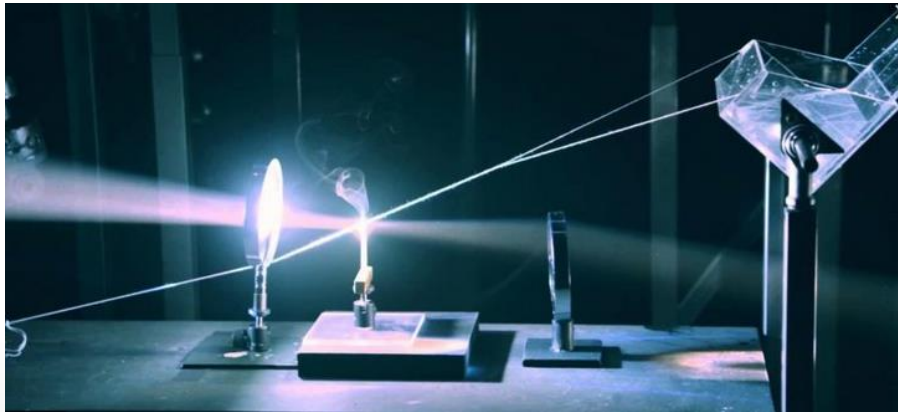


Engineering Physics (PHY109)



Course overview

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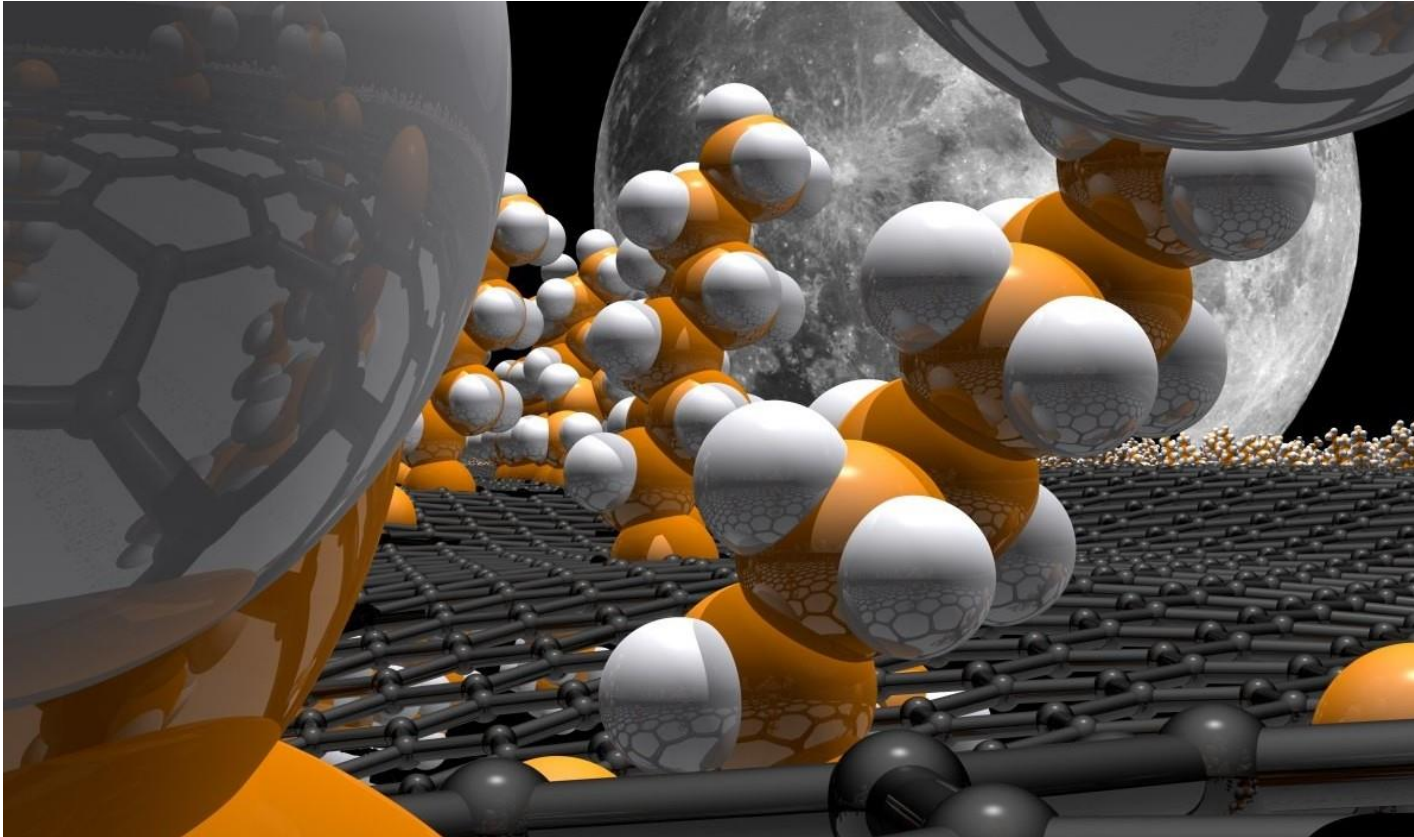
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Credits:4

- Unit 1: Electromagnetic theory
- Unit 2: Lasers and applications
- Unit 3: Fiber optics
- Unit 4: Quantum mechanics
- Unit 5: Waves
- Unit 6: Solid state physics

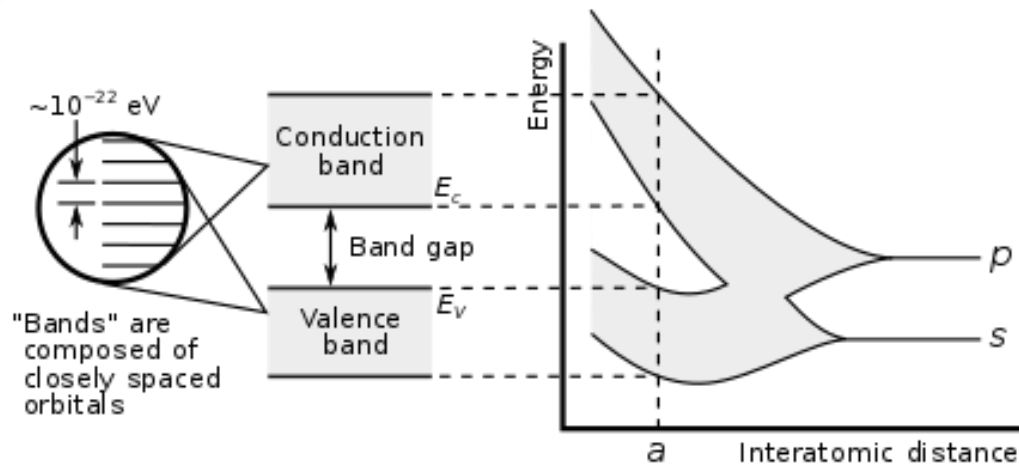
Unit-6: Solid state physics



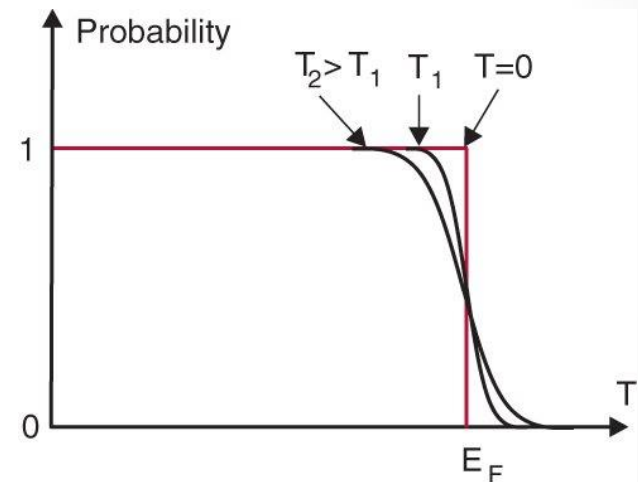
Unit-6: Solid state physics

- Free electron theory (Introduction)
- Diffusion and drift current (qualitative)
- Fermi energy
- Fermi-dirac distribution function
- Band theory of solids (formation of allowed and forbidden energy bands)
- Concept of effective mass - electrons and holes
- Hall effect
- Semiconductors and insulators
- Fermi level for intrinsic and extrinsic semiconductors
- Direct and indirect band gap semiconductors

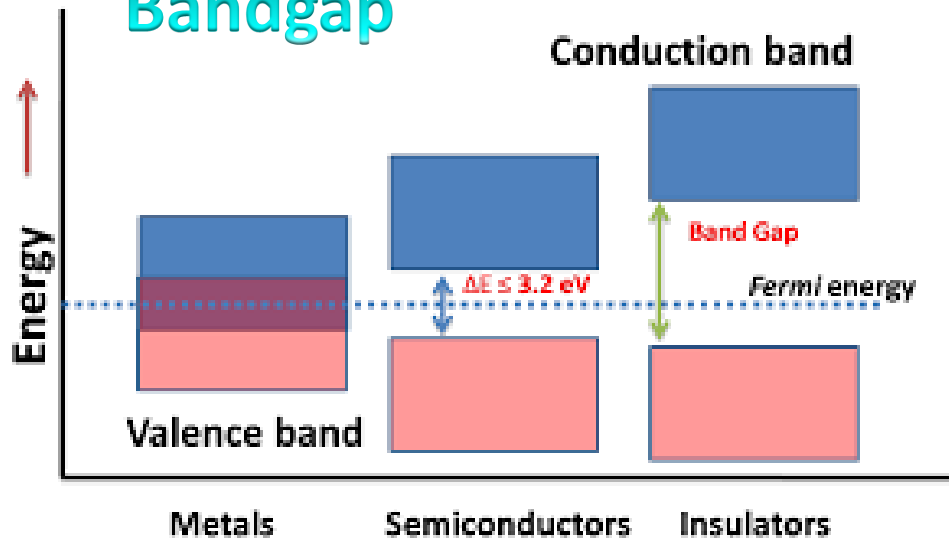
Band theory



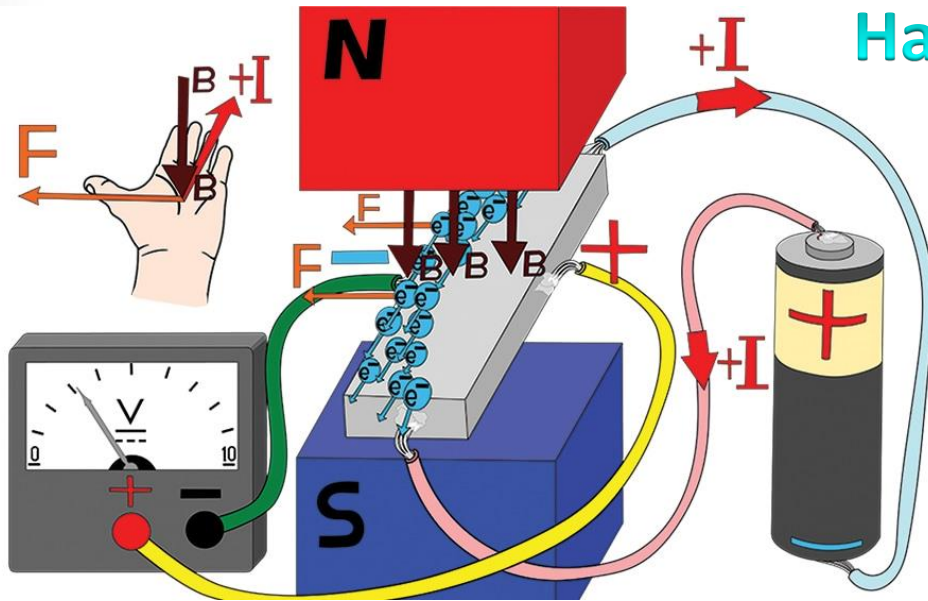
Fermi energy



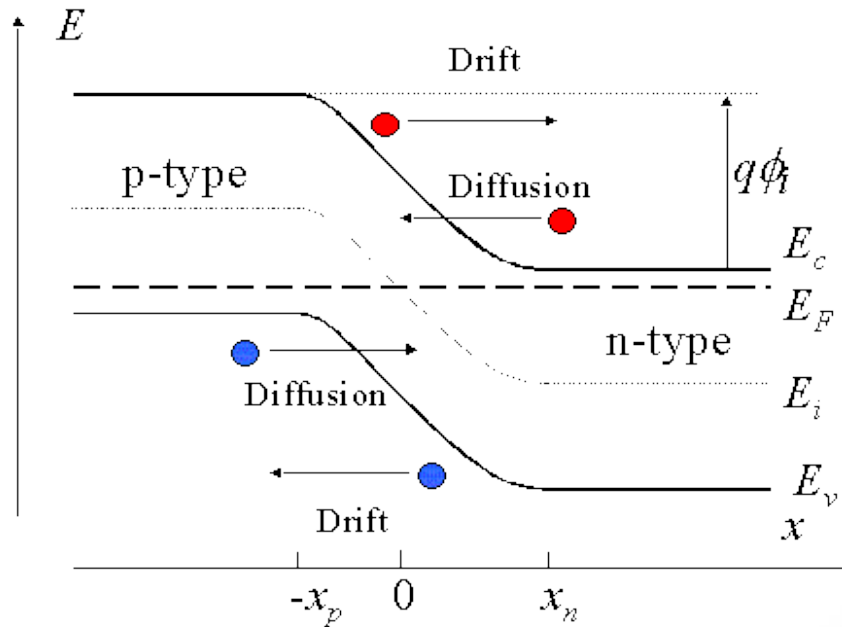
Bandgap



Hall effect



Drift current & diffusion current



Solid state devices...



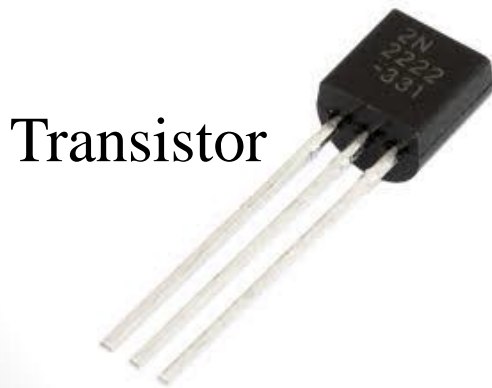
Diode



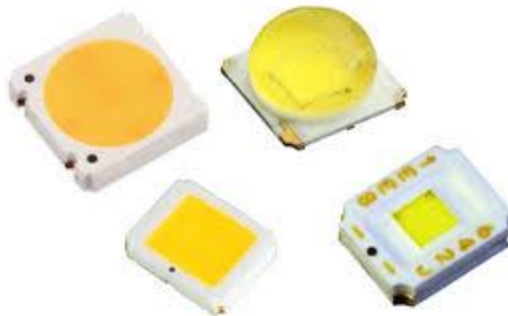
Solar Cell



Photodiode



Transistor



LEDs



Amplifier

CO6: understand physics of various solid state operating/functional devices

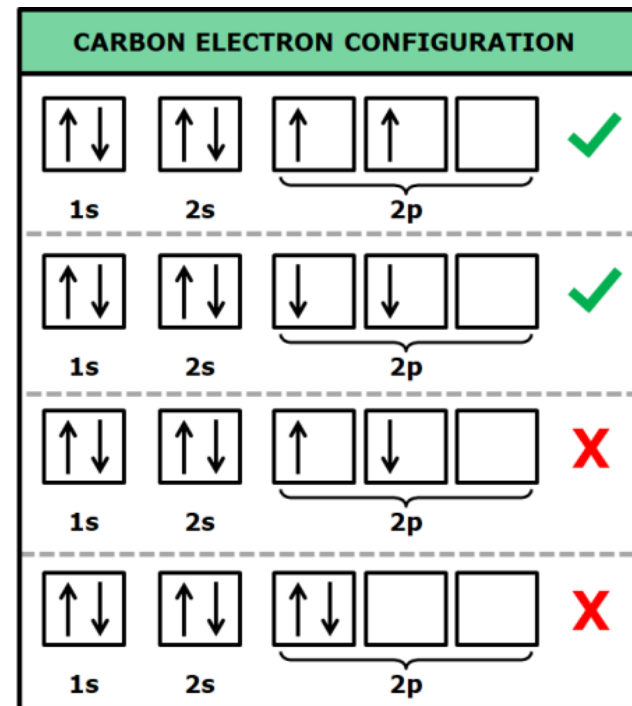
Unit-6: Solid state physics

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Hund's rule and Pauli's exclusion principle

Quantum numbers

- Principle QN: n (size and energy of levels)
- Angular momentum QN: l (shape of the orbital)
- Magnetic QN: m_l (orientation of orbitals)
- Electron spin: m_s (spin)



Background

- QM helped us to understand single particle (electron) in terms of the position and energy
- But any functional device (metal or semiconductor) have large number of particles (electrons/holes) to get operational
- Use of statistical model/theory to understand the behavior of large number of electrons in a device

Free electron theory

Model of free electron gas (theory) was first of its kind to study electrons in solid

According to which,

- Say, Electronic configuration: Cu^{29} ($1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^{10}, 4s^1$)
- Outermost electron ($4s^1$) assumed to behave as a free electron
- The movement of this free electron is assumed to be independent of details of the 'nuclei' and all the other core electrons in the metal
- These free electrons are known as conduction electrons since they are the responsible for electrical conduction in metals

Free electron theory

- The first version of free electron model was introduced by Drude in the early 1900s, with improvement soon after by H A Lorentz
- This theory is known as Drude-Lorentz free electron theory of metals
- Other theories: Sommerfeld's free electron theory and Zone theory

Drude-Lorentz theory

- According to Drude, metals must have two types of particles as against only one type in the simplest gases
- Later on, discovery of negatively charged electrons, made it mandatory to accept the existence of its counter particle (who has positive charge) to fulfill the condition of charge neutrality
- In this model, it is assumed that, when more than two metal atoms come together, their valence electrons get liberated and move freely within the metal
- The remainder of the atom is a positive ion (as heavy and immobile) carrying the major portion of the atomic mass

Drude-Lorentz theory

- When a metal is subjected to an external electric field, the free electrons (conduction electrons) moves in the background of these immobile positive ions (nuclei)
- The movement of electrons obeys the classical kinetic theory of gases
- This theory explained a number of properties of metal, e.g., electrical conductivity, thermal conductivity and opacity of metals

Lorentz contribution

- Lorentz in 1909, applied Maxwell-Boltzmann statistics to the electron gas with two assumptions:

$$f(E) = \frac{1}{Ae^{E/kT}}$$

Maxwell-Boltzmann

Normalization

Boltzmann

1. The mutual repulsion between the negatively charged electrons is negligible
2. Constant potential field due to positive ions within the crystal

Drawbacks of theory

- Theory correctly predicted the room temperature resistivity of metals but the temperature dependence of resistivity could not be established accurately
- The theory predicted that the resistivity varies as $T^{1/2}$ whereas actually it is found to vary linearly
- The theory cannot find magnitudes of specific heat and paramagnetic susceptibility of metals
- Unable to explain the concept of mean-free path at low temperatures

How we overcame?

- Sommerfeld in 1928, applied Fermi-Dirac statistic (instead of MB), and treated the problem quantum mechanically.

The probability that a particle will have energy E

At absolute zero, fermions will fill up all available energy states below a level E_F called the Fermi energy with one (and only one) particle. They are constrained by the Pauli exclusion principle. At higher temperatures, some are elevated to levels above the Fermi level.

$$f(E) = \frac{1}{e^{(E - E_F)/kT} + 1}$$

Fermi-Dirac

See the Maxwell-Boltzmann distribution for a general discussion of the exponential term.

For low temperatures, those energy states below the Fermi energy E_F have a probability of essentially 1, and those above the Fermi energy essentially zero.

The quantum difference which arises from the fact that the particles are indistinguishable.

Fermi energy

- Consider that N free electrons are contained in a box at absolute zero temperature
- At absolute zero all the energy levels below a certain level will be filled with electrons and the levels above this level will be empty
- The energy level which divides the filled and empty levels is called 'Fermi level' and the corresponding energy of that level is called 'Fermi energy' E_F

Fermi Dirac distribution

- The **Fermi-Dirac distribution** applies to fermions, particles with half-integer spin which must obey the Pauli exclusion principle
- According to FD distribution law, the most probable distribution is given by,

The probability that a particle will have energy E

$$f(E) = \frac{1}{e^{(E - E_F)/kT} + 1}$$

Fermi-Dirac

At absolute zero, fermions will fill up all available energy states below a level E_F called the Fermi energy with one (and only one) particle. They are constrained by the Pauli exclusion principle. At higher temperatures, some are elevated to levels above the Fermi level.

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The quantum difference which arises from the fact that the particles are indistinguishable.

Fermi Dirac distribution

$$f(E) = \frac{1}{e^{(E - E_F)/kT} + 1}$$

Fermi-Dirac

- At absolute zero ($T=0$),

$$E - E_F / kT = -\infty \quad \text{for } (E < E_F)$$

$$E - E_F / kT = +\infty \quad \text{for } (E > E_F)$$

Hence FD function will be,

$$f(E) = 1 \quad \text{for } (E < E_F)$$

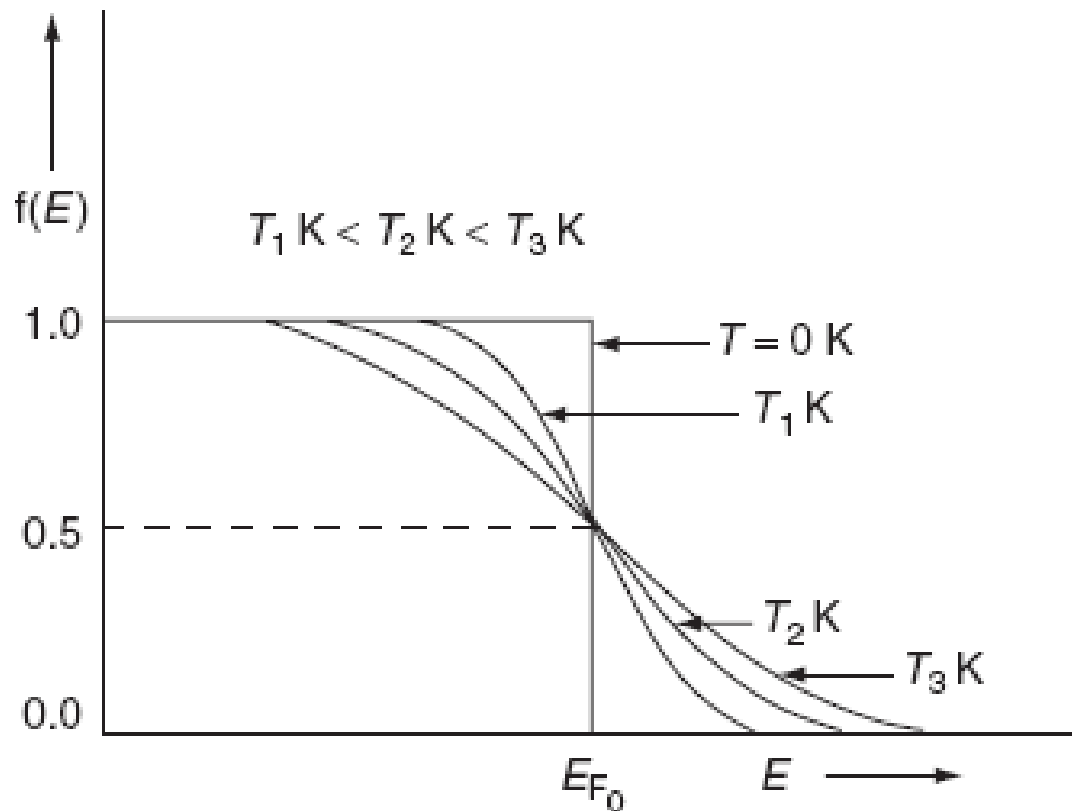
$$f(E) = 0 \quad \text{for } (E > E_F)$$

- At any temperature (T) and for $E = E_F$

$$f(E) = \frac{1}{2}$$

Fermi level is defined as the energy level at which the probability of finding an electron is $\frac{1}{2}$.

Fermi Dirac distribution



Density of states

- The number of energy states per unit energy range, $D(E)$
- In other words, the 'density of states' for electrons in a band gives the number of orbitals (states) in a certain energy range
- Hence the number of filled states having the energy in the range E and $E+dE$ is,

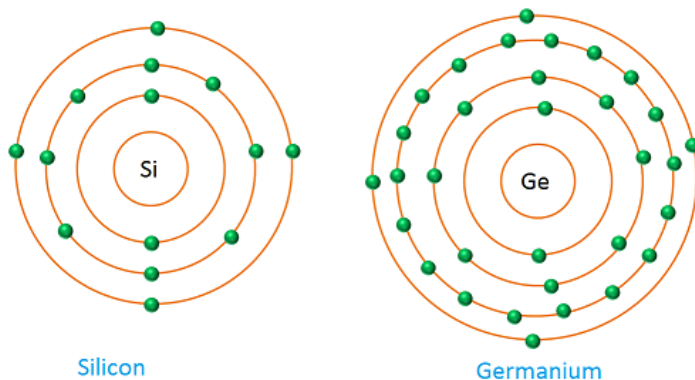
$$N dE = D(E) f(E) dE$$

Band theory of solids

- In solids, there are enormous number of atoms (N) closely packed together
- When these N number of atoms are well separated, they can possess N -degenerate levels (energy) of the solid
- As these atoms approach one another (to form solid), separation decreases, hence internal interactions increase

Band theory of solids

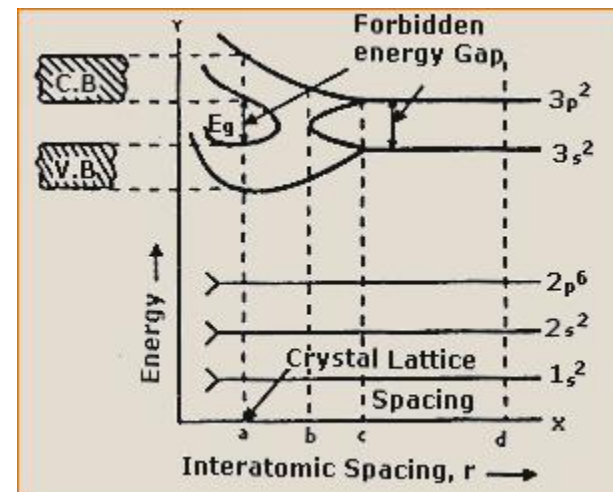
- This causes each of the levels to split into N distinct levels
- For larger number of atoms ($N \sim 10^{23}$), as the distance decreases, the splitting becomes numerous and closely spaced, forming a kind of continuous energy band



Silicon

Germanium

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Different energy levels will split differently

- Lower energy levels are found to spread/split less than a higher energy levels
- This means lowest energy levels are almost unsplit. Because the inner most orbit (Lowest energy/inner subshells) will not interact/least probable to interact with nearby atoms
- Having lowest energy, these electrons feel higher potential barrier and hence behave like a localized electron (for that atom)
- Least influenced by neighboring atoms

Higher energy electrons

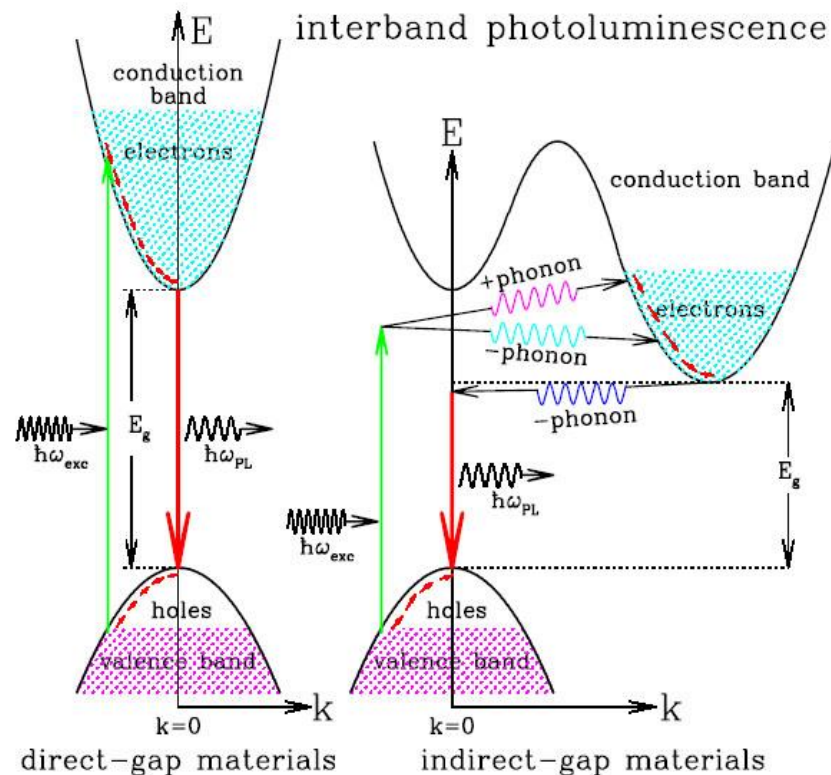
- However, electrons in the higher energy levels are the valence electrons and are not localized for smaller interatomic distance (r). They behave like a part of whole system (move freely in crystal)
- The allowed band corresponding to inner subshells are extremely narrow
- On the other bands become progressively wider for the outer occupied subshells

Bandgap

- Energy bands in solid correspond to energy levels in an atom
- Thus, an electron in a solid can occupy only energy that falls within these energy bands
- The overlapping of the bands depends on the structure of the solid
- If the bands do not overlap, then the interval between them represents energies which the electrons in the solid cannot occupy (these intervals are called forbidden bands/energy gap/bandgap)

Direct indirect semiconductors

- Direct bandgap semiconductors: GaAs, InAs, CdTe, CdSe, CdS, ZnO, ZnS
- Indirect bandgap semiconductors: Si, Ge, AlGaP, SiC, AlP



Semiconductors v/s insulators

- Based on energy gap and the conduction, the solids are classified into different categories named as insulators, semiconductors and conductors
- Metals: overlapped energy bands...free for conduction, lowest resistance
- Insulators: widest energy gap, >3 eV, not possible to excite electrons from VB to jump into CB, most resistive

Holes in semiconductors

- Energy gap (in semiconductors) intermediate of conductors and insulators
- Electrons can be excited to CB from VB via photo excitation, intraband-assisted thermal excitation
- Once electron leaves the VB, absence of electron is called hole (positive charge), also can contribute to conduction mechanism by moving in VB (in the opposite direction to the movement of electrons)

Types of semiconductors

- **Based on doping:**
 - Intrinsic (without doping, e-h generation only by thermal excitation, produces equal number of e/h in semiconductor) intrinsic conductivity
 - Extrinsic (with doping, n/p-type)
- **Based on conductivity:**
 - n-type: number of electrons > holes
 - p-type: number of holes > electrons

Majority charge carrier: n-type: electrons
p-type: holes

n-type and p-type semiconductors

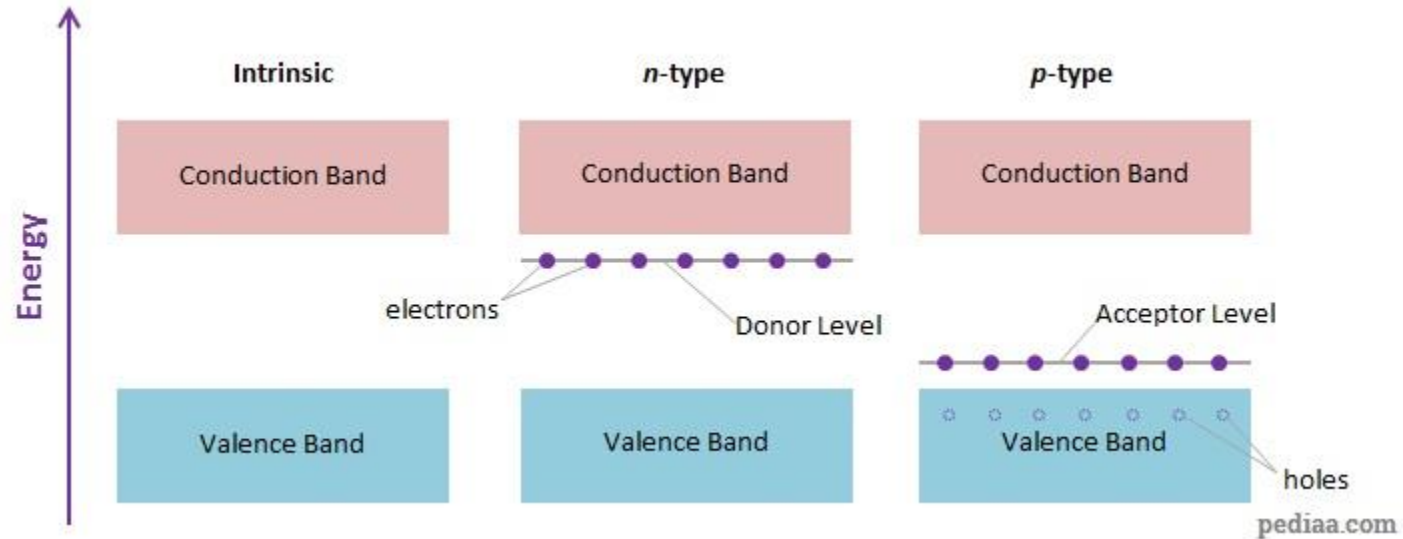
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Trivalent

Pentavalent

I A		II A		Group IUPAC		Group cas		Nonmetals		Metals		IV A		V A		VI A		VII A		VIII A		IX A		X A		XI A		XII A	
3	4			1									5	6	7	8	9	10											
Li 1.941 Lithium	Be 9.0122 Beryllium			K 39.098 Potassium									B 10.811 Boron	C 12.011 Carbon	N 14.007 Nitrogen	O 15.999 Oxygen	F 18.998 Fluorine	Ne 20.180 Neon											
				Atomic number		Symbol		Relativ atomic mass		Element name																			

Band diagrams

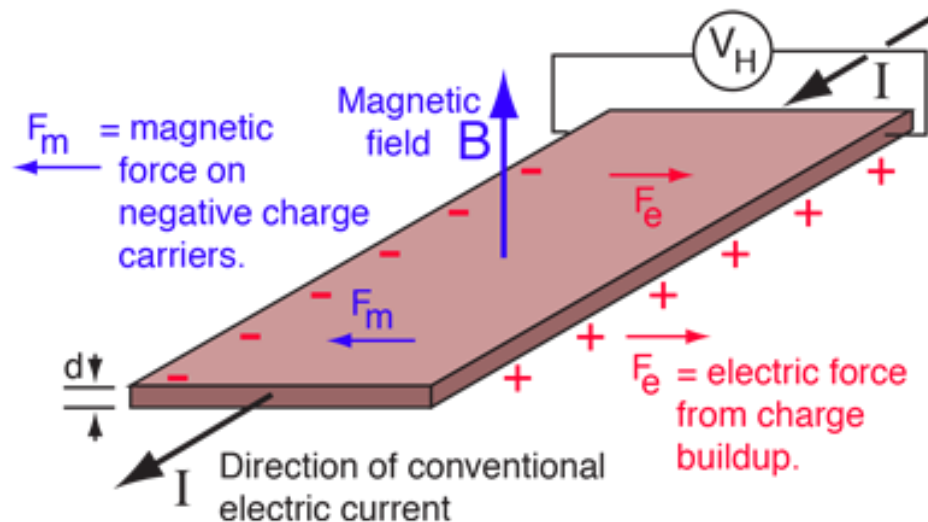


Drift diffusion current

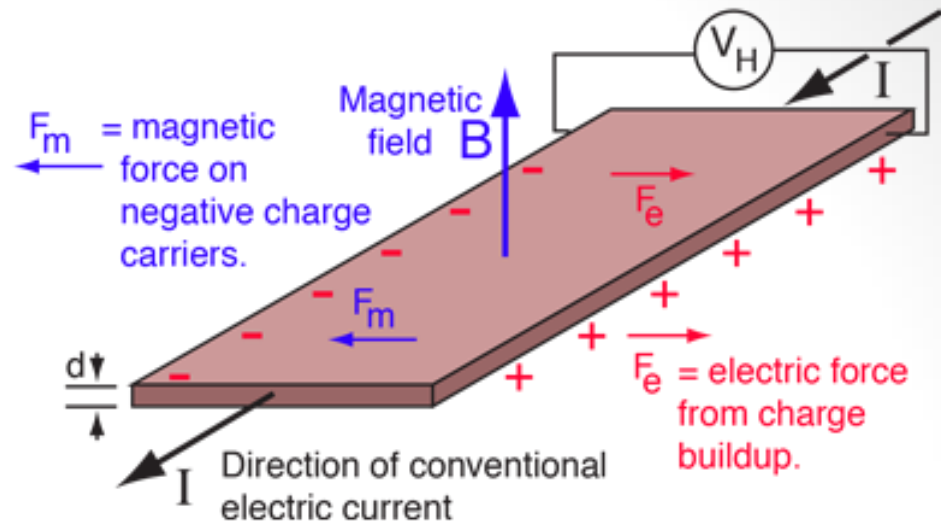
- p-n junction in equilibrium
- Band edge positions in equilibrium
- Movement of carries in no bias/equilibrium: due to concentration gradient: Diffusion current (FB)
- Generation of potential barrier
- Movement of carriers in applied bias: due to applied reverse bias: Drift current (RB)

Hall effect

Statement: When a current carrying conductor placed in a transverse magnetic field, a potential difference is developed across the conductor in the direction perpendicular to both current and magnetic field



Hall effect



The force on the charge carriers $= q\vec{E}_H$

The force on charge carriers due to magnetic field $B = q(\vec{v}_d \times \vec{B})$

At the stationary state both these forces balance each other. Hence

$$q\vec{E}_H = q(\vec{v}_d \times \vec{B}) \quad \text{or} \quad \vec{E}_H = \vec{v}_d \times \vec{B}$$

Thus by measuring E_H and B , the drift velocity v_d can be determined both in magnitude and direction. If we talk about magnitude only, then Eq. gives

$$E_H = v_d B \quad [\because v_d \text{ and } B \text{ are at right angle}]$$

The current density J in terms of the drift velocity v_d is written as

$$J = -nev_d \quad [n = \text{number of charge carriers per unit volume}]$$

From Eqs.

$$E_H = -\frac{JB}{ne}$$

Hall effect

The above relation shows that

$$E_H \propto B$$

If d be the width of the strip, then the transverse Hall electric field E_H can be related to the Hall potential difference V_H as

$$E_H = \frac{V_H}{d}$$

or

$$V_H = E_H d = -\frac{JBd}{ne}$$

V_H is also known as *Hall Voltage*.

The coefficient of proportionality $-\frac{1}{ne}$ is called *Hall coefficient* and is denoted by R_H . It is given below

$$R_H = -\frac{1}{ne}$$

Hall coefficient is negative if the charge carriers are electrons and it will be positive if the charge carriers are holes.

Applications of Hall effect

- Hall coefficient: $R_H = -1/ne$ (unit: m^3/C)
where, $n = i B / V_H e L$
- To determine sign of charge carrier
- To determine carrier concentration
- To measure the mobility of charge carriers
- To find the conductivity of a material

Effective mass

- Electrons in a crystal are not completely free but interact with the crystal lattice.
- As a result, their behavior towards external force is different from the free electron.
- This can be taken into consideration simply by considering the electron to have an altered value of mass, called the “effective mass” m^* .
- m^* depends on nature of crystal lattice and varies with the direction of the free electron in the lattice
- m^* can be $<$ or $>$ m (depending on the direction of the force/field)

Good luck