Slide Set 0

- Wavelength Utilization
- Growth of Internet Traffic
- Link Capacity Improvements
- Technological Trends
- Optoelectronics

What determines the wavelengths utilized?

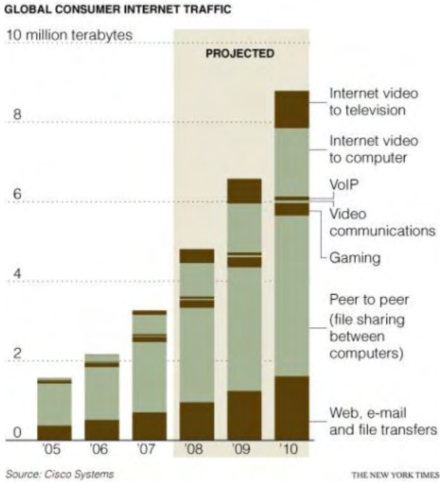
1) Human eye response (indicators and displays)

2) Transmission media
   - Fibers
   - Atmospheric Transmission

3) Source of radiation (detectors)
   - Sun (Solar Spectrum)
   - Black body – T
   - Lasers

4) Technologically available materials

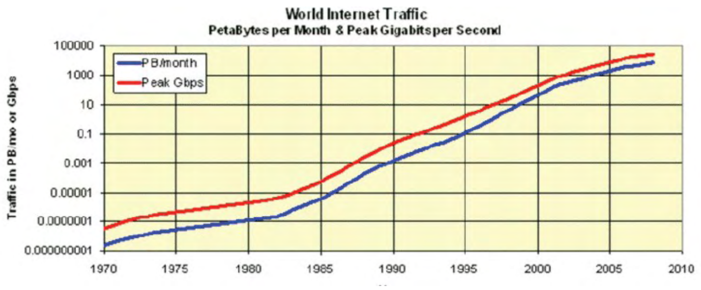
Growth of Internet Traffic



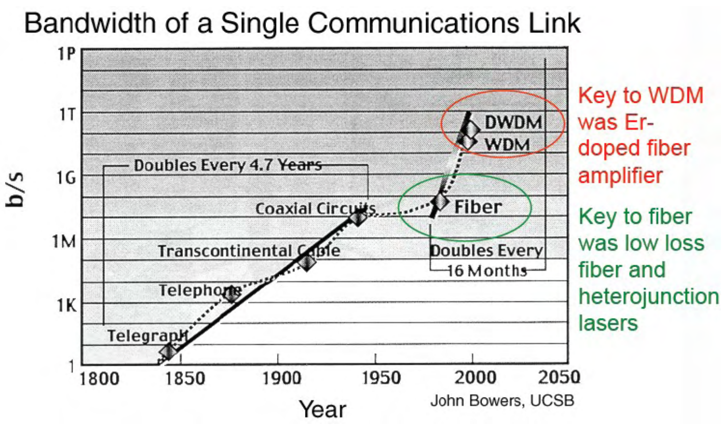
Source: Cisco Systems

THE NEW YORK TIMES

Growth of Internet Traffic



Link Capacity Improvements



Key to WDM was Er-doped fiber amplifier

Key to fiber was low loss fiber and heterojunction lasers

John Bowers, UCSB

SONET/SDH Specifications

Beginner	Intermediate	Advanced	Extreme
●	🟦	◆	🟥
OC-48 2.5 Gb/s	OC-192 10 Gb/s	OC-768 40 Gb/s	OC-3072 160 Gb/s

OC – Optical Carrier rate, OC-1 = 51.84 Mbps

Technological Trends

Computer performance continues to follow Moore's Law
- **> Doubling of computing power every 18 months**
- **> Device research indicates exponential growth until 2020**

Network capacity is also increasing exponentially
- **> Gilder's Law – "Communication capacity triples every 12 months"**
- **> Growth at a rate greater than Moore's law requires new integrated, lower cost technologies**

Required network capacity
- **>Desktop bandwidth needs limited only by the human eye (**~2Gbps)
- **>Internet traffic is non local**
- **>Number of users and hosts is growing exponentially**

∴ Need long wavelength, high speed, low cost, vertical-cavity surface-emitting lasers (VCSELs) and integrated photonic ICs with higher functionality

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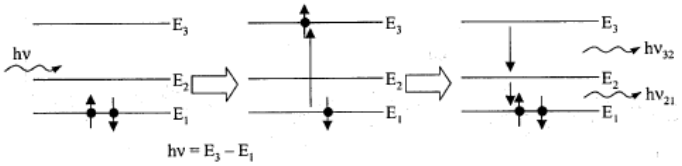
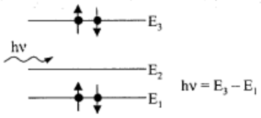
What is Optoelectronics?

Involving both electronic and optical (photonic) processes:
- – Electronic excitation through photon absorption
- – Photon emission through electron relaxation
- – Energy converted from electrical to optical or vice versa

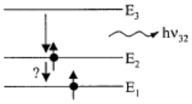


Absorption and Emission Issues

- What if E_3 occupied?



- What if E_1 has the same spin?



Classification of Optoelectronic Devices

- **Light Emitting Devices**
  - LED, Lasers, LEEC (Light-emitting electrochemical Cell)
- **Light Absorbing Devices**
  - Photodetector, Solar Cell, Photoresistor (LDR)
- **Light Manipulation Devices**
  - Involved in modulation, switching and guiding

Applications of Optoelectronic Devices

- **PhotoVoltaics**
  - Convert solar energy into electrical energy (PV)
- **Displays**
  - LCD, LED, TFT, OLED
- **Communications**
  - Optical Communication: Fibre Optics (FO), Free-Space Optics (FSO)
- **Sensing & Monitoring**
  - CCD (Charge-Coupled Device), Infrared

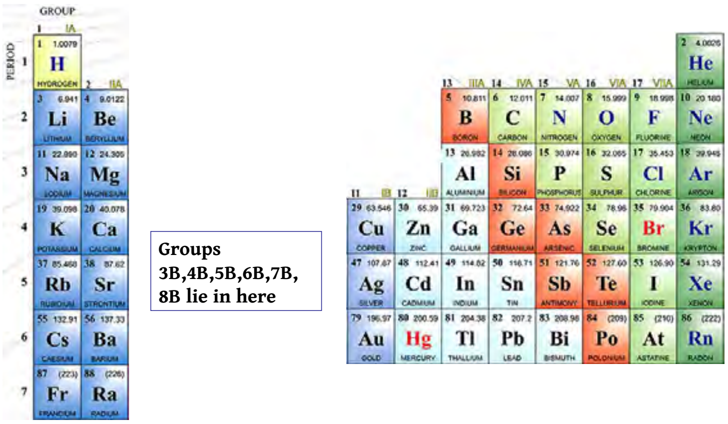
Slide Set 1

- Atoms Bonding
- Types of Solids
- Energy Bands

Atoms and Bonding

- In order to understand the physics of semiconductor (s/c) devices, we should first learn how atoms bond together to form the solids.
- Atom is composed of a nucleus which contains protons and neutrons; surrounding the nucleus are the electrons.
- Atoms can combine with themselves or other atoms. The valence electrons, i.e. the outermost shell electrons govern the chemistry of atoms.
- Atoms come together and form gases, liquids or solids depending on the strength of the attractive forces between them.
- The atomic bonding can be classified as ionic, covalent, metallic, van der Waals, etc.
- In all types of bonding the ***electrostatic force acts between charged particles.***

The Periodic Table



Groups 3B,4B,5B,6B,7B, 8B lie in here

The Periodic Table

- Ionic solids

  Group 1A (alkali metals) contains lithium (Li), sodium (Na), potassium (K),... and these combine easily with group 7A (halogens) of fluorine (F), chlorine (Cl), bromine (Br),... to produce ionic solids of NaCl, KCl, KBr, etc.

- Rare (noble) gases

  Group 8A elements of noble gases of helium(He), neon (Ne), argon (Ar),... have a full complement of valence electrons and so do not combine easily with other elements.

- Elemental semiconductors

  Silicon(Si) and Germanium (Ge) belong to group 4A.

- Compound semiconductors

  1) III-V compound s/c's; GaP, InAs, AlGaAs (group 3A-5A)

  2) II-VI compound s/c's; ZnS, CdS, etc. (group 2B-6A)

Covalent Bonding

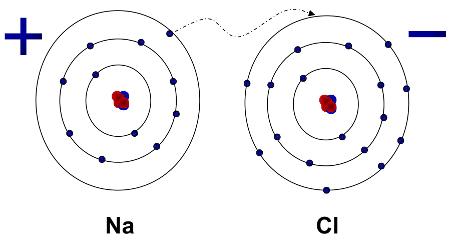
- Elemental semiconductors of Si, Ge and Carbon (as diamond) are bonded by this mechanism and these are purely covalent.
- The bonding is due to the ***sharing of electrons***.
- Covalently bonded solids are hard, high melting points, and insoluble in all ordinary solids.
- Compound s/c's exhibit a mixture of both ionic and covalent bonding.

Ionic Bonding

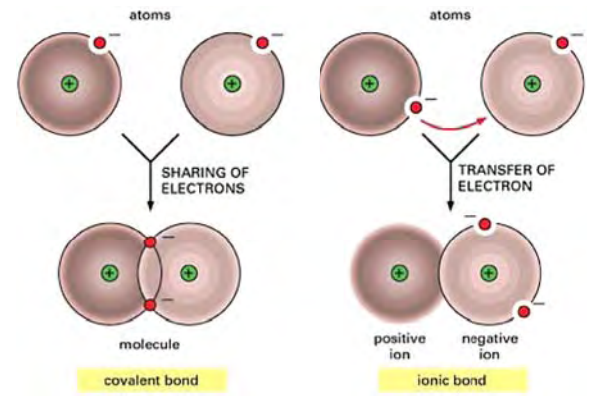
- Ionic bonding is due to the electrostatic force of attraction between positively and negatively charged ions (between 1A and 7A).
- This process leads to electron transfer and formation of charged ions; a ***positively*** charged ion for the atom that has ***lost the electron*** and a *negatively* charged ion for the atom that has ***gained an electron.***
- All ionic compounds are ***crystalline solids*** at room temperature.
- NaCl and CsCl are typical examples of ionic bonding.
- Ionic crystals are hard, high melting point, brittle and can be dissolved in ordinary liquids.

Ionic Bonding

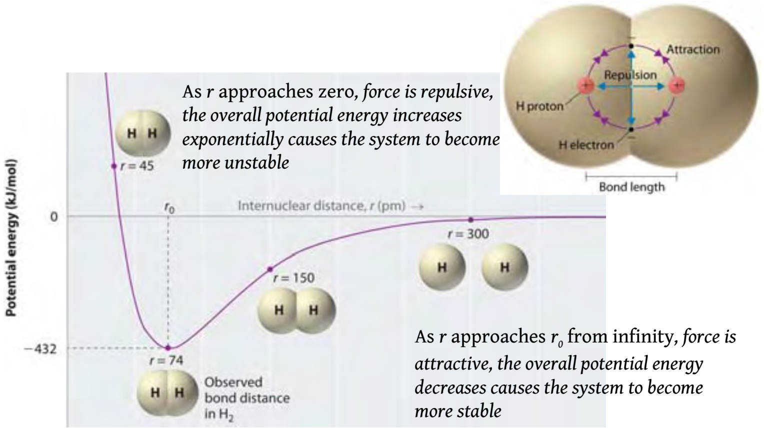
The metallic elements have only up to the valence electrons in their outer shell will lose their electrons and become positive ions, whereas electronegative elements tend to acquire additional electrons to complete their octet and become negative ions, or anions.



Covalent vs. Ionic Bonding



Potential Energy Diagram for a Hydrogen Molecule



As *r* approaches zero, *force is repulsive, the overall potential energy increases exponentially causes the system to become more unstable*

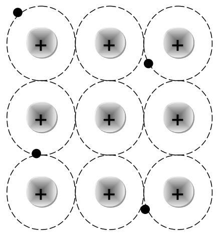
As *r* approaches r_0 from infinity, *force is attractive, the overall potential energy decreases causes the system to become more stable*

This typical curve has a minimum at equilibrium distance r_0 *, i.e. Bond length is 74 pm*

Metallic Bonding

❖ Valence electrons are relatively bound to the nucleus and therefore they move freely through the metal and they are spread out among the atoms in the form of a low-density electron cloud.

❖ A metallic bond result from the sharing of a variable number of electrons by a variable number of atoms. A metal may be described as a ***cloud of free electrons.***



❖ Therefore, metals have high electrical and thermal conductivity.

Metallic Bonding

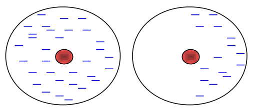
- All valence electrons in a metal combine to form a "sea" of electrons that *move freely between the atom* cores. The more electrons, the stronger the attraction. This means the melting and boiling points are higher, and the metal is stronger and harder.
- The positively charged cores are held together by these negatively charged electrons.
- The free electrons act as the bond (or as a "glue") between the positively charged ions.
- This type of bonding is non-directional and is rather insensitive to structure.
- As a result we have a high ductility of metals - the "bonds" do not "break" when atoms are rearranged – metals can experience a significant degree of plastic deformation.

Van Der Waals' Bonding

- It is the weakest bonding mechanism.
- It occurs between neutral atoms and molecules.
- The explanation of these weak forces of attraction is that there are natural fluctuation in the electron density of all molecules and these cause small temporary dipoles within the molecules. It is these temporary dipoles that attract one molecule to another. They are as called van der Waals' forces.
- Such a weak bonding results low melting and boiling points and little mechanical strength.

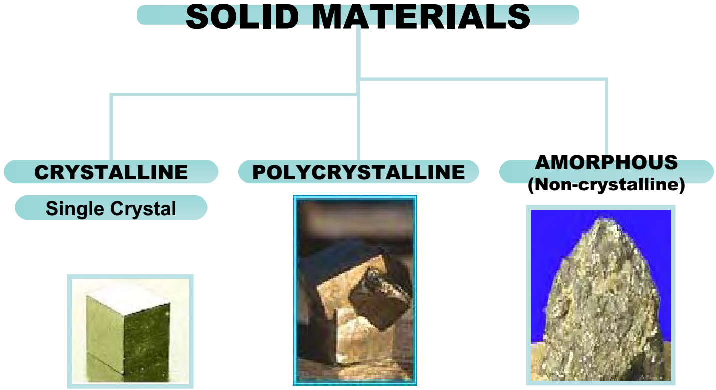
Van Der Waals' Bonding

The dipoles can be formed as a result of ***unbalanced distribution of electrons in asymettrical molecules***. This is caused by the instantaneous location of a few more electrons on one side of the nucleus than on the other.



Therefore atoms or molecules containing dipoles are attracted to each other by electrostatic forces.

Classification of Solids



SOLID MATERIALS

CRYSTALLINE

Single Crystal

POLYCRYSTALLINE

AMORPHOUS (Non-crystalline)

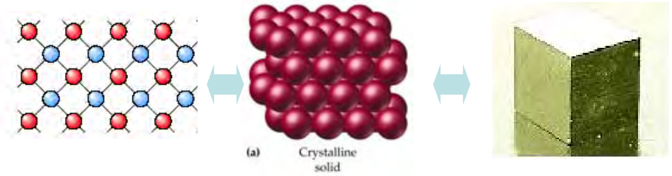
e.g. salt

e.g powder metal

e.g. rubber

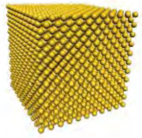
Crystalline Solid

- Crystalline Solid is the solid form of a substance in which the atoms or molecules are arranged in a definite, repeating pattern in three dimension.



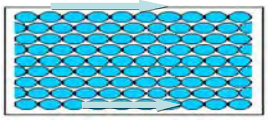
Crystalline Solid

- Single crystal has an atomic structure that repeats periodically across its whole volume. Even at infinite length scales, each atom is related to every other equivalent atom in the structure by translational symmetry



Single Crystal

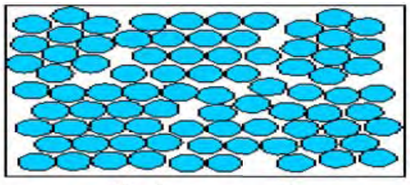
Single Pyrite Crystal



Amorphous Solid

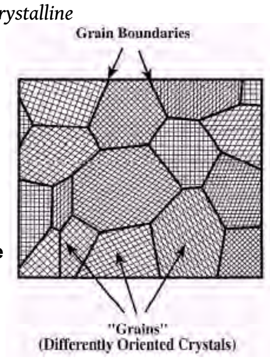
Polycrystalline Solids

- Polycrystal is a material made up of an aggregate of many small single crystals (also called crystallites or grains).
- The grains are usually 100 nm - 100 microns in diameter. Polycrystals with grains that are <10 nm in diameter are called *nanocrystalline*



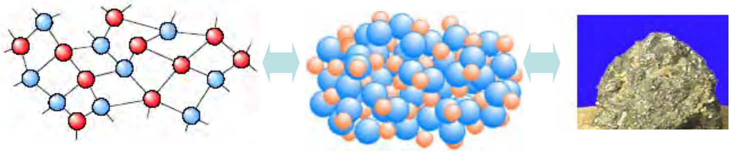
Polycrystal

Polycrystalline Pyrite form (Grain)

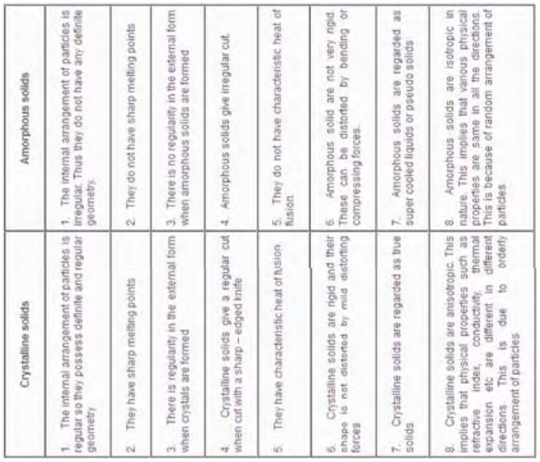


Amorphous Solids

- Amorphous (non-crystalline) Solid is composed of randomly orientated atoms, ions, or molecules that do not form defined patterns or lattice structures.



Difference between Solids



Crystalline solids	Amorphous solids
1. The internal arrangement of particles is regular so they possess definite and regular geometry	1. The internal arrangement of particles is irregular. Thus they do not have any definite geometry.
2. They have sharp melting points	2. They do not have sharp melting points
3. There is regularity in the external form when crystals are formed	3. There is no regularity in the external form when amorphous solids are formed
4. Crystalline solids give a regular cut when cut with a sharp – edged knife	4. Amorphous solids give irregular cut.
5. They have characteristic heat of fusion	5. They do not have characteristic heat of fusion.
6. Crystalline solids are rigid and their shape is not distorted by mild distorting forces	6. Amorphous solid are not very rigid. These can be distorted by bending or compressing forces.
7. Crystalline solids are regarded as true solids	7. Amorphous solids are regarded as super cooled liquids or pseudo solids
8. Crystalline solids are anisotropic. This implies that physical properties such as refractive index, conductivity, thermal expansion etc are different in different directions. This is due to orderly arrangement of particles	8. Amorphous solids are isotropic in nature. This implies that various physical properties are same in all the directions. This is because of random arrangement of particles

Semiconductors, Insulators and Metals

The electrical properties of metals and insulators are well known to all of us.

Everyday experience has already taught us a lot about the electrical properties of metals and insulators.

But the same cannot be said about "semiconductors".

What happens when we connect a battery to a piece of a silicon;

would it conduct well ?

Or would it act like an insulator ?

Difference between Solids

The name "semiconductor" implies that it conducts somewhere between the two cases (conductors or insulators)

Conductivity : σ

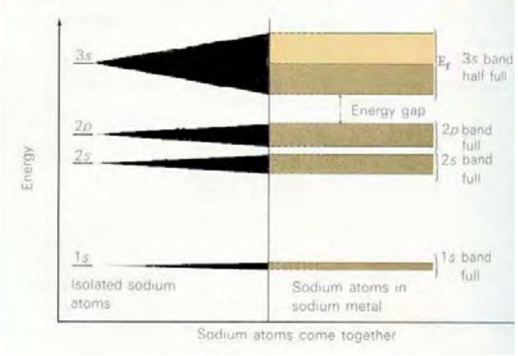
$\sigma_{metals} \sim 10^{10}$ /Ω-cm

S/C

$\sigma_{insulators} \sim 10^{-22}$ /Ω-cm

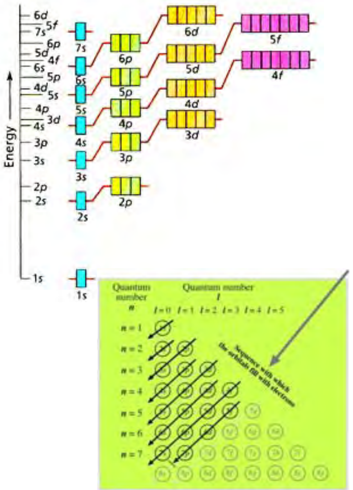
The conductivity (σ) of a semiconductor (S/C) lies between these two extreme cases.

Band Theory of Solids



- The electrons orbiting around the nucleus have certain well-defined energy-levels.
- Electrons don't like to have the same energy in the same potential system.
- The most we could get together in the same energy-level was two, provided thet they had opposite spins. This is called ***Pauli Exclusion Principle.***

Difference between Solids



- The difference in energy between each of these smaller levels is so tiny that it is more reasonable to consider each of these sets of smaller energy-levels as being continuous *bands* of energy, rather that considering the enormous number of discrete individual levels.
- Each ***allowed band*** is seperated from another one by a ***forbidden band***.
- Electrons can be found in ***allowed bands*** but they can not be found in ***forbidden bands***.

Example

- ***Consider 1 cm³ of Silicon. How many atoms does this contain ?***
- Solution:

The atomic mass of silicon is 28.1 g which contains Avagadro's number of atoms.

Avagadro's number N is 6.02×10^{23} atoms/mol .

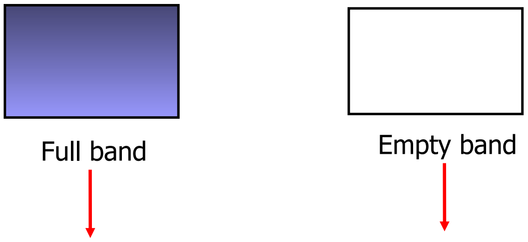
The density of silicon: 2.3×10^{3} kg/m³

so 1 cm³ of silicon weighs 2.3 gram and so contains

$$\frac{6.02 \times 10^{23}}{28.1} \times 2.3 = 4.93 \times 10^{22} \; atoms$$

This means that in a piece of silicon just one cubic centimeter in volume, each electron energy-level has split up into 4.93×10^{22} smaller levels !

Semiconductor, Insulators, Conductors



Full band

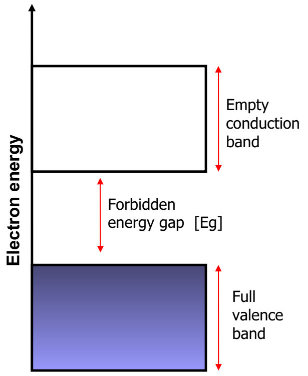
All energy levels are occupied by electrons

Empty band

All energy levels are empty (no electrons)

Both full and empty bands do not partake in electrical conduction.

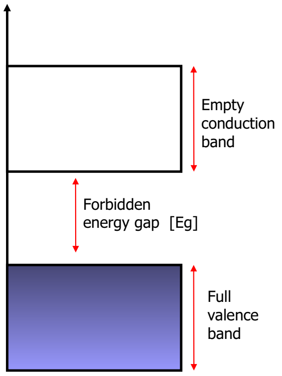
Semiconductor energy bands at low temperature



- At low temperatures the valence and the conduction band is empty.
- Recall that a full band can not conduct, and neither can an empty band.
- At low temperatures, s/c's do not conduct, they behave like insulators.
- The ***thermal energy*** of the electrons sitting at the top of the full band is much lower than that of the ***Eg at low temperatures.***

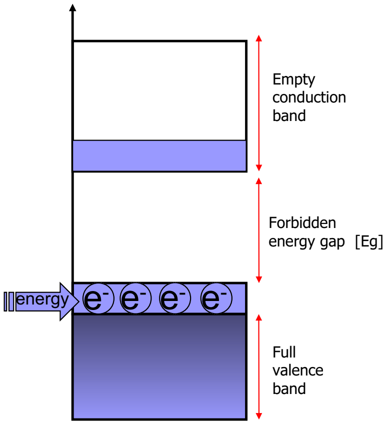
Conduction Electrons

- Assume some kind of energy is provided to the electron (valence electron) sitting at the top of the *valence band.*
- This electron gains energy from the applied field and it would like to move into higher energy states.
- This electron contributes to the ***conductivity*** and this electron is called as a ***conduction electron***.
- At 0^0K, electron sits at the lowest energy levels. The valence band is the highest filled band at zero kelvin.



Semiconductor energy bands at room temperature

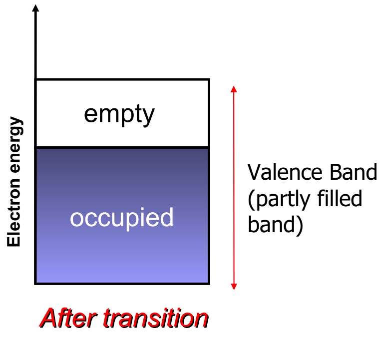
- When enough ***energy*** is supplied to the ***e^-*** sitting at the top of the valence band, ***e^-*** can make a transition to the bottom of the conduction band.
- When electron makes such a transition it leaves behind a ***missing electron state.***
- This missing electron state is called as a ***hole.***
- Hole behaves as a ***positive charge carrier.***
- Magnitude of its charge is the same with that of the electron but with an opposite sign.



Conclusion

- Holes contribute to current in ***valence band*** (VB) as electrons are able to create current in ***conduction band*** (CB).
- Hole is ***not*** a free particle. It can only exist within the crystal. A hole is simply a vacant electron state.
- A transition results an equal number of e^- in CB and holes in VB. This is an important property of *intrinsic* or *undoped* semiconductors. For *extrinsic* or *doped* semiconductors this is no longer true.

Bipolar (two carrier) conduction

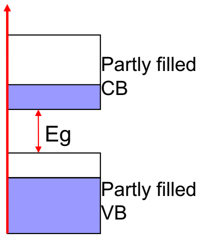


- ***After transition***, the valence band is now no longer full, it is *partly filled* and may conduct electric current.
- The ***conductivity*** is due to both electrons and holes, and this device is called a ***bipolar conductor*** or ***bipolar device.***

What kind of excitation mechanism can cause an e^- to make a transition from the top of the valance band (VB) to the minimum or bottom of the conduction band (CB) ?

Answer :

- Thermal energy ?
- Electrical field ?
- Electromagnetic radiation ?



Energy band diagram of a s/c at a finite temperature.

To have a partly field band configuration in a s/c, one must use one of these excitation mechanisms.

1 - Thermal Energy

Thermal energy at RTP = *k* x *T* = 1.38 x 10^{-23} J/K x 298 K = 25.7 meV

Excitation rate = *constant* x *exp(-Eg / kT)*

Although the thermal energy at room temperature is very small, *i.e.* 25 meV, a few electrons can be promoted to the CB.

Electrons can be promoted to the CB by means of thermal energy.

This is due to the exponential increase of excitation rate with increasing temperature.

Excitation rate is a strong function of temperature.

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2 - Electric Field

- For low fields, this mechanism doesn't promote electrons to the CB in common s/c's such as Si and GaAs.
- An electric field of 10^{18} V/m can provide an energy of the order of 1 eV. This field is enormous.

So , the use of the electric field as an excitation mechanism is not useful way to promote electrons in s/c's.

3- Electromagnetic Radiation

$$E = h\nu = h\frac{c}{\lambda} = (6.62x10^{-34}J-s)x(3x10^{8}m/s)/\lambda(m) \Rightarrow E(eV) = \frac{1.24}{\lambda\,(\text{in }\mu m)}$$

h = 6.62 x 10^{-34} Js
c = 3x10^{8} m/s
1 eV=1.6x10^{-19} J

Near infrared

$$for \quad \text{Silicon} \quad E_g = 1.1eV \qquad \lambda(\mu m) = \frac{1.24}{1.1} = 1.1\mu m\text{n}$$

To promote electrons from VB to CB Silicon , the wavelength of the photons must 1.1 μm or less

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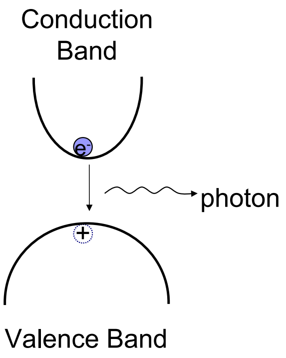
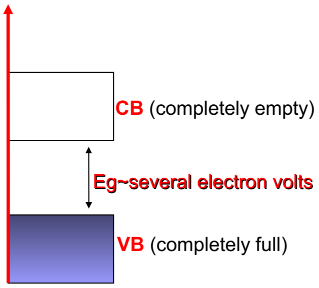
Direct Band-Gap



- The converse transition can also happen.
- An electron in CB recombines with a hole in VB and generate a photon.
- The energy of the photon will be in the order of Eg.
- If this happens in a direct band-gap s/c, it forms the basis of LED's and LASERS.

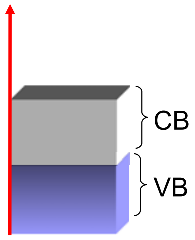
Insulators

- The magnitude of the band gap determines the differences between insulators, s/c's and metals.
- The excitation mechanism of thermal is not a useful way to promote an electron to CB even the melting temperature is reached in an insulator.
- Even very high electric fields is also unable to promote electrons across the band gap in an insulator.

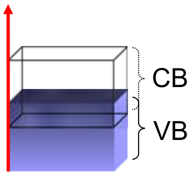


Wide band gaps between VB and CB

Metals



Touching VB and CB



Overlapping VB and CB

- These two bands looks like as if partly filled bands and it is known that partly filled bands conducts well.
- This is the reason why metals have high conductivity.

- No gap between ***valance band*** and ***conduction band***

The Concept of Effective Mass

Comparing

Free e⁻ in vacuum

In an electric field
↓
$m_o = 9.1 \times 10^{-31}$
↓
Free electron mass

An e⁻ in a crystal

In an electric field
↓
In a crystal
↓
m = ?
↓
m^* → effective mass

- If the same magnitude of electric field is applied to both electrons in vacuum and inside the crystal, the electrons will accelerate at a different rate from each other due to the existence of different potentials inside the crystal.
- The electron inside the crystal has to try to make its own way.
- So the electrons inside the crystal will have a different mass than that of the electron in vacuum.
- This altered mass is called as an ***effective-mass***.

What is the expression for m^*

- Particles of electrons and holes behave as a wave under certain conditions. So one has to consider the *de Broglie* wavelength to link partical behaviour with wave behaviour.
- Particles such as electrons and waves can be diffracted from the crystal just as X-rays .
- Certain electron momentum is not allowed by the crystal lattice. This is the origin of the energy band gaps.

$$n\lambda = 2d\sin\theta$$

n = the order of the diffraction
λ = the wavelength of the X-ray
d = the distance between planes
θ = the incident angle of the X-ray beam

$$n\lambda = 2d \qquad (1)$$

The waves are standing waves

$$\lambda = \frac{2\pi}{k}$$

k is the propagation constant

The momentum is

$$P = \hbar k \qquad (2)$$

The energy of the free electron can be related to its momentum

$$E = \frac{P^2}{2m} \qquad P = \frac{h}{\lambda}$$

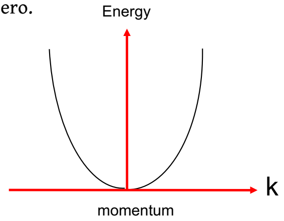
$2m$: free e⁻ mass , m_0

$$E = \frac{h^2}{2m}\frac{1}{\lambda^2} = \frac{h^2}{2m}\frac{k^2}{(2\pi)^2}$$

$$\hbar = \frac{h}{2\pi} \quad E = \frac{\hbar^2 k^2}{2m}$$

The energy of the free e⁻ is related to the k

By means of equations (1) and (2) certain e⁻ momenta are not allowed by the crystal. The velocity of the electron at these momentum values is zero.



E versus k diagram is a parabola.

Energy is continuous with k, i,e, all energy (momentum) values are allowed.

E versus k diagram
or
Energy versus momentum diagrams

To find effective mass , m^*

We will take the derivative of ***energy*** with respect to ***k*** ;

$$\frac{dE}{dk} = \frac{\hbar^2 k}{m}$$

$$\frac{d^2E}{dk^2} = \frac{\hbar^2}{m}$$

- ***m**** is determined by the curvature of the E-k curve
- ***m**** is inversely proportional to the curvature

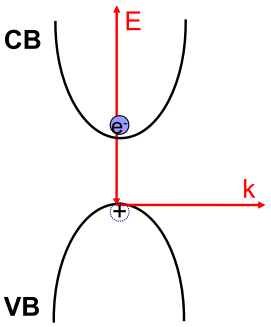
Change ***m**** instead of ***m***

$$m^* = \frac{\hbar^2}{d^2E/dk^2}$$

This formula is the ***effective mass*** of an electron inside the crystal.

Direct-band gap materials

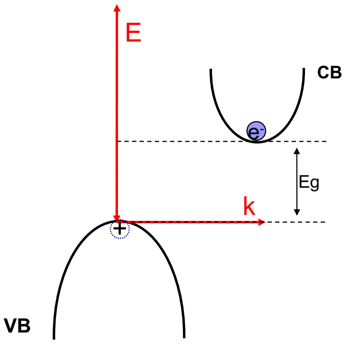
Direct-band gap s/c's (e.g. GaAs, InP, AlGaAs)



- For a ***direct-band gap material***, the minimum of the conduction band and maximum of the valence band lies at the same momentum, k, values.
- When an electron sitting at the bottom of the CB recombines with a hole sitting at the top of the VB, there will be no change in momentum values.
- Energy is conserved by means of emitting a photon, such transitions are called as radiative transitions.

Indirect-band gap materials

Indirect-band gap s/c's (e.g. Si and Ge)



- For an indirect-band gap material; the minimum of the CB and maximum of the VB lie at different k-values.
- When an e⁻ and hole recombine in an indirect-band gap s/c, phonons must be involved to conserve momentum.

Phonon

- Atoms vibrate about their mean position at a finite temperature.These vibrations produce vibrational waves inside the crystal.
- Phonons are the quanta of these vibrational waves. Phonons travel with a velocity of sound .
- Their wavelength is determined by the crystal lattice constant. Phonons can only exist inside the crystal.

Conclusion

- The transition that involves phonons without producing photons are called *non-radiative (radiationless) transitions*.
- These transitions are observed in an *indirect band gap* s/c and result in inefficient photon producing.
- So in order to have efficient LED's and LASER's, one should choose materials having direct band gaps such as compound s/c's of GaAs, AlGaAs, etc...

Calculation

- *For GaAs, calculate a typical (band gap) photon energy and momentum , and compare this with a typical phonon energy and momentum that might be expected with this material.*

photon

E(photon) = Eg(GaAs) = 1.43 ev

E(photon) = h υ= hc / λ

c= 3x10^8 m/sec

P = h / λ h=6.63x10^{-34} J-sec

λ (photon)= 1.24 / 1.43 = 0.88 μm

P(photon) = h / λ = 7.53 x 10^{-28} kg-m/sec

phonon

E(phonon) = h υ= hv_s / λ = hv_s / a_0

λ (phonon) ~a_0 = lattice constant =5.65x10^{-10} m

V_s= 5x10^3 m/sec (velocity of sound)

E(phonon) = hv_s / a_0 =0.037 eV

P(phonon)= h / λ = h / a_0 = 1.17x10^{-24} kg-m/sec

Phonons vs Photons

- Photon energy = 1.43 eV
- Phonon energy = 37 meV
- Photon momentum = 7.53 x 10^{-28} kg-m/sec
- Phonon momentum = 1.17 x 10^{-24} kg-m/sec

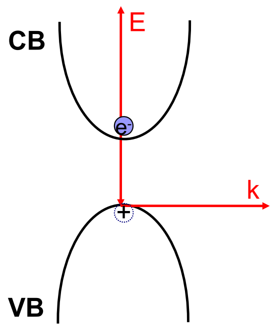
Photons carry large energies but negligible amount of momentum.

On the other hand, phonons carry very little energy but significant amount of momentum.

Positive and Negative effective mass

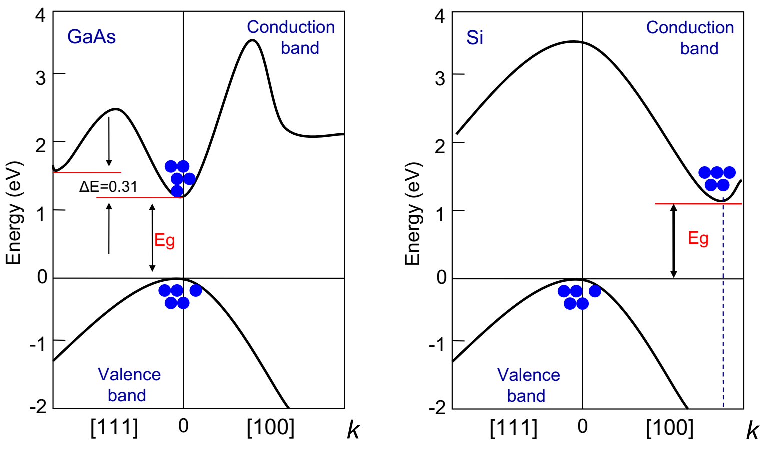
Direct-band gap s/c's (e.g. GaAs, InP, AlGaAs)

$$m^* = \frac{h^2}{d^2E/dk^2}$$

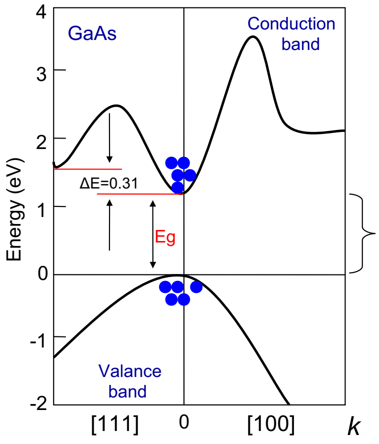


- The sign of the effective mass is determined directly from the sign of the curvature of the E-k curve.
- The curvature of a graph at a minimum point is a positive quantity and the curvature of a graph at a maximum point is a negative quantity.
- Particles(electrons) sitting near the minimum have a ***positive effective mass***.
- Particles(holes) sitting near the valence band maximum have a ***negative effective mass***.
- A negative effective mass implies that a particle will go ***'the wrong way'*** when an extrernal force is applied.

Energy band structures of **GaAs** and **Si**



Energy band structure of **GaAs**



Band gap is the smallest energy separation between the valence and conduction band edges.

The smallest energy difference occurs at the same momentum value

⇩

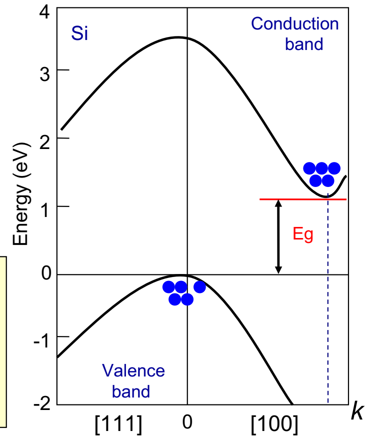
Direct-band gap semiconductor

Energy band structure of *Si*

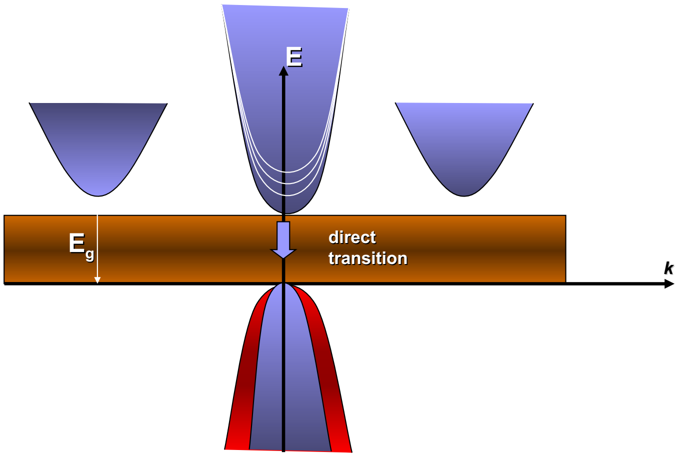
The smallest energy gap is between the top of the VB at k=0 and one of the CB minima away from k=0

Indirect band gap semiconductor

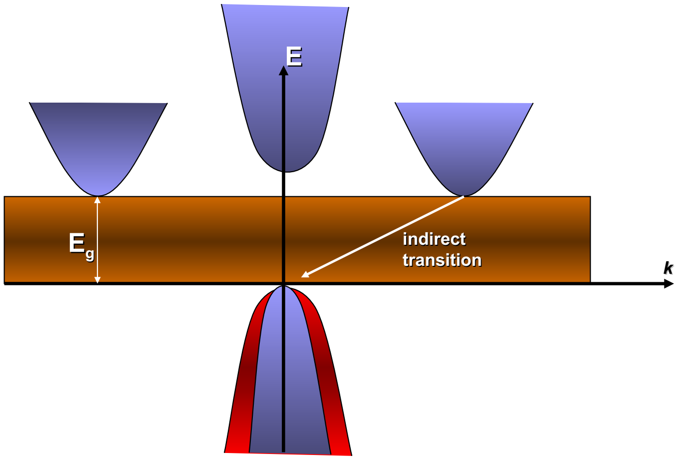
- •Band structure of AlGaAs?
- •Effective masses of CB satellites?
- •Heavy- and light-hole masses in VB?



Direct transition



Indirect transition



Slide Set 2

Carrier Concentration in Semiconductors

CARRIER CONCENTRATIONS IN SEMICONDUCTORS

Donors and Acceptors

Fermi level , E_f

Carrier concentration equations

Donors and acceptors both present

Donors and Acceptors

The conductivity of a pure (intrinsic) s/c is low due to the low number of free carriers.

- The number of carriers are generated by thermally or electromagnetic radiation for a pure s/c.

- For an intrinsic semiconductor

$$n = p = n_i$$

n = concentration of electrons per unit volume
p = concentration of holes per unit volume
n_i = the intrinsic carrier concentration of the semiconductor under consideration.

$n.p = n_i^2$

n = p

number of e^-'s in CB = number of holes in VB

- This is due to the fact that when an e^- makes a transition to the CB, it leaves a hole behind in VB. We have a bipolar (two carrier) conduction and the number of holes and e^-'s are equal.

$$n.p = n_i^2$$

This equation is known as **mass-action law.**

$n.p = n_i^2$

The intrinsic carrier concentration n_i depends on; the semiconductor material, and the temperature.

- For silicon at 300 K, n_i has a value of 1.4×10^{10} cm^{-3}.
- Clearly , equation ($n = p = n_i$) can be written as

$$n.p = n_i^2$$

- This equation is valid for **extrinsic** as well as **intrinsic** material.

What are doping and dopants impurities ?

To increase the conductivity, one can dope pure s/c with atoms from column lll or V of periodic table. This process is called as doping and the added atoms are called as dopants impurities.

There are two types of doped or extrinsic s/c's;

- n-type
- p-type

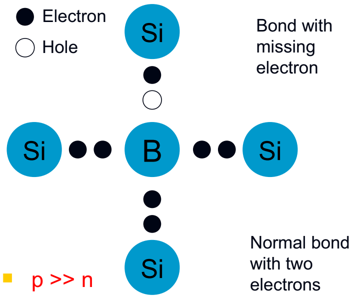
Addition of different atoms modify the conductivity of the intrinsic semiconductor.

P-type doped semiconductor

- Si + Column III impurity atoms

Have four valence electrons

Boron (B) has three valence electrons



- Boron bonding in Silicon
- Boron sits on a lattice side
- p >> n

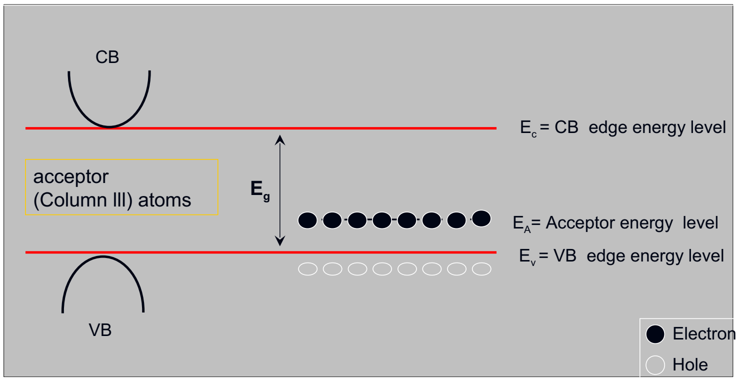
P-type doped semiconductor

Boron (column III) atoms have three valence electrons, there is a deficiency of electron or missing electron to complete the outer shell.

This means that each added or doped Boron atom introduces a single hole in the crystal.

- There are two ways of producing holes
  1) Promote electrons from VB to CB,
  2) Add column lll impurities to the s/c.

Energy Diagram for a P-type s/c



The energy gap is forbidden only for pure material, i.e. Intrinsic material.

P-type semiconductor

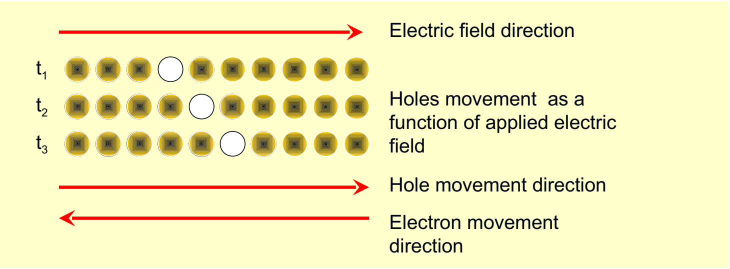
- ***The impurity atoms from column lll occupy at an energy level within E_g These levels can be:***

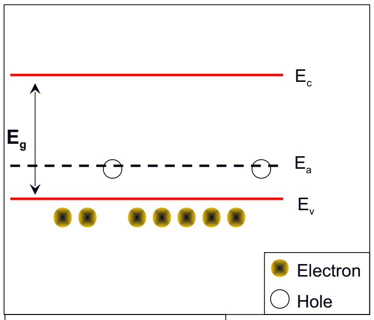
1. Shallow levels which is close to the band edge,
2. Deep levels which lies almost at the mid of the band gap.

- If the E_A level is shallow i.e. close to the VB edge, each added boron atom accepts an e^- from VB and have a full configuration of e^-'s at the outer shell.
- These atoms are called as acceptor atoms since they accept an e^- from VB to complete its bonding. So each acceptor atom gives rise a hole in VB.
- The current is mostly due to holes since the number of holes are made greater than e^-'s.

Majority & Minority carrier in a P-type semiconductor

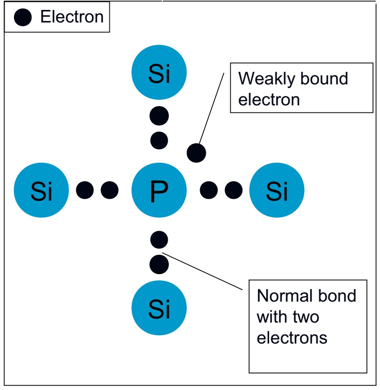
Holes = p = majority carriers
Electrons = n = minority carriers

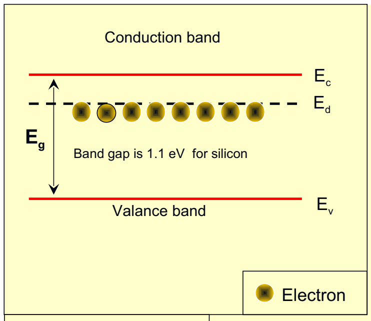




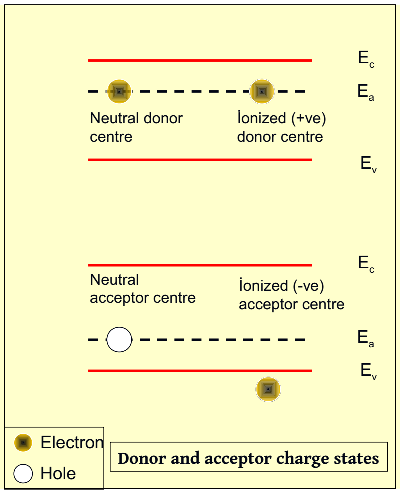
Shallow acceptor in silicon

Phosporus bonding in silicon



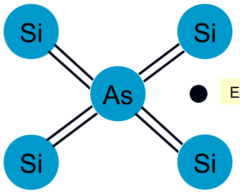


Shallow donor in silicon



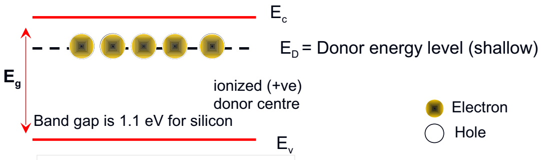
Donor and acceptor charge states

N-type doped semiconductor



Extra e^- of column V atom is weakly attached to its host atom

Si + column V (with five valance e^-)



n - type semiconductor

Np vs. Pn semiconductors

n-type , $n >> p$; n is the majority carrier concentration n_n

p is the minority carrier concentration p_n

p-type , $p >> n$; p is the majority carrier concentration p_p

n is the minority carrier concentration n_p

n_p p_n

Type of semiconductor

Calculation

Calculate the hole and electron densities in a piece of P-type silicon that has been doped with 5 x 10^{16} acceptor atoms per cm^3.

n_i = 1.4 x 10^{10} cm^{-3} (at room temperature)

Undoped

$n = p = n_i$

P-type ; p >> n

$n.p = n_i^2$ $\quad N_A = 5 \times 10^{16}$ $\quad p = N_A = 5 \times 10^{16}\ cm^{-3}$

$$n = \frac{n_i^2}{p} = \frac{(1.4x10^{10} cm^{-3})^2}{5x10^{16} cm^{-3}} = 3.9x10^3 \quad \text{electrons per cm}^3$$

p >> n_i and n << n_i in a p-type material. The more holes you put in the less electrons you have and vice versa.

Fermi level , E_F

This is a reference energy level at which the probability of occupation by an electron is ½.

Since E_f is a reference level therefore it can appear anywhere in the energy level diagram of a S/C .

Fermi energy level is not fixed.

Occupation probability of an electron and hole can be determined by Fermi-Dirac distribution function, F_{FD} ;

$$F_{FD} = \frac{1}{1 + \exp(\frac{E - E_F}{k_B T})}$$

E_F = Fermi energy level

k_B = Boltzman constant

T = Temperature

Fermi level , E_F

$$F_{FD} = \frac{1}{1 + \exp(\frac{E - E_F}{k_B T})}$$

E is the energy level under investigation.

F_{FD} determines the probability of the energy level E being occupied by electron.

$$if\ E = E_F \longrightarrow f_{FD} = \frac{1}{1 + \exp 0} = \frac{1}{2}$$

$1 - f_{FD}$ determines the probability of not finding an electron at an energy level E; the probability of finding a hole .

Carrier concentration equations

The number density, i.e., the number of electrons available for conduction in CB is

$$n = 2\left(\frac{2\pi\, m_n^* kT}{h^2}\right)^{3/2} \exp - (\frac{E_C - E_F}{kT})$$

$$n = N_C \exp - (\frac{E_C - E_F}{kT}) \qquad n = n_i \exp(\frac{E_F - E_i}{kT})$$

The number density, i.e., the number of holes available for conduction in VB is

$$p = 2\left(\frac{2\pi\, m_p^* kT}{h^2}\right)^{3/2} \exp - (\frac{E_F - E_V}{kT})$$

$$p = N_V \exp - (\frac{E_F - E_V}{kT}) \qquad p = n_i \exp(\frac{E_i - E_F}{kT})$$

Donors and acceptors both present

Both donors and acceptors present in a s/c in general. However one will outnumber the other one.

In an n-type material the number of donor concentration is significantly greater than that of the acceptor concentration.

Similarly, in a p-type material the number of acceptor concentration is significantly greater than that of the donor concentration.

A p-type material can be converted to an n-type material or vice versa by means of adding proper type of dopant atoms. This is in fact how p-n junction diodes are actually fabricated.

Example

- How does the position of the Fermi Level change with

(a) increasing donor concentration, and

(b) increasing acceptor concentration ?

(a) We shall use equation

$$n = N_C \exp - (\frac{E_C - E_F}{kT})$$

If n is increasing then the quantity E_C-E_F must be decreasing i.e. as the donor concentration goes up the Fermi level moves towards the conduction band edge E_C.

Example

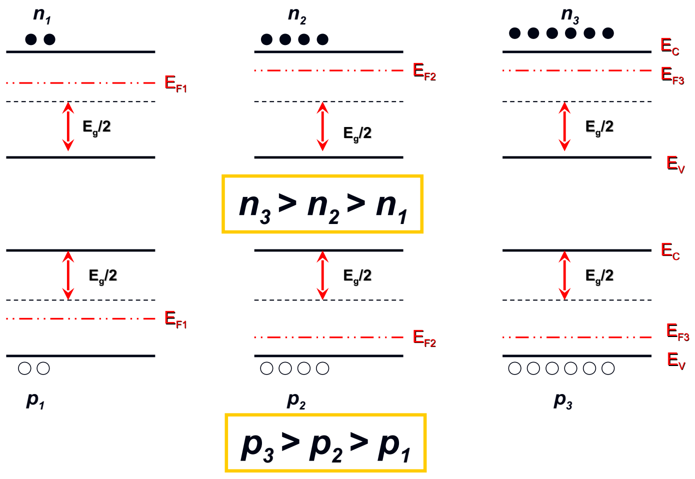
But the carrier density equations such as;

$$n = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{\frac{3}{2}} \exp-\left(\frac{E_c - E_F}{kT}\right) \quad and$$

$$p = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

aren't valid for all doping concentrations! As the fermi-level comes to within about **3kT** of either band edge the equations are no longer valid, because they were derived by assuming the simpler **Maxwell Boltzmann statistics** rather than the proper Fermi-Dirac statistic.

Example



$n_3 > n_2 > n_1$

$p_3 > p_2 > p_1$

Example

(b) Considering the density of holes in valence band;

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

It is seen that as the acceptor concentration increases, Fermi-level moves towards the *valance band edge.* These results will be used in the construction of device (energy) band diagrams.

Donors and acceptor both present

- In general, both donors and acceptors are present in a piece of a semiconductor although one will outnumber the other one.
- The impurities are incorporated unintentionally during the growth of the semiconductor crystal causing both types of impurities being present in a piece of a semiconductor.
- How do we handle such a piece of s/c?

1) Assume that the shallow donor concentration is significantly greater than that of the shallow acceptor concentration. In this case the material behaves as an n-type material and

$$n_n = N_D - N_A$$

2) Similarly, when the number of shallow acceptor concentration is signicantly greater than the shallow donor concentration in a piece of a s/c, it can be considered as a p-type s/c and

$$p_p = N_A - N_D$$

Donors and acceptor both present

For the case **N_A>N_D , i.e.** for p-type material

$$n_p . p_p = n_i^2$$

$$n_p + N_A^- = N_D^+ + p_P \Rightarrow p_p + N_D - n_p - N_A = 0$$

$$p_p \times \left[p_p + N_D - \frac{n_i^2}{p_p} - N_A = 0 \right] \Rightarrow \boxed{p_p^2 + (N_D - N_A)p_p - n_i^2 = 0}$$

Donors and acceptor both present

$$\boxed{p_p^2 + (N_D - N_A)p_p - n_i^2 = 0}, \text{ solving for } p_p \,;\, x_{1,2} = \frac{-b \mp \sqrt{b^2 - 4ac}}{2a}$$

$$p_p = \frac{1}{2}\left\{ N_A - N_D + \left[(N_A - N_D)^2 + 4n_i^2 \right]^{1/2} \right\}$$

majority

$$n_p = \frac{n_i^2}{p_p}$$

minority

Donors and acceptor both present

For the case **$N_D > N_A$, i.e. n-type material**

$$n_n . p_n = n_i^2 \Rightarrow p_n = \frac{n_i^2}{n_n}$$

$$n_n + N_A = N_D + P_n \quad \Rightarrow n_n + N_A - p_n - N_D = 0$$

$$n_n \times \left[n_n + N_A - \frac{n_i^2}{n_n} - N_D = 0 \right] \Rightarrow n_n^2 + (N_A - N_D) n_n - n_i^2 = 0$$

$$\text{solving for } \mathrm{n}_n \text{ ; } x_{1,2} = \frac{-b \mp \sqrt{b^2 - 4ac}}{2a}$$

$$n_n = \frac{1}{2}\left(N_D - N_A + \left[(N_D - N_A)^2 + 4 n_i^2 \right]^{1/2} \right)$$

$$p_n = \frac{n_i^2}{n_n}$$