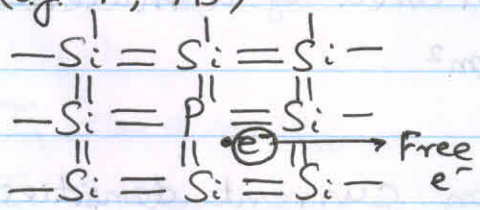
↳ Created by adding group III or V materials

III → Trivalent impurities

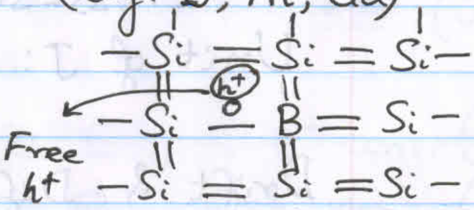
V → Pentavalent impurities.

Extrinsic S-C (Doped S-C)

n-type	p-type
① Added group-V impurities (eg. P, As)	① Added group III impurities. (e.g. B, Al, Ga)



② Donor impurity (P)



② Acceptor impurity (B)

Semiconductors

1) Intrinsic Carrier Conc. (n_i) = $BT^{\frac{3}{2}} e^{\left(\frac{-E_g}{2KT}\right)}$

$\forall$ E_g = Bandgap Energy
K = Boltzman Const.
B = Coeff related to specific S-C material.

	E_g	B	n_i (300K)
Si	1.1eV	5.23×10^{15} $cm^3 K^{-\frac{3}{2}}$	1.5×10^{10}
Ge	0.66eV	1.66×10^{15} ,,	~~1.8×10^{6}~~ 2.4×10^{13}
GaAs	1.43eV	0.21×10^{15} ,,	~~2.4×10^{3}~~ 1.8×10^{6}
C	5.4eV	—	—

2) $n_0 p_0 = n_i^2$ $\forall$ n_0 = Thermal Equil. conc. of e^-
p_0 = ,, ,, ,, ,, h^+
(Const. for a given semiconductor) n_i = Intrinsic carrier conc.

Diffusion :- Caused by diffusion of charge carriers (e^- or h^+) / conc. gradient inside the material.

Drift :- Caused by external force exerted for movement of e^-/h^+.

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 ⇒ $n_o \cong N_d$ (no. of e^-) (n-type)

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

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

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

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

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

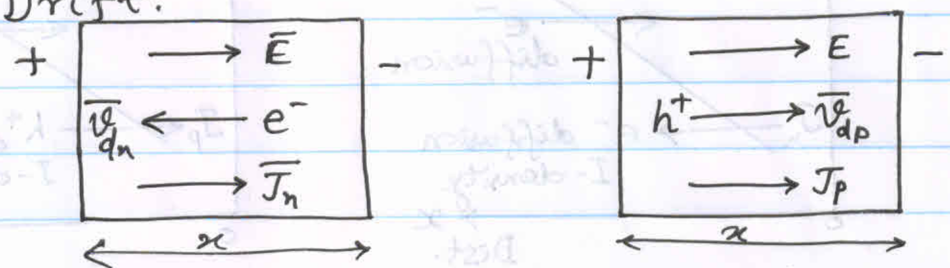
Drift & Diffusion current densities.

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 extered (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 velocity) v_{dn} or v_{dp} 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) $\left[\frac{1}{\Omega\text{-cm}}\right]$

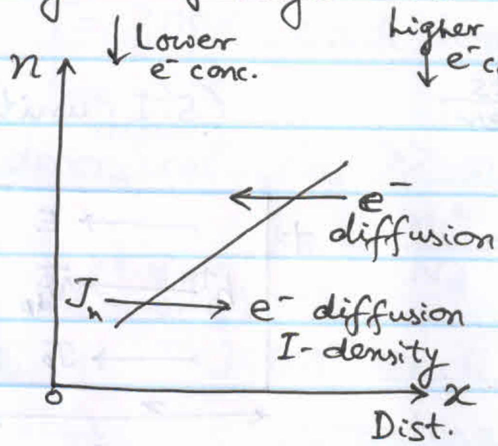
$$\sigma = q \cdot n \cdot \mu_n + q \cdot p \cdot \mu_p.$$

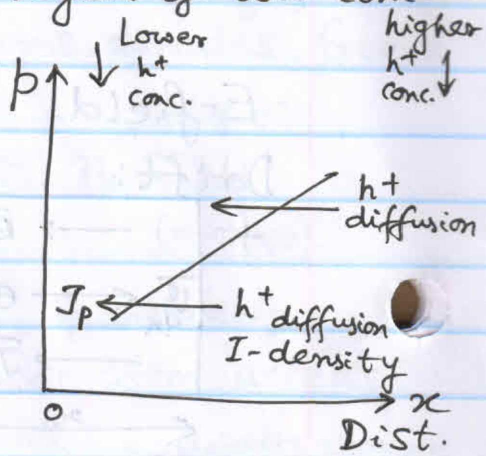
In n-type S-C : $n >> p$

" p-type S-C : $p >> n$

$$\boxed{J_{total} = \sigma E}$$

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





$$J_n = q \cdot D_n \cdot \frac{dn}{dx} \qquad J_p = -q \cdot D_p \cdot \frac{dp}{dx}$$

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

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

D_n : e^- diffusion coefficient

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).

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

$$p = p_0 + \delta_p$$

δ_p ← Excess carriers (only for a time)

p_0 ← At thermal equilibrium

With diffusion, particles flow from a region of high concentration to a region of lower concentration. This is a statistical phenomenon related to kinetic theory. To explain, the electrons and holes in a semiconductor are in continuous motion, with an average speed determined by the temperature, and with the directions randomized by interactions with the lattice atoms. Statistically, we can assume that, at any particular instant, approximately half of the particles in the high-concentration region are moving *away* from that region toward the lower-concentration region. We can also assume that, at the same time, approximately half of the particles in the lower-concentration region are moving *toward* the high-concentration region. However, by definition, there are fewer particles in the lower-concentration region than there are in the high-concentration region. Therefore, the net result is a flow of particles away from the high-concentration region and toward the lower-concentration region. This is the basic diffusion process.

1.1.4 Excess Carriers

Up to this point, we have assumed that the semiconductor is in thermal equilibrium. In the discussion of drift and diffusion currents, we implicitly assumed that equilibrium was not significantly disturbed. Yet, when a voltage is applied to, or a current exists in, a semiconductor device, the semiconductor is really not in equilibrium. In this section, we will discuss the behavior of nonequilibrium electron and hole concentrations.

Valence electrons may acquire sufficient energy to break the covalent bond and become free electrons if they interact with high-energy photons incident on the semiconductor. When this occurs, both an electron and a hole are produced, thus generating an electron–hole pair. These additional electrons and holes are called **excess electrons** and **excess holes**.