A

Seminar report

On

Semiconductors

Submitted in partial fulfillment of the requirement for the award of degree of ECE

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Acknowledgement

I would like to thank respected Mr…….. and Mr. ……..for giving me such a wonderful opportunity to expand my knowledge for my own branch and giving me guidelines to present a seminar report. It helped me a lot to realize of what we study for.

Secondly, I would like to thank my parents who patiently helped me as i went through my work and helped to modify and eliminate some of the irrelevant or un-necessary stuffs.

Thirdly, I would like to thank my friends who helped me to make my work more organized and well-stacked till the end.

Next, I would thank Microsoft for developing such a wonderful tool like MS Word. It helped my work a lot to remain error-free.

Last but clearly not the least, I would thank The Almighty for giving me strength to complete my report on time.

Preface

I have made this report file on the topic **Semiconductors**; I have tried my best to elucidate all the relevant detail to the topic to be included in the report. While in the beginning I have tried to give a general view about this topic.

My efforts and wholehearted co-corporation of each and everyone has ended on a successful note. I express my sincere gratitude to …………..who assisting me throughout the preparation of this topic. I thank him for providing me the reinforcement, confidence and most importantly the track for the topic whenever I needed it.

Introduction

Semiconductors materials such as silicon (Si), germanium (Ge) and gallium arsenide (GaAs), have electrical properties somewhere in the middle, between those of a "conductor" and an "insulator". They are not good conductors nor good insulators (hence their name "semi"-conductors). They have very few "free electrons" because their atoms are closely grouped together in a crystalline pattern called a "crystal lattice" but electrons are still able to flow, but only under special conditions.

The ability of semiconductors to conduct electricity can be greatly improved by replacing or adding certain donor or acceptor atoms to this crystalline structure thereby, producing more free electrons than holes or vice versa. That is by adding a small percentage of another element to the base material, either silicon or germanium.

On their own Silicon and Germanium are classed as intrinsic semiconductors, that is they are chemically pure, containing nothing but semi-conductive material. But by controlling the amount of impurities added to this intrinsic semiconductor material it is possible to control its conductivity. Various impurities called donors or acceptors can be added to this intrinsic material to produce free electrons or holes respectively.

This process of adding donor or acceptor atoms to semiconductor atoms (the order of 1 impurity atom per 10 million (or more) atoms of the semiconductor) is called **Doping**. The as the doped silicon is no longer pure, these donor and acceptor atoms are collectively referred to as "impurities", and by doping these silicon material with a sufficient number of impurities, we can turn it into a *semi-conductor*.

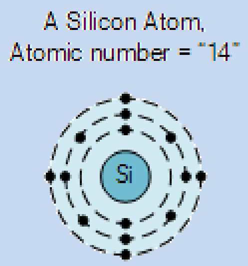
The most commonly used semiconductor basics material by far is **silicon**. Silicon has four valence electrons in its outermost shell which it shares with its neighbouring silicon atoms to form full orbital's of eight electrons. The structure of the bond between the two silicon atoms is such that each atom shares one electron with its neighbour making the bond very stable.

As there are very few free electrons available to move around the silicon crystal, crystals of pure silicon (or germanium) are therefore good insulators, or at the very least very high value resistors.

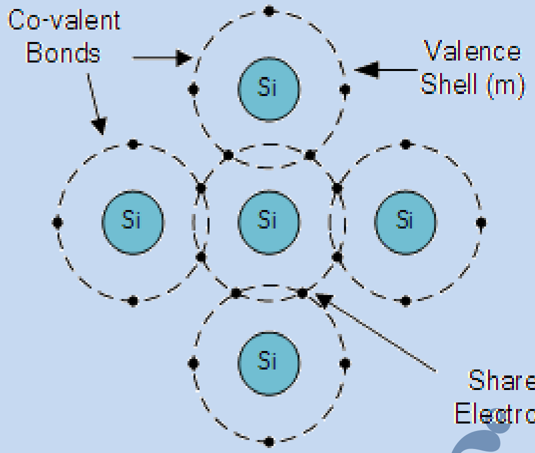
Silicon atoms are arranged in a definite symmetrical pattern making them a crystalline solid structure. A crystal of pure silica (silicon dioxide or glass) is generally said to be an intrinsic crystal (it has no impurities) and therefore has no free electrons.

But simply connecting a silicon crystal to a battery supply is not enough to extract an electric current from it. To do that we need to create a "positive" and a "negative" pole within the silicon allowing electrons and therefore electric current to flow out of the silicon. These poles are created by doping the silicon with certain impurities.

A Silicon Atom Structure



Silicon atom showing 4 electrons in its outer valence shell (m)



Silicon Crystal Lattice

The diagram above shows the structure and lattice of a 'normal' pure crystal of Silicon.

N-type Semiconductor Basics

In order for our silicon crystal to conduct electricity, we need to introduce an impurity atom such as Arsenic, Antimony or Phosphorus into the crystalline structure making it extrinsic (impurities are added). These atoms have five outer electrons in their outermost orbital to share with neighbouring atoms and are commonly called "Pentavalent" impurities.

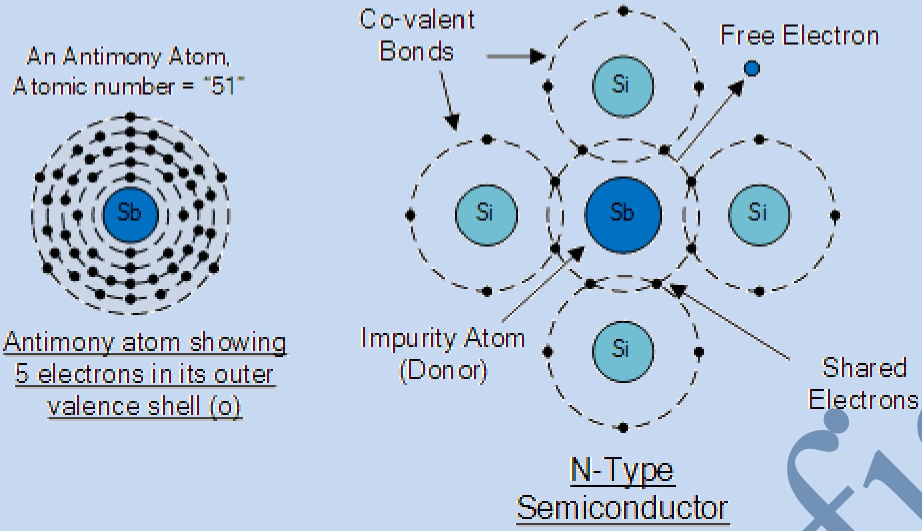
This allows four out of the five orbital electrons to bond with its neighbouring silicon atoms leaving one "free electron" to become mobile when an electrical voltage is applied (electron flow). As each impurity atom "donates" one electron, pentavalent atoms are generally known as "donors".

Antimony (symbol Sb) or **Phosphorus** (symbol P), are frequently used as a pentavalent additive to the silicon as they have 51 electrons arranged in five shells around their nucleus with the outermost orbital having five electrons. The resulting semiconductor basics material has an excess of current-carrying electrons, each with a negative charge, and is therefore referred to as an **N-type** material with the electrons called "Majority Carriers" while the resulting holes are called "Minority Carriers".

When stimulated by an external power source, the electrons freed from the silicon atoms by this stimulation are quickly replaced by the free electrons available from the doped Antimony atoms. But this action still leaves an extra electron (the freed electron) floating around the doped crystal making it negatively charged.

Then a semiconductor material is classed as N-type when its donor density is greater than its acceptor density, in other words, it has more electrons than holes thereby creating a negative pole as shown.

Antimony Atom and Doping



The diagram above shows the structure and lattice of the donor impurity atom Antimony.

P-Type Semiconductor Basics

If we go the other way, and introduce a "Trivalent" (3-electron) impurity into the crystalline structure, such as Aluminium, Boron or Indium, which have only three valence electrons available in their outermost orbital, the fourth closed bond cannot be formed. Therefore, a complete connection is not possible, giving the semiconductor material an abundance of positively charged carriers known as holes in the structure of the crystal where electrons are effectively missing.

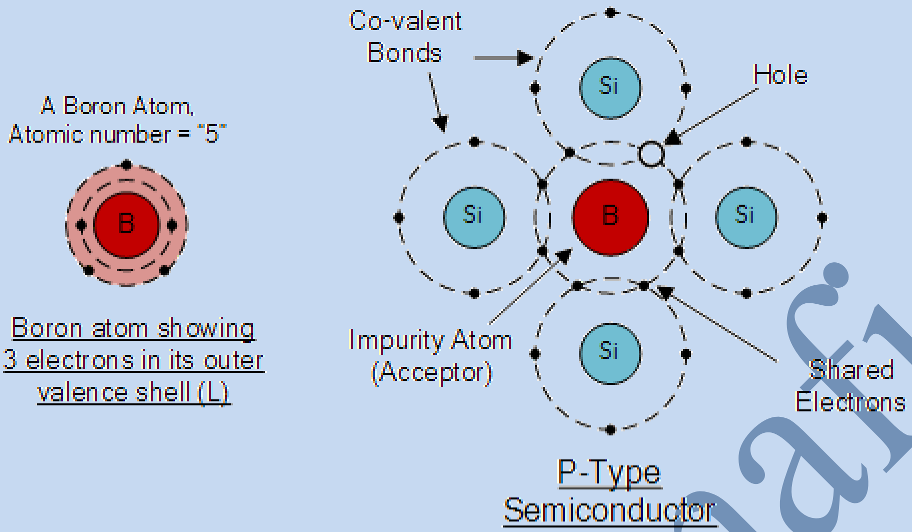
As there is now a hole in the silicon crystal, a neighbouring electron is attracted to it and will try to move into the hole to fill it. However, the electron filling the hole leaves another hole behind it as it moves. This in turn attracts another electron which in turn creates another hole behind it, and so forth giving the appearance that the holes are moving as a positive charge through the crystal structure (conventional current flow).

This movement of holes results in a shortage of electrons in the silicon turning the entire doped crystal into a positive pole. As each impurity atom generates a hole, trivalent impurities are generally known as "**Acceptors**" as they are continually "accepting" extra or free electrons.

Boron (symbol B) is commonly used as a trivalent additive as it has only five electrons arranged in three shells around its nucleus with the outermost orbital having only three electrons. The doping of Boron atoms causes conduction to consist mainly of positive charge carriers resulting in a **P-type** material with the positive holes being called "Majority Carriers" while the free electrons are called "Minority Carriers".

Then a semiconductor basics material is classed as P-type when its acceptor density is greater than its donor density. Therefore, a P-type semiconductor has more holes than electrons.

Boron Atom and Doping



The diagram above shows the structure and lattice of the acceptor impurity atom Boron.

Semiconductor Basics Summary

N-type (e.g. doped with Antimony)

These are materials which have **Pentavalent** impurity atoms (Donors) added and conduct by "electron" movement and are therefore called, **N-type Semiconductors**.

In N-type semiconductors there are:

- 1. The Donors are positively charged.
- 2. There are a large number of free electrons.
- 3. A small number of holes in relation to the number of free electrons.
- 4. Doping gives:
    - positively charged donors.
    - negatively charged free electrons.
- 5. Supply of energy gives:
    - negatively charged free electrons.
    - positively charged holes.

P-type (e.g. doped with Boron)

These are materials which have **Trivalent** impurity atoms (Acceptors) added and conduct by "hole" movement and are therefore called, **P-type Semiconductors**.

In these types of materials are:

- 1. The Acceptors are negatively charged.
- 2. There are a large number of holes.
- 3. A small number of free electrons in relation to the number of holes.
- 4. Doping gives:
  - negatively charged acceptors.
  - positively charged holes.
- 5. Supply of energy gives:
  - positively charged holes.
  - negatively charged free electrons.

and both P and N-types as a whole, are electrically neutral on their own.

Antimony (Sb) and Boron (B) are two of the most commonly used doping agents as they are more feely available compared to other types of materials. They are also classed as “metalloids”. However, the periodic table groups together a number of other different chemical elements all with either three, or five electrons in their outermost orbital shell making them suitable as a doping material.

These other chemical elements can also be used as doping agents to a base material of either Silicon (S) or Germanium (Ge) to produce different types of basic semiconductor materials for use in electronic semiconductor components, microprocessor and solar cell applications. These additional semiconductor materials are given below.

Periodic Table of Semiconductors

Elements Group 13	Elements Group 14	Elements Group 15
3-Electrons in Outer Shell (Positively Charged)	4-Electrons in Outer Shell (Neutrally Charged)	5-Electrons in Outer Shell (Negatively Charged)
(5) Boron (B)	(6) Carbon (C)	
(13) Aluminium (Al)	(14) Silicon (Si)	(15) Phosphorus (P)
(31) Gallium (Ga)	(32) Germanium (Ge)	(33) Arsenic (As)
		(51) Antimony (Sb)

In the next tutorial about semiconductors and diodes, we will look at joining the two semiconductor basics materials, the P-type and the N-type materials to form a PN Junction which can be used to produce diodes.

Semiconductors

Intrinsic semiconductors – pure, no impurities

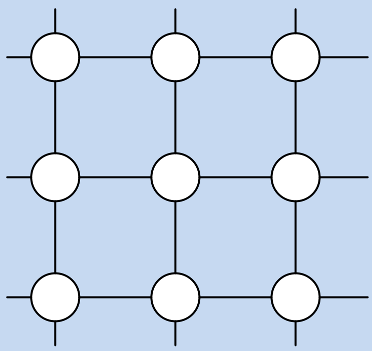
Extrinsic semiconductors – contain small amounts of deliberately added impurity (doped)

Intrinsic Semiconductors

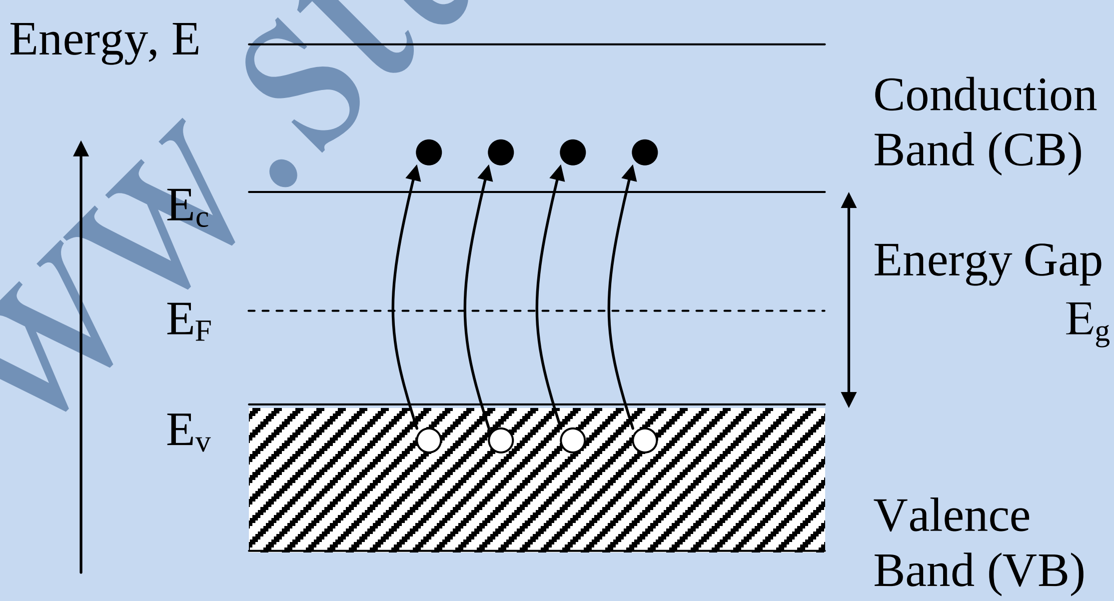
Semiconducting elements e.g. Si, Ge (Group IV)

- each atom bonded to 4 nearest neighbours i.e. tetrahedral bonding

(2D – representation)



<u>Energy Band Diagram for Intrinsic Semiconductor (in real space)</u>



Recall idea of energy bands for electrons in solids.

energies of electrons lie in regions or bands. Bands separated by forbidden regions or energy gaps.

Consider a material with either cimpletely filled or completely empty bands.

T = 0 - Insulator

T > 0 - some electrons from VB are excited into CB.

Vacancies or “holes” are created in VB.

For an intrinsic semiconductor

$$n_c = p_v$$

n_c = electron conc’n in CB
p_v = hole conc’n in VB

Both electrons in CB and (positive) holes in VB contribute to electrical conduction (in applied E-field)

So for intrinsic semiconductor, electrical conductivity σ is given by:

$$\sigma = n_c e \mu_e + p_v e \mu_h$$

μ_e – electron mobility
μ_h - hole mobility

Definition of μ:

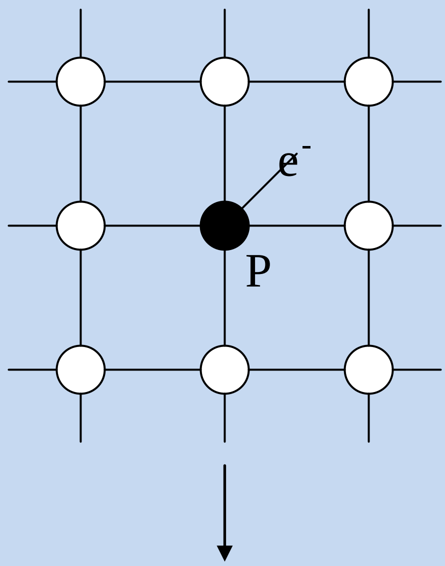
$$\mu = (v/E)$$

[v = carrier velocity in electric field E]

Extrinsic (or Doped) Semiconductors

n-type Doped Semiconductors

These have small amounts of groupV impurities e.g. P, As



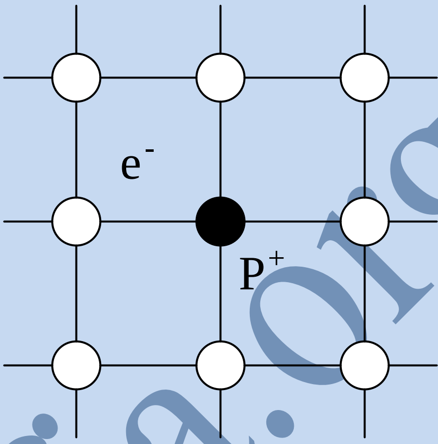
bonds with neighbouring atoms

4 go to form bonds with neighbouring Si atoms

5th electron is unpaired and weakly bound to P.

Thermal excitation is usually enough to break bond between P and unpaired electron.

This leaves an ionised P (donor atom) bonded to the Si network, and a free (donor) electron which can carry charge

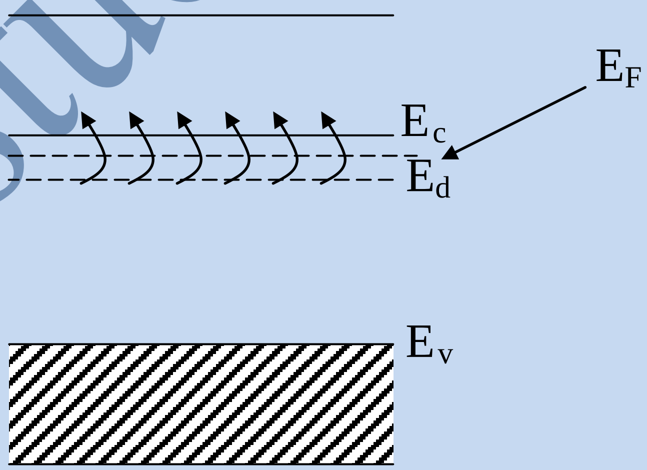


Donors can usually be considered to be completely ionised at room temperature.

Energy Band Diagram for n-type Semiconductor

conduction band

valence band



At T = 0, all donor electrons are weakly bound to P atoms.

Represented on energy diagram by putting electrons in levels at E_d (donor levels) – just below E_c.

Typically $E_c - E_d = \sim 0.01 - 0.1$ eV

This is small or comparable with thermal energies ($kT = \sim 0.025$ eV at room temperature).

So at room temperature, most of the donor atoms have given up their excess electron

→ large increase in n_c (concentration of electrons in conduction band)

→ large increase in conductivity σ.

So assuming all donors ionised, charge neutrality gives

$$n_c = p_v + N_d$$

[N_d = conc'n of donor atoms]

which can normally approximate to

$$n_c \approx N_d$$

i.e. for n-type semiconductor, can normally neglect hole contribution

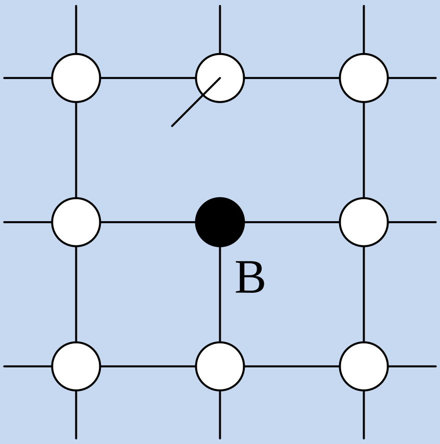
Hence, for n-type at room temp, conductivity σ is

$$\sigma \approx n_c e \mu_e \approx N_d e \mu_e$$

p-type Doped semiconductors

Small amounts of Group III impurities e.g. B, Al

B has 3 available electrons to form with neighbouring atoms.

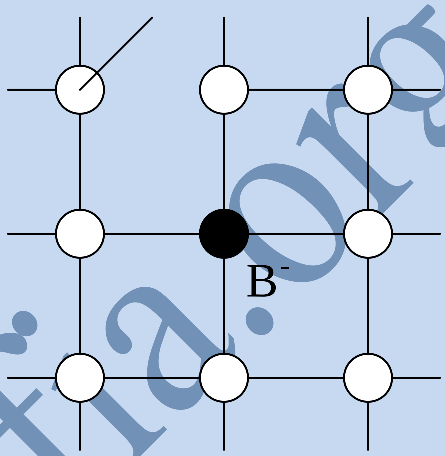


B adopts tetrahedral bonding but with broken bond. [In fact, broken bond shared between all 4 bonds to neighbouring Si's]

Can regard as tetrahedrally bonded B binding a hole.

B can capture (accept) an electron from a Si-Si bond elsewhere.

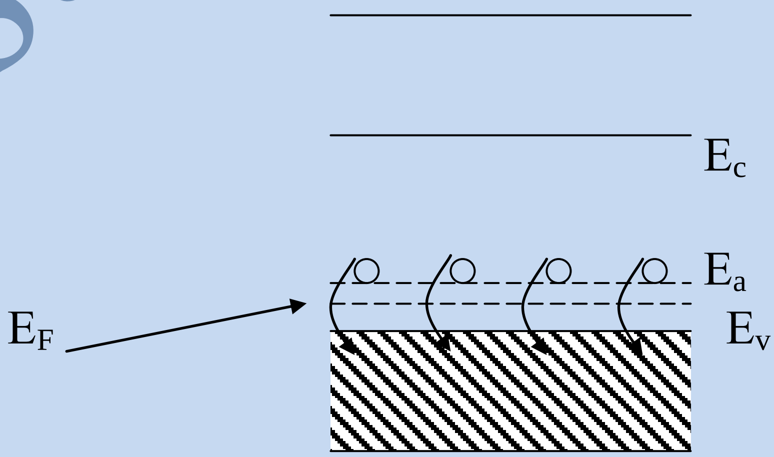
This leaves a negatively ionised B atom (acceptor), and a broken Si-Si bond (mobile or free hole).



Can think of B as donating a free hole.

Process occurs easily at thermal energies (room temp').

Band diagram for p-type Semiconductor



At T = 0, all B atoms have a weakly bound hole.

Represented on energy diagram by putting holes on levels at E_a (acceptor levels) – just above E_v.

Typically $E_a - E_v = \sim 0.01 - 0.1$ eV

At room temperature, large numbers of electrons excited from VB into acceptor level E_a – leaves large number of holes in VB.

[Alternatively: large numbers of holes excited down into VB - as in diagram]

$\rightarrow$ large increase in p_v

$\rightarrow$ large increase in conductivity σ

So assuming all acceptors ionised, charge neutrality gives

$$p_v = n_c + N_a \quad [N_a = \text{acceptor conc'n}]$$

which can normally approximate to

$$p_v \approx N_a$$

i.e. for p-type, can normally neglect electrons

Hence, for p-type at room temp', conductivity σ is

$$\sigma \approx p_v e \mu_h \approx N_a e \mu_h$$

Temperature Dependence of n_c and p_v

Important since this governs T-dependence of σ.

Conc'n of electrons in conduction band, n_c given by

$$n_c = N_c \exp\left\{-\frac{(E_c - E_F)}{kT}\right\}$$

N_c - effective density of states at the conduction band edge.

$$N_c = 2\left(\frac{m_e^* kT}{2\pi\hbar^2}\right)^{\frac{3}{2}}$$

[m_e^* - effective electron mass]

Conc'n of holes in valence band, p_v given by

$$p_v = N_v \exp\left\{-\frac{(E_F - E_V)}{kT}\right\}$$

N_v - effective density of states at the valence band edge.

$$N_v = 2\left(\frac{m_h^* kT}{2\pi\hbar^2}\right)^{\frac{3}{2}}$$

[m_h* - effective hole mass]

Law of Mass Action

Above expressions for n_c and p_v give for the product $n_c p_v$

$$n_c p_v = N_c N_v \exp\left\{-\frac{(E_c - E_v)}{kT}\right\}$$

Since energy gap $E_g = E_c - E_v$

$$n_c p_v = N_c N_v \exp\left\{-\frac{E_g}{kT}\right\}$$

True for any semiconductor, whether intrinsic or doped.

For an intrinsic semiconductor $n_c = p_v = n_i$
[n_i - intrinsic carrier concentration]

Hence

$$n_c p_v = n_i^2 = N_c N_v \exp\left\{-\frac{E_g}{kT}\right\}$$

Law of Mass Action

Using $N_c = 2\left(\frac{m_e^* kT}{2\pi\hbar^2}\right)^{\frac{3}{2}}$ and $N_v = 2\left(\frac{m_h^* kT}{2\pi\hbar^2}\right)^{\frac{3}{2}}$

$$n_i = (N_c N_v)^{\frac{1}{2}} \exp\left\{-\frac{E_g}{2kT}\right\}$$

$$n_i = 2(m_e^* m_h^*)^{\frac{3}{4}}\left(\frac{kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} \exp\left\{-\frac{E_g}{2kT}\right\}$$

Exponential term dominates over $(kT)^{\frac{3}{2}}$ term.
How do we obtain the expressions for n_c and p_v?

Basic idea - integrate over all available energies in conduction band

Conc'n of electrons between energy E and E + dE is

P(E)D(E)dE

P(E) is the Fermi-Dirac function

$$P(E) = \frac{1}{1 + \exp\{\frac{E - E_F}{kT}\}}$$

[E_F = Fermi level; T = temperature]

i.e. P(E) is the probability of occupation

D(E) is the density of states (per unit volume) in the conduction band. Assume D(E) is free-electron-like:

i.e. $D(E) = A(E - E_c)^{\frac{1}{2}}$ $\quad A = \frac{(2m_e^{*3})^{\frac{1}{2}}}{\pi^2\hbar^3}$

[m_e^* - effective electron mass]

Hence total conc'n of electrons in conduction band n_c is

$$n_c = \int_{E_c}^{\infty} P(E)D(E)dE$$

p_v (hole conc'n in valence band) obtained in similar way

Semiconductor Devices

pn Junction

Possible to fabricate wide range of devices by joining together different semiconductor types.

One of the simplest of these - pn junction.

Large number of devices based on this –

lasers, solar cells, LEDs (remember the PBL??)

Reminder of I-V behaviour of pn diode

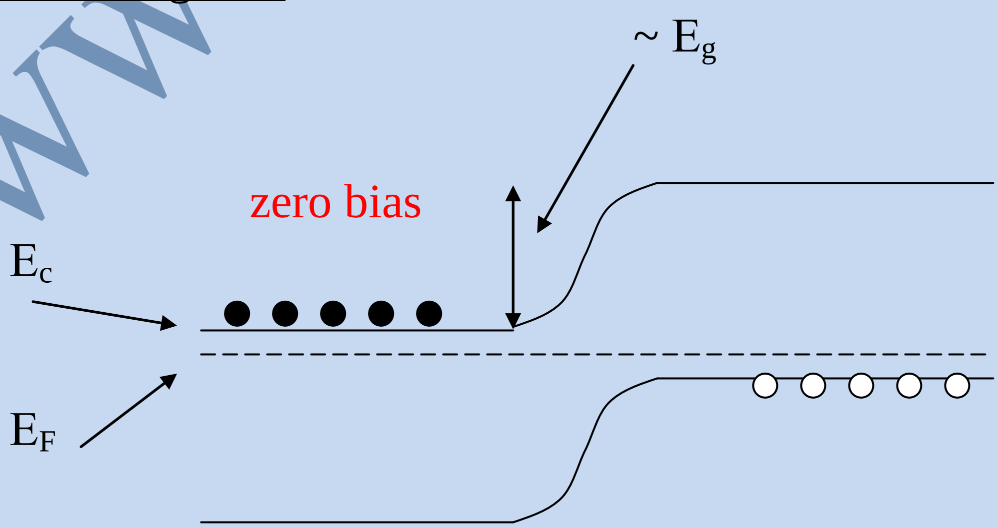
What happens when external bias (voltage) V is applied?

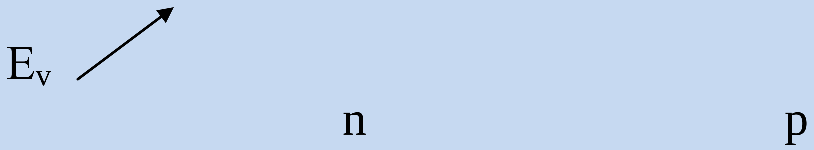
How does I vary?

What does it tell you?

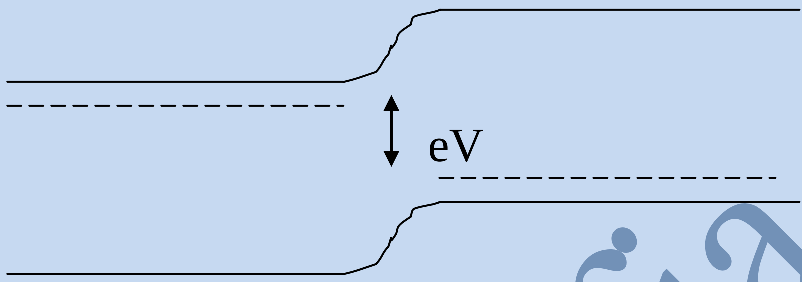
Operation of LED

Band Diagrams

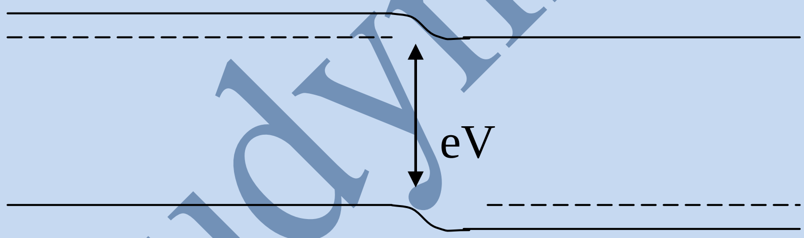




modest forward bias V



large forward bias V



large numbers of electrons flow from n to p (and holes from p to n) when $eV > E_g$

Ideal I-V behaviour

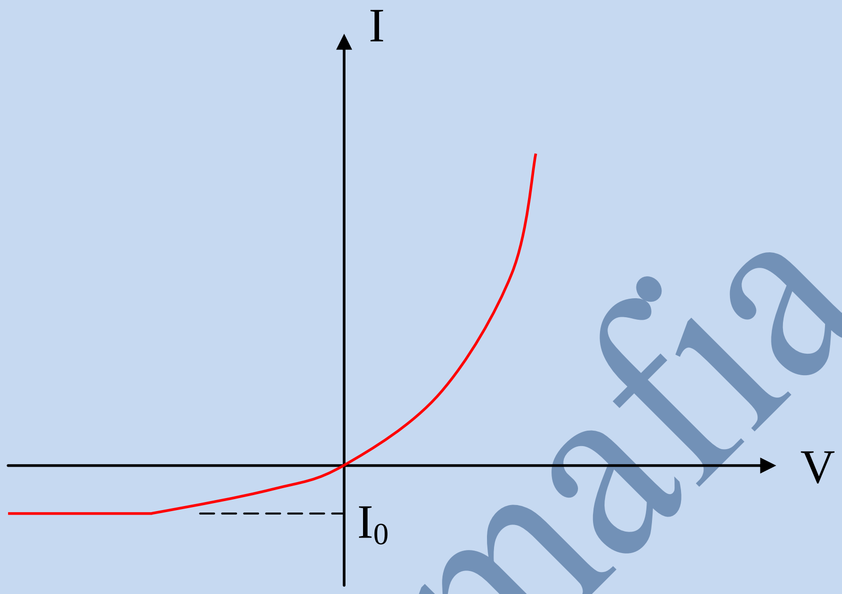
→ $I = I_0[\exp(eV/kT) - 1]$ - forward bias

→ $I = I_0[1 - \exp(-eV/kT)]$ - reverse bias

N.B. - 2 carrier types.

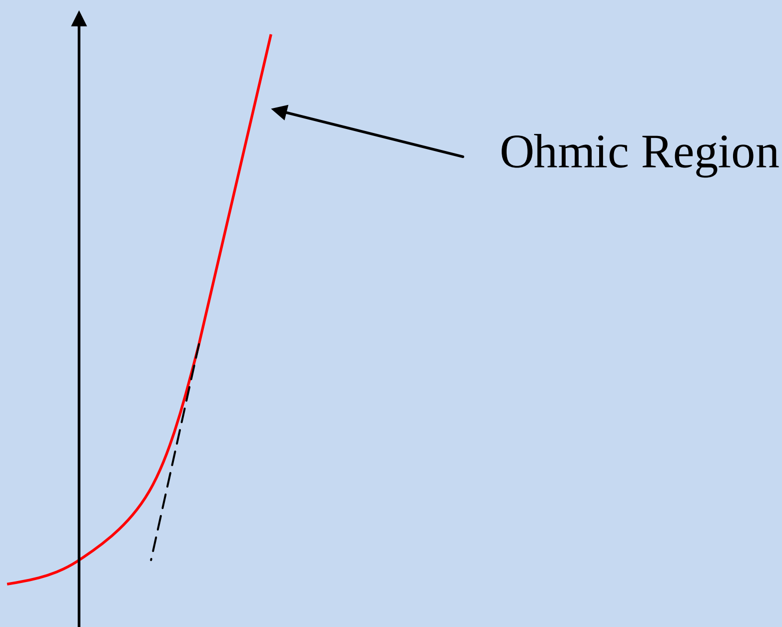
negative electrons flow from n to p

positive holes flow in opposite direction.



So at large V, I predicted to increase ~ exponentially.

In practice, I increases linearly with V for large V.



V

E_g/e

Once pn junction is forward biased by value greater than ~ E_g/e, large numbers of electrons injected from n to p, and holes from p to n

I becomes large and limited by series resistance of device. Ohmic behaviour is observed.

[Could be due to contact resistance between metal and semiconductor, resistivity of the semiconductor, or series resistance of connecting wires].

Can extrapolate linear region back to I = 0 to obtain estimate for E_g (as done in PBL).

<u>LED (Light Emitting Diode)</u>

<u>Emission Process</u>

Recombination of electron in conduction band with hole in valence band; energy released emitted as photon of well-defined frequency.

For process to occur, semiconductor must have direct gap.

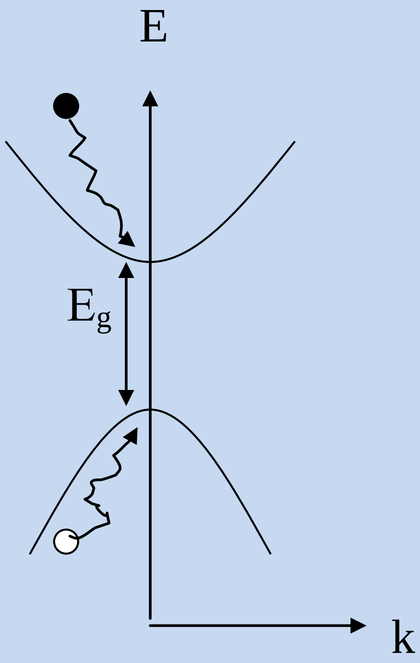


Fig.1

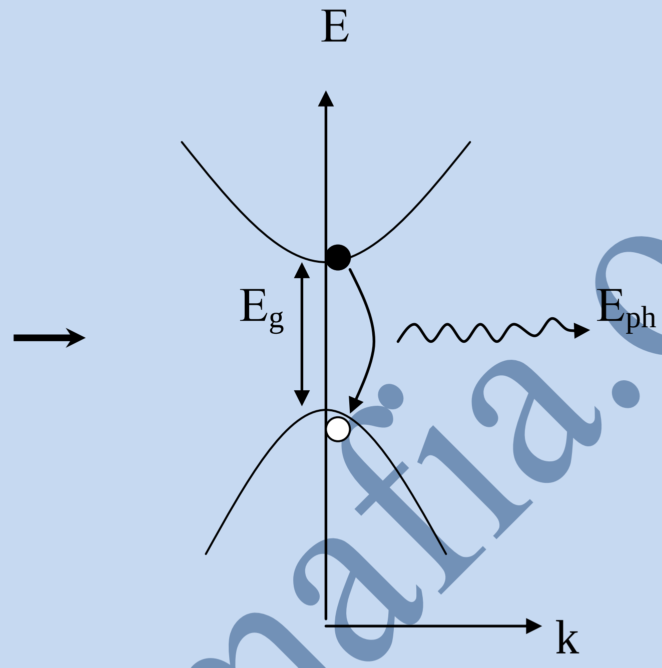


Fig.2

See original notes from Unit 4.

Energy released in recombination event is E_g i.e. $E_{ph} = E_g$

Both energy and momentum conserved ($\hbar\Delta k \approx 0$)

LEDs make use of emission process in semiconductors.

Consist of pn junction of a direct gap semiconductor, operated in forward bias.

Basic operation

1. Electrons from n-region diffuse across depletion layer into narrow region just inside p-side.

2. Here, they recombine with holes, emitting photons.

3. Wavelength λ of light determined by energy gap E_g.

$$E_g = \frac{hc}{\lambda}$$

So could measure λ of emitted light by e.g. diffraction

Could also use the I-V analysis

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