Twenty three-twenty seven weeks

Material structure

To understand the fundamental concepts of semiconductors, one must know material structure. There are two type of the material according to the doping with impurities or not.

Material doped with material (donor) that has negative charge called N- type and material doped with material (acceptor) that has positive charge called P- type. It could change from intrinsic to extrinsic and vise verse by introduction impurity, temperature, light and magnetic field

Some term in material structure

Order: it is concept that used to distinguish the regularity or other atomic packing.

Phase: a volume of the material which contain no discontinuity in either composition or structure.

Grain: a single crystal in polycrystalline aggregate.

Crystal: a substance that has definite solidified geometrical form.

Amorphous: non-crystalline has no definite form or shape

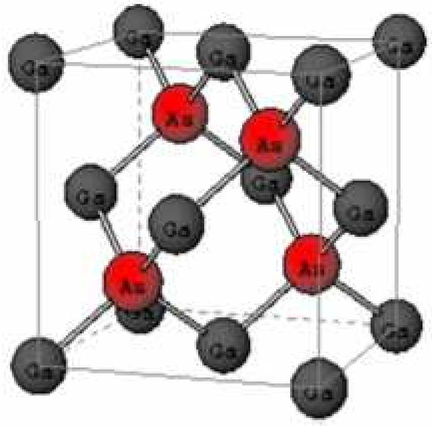
Single crystal: a monolithic material grown and has a regular molecules pattern in repetitive 3-D.

Polycrystalline: a monolithic material contain more than one crystal oriented in random and separated by boundaries.

factors specify the crystal structure are

1- Geometric framework
2- Atom arrangement
3- Distribution in that framework

Typical semiconductor



GaAs

ZnS (Zinc Blende) Structure
4 Ga atoms at (0,0,0)+ FCC translations
4 As atoms at (¼,¼,¼)+FCC translations
Bonding: covalent, partially ionic

Two properties of crystals are of particular interest, since they are needed to calculate the current in a semiconductor.

First, we need to know how many fixed and mobile charges are present in the material.

Second, we need to understand the transport of the mobile carriers through the semiconductor

Semiconductors and Insulators have totally full valence bands and empty conduction bands with a band gap between them. When carriers transfer valence band to conduction band that lead to conduct the material.

Crystal structure

Most metals crystallize in one of three structure

1- FCC- Face Center Cubic
2- BCC- Body Center Cubic
3- CPH- Close Packed Hexagonal

FCC and CPH systems are both equally dense and made by the stacking of closed- packed layers, the difference being in the stacking pattern. A crystal structure is formed only when a regular sequence is followed. If alternate layers are above one another giving the sequence.

ABABAB or BCBCBC or CACACA

Then the structure is CPH where as if sequence repeats at every third layer ABCABC

Silicon

Fabrication:

1- Crystalline: wafers
2- Polycrystalline: thin film deposition
3- Amorphous: think film deposition

Optics

1- Not an active optical material (indirect band gap)
2- Transparent at IR

Chemistry/ biology

1- Stable and resistant (brake fluid, biological medium)

2- Suitable for high purity gases
3- Benign in the body, does not release toxic substances

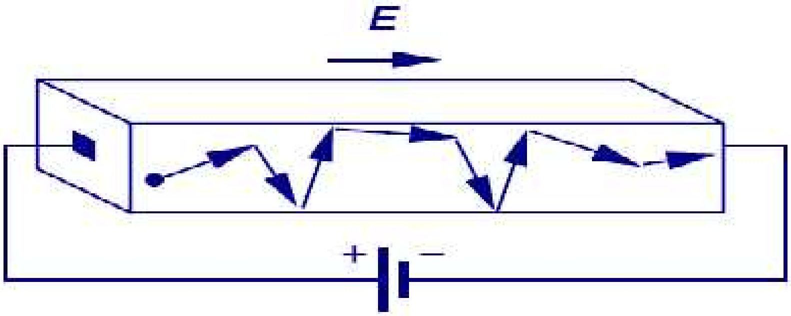
Cost

Low- ultra pure electronic grade silicon wafers are available for IC

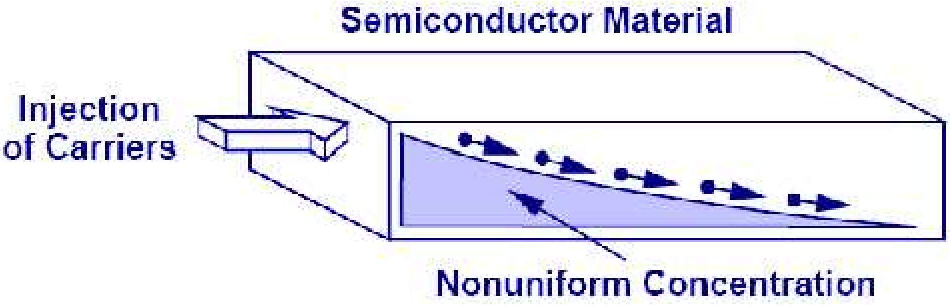
Drift and Diffusion

There are two types of motion that we want to consider: drift and diffusion. Electrons (and holes) can be driven by electric field

Drift Current: the current caused by the free charge carrier when direct voltage applied to the element



Diffusion current: The random thermal motion of electrons causes a net flow of electrons from a region of high concentration to region of low concentration.



Scattering mechanism

There are two abstract for smooth movement of the charge carrier is

1- **Latticing scattering:** due to collision of the moving carrier disturbance in the periodic internal potential inside the semiconductor crystal. The disturbance reason is variation of the crystal lattice atoms because of their thermal energy. The lattice thermal variation wave –particle entities is called “Phonon”.

2- **Impurity scattering** : caused by the ionized impurity atom in various position in crystal lattice

Average Drift Velocity and Mobility

The average velocity of charge carrier under the effect of electric field “E” could find as fallow:

Assume

n_o: number of carrier at start when t=0

$$-dn = \frac{1}{2} n\, dt$$

$$n = n_o \exp(\frac{-t}{2})$$

where

1/τ proportional factor mean the average time between collision

The probability of collision during time (dt) is dn/n_o

From equ. 1 and equ. 2 we get that

$$-\frac{dn}{n_o} = \frac{1}{2} \exp(\frac{-t}{2}) dt$$

Equ. 3 gives the distribution of the time that carrier moves till it collides. This equation called “Poisson equation”

Mobility and Electrical conductivity

- The electron mobility characterizes how quickly an electron can move through a metal or semiconductor, when pulled by an electric field. In semiconductors, there is an analogous quantity for holes, called hole mobility. The term carrier mobility refers in general to both electron and hole mobility in semiconductors.
- Electron and hole mobility are special cases of electrical mobility of charged particles in a fluid under an applied electric field.

Assume a proper weight for each time t depending on n(t). this weight function is dn/n_o

Assume that

Carrier velocity = V_o and this velocity immediately after collision and it is completely random.

Now when the electric field E is applied then carrier will be at

$$r = r_o + V_o\, t + \frac{qE}{m} . \frac{t^2}{2}$$

R_o= original position

M= effective mass of electron and proton

$$\text{Charge carrier accleration} = \frac{q\,E}{m^*}$$

$$\text{Carrier drift velocity } (\mathrm{V_d}) = acceleration * lifetime$$

$$V_d = \frac{qE}{m^*} 2$$

$$\therefore V_d = \frac{q2}{m^*} E$$

$$\therefore V_d = « \, E$$

$$« \; (mobility) = \frac{q2}{m^*}$$

The mobility depends on temperature and scattering

$$\mu_L \propto T^{-3/2}$$

$$-dn = -(dn1 + dn2)$$

$$-dn = \frac{n}{\tau 1} dt + \frac{n}{\tau 2}$$

τ_1 *average time between lattice collision*

τ_2 *average time between impurity collision*

$$\frac{1}{\tau_t} = \frac{1}{\tau_1} + \frac{1}{\tau_2}$$

$$\frac{1}{\mu_t} = \frac{1}{\mu_1} + \frac{1}{\mu_2}$$

Conductivity

The drift current density "J" given by :

$$J_e = -qnV_d = -qn\mu_e E$$

$$J_p = -qnV_d = -qn\mu_p E$$

Total drift current density is :

$$J_T = J_e + J_p$$

q: electron charge $1.6*10^{-19}$ J/C

n: number of electron

p: number of hole

V_d : drift velocity

E: electric field

µ: mobility

$J_{e:}$ electron drift current density

$J_{h:}$ hole drift current density

The specific conductance "±" given by :

$$\pm = \frac{J}{E}$$

$$\pm = q(n«_n + p«_p)$$

for internsic material:

$$\pm = qn(«_n + «_p)$$

for exterinsic material

$$\pm_e = qn«_e \qquad (n - type)$$

$$\pm_p = qn«_p \qquad (p - type)$$

In a semiconductor, both electrons and holes conduct current:

$$J_{p,drift} = qp«_p E \qquad J_{n,drift} = -qn(-«_n E)$$

$$J_{tot,drift} = J_{p,drift} + J_{n,drift} = qp«_p E + qn«_n E$$

$$J_{tot,drift} = q(p«_p + n«_n)E \equiv \pm E$$

The ***conductivity*** of a semiconductor is $\pm \equiv qp«_p + qn«_n$

The ***resistivity*** of a semiconductor is $° \equiv \frac{1}{\pm}$

The specific conductivity varying with temperature due to

1- The dependence of number of carrier “n” on temperature. This is very clear at high and low temperature.
2- The dependence of mobility on the temperature.

The mobility obtained from the conductivity called “conductivity mobility” which refer to majority carrier. The mobility of minority carrier called “drift mobility”

Excess Carrier and Life Time

Any semiconductor material under equilibrium means that :

1- The temperature is uniform and equal to the surrounding ambient temperature.
2- No external carrier injected , such as :

-Irradiation light

- Forces (electric field , magnetic field , …….etc)

3- carrier concentration are uniform in time and position.

Which parameters determines the carrier concentration?

1- Temperature
2- Dopant density
3- Semiconductor material

What happen if equilibrium is disturbed?

The carrier concentration is increased and we say that semiconductor contains “Excess Carrier”

The total carrier concentration are:

$n = \bar{n} + \hat{n}$

$p = \bar{p} + \hat{p}$

Where

$\bar{n}$, $\bar{p}$ equilibrium value of carrier (electron and hole)

$\hat{n}, \hat{p}$ excess carrier value (electron and hole)

What happen if the semiconductor is not at equilibrium (irradiate light for sometime to generate carrier and then turn- off)?

So that some time will pass before the excess carrier recombines and the semiconductor return to :equilibrium.

The excess recombination over the generation given by:

$$\hat{R} = R - \hat{R}$$

Where R: recombination rate of electron with holes (pair/ volume and time)

$\hat{R}$: Excess of recombination

$\hat{R}$: recombination at equilibrium which depends on temperature.

After time “t” second from switching off the light the decay is only at the excess minority carrier (holes for N-type and electron for P-type).

The time at which the carrier stay before vanished called “ excess carrier life time”

t_c :life time of excess carrier

t_{ce}: electron life time

t_{ch}: hole life time

the concentration of excess carrier given by:

Access carrier and Enstien relation :

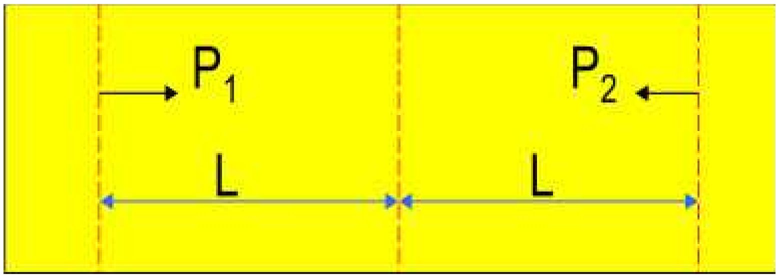
$$\hat{p} = \hat{p}_o \ \exp(\frac{-t}{t_{ch}})$$

$$\hat{n} = \hat{n}_o \ \exp(\frac{-t}{t_{ce}})$$

Einstein’s Relations

It is an expression for the particle flux resulting from diffusion. It could derive as follow:

Take a semiconductor material bar in which “L” the average distances that holes travels between two successive collisions (mean free path)



P_1: hole concentration between planes A&B

P_2: holes concentration between planes B&C

No. of holes move from left to the right =1/6 P_1L

No. of holes move from right to the left =1/6 P_1L

So

The net flow of the hole through plane “B” per unit time in the +ve direction is:

$$\emptyset = \frac{\frac{1}{6}P_1L - \frac{1}{6}P_2L}{t} = \frac{\frac{1}{6}L(P_1 - P_2)}{\frac{L}{V_{th}}}$$

$$\emptyset = \frac{-L\,V_{th}\,(P_2 - P_1)}{6\,L}$$

Where

V_{th}: average thermal velocity of the holes.

$(P_2 - P_1)/L$: concentration gradient in the x- direction

The diffusion constant D_h is:

$$D_h = \frac{L V_{th}}{6} \quad \text{m}^2\ \text{s}^{-1}$$

diffusion lenght

$l_e = \sqrt{2\,{}_e\,D_e}$ for electron

$l_e = \sqrt{2\,{}_e\,D_e}$ for hole

$$\text{¤} = -D_h \frac{dP(x)}{dx}$$

$\frac{dP(x)}{dx}$: concetration gradiant in direction - x

$$\frac{dP(x)}{dx} = \frac{P_2 - P_1}{L}$$

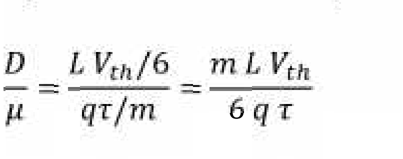
Now we have two expressions for the carrier motions:

$$D_h = \frac{L V_{th}}{6}$$

$$\text{«}\ (mobility) = \frac{q^2}{m^*}$$

Which involves also the carrier with free distance between collision of L=t V_{th}

Note: do not confuse between the life time "t_c" of excess carrier and relaxation time "τ" which mean the time between collisions approximately 10^{-12} sec



By division both above equations as follow:

$$\frac{D}{\mu} = \frac{L\,V_{th}/6}{q\tau/m} = \frac{m\,L\,V_{th}}{6\,q\,\tau}$$

This equation is not very accurate because it uses the average values the accurate relation will be:

$$\frac{D}{\mu} = \frac{2m\,V_{th}^2}{6\,q}$$

But we have previously

$$\frac{m\,V_{th}^2}{2} \approx \frac{3}{2}\,KT$$

$\frac{D_{e,h}}{\mu_{e,h}} = \frac{KT}{q}$ this equation called “Einstein relation”