Electronic Devices & Circuits

For

Electronics & Communication Engineering

By

THE GATE ACADEMY

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Syllabus for Electronic Devices

Energy Bands in Intrinsic and Extrinsic Silicon, Carrier Transport, Diffusion Current, Drift Current, Mobility and Resistivity, Generation and Recombination of Carriers, Poisson and Continuity Equations, P-N Junction, Zener Diode, BJT, MOS Capacitor, MOSFET, LED, Photo Diode and Solar cell, Integrated Circuit Fabrication Process: Oxidation, Diffusion, ion Implantation, Photolithography and twin-tub CMOS Process.

Analysis of GATE Papers

Year	Percentage of marks	Overall Percentage
2015	10.00	8.4 %
2014	9.75	
2013	3.00	
2012	8.00	
2011	9.00	
2010	10.00	
2009	8.00	
2008	7.00	
2007	11.00	
2006	8.00	

Contents

“To climb steep hills requires a slow pace at first.”

.... William Shakespeare

CHAPTER 1

Semiconductor Theory

Learning Objectives

After reading this chapter, you will know:

1. Atomic Structure
2. Energy Band Theory of Crystals
3. Insulators, Semiconductors and Metals
4. Mobility and Conductivity
5. Energy Bands in Silicon, Holes and Electrons Intrinsic and Extrinsic Silicon.
6. Donor and Acceptors Impurities
7. Charge Densities in Semiconductors
8. Hall Effect

Atomic Structure

- Everything in this universe is formed by combination of various constituent elements.
- Every element has characteristic atoms.
- Atoms of different elements contain electrons, which are completely identical.
- Atoms of every element have a positively charged nucleus. Almost entire mass of the atom is concentrated in the nucleus.
- The atom is composed of a positively charged nucleus surrounded by negatively charged electrons and the neutrons carry no charge.
- Mass of an atom is very small **E.g.:** mass of a carbon atom, C – 12 is only 1.992678×10^{-26} kg.
- Protons and neutrons are the constituents of a nucleus. The number of protons (called the atomic number) and the number of neutrons are represented by the symbol Z and N respectively.
- The total number of neutrons and protons in a nucleus is called its mass number $A = Z+N$.
- Atom as a whole is electrically neutral and therefore contains equal amount of positive and negative charges.
- The radius of the electron is about 10^{-15}m , and that of an atom as 10^{-10}m.
- The electrons surrounding the nucleus in an atom occupies different orbits.
- The mass of the electron is negligible compared to that of protons and neutrons the mass of the atom depends mostly on the number of protons and neutrons in the nucleus.
- The basic unit of charge is the charge of the electron. The MKS unit of charge is the Coulomb. The electron has a charge of 1.602×10^{-19} Coulomb and its rest mass is 9.109×10^{-31} kg.
- The electron has a charge of 1.602×10^{-19} Coulomb, it follows that a current of l ampere corresponds to the motion of $1/(1.602\times 10^{-19}) = 6.24\times 10^{18}$ electrons past any cross section of a path in one second.

- If an atom loses an electron, it becomes a positive ion with a net charge of '+1'. If it gains an extra electron, it becomes negative ion with a charge of '−1'.
- "Ionization potential" is the energy required to remove an electron from the outer orbit of an atom. The size of the atom decreases considerably as more and more electrons are removed from the outer orbit.
- The work done by the system, when the extra electron is attracted from infinity to the outer orbit of the neutral atom is known as the electron affinity and correspondingly an increase in the size of the atom.
- The tendency of an atom to attract electrons to itself during the formation of bonds with other atoms is measured by the "electro – negativity" of that atom.
- The magnitude of energy released, when two atoms come together from a large distance of separation to the equilibrium distance is called the "bond energy".
- "Ionic bonding" forms between two oppositely charged ions which are produced by the transfer of electrons from one atom to another.
- Sharing of electrons between neighboring atoms results in a "covalent bond" which is directional.
- Covalent bonding occurs by the sharing of electrons between neighboring atoms. This is in contrast to the transfer of electrons from one atom to another in the ionic bonding.
- The force on a unit positive charge at any point in an electric field is, by definition, the electric field intensity E at that point.
- The force on a positive charge q in an electric field of intensity E is given by qE, the resulting force being in the direction of the electric field. Thus, $F_q = qE$ where Fq is in newtons, q is in Coulombs and ε is in Volts per meter.
- The magnitude of the charge on the electron is e, the force on an electron in the field is $F = -eE$. The minus sign denotes that the force is in the direction opposite to the field
- A unit of work or energy, called the electron Volt (eV), is defined as follows:
  1 eV $=1.602\times10^{-19}$J.
- The name electron volt arises from the fact if an electron falls through a potential of one Volt eV = $(1.602\times10^{-19}\text{C})$ (1V) $=1.602\times10^{-19}$J=1 eV.
- The force of attraction between the nucleus and the electron is $-e^2/4\pi\varepsilon_0 r^2$ in newtons, where
  e = Electron charge coulombs,
  r = Separation between the two particles in meters,
  ϵ_0= Permittivity of free space.
- The potential energy of the electron at a distance r from the nucleus is $-e^2/(4\pi\epsilon_0 r)$ and its kinetic energy is (1/2) mV^2.
- The total energy of the electron in Joules is $W = -e^2/(8\pi\varepsilon_0 r)$ [Rutherford atomic model].
- The expression shows that the energy of the electron becomes smaller (i.e., more negative) as it approaches closer to the nucleus.
- The minimum energy required for the electron to escape from the metal at absolute zero temperature is called the "work function E_w".
- The total energy of electron in stationary states in joules and in electron volts is given by [Bohr atomic model].

$$W_n = \frac{(-me^4)}{(8\varepsilon_0^2 h^2 n^2)} \text{ Joules}$$

$$W_n = \frac{(-me^3)}{(8\varepsilon_0^2 h^2 n^2)} \text{ eV}$$

$$= \frac{-13.6}{n^2} \text{eV}$$

Where m = Electronic mass in kilograms,
h = Planck's constant in Joules – seconds,
n = Orbit number

- It should be noted that the energy is negative and therefore, the energy of an electron in its orbit increases as 'n' increases.
- To remove an electron from the first orbit (n = 1) of the hydrogen atom, to outside of the atom, that is to ionize the atom, the energy required is 13.6 eV. This is known as the "Ionization Energy" or the "Ionization Potential" of the atom.
- The energy associated with an electron in n^{th} orbit of the hydrogen atom is $E_n = (13.6)/n^2$ eV. Thus the energies E_1, E_2, E_3……… of the first, second, third ,……. ∞ orbits are respectively $-13.6, -3.4, 1.51, \ldots\ldots$ 0 eV. The energy required to raise the atom from the ground state (n = 1) to the first excited state is (13.6 − 3.4) = 10.2 eV. The energy required to raise it to the second excited state is (13.6 -1. 51) = 12.09 eV and so on. It is clear that 10.2 eV, 12.09 eV are excitation potentials, while 13.6 eV is the ionization potential of the hydrogen atom.
- The lowest energy level E_1 is called the normal or the ground state of the atom and the higher energy levels E_2, E_3, E_4,…... are called the excited states.
- The emitted radiation by its wavelength λ in Angstroms , when electron transition from one state to the other state is

$\lambda = \dfrac{12{,}400}{E_2 - E_1} A^{0 energy}$ is emitted in the form of a photon of light.

Atomic Concentration $n = (A_0 d)/A$ atoms $/cm^2$

A = Atomic Weight, d = Density, A_0 = Avogadro Number

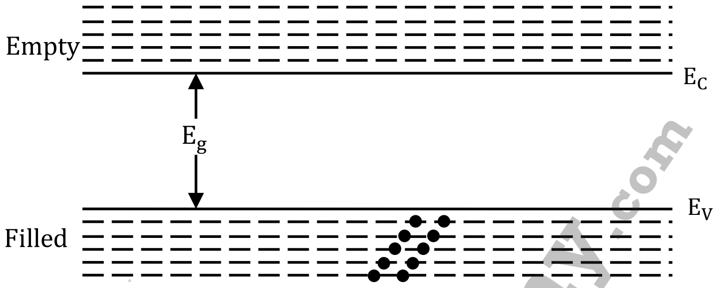
For Germanium	For Silicon
A= 72.6	A=28
$D = 5.32. g/cm^3$	$D = 2.33\ g/cm^3$
$A_0 = 6.023 \times 10^{23}$ molecules/mole	A_0 =6.023×10^{23} molecules/mole
Then, n = 4.4×10^{22} atoms/cm^3	Then, n = 5×10^{22} atoms/cm^3

$n_{si} > n_{Ge}$, because atomic number of silicon is less than atomic number of Germanium.

Energy Band Theory of Crystals

- As the inter - atomic spacing gradually decreases, there will be a gradual increase in the interaction between the neighboring atoms. Due to this interaction, the atomic wave functions overlap and the crystal becomes an electronic system which should obey the Pauli's exclusion principle .
- An energy gap exists between the two energy bands. This energy gap is called as forbidden energy gap E_G, as no electrons can occupy states in this gap.

- The band below energy gap E_G is called valence band. The band above the energy gap E_G is called conduction band.
- The upper band, called the conduction band, consists of infinitely larger number of closely spaced energy states. The lower band, called the valence band consists of closely spaced completely filled energy states and only two electron are allowed in each energy state according to Pauli's exclusion principle as shown in below Figure.



- The electrons in the valence band would not move under the action of applied voltage or field because of completely filled energy states. Therefore, the valence electrons do not conduct.
- The electrons in the conduction band can, however, gain momentum and move since there are closely spaced empty available states in the band.
- At equilibrium spacing, the lowest conduction band energy is E_C and highest valence band energy is $E_{V.}$
- The gap between the top of the valence band and bottom of the conduction band is called 'energy band gap' (Energy gap). It may be large, small or zero depending upon the material.
- The bottom of the conduction band corresponds to zero electron velocity or kinetic energy and simply gives us the potential energy at that point in space.
- For holes, the top of the valence band corresponds to zero kinetic energy.

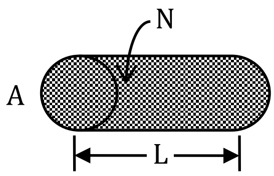
Insulators, Semiconductors and Metals

- A very poor conductor of electricity is called an insulator, an excellent conductor is a metal and a material whose conductivity lies between these extremes is semiconductor.
- **Insulator:** For a diamond (Carbon) crystal the region containing no quantum states is several electron volts high ($E_G \approx 6$eV). This large forbidden band separates the filled valence region from the vacant conduction band and therefore no electrical conduction is possible. Insulator has a negative temperature coefficient of resistance.
- The energy gap is so large that electrons cannot be easily excited from the valence band to the conduction band by any external stimuli (Electrical, Thermal or Optical).
- **Metal:** This refers to a situation where the conduction and valence bands are overlapping. This is the case of a metal where $E_G = 0$. This situation makes a large number of electrons available for electrical conduction and, therefore the resistance of such materials is low or the conductivity is high.
- **Semiconductor:** A substance for which the width of the forbidden energy region is relatively small ($\sim$1 eV) is called a semiconductor.
- The most important practical semiconductor materials are germanium and silicon, which have values of E_G of 0.785 and 1.21 eV, respectively at 0 K.
- Energies of this magnitude normally cannot be acquired from an applied field.

- Hence the valence band remains full, the conduction band empty and these materials are insulators at very low temperatures (≈ 0 K).
- However, the conductivity increases with temperature as we explain below and for this reason these substances are known as " Intrinsic Semiconductors".
- As the temperature is increased, some of these valence electrons acquire thermal energy greater than E_G and hence move into the conduction band.
- These thermally excited electrons at $T > 0$ K, partially occupy some states in the conduction band which have come from the valence band leaving equal number of holes there.
- The phrase "holes in a semiconductor" refers to the empty energy levels in an otherwise filled valence band.
- The importance of the hole is that it may serve as a carrier of electricity, comparable in effectiveness with the free electron.
- As the temperature of a semiconductor is reduced to zero, all valence electrons remain in valence band.
- If a certain impurity atoms are introduced into the crystal, these result in allowable energy states which lie in the forbidden energy gap. These impurity levels also contribute to increase in conduction.
- A semiconductor material where the impurities are added to improve conductivity is called an "Extrinsic (impurity) Semi conductor".
- The energy gap E_G for silicon decreases with temperature at the rate of 3.60×10^{-4}eV /K.
  Hence, for Silicon,
  $E_G(T) = 1.21 - 3.60 \times 10^{-4}T$
  and at room temperature 300 K, $E_G = 1.1$ eV.
- Similarly for Germanium,
  $E_G(T) = 0.785 - 2.23 \times 10^{-4}T$
  and at room temperature, $E_G = 0.72$ eV.
- The fundamental difference between a metal and a semiconductor is that the former is unipolar (conducts current by means of charges (electrons) of one sign only); where as a semiconductor is bipolar (contains two charge carrying "particles" of opposite sign (electrons and holes)).

Current Density

If N electrons are contained in a length L of conductor (fig) and if it takes an electron a time T sec to travel a distance of L meter in the conductor, the total number of electrons passing through any cross section of wire in unit time is N/T.



Thus the total charge per second passing any point, which by definition is the current in amperes, is

$I = Nq / T$............(1) Where $q = 1.602 \times 10^{-19}$ C

By definition, the current density, denoted by the symbol J, is the current per unit area of the conducting medium, i.e., assuming a uniform current distribution.

$J = I / A$.................(2)

Where J is in amperes per meter square, and A is the cross - section area (in meter square) of the conductor. This becomes, by (1)

$J = Nq / TA$…………(3)

But it has been pointed out that the average, or drift, speed v m/sec of the electrons, is

$v = L/T$ i.e., $T = L/v$

Then, the (3) becomes

$J = Nqv / LA$…………(4)

From above fig. it is evident that LA is simply the volume containing the N electrons and so (N/LA) is the electron concentration n (in electrons per cubic meter). Thus

$n = N/LA$ And (4) reduces to

$J = n\,qv = \rho v$…………(5)

Where $\rho = nq$ is the charge density, in coulombs per cubic meter, and v is in meters per second.

Mobility and Conductivity

- If a constant electric field ε (Volts per meter) is applied to a substance, the electrons would be accelerated and a finite value of drift velocity v is attained.
- This drift velocity v is in the direction opposite to that of the electric field, and its magnitude is proportional to E. Thus,
  $v = \mu E$
  Where, μ (m^2 / V - s) is called the mobility of the electrons.
- The directed flow of electrons with a drift velocity v constitutes a current.
- If the concentration of free electrons is n (electrons per cubic meter), the current density J (Amperes per Square Meter) is
  $J = nqv = nq\mu E$ Where q = electron charge = 1.602×10^{-19} C and
  σ = is the conductivity of the material in $(\text{ohm meter})^{-1}$
- The conductivity is proportional to the concentration of free electrons.

Mobilities of Electrons and Holes in Silicon and Germanium

Species	Mobility at Room Temperature, m^2 / V-sec	
	Silicon	Germanium
Electrons	0.14	0.39
Holes	0.05	0.19

- By observing the above table, the electron mobility is about 2.5 times the hole mobility.
- For a good conductor, n is very large (~ 10^{28} electrons / m^3); for an insulator, n is very small (~ 10^{7} electrons/m^3); and for a semiconductor, n lies between these two values.
- In a certain temperature range, the electrical conductivity of a semiconductor increases with increase in temperature. This is because the carrier concentration increases substantially, but the mobility of carriers decreases with increase in temperature.
- The parameter μ varies as T^{-m} over a temperature range of 100 to 400 K. For silicon, m = 2.5 (2.7) for electrons (holes) and for germanium, m = 1.66 (2.33) for electrons (holes). The mobility is also found to be a function of electric field intensity E remains constant only if $E < 10^3$ V/cm in n type silicon. For $10^3 < E < 10^4$ V/cm, μ_n varies approximately as $E^{-1/2}$. For higher fields, μ_n is inversely proportional to ε and the carrier speed approaches the constant value of 10^7 cm/s.