Solid State Electronics

Design of electronic components

⇓

knowledge of solid state Physics

semiconductor devices

Goal of study:

i) Explore characteristics of crystalline materials (emphasis on silicon)

ii) Electric conductivity & resistivity

iii) mechanism of electronic conduction

iv) impurity doping

Solid State Materials

MATERIALS	RESISTIVITY [$\Omega \cdot cm$]
insulators	$\rho > 10^5$
semiconductors	$10^{-3} < \rho < 10^5$
conductors	$\rho < 10^{-3}$

doping → controls resistivity

We have two classes of semiconductors:

a) Elementary semiconductors

They are formed from a single type of atom (Column IV of the Periodic Table)

Example Silicon (Si)
Germanium (Ge)

b) Compound Semiconductors

Combinations of:

i) Columns III - V (3-5)
i.e GaAs (Galium Arsenide)

ii) Columns II - VI (2-6)
i.e CdTe (Cadmium Telluride)
CdZnTe (Cadmium Zinc Telluride)

Here, it is important to develop the knowledge of bandgap.

In the next session we introduce the basics of Bohr atom in order to understand the ENERGY GAP

Bohr Model

e^- travel in orbital shells (bands)

each orbital shell has specific energy

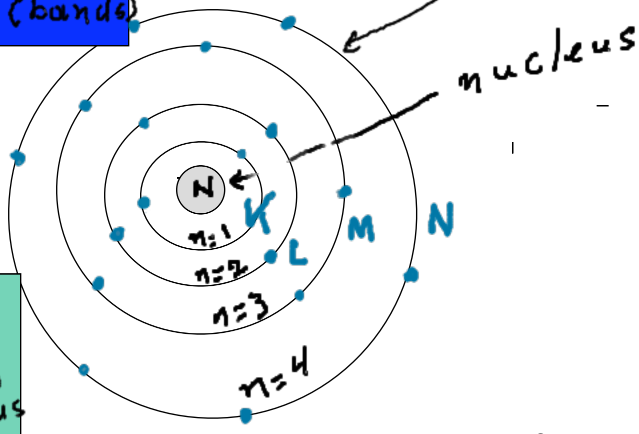
energy level increases as you move a way from the nucleus

valence shell
Determines the conductivity

If max number of valence electrons = 8 ⇒ no conduction (insulator)

If max. number of valence electrons = 1 ⇒ conductor

If 4 ⇒ semiconductor



n = principal quantum number = 1, 2, 3 ...

constant

because of n we have quantized (discrete) orbits

$$r = \boxed{\left(\frac{h^2}{4\pi^2 m q^2}\right)} n^2$$ = radius of electron orbit

h = Planck Constant $= 6.6\times10^{-34}$ J.s

m = mass of electron

q = electron charge $= 1.6\times10^{-19}$ C

for $n = 1$ $r = 5.3\times10^{-9}$ m $= 5.3$ nm

Energy of an electron in an orbit:

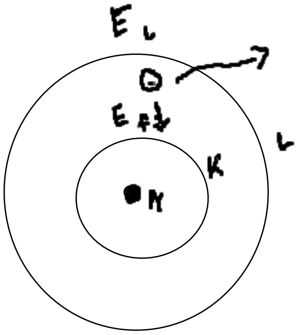
$$E_n = -\frac{13.5}{n^2}\ \text{eV}$$

Atomic shells are characterized as
K, L, M, N ....

K-shell: smaller energy (E_f)

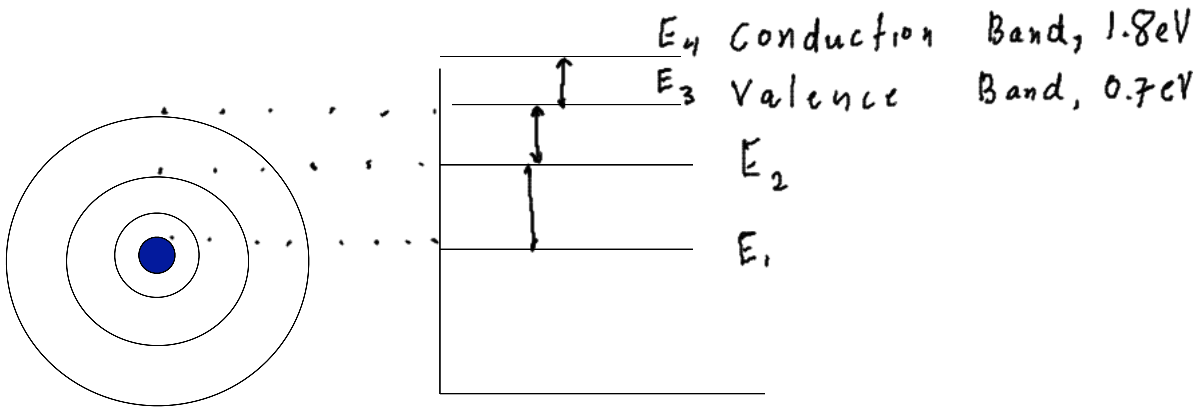
external shell: larger energy (E_i)

$hf = E_i - E_f$ ← Eq. 1



Transition of electrons between two shells produces an emission or absorption of a photon according to Eq. 1

Energy Gap



The space between orbital shells is called Energy gap.

In the specific example, for an electron to jump from the valence band to the conduction band must has to absorb an amount of energy equal to;

1.8eV- 0.7eV = 1.1eV (energy gap)

The higher the energy gap the harder to have conduction

	Band gap (eV)
Carbon	5.47
Silicon	1.12
Germanium	0.66
Gallium Arsenide	1.42
Indium Phosphide	1.35
Silicon carbide	3
Cadmium Selenide	1.70

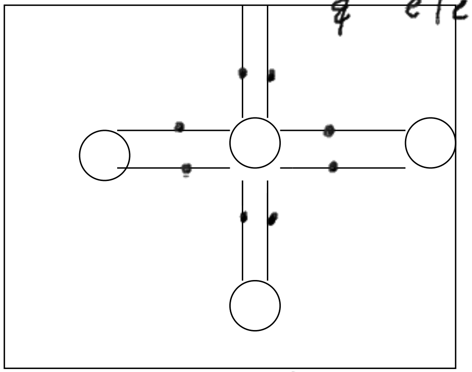
COVALENT BOND MODEL

Covalent bonding is the method by which atoms complete their valence shells by "sharing" valence electrons with other atoms.

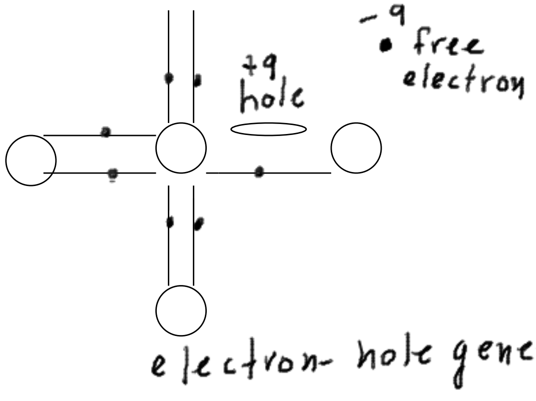
It is an important concept because it explains the operation of semiconductors devices, at least at the very early stage.

Example.
Consider a single crystal material (column IV), wher typically semiconductor properties occur.
Silicon: It has 4 valence electrons.

At absolute zero temperatures:
-273.15°C or -479.67°F, or 0°K
all molecular motion cease to exist
⇒ no free electrons for conduction
As temperature increases, some bonds break & electrons are free.



insulator
(no-free electrons)



electron-hole generation

The density of free electrons is equal to the the intrinsic carrier density n_i (cm^{-3}), is determined by:

$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{KT}\right) \; cm^{-6}$$

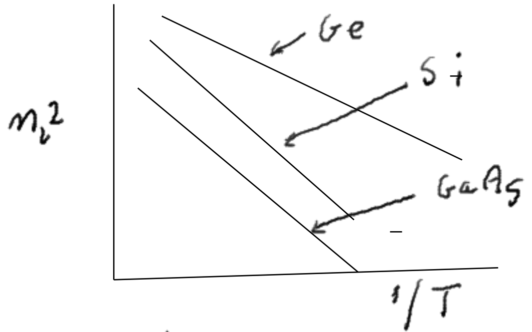
where E_G = semiconductor band gap energy
K = Boltzman constant = 8.62×10^{-5} eV/K
T = absolute temperature, in K
B = material dependent parameter.
n_i = e^-/cm^3

For intrinsic semiconductors:

$$n = n_i$$

intrinsic means pure.

We'll see later the real advantage of doped silicon over intrinsic one, because they control the resistivity. As a result, an intrinsic silicon behaves as an insulator, while a doped silicon is a mid-range semiconductor



	E_G (eV)
Si	1.12
Ge	0.66
GaAs	1.42

Si is a mature technology

Temperature dependence of intrinsic carrier density

Note: Ge is highly temperalture dependent.
but lowest E_G
GaAs highest E_G, but suitable for high-speed communications

Example

Calculate intrinsic carrier concentration n_i for silicon at $T = 300\,K$ (room temperature)

$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{KT}\right) \; cm^{-6}$$

$$= \underbrace{1.08 \times 10^{31} (K^{-3} \cdot cm^{-6})}_{B} \, (\underbrace{300\,K}_{T})^3 \exp\left[\frac{-1.12\,eV}{\underbrace{(8.62\times10^{-5}\,eV/K)}_{K}\underbrace{(300K)}_{T}}\right]$$

$= 4.52 \times 10^{19} / cm^6$, & $\boxed{n_i = 6.7\times10^9/cm^3 \\ \simeq 10^{10}/cm^3}$ ← remember this number, helpful to solve problems

Overall:

A free electron give rise to a hole

$\Rightarrow \quad n = n_i = p \qquad p =$ hole concentratio

& $\quad pn = n_i^2$ thermal equlibrium (no other stimulus apply).

Drift Currents & Mobility

ρ = Electric resistivity $[\Omega \cdot cm]$

σ = electric conductivity $[\Omega\, cm]^{-1}$

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

$$\vec{J} = \rho \vec{v} \quad \underbrace{(C/cm^3)}_{\rho} \underbrace{(cm/s)}_{v}$$

$$= A/cm^2 \, ?$$

$\vec{J}$ = current density

ρ = charge density

$\vec{v}$ = velocity of the charge in an electric field.

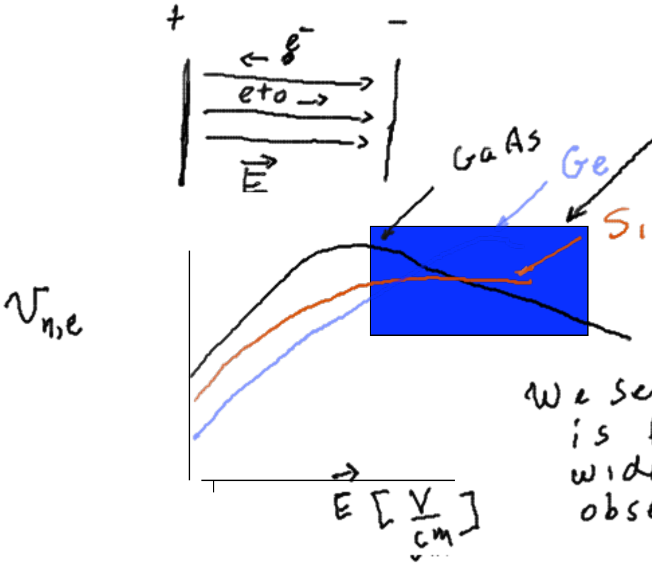
$\vec{v}_n = -\mu_n \vec{E}$ velocity of electrons in an electric field

$\vec{v}_p = \mu_p \vec{E}$ velocity of holes in an Electric field

μ_n, μ_p electron & hole mobility, respectively.

for intrinsic silicon: $\mu_n = 1350\ cm^2/Vs$

$\mu_p = 500\ cm^2/Vs$



velocity saturation place an upper limit on the frequency response

We see that GaAs is faster for a wide range of observations.

Resistivity of Intrinsic Silicon

The purpose of this study is the following:

i) Define resistivity & conductivity of the intrinsic silicon

ii) Using numerical values estimate the resistivity & conductivity of the intrinsic silicon so that in the next chapter compare these with those of the doped semiconductors

Considering 1-d current:

$$J_n^{drift} = \rho_n v_n$$
$$= (-qn)(-\mu_n E)$$
$$= qn\mu_n E \qquad A/cm^2$$

$$J_p^{drift} = Q_p v_p$$
$$= (+qp)(+\mu_p E)$$
$$= qp\mu_p E \qquad A/cm^2$$

where:

$$Q_n = (-qn) \qquad [C/cm^3]$$
$$\rho_p = (+qp) \qquad [C/cm^3]$$

are the charge densities of the electrons and holes, respectively.

The total drift current is :

$$J_T^{drift} = J_n + J_p$$

$$= q\underbrace{(n\mu_n + p\mu_p)}_{\sigma} E$$

$$= \sigma E \qquad (1)$$

where

$$\sigma = q(n\mu_n + p\mu_p) \ [\Omega \cdot cm]^{-1}$$

$$= \text{conductivity} \qquad (2)$$

&

$$\rho = \text{resistivity}$$

$$= \frac{1}{\sigma} \ [\Omega . cm] \qquad (3)$$

Example

Calculate the resistivity of intrinsic silicon. Substituting the following values on (2)

$q = 1.6 \times 10^{-19}$ C

$n \cong 10^{10}$

$\mu_n = 1350$

$\mu_p = 500$

$p = 500$

$$\sigma = (1.6 \times 10^{-19}) \left[(10^{10})(1350) + (10^{10})(500) \right] [\Omega . cm]^{-1}$$

$$= 2.96 \times 10^{-6} \ [\Omega . cm]^{-1}$$

$$\rho = \frac{1}{\sigma} = 3.38 \times 10^{5} \ \Omega . cm$$

intrisic silicon is an insulator!!

Impurities in Semiconductors

Impurity, Doping or Doping.

Why doping?

a) change the resistivity of the material

b) Fabricate material so that resistivity is controlled by electrons (n-type material) or holes (p-type).

Impurities used with Silicon are taken from columns III & V.

We'll discuss to kind of impurities:

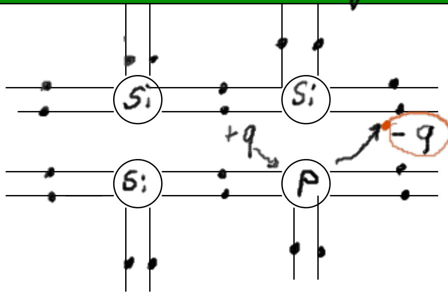
i) donor impurities.
ii) acceptor impurities

Based on whether donor or acceptor impurities prevail one over the other we have n-type material ($N_D > N_A$) or p-type material ($N_A > N_D$) where N_D, N_A are donor impurity concentration [atoms/cm^3]

Donor Impurities

The idea is to substitute one atom of Silicon (4 valence electrons with one impurity atom from periodic Table column V (5 valence electrons) i,e phosphorus (P),

Therefore: the extra electron from the P atom is freed for conduction, and a positive P ion is left fixed (net charge +q).



extra electron from P atom is freed.

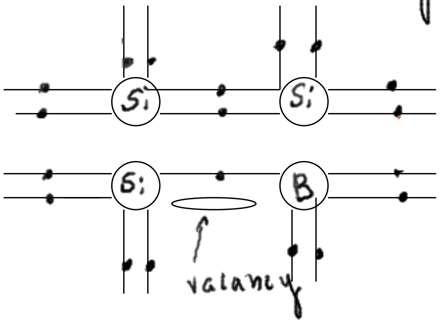
Acceptor Impurities

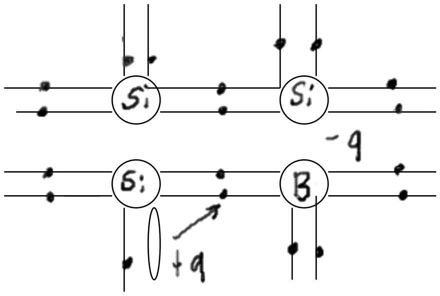
The idea is to substitute on atom of silicon (4 valence electrons) with one impurity atom from Periodic Table column III (3 valence electrons)

Therefore exists a vacancy:

A nearby electron occupies this vacancy creating a new vacancy

⇒ motion of vacancies, i.e motion of holes





Electrons & Holes in DOPED Semiconductors

if $n > p$ ⇒ n-type material

n = majority carrier
p = minority carrier

if $p > n$ ⇒ p-type semiconductor

p = majority carrier
n = minority carrier

In a doped medium:

i) the semiconductor material must be neutral:

i.e Sum of positive & negative charge is zero.

How comes from these charges?

We have:
- donor impurity concentration, N_D (which are positive ions)
- electrons, n
- acceptor impurity concentration N_A (negative ions)
- holes, p

Charge neutrality requires:

$$q(N_D + p - N_A - n) = 0 \qquad (1)$$

ii) still, in doped media

$$pn = n_i^2 \quad \text{(found earlier)} \qquad (2)$$

N-type Material ($N_D > N_A$)

$$pn = n_i^2$$

$$p = \frac{n_i^2}{n} \qquad (3)$$

3 → 2

$$\boxed{n = \frac{(N_D - N_A) \pm \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2} \qquad (4)}$$

& $p = \frac{n_i^2}{n}$.

In reality $(N_D - N_A) \gg 2n_i$

$$\Rightarrow \boxed{n \simeq (N_D - N_A) \quad (5)} \Rightarrow \boxed{p = \frac{n_i^2}{(N_D - N_A)}} \qquad (6)$$

Eq 4 is a key-formula that allow us to estimate n in case where $N_D > N_A$

P-type Material ($N_A > N_D$)

$$\boxed{p = \frac{(N_A - N_D) \pm \sqrt{((N_A - N_D)^2 + 4n_i^2}}{2} \qquad (7)}$$

$$n = \frac{n_i^2}{p} \qquad (8)$$

Since $N_A - N_D \gg 2n_i$

$$\Rightarrow \boxed{p \simeq N_A - N_D} \qquad (9)$$

$$\Rightarrow \boxed{n = \frac{n_i^2}{N_A - N_D}} \qquad (10)$$

Example

We have to characterize a semiconductor material:

a) whether is n-type orp-type.

b) Find the electron & hole concentration.

Data: A silicon sample, at room temperature, with
Boron concentration $= 10^{16}/cm^3$
Phosphorus concentration $= 2 \times 10^{15}/cm^3$.

Solution

at room temperature, $n_i = 10^{10}/cm^3$
= intrinsic carrier concentration

Boron = Acceptor $\Rightarrow N_A = 10^{16}/cm^3$
Phosphoruse Donor $\Rightarrow N_D = 2 \times 10^{15}/cm^3$

$N_A > N_D \Rightarrow$ p-type material

from Eq (9)

$$p \simeq N_A - N_D$$
$$= 8 \times 10^{15} \quad \text{holes/cm}^3$$

& from (10)

$$n = \frac{n_i^2}{p} = \frac{10^{20}/cm^6}{8 \times 10^{15}/cm^3}$$
$$= 1.25 \times 10^4 \text{ electrons/cm}^2$$

check our result:

$$pn = 10^{20}/cm^6 = n_i^2$$

Resistivity Calculation in Doped Silicon
Comparison with Intrinsic Silicon

Data: $N_D = 2 \times 10^{15} / cm^3$

i) Find the material type: n-type or p-type.
Classify the material: conductor?
insulator?
semiconductor?

ii) Resistivity

assume $N_A = 0$ (since is not mentioned)

$\Rightarrow N_D > N_A \Rightarrow$ n-type material

$$n = N_D - \underset{\overset{\shortparallel}{0}}{N_A} = 2 \times 10^{15} e^- / cm^3$$

for silicon

$$p = \frac{n_i^2}{n} = \frac{\boxed{10^{20}}}{2 \times 10^{15}} =$$

$$= 5 \times 10^4 \text{ holes}/cm^3$$

$\mu_n = 1260 \ cm^2/Vs$ (value obtained from the μ - % concentration graph, on page 61)

$$\sigma_T = q\{\mu_n n + \mu_p p\}$$

$$= 1.6 \times 10^{-19} \left[(1260)(2 \times 10^{15}) + 460 (5 \times 10^4) \right]$$

$$= 0.403 \ \Omega . cm^{-1}$$

semiconductor

$$\rho = 1/\sigma = 2.48 \ \Omega . cm$$

We found erlier: $\sigma = 2.96 \times 10^{-6} \ (\Omega cm)^{-1}$
$\rho = 3.38 \times 10^5 \ \Omega . cm$
} intrinsic silicon is insulato

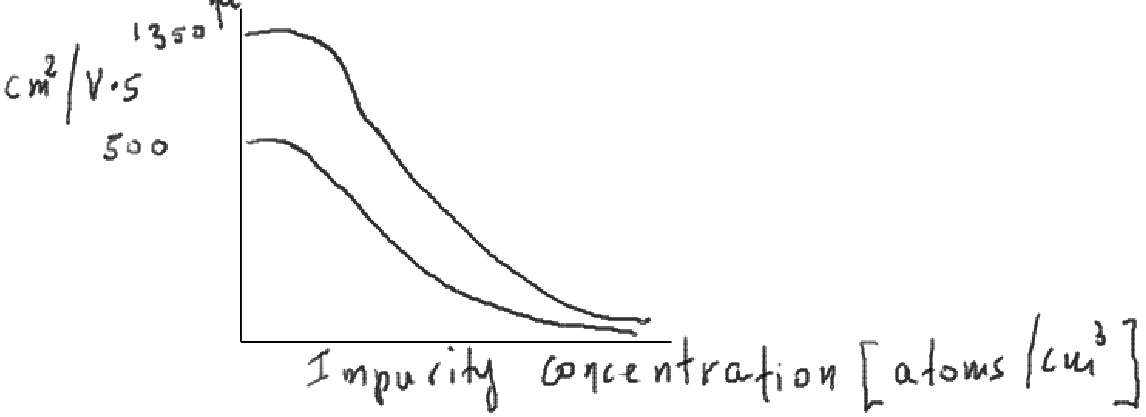
MOBILITY & RESISTIVITY IN DOPED SEMICONDUCTORS

Impurities introduce reduced mobility, because.

i) disruption of the periodicity of the lattice of the crystal, due to their different size from Si atoms

ii) they form region of localized charge

⇒ scattering effects, space-charge effects



$$\sigma \simeq q\mu_n n \simeq q\mu_n (N_D - N_A) \quad \text{n-type}$$

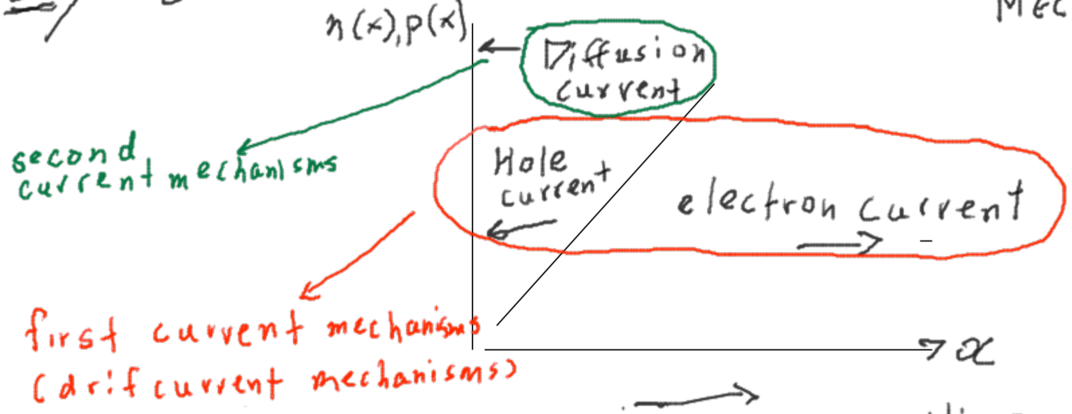
$$\sigma = q\mu_p p \simeq q\mu_p (N_A - N_D) \quad \text{p-type}$$

Diffusion Currents

Changes in doping introduces:

- gradients in electrons & hole concentrations

⇒ second current mechanisms, i.e. DIFFUSION MECHANISMS



⟶ Gradient positive in +x direction.

But carrier diffuses in −x direction ⟵

Overall diffusion occurs from high concentration to low concentration.

DIFFUSION CURRENT DENSITIES

$$J_p^{diff} = (+q) D_p \left(-\frac{\partial p}{\partial x}\right) = -q D_p \frac{\partial p}{\partial x} \qquad A/cm^2$$

$$J_n^{diff} = (-q) D_n \left(-\frac{\partial n}{\partial x}\right) = +q D_n \frac{\partial n}{\partial x}$$

D_p = hole diffusivity $[cm^2/s]$

D_n = electron diffusivity $[cm^2/s]$

Obviously, total current density is the sum of the drift current & the diffusion current ⇒

Total current is:

$$J_n^T = \underbrace{q\mu_n n E}_{\text{drift}} + \underbrace{q D_n \frac{\partial n}{\partial x}}_{\text{diffusion}} \qquad (1)$$

$$J_p^T = q\mu_p p E - q D_p \frac{\partial p}{\partial x} \qquad (2)$$

But

$$\frac{D_n}{\mu_e} = \frac{\kappa T}{q} = \frac{D_p}{\mu_p} = V_T \qquad (3)$$

Einstein's Relationship

$$\frac{\kappa T}{q} = V_T = \text{thermal voltage potential} \qquad (4)$$
$$\simeq 0.025V$$

Eqs (1) + (2) can be re-written in terms of 3+4 as:

$$J_n^T = q\mu_n n \left(E + V_T \frac{1}{n} \frac{\partial n}{\partial x}\right) \qquad (5)$$

$$J_p^T = q\mu_p p \left(E - V_T \frac{1}{p} \frac{\partial p}{\partial x}\right) \qquad (6)$$

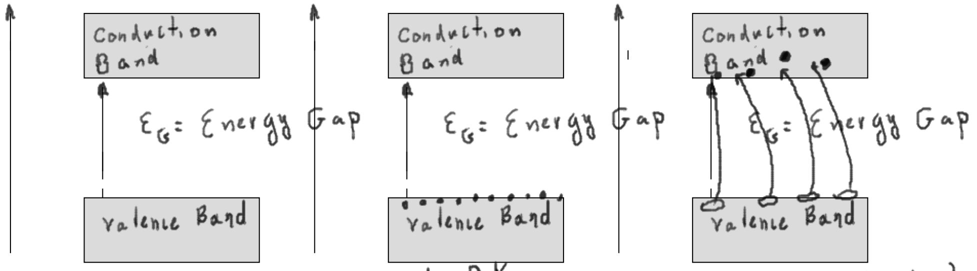
(obseration: we factorized $n, p, \mu_{n,p}$).
by expressing $D_{n,p} = \mu_{n,p} V_T$

Energy Band Model

Band gap energy: $E_G = E_c - E_v$

conduction Band energy (E_c); valence band energy (E_v)

Intrinsic Semiconductors

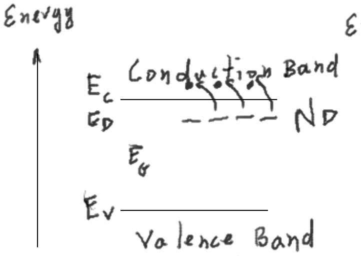


Energy Band Model

at 0K (filled valence band)

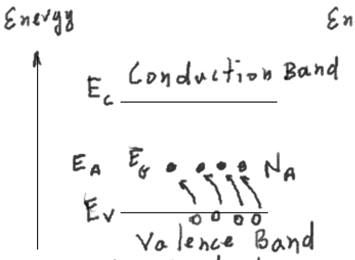
(thermal excitation)

Energy BandGap of Doped Semiconductors



Donor level
Activation energy: $E_c - E_D$
$= 0.045eV$

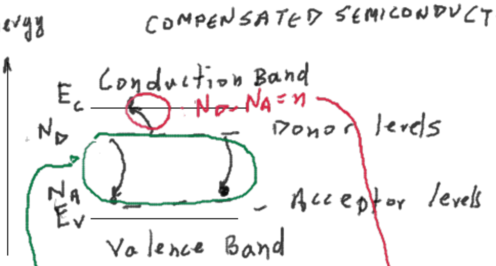
Phosphorous dopants



Acceptor level
Activation energy: $E_A - E_v$
$= 0.044$

Boron dopants

COMPENSATED SEMICONDUCTORS



Both acceptors & Donors
(More Donors than Acceptors are shown on the Diagram)

Electrons fall & occupy the acceptor levels the remaining contribute to the conduction band according to $n = N_D - N_A$