Basic Concepts of Semiconductors

Comprehensive Course on Analog Electronics

Ankit Goyal • Lesson 1 • Mar 17, 2021

Introduction / Syllabus → Special class

Course structure

1. Daily live class at 7am (Mon-Sat)
2. Every sunday → Quiz
3. Teaching methodology
   - Handwritten notes
   - PDF notes
     - ↳ text & images typed
     - ↳ explanation & derivation hand written

Handwritten	PDF
① speed = slow	speed = moderate
② more focus on theory & derivation	more focus on problem solving
③ DPP once every 2-3 days	daily assignment
④ 200 - 300 ques	500 - 600 ques (in class)
TRUE (19%)	FALSE (81%)

Q How to utilize my lectures?

Ans ① watch the live class

② merge pdf s.t. 4 slides per page are present

③ for handwritten preferring students

↳ make handwritten notes post class (1hr post class)

④ Others make short notes after solving daily assignment highlighting important formulas & concepts.

↳ we can make short notes after every assignment.

Resources to be used

1. daily assignment → 500 Q
2. PYQ (EE/EC/IN) → 500-600 Q

} 1100 Q — preference order ↓

3. Unacademy app practice
4. weekly quiz

* we will start PYQ series after diode circuits

If you want to use standard book (Theory)
- ↳ Electronic Circuits by Donald Neamen (most detailed)
- ↳ Sedra smith
- ↳ Boylestad
- ↳ Razavi

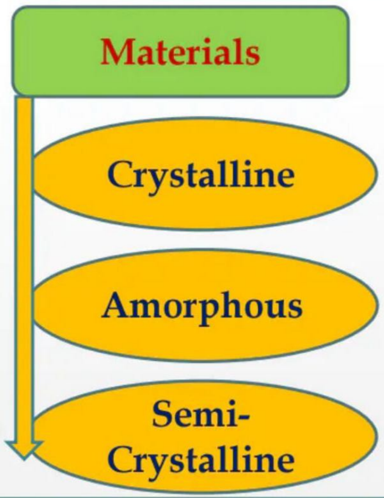
ANALOG ELECTRONICS

Topic covered

1. Semiconductor physics ← today
2. Diode circuit ← from tomm
3. BJT (Biasing, amplifier, frequency response)
4. JFET (ESE not in Gate) ← not covered
5. MOSFET ← GATE
6. Op-amp and application ← most important
7. Feed Back Amplifier
8. Oscillators and 555 timers
9. Power Amplifiers (ESE) ← not covered

* Networks (upto transients) : important for analog

Semiconductor Physics



Pseudo crystalline

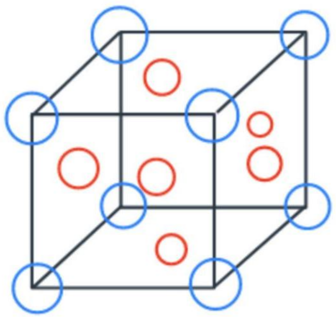
Crystalline

When material have long range order of atoms and they are perfectly arranged the material is called crystalline.

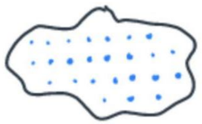
The repeat unit in the crystal is called as unit cell.

Amorphous

When there is no ordering of atom or the atom are at random then material is called as amorphous.



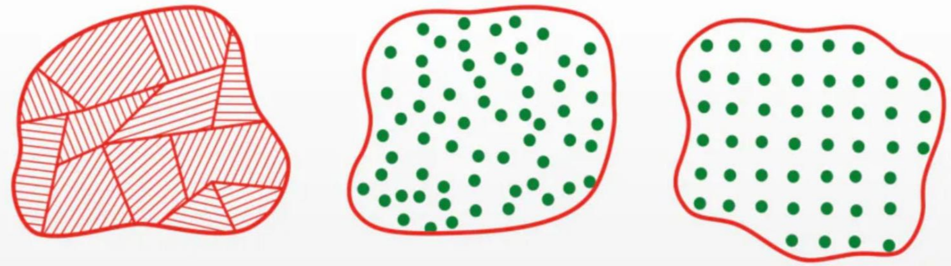
Crystalline
all atoms are present at fixed locations



Amorphous
random arrangement of atoms

Semi-Crystalline

The atom are perfectly arranged but only over short distance , over large distance arrangement is random .



Classification based on electrical conductivity

Based on conductivity material can be classified in three category.

⇛ Insulator
⇛ Semiconductor
⇛ Conductors

$\sigma \propto$ Carrier Concentration ; where σ = conductivity. ← conc. of free electron

Conductors:

$\sigma = \frac{ne^2\tau}{m}$; n = no of electron / cm^3

$\sigma \propto n$ ← not important

- In semiconductor material the conductivity can easily be varied over a large range.
- Hence semiconductor materials are popular in electronic design.

* Conductors have large number of free electrons that take part in conduction so current can easily flow.

free electron → electron ionized from atom

* While going from conductors to insulators the no. of free electrons drastically reduce

↳ conduction becomes more difficult

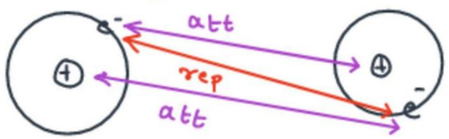
Ionisation

- In semiconductors, we can modify charge concentration by means of
  - * adding impurity
  - * increasing temp. (bonds break → free e^- are generated)
- Semiconductors can be used in applications requiring less conductivity as well as applications requiring high conductivity.

Band Diagram ← used to diff. b/w cond^r, sc & insulator

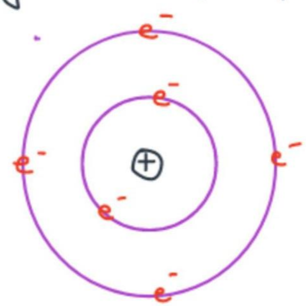
- Every atom contains electron in various state or energy level.
- When two or more than two atom combines these energy level these energy level split and merge to from multiple energy level which are closely spaced and called ENERGY BAND.
- Bond formation → only outermost e^- (balance electron)

- Each electron in an atom has different state (or energy level) given by its Quantum number.
- When 2 atoms come closer to form a bond the charges in atoms interact with each other & so their electrostatic potential energy changes & we say their energy level splits



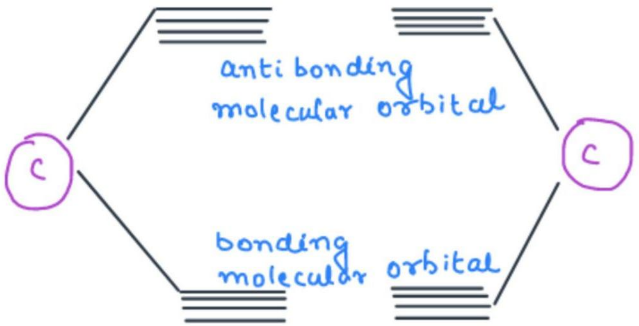
- While forming bond only outermost electrons are involved so in band diagram only outermost electron are considered.

eg: Carbon (Z = 6)



- In outermost shell. 4 e^- are present whereas outermost shell can contain upto 8 electrons
- In other words, there are 8 possible states out of which 4 are occupied & 4 are empty.

* When n such Carbon atoms combine then we have 8n possible states out of which 4n are occupied



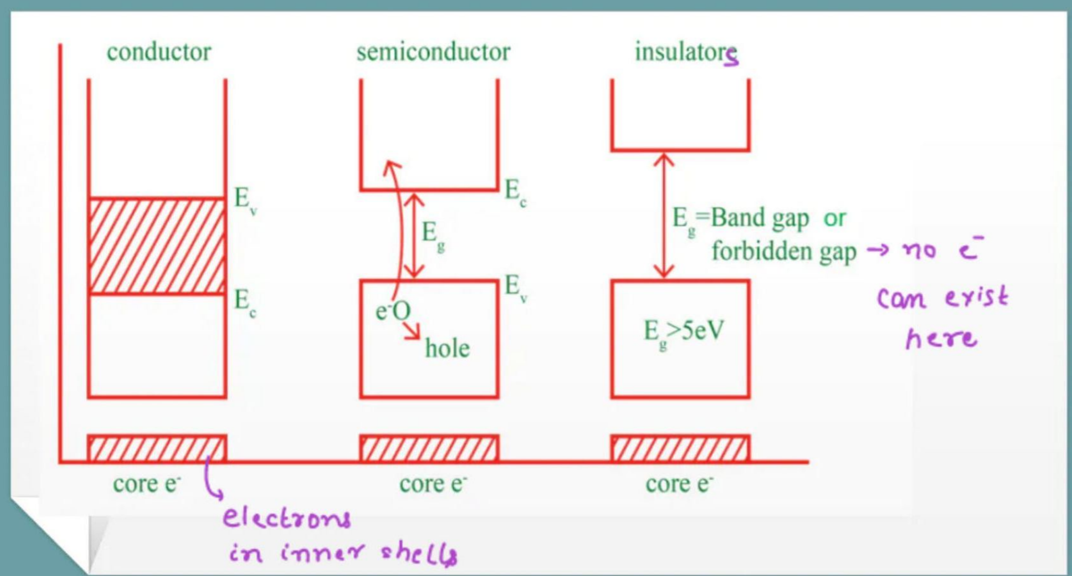
When n- such atoms combine the higher energy states are very closely spaced & so treated as continuous energy called band & same thing happens to lower energy states.

- Higher energy states are called as Conduction Band.
- Lower energy states are called as Valence Band.

Conduction Band : contains electrons that are ionized & take part in conduction

Valence Band: contains electrons in outermost shell

* At T = 0K, no electron can be ionized so CB is empty & VB is full & as temperature ↑ electrons move from VB to CB.



- E_v : edge of valence band
  - ↳ maximum energy that an e^- can possess if it lies in valence band.
- E_c : edge of conduction band
  - ↳ minimum energy that an e^- can possess if it lies in Conduction Band.
- E_g : band gap
  - ↳ energy required to promote an e^- from valence band to conduction band.

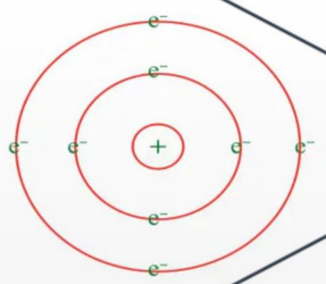
- The electrons that are bound to the nucleus in the outer most shell and do not take part in conduction are said to lie in ~~valance~~ valence band.
- The electrons that are ionized from the atom and are part of conduction are said to lie in conduction band.
- In conductors both valance band and conduction band overlap, which means the valance e^- are by default part of conduction.
- In semi-conductors the V.B and C.B and separated by a small energy gap called as band gap which is almost 1 eV
- At T = 0k , the valance band is completely filled and the conduction band is completely empty.

- But as temperature increases e^-s are promoted from valence band to conduction band so valence band became partially empty and conduction band partially filled.
- The vacancies left by electrons in the valance band are called as holes and conduction in semi-conductor is due to both electrons and holes.
- In an insulator the energy gap between V.B and C.B is higher than 5eV.
- ~~In an insulator the energy gap between V.B and C.B is higher than 5eV~~

1 Joule = 1.6×10^{-19} eV

Carbon

Z=6 (atomic number)



Classification of Semiconductor

Pure Semi-Conductor

- The semiconductors in which there are no crystal defect as well as there is no impurity are called as pure semiconductors
- Hole concentration = e^- concentration
  (→ valence band; → conduction band)
- $p_0 = n_0$
- p_0 = hole concentration at ~~terminal~~ thermal equilibrium.
- n_0 = e^- concentration at thermal equilibrium.

at any T, no. of e^- going from VB to CB is same as no. of e^- coming from CB to VB so that conc. = const

- Electron hole pair (EHP) when $1e^-$ goes from V.B ~~is from~~ forms a hole in V.B and in C.B there is $1\ e^-$ and this is called EHP.

- Thermal equilibrium ⟶ when e^- from V.B goes to C.B and $1e^-$ from C.B comes back to V.B (after transient state)

Intrinsic Semi-Conductors

- The semiconductors in which there is no impurity but there can be crystal defect is called intrinsic semiconductor.

- $n_0 = p_0$ ← holes have been created when e^- have moved from VB to CB
  no. of e^- going from VB to CB = no. of vacancies in VB

Extrinsic Semi- Conductor

- If impurity is added to a crystal structure then it is called as extrinsic semi-conductor.
- $n_0 > p_0 \longrightarrow$ n–type ← e^- conc > hole conc
- $n_0 < p_0 \longrightarrow$ p – type ← hole conc > e^- conc

Classification based on chemical formulae

1. Elemental Semi-Conductor

- Group IV elements : Si , Ge ← all atoms belong to single element

2. Compound Semi-Conductor

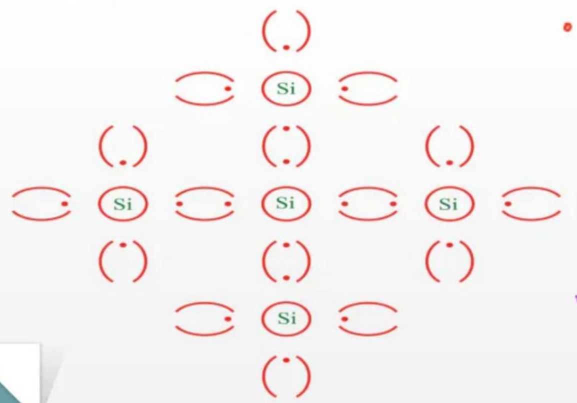
Group III / V
- GaAs , InP

Group II / VI
- PbS, ZnS

atoms belong to more than one element

Intrinsic

- Intrinsic semi-conductors behave as insulator at T =0K because the energy is not sufficient to break a bond.



- Every Si atoms form covalent bond with 4 other Si atoms so that octet can get completed.
- Octet: an atom needs 8 e^- in outer shell to have stable atomic configuration.

Law of mass action

- In semiconductor under thermal equilibrium (constant temperature) the product of electrons and holes concentrations is always a constant and is equal to the square of intrinsic carrier concentration . ← e^- & hole conc. are fixed

$$\Rightarrow \boxed{n_0 p_0 = n_i^2}$$

$$n_0 = p_0 = n_i$$

* In intrinsic semiconductor, e^- & hole concentration are equal which is equal to Intrinsic carrier concentration. $n_0 = p_0 = n_i$

* In any SC at any temp. product of e^- & hole conc. remains constant at n_i^2. (n_0 & p_0 may not be equal)

Doping

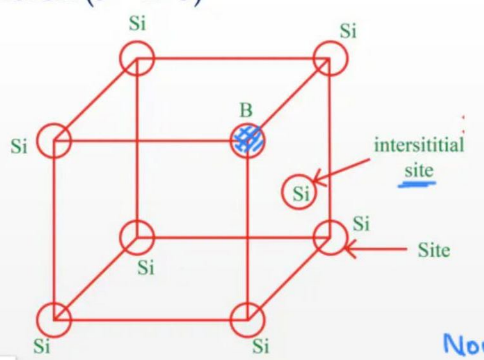
- Doping is a process in which external impurities are added to a crystal structure
- If group III elements are added then a semiconductor becomes a p-type semiconductor having more holes than e^-
- If group v elements are added then semiconductor becomes n type semiconductor with more electrons than holes.

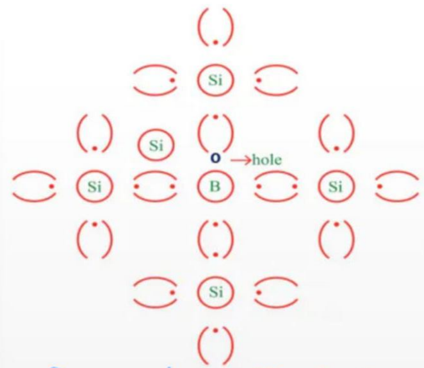
* Group-3 elements have 3 electrons in outermost shell whereas Group-5 elements have 5 electrons in outermost shell.

* When foreign atom is introduced, it replaces main atom inside a crystal & main atom is pushed to an intersititial site.
  ↳ location b/w atoms or location b/w sites.

P-type :

- Group iii elements:
- Boron (5 = 2+3)





Now, Boron has 7 electrons in outermost shell.

* Boron needs 8 electrons to complete stable electronic configuration so there is a vacancy or hole created by introduction of Boron.
  ↳ This vacancy is not created due to electron going from VB to CB but due to introduction of Boron.

* If concentration of Boron atom = N_A ($/cm^3$)
  hole conc. due to Boron = N_A (one hole per atom)

* Boron atom would like to accept an electron to complete octet & that is why it is called acceptor impurity.

Doping Concentration

- Doping concentration = $N_A/\ cm^3$
- Na : acceptor impurity concentration, each acceptor atom → 1 hole
- $p_0 = n_i + N_A \simeq N_A$
- $N_A = 10^{16}/cm^3$
- $n_i = 10^{10}/\ cm^3$
- $n_0 p_0 = n_i^2$ (law of mass action)
- $n_0 = n_i^2/NA$ [∵ $p_0 = N_A$]

$p_0 \simeq 10^{16}$ $n_0 = \frac{10^{20}}{10^{16}} = 10^4$

n_i = no. of holes in intrinsic SC

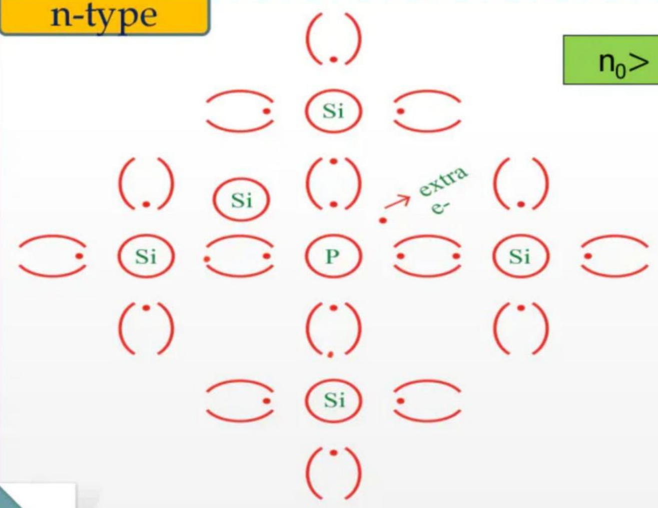
N_A : additional holes are introduced

$p_0 >> n_0$

↳ p-type semicond^r

n-type

$n_0 > p_0$



* Phosphorus has 5 electrons in outermost shell & it forms a bond with 4 other Si atoms

Total e^- = 9 electrons

* P needs 8 e^- to complete octet & form stable electronic configuration.

* P donates excess e^- & hence called donor impurity.

* each phosphorus contributes 1 free electrons & these are not the electron promoted from VB to CB but they are extra electron donated by impurity.

- Doping concentration = $N_D/\ cm^3$
- N_D : Donor impurity concentration, each ~~acceptor~~ donor atom → $1\ e^-$
- $n_0 = n_i + N_D \simeq N_D$
- $N_D = 10^{16}/cm^3$
- $n_i = 10^{10}/\ cm^3$
- $n_0 p_0 = n_i^2$
- $p_0 = n_i^2/ND \simeq 10^4$
- The charge carrier which have higher concentration are called as majority carrier and the charge carrier which have lower concentration are called as minority carrier.

* $n_0 >> p_0$: n-type semiconductor

* n-type : e^- majority, hole minority

* p-type : e^- minority, hole majority

- n: type
  holes : minority carrier
  e^- : majority carrier

- p : type
  e^-: minority carrier
  holes : majority carrier

Q Does a semiconductor remain electrically neutral after doping?

Ans YES

* Boron is electrically neutral atom (proton = e^-) & so is Phosphorus & Silicon.

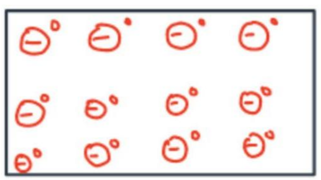
* When we add neutral atom to a crystal net charge must remain 0.

eg: Boron has 3 electron in outer shell : 5 vacancy
↳ that does not make Boron B^{+5}

Representation of p-type & n-type SC

① When Boron atom accepts an e^- to complete octet it becomes negatively charged

② When Phosphorus donates an e^- it becomes positively charged.



p-type
if Boron accepts e^- hole vanishes & Boron becomes -ve ion

n-type
If P donates e^- then e^- vanishes & P becomes +ve ion

Question:

How does a hole take part in conduction ?

* Hole means vacancy of e^- or a vacant state

* When e^- jump from one atom to another hole is transferred in opp. direction.