JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY ANANTAPUR
ANANTHAPURAMU – 515 002 , ANDHRA PRADESH

GATE Coaching Classes as per the Direction of
Ministry of Education
GOVERNMENT OF ANDHRA PRADESH

Electronic Devices and Circuits

11-05-2020 to 23-05-2020

Prof. S. Srinivas Kumar
Vice Chancellor

You Tube link is to be downloaded for every class on every day as per the given schedule

https://jntua.ac.in/gate-online-classes/registration/

Tentative Schedule of Lectures

First Class (Prof. S. Srinivas Kumar)

1. Energy band diagram of Insulators, Semiconductors and Metals
2. Mobility and Conductivity
3. Electrons and Holes in an Intrinsic Semiconductor
4. Donor and Acceptor impurities
5. Charge Densities in a Semiconductors
6. Hall Effect
7. Diffusion
8. Exercise Problems & Objective Type Questions

Second Class (Prof. S. Srinivas Kumar)

1. Generation and Recombination of Charges
2. Continuity equation and Poisson Equation
3. Injected Minority carrier charges
4. Potential variation within a Graded Semiconductor
5. Fermi level
6. Fermi level in Intrinsic and Extrinsic semiconductor
7. Exercise Problems & Objective Type Questions

Third class (Prof. R. Ramana Reddy)

1. Exercise problems and Objective type questions pertaining to first and second chapter

Fourth class (Prof. S.Srinivas Kumar)

1. The Open-Circuited p-n junction
2. The p-n Junction as a Rectifier
3. The current components in a p-n diode
4. V-I Characteristic of semi-conductor diode
5. Diode Equation
6. Temperature dependence of the V/I characteristic
7. Exercise Problems & Objective Type Questions

Fifth class (Prof. R. Ramana Reddy)

1. Exercise problems and Objective type questions pertaining to fourth class

Sixth Class (Prof. S.Srinivas Kumar)

1. Diode Resistance
2. Space-Charge or Transition Capacitance
3. Diffusion capacitance
4. Energy band diagram of p-n diode
5. Zener Diode and its application
6. Exercise Problems & Objective Type Questions

Seventh Class (Prof. R. Ramana Reddy)

Exercise problems and Objective type questions pertaining to fourth class

Eighth Class (Prof. S. Srinivas Kumar)

1. The Junction Transistor
2. Transistor current Components
3. Common-Base Configuration
4. Common Emitter Configuration
5. Exercise Problems & Objective Type Questions

Ninth Class (Prof. S. Srinivas Kumar)

1. CE Cutoff Region
2. CE saturation Region
3. Typical Transistor – Junction Voltage Values
4. Common-Emitter Current gain
5. Common Collector configuration
6. Exercise Problems & Objective Type Questions

Tenth Class (Prof. R. Ramana Reddy)

Exercise problems and solultions

Eleventh class (Prof. S.Srinivas Kumar)

1. JFET V-I Characteristics
2. The Pinch-off voltage
3. The JFET Volt- Ampere Characteristics
4. Low frequency model of FET
5. FET as voltage variable Resistor
6. Exercise Problems & Objective Type Questions

Twelth classes (Prof. S.Srinivas Kumar)

1. MOSFET (Depletion mode and Enhancement)
2. MOS Capacitor
3. Light Emitting Diode
4. Photo diode
5. Solar cell
6. Exercise Problems & Objective Type Questions

Thirteenth Class (Prof. R. Ramana Reddy)

Integrated circuit fabrication process:

- ❖ Oxidation,
- ❖ Diffusion,
- ❖ Ion implantation,
- ❖ Photolithography
- ❖ Twin-tub CMOS process
- ❖ Exercise Problems & Objective Type Questions

Energy band diagram of Insulators, Semiconductors and Conductors

Classification of Materials

- Insulators
- Semi Conductors
  - Intrinsic Semi Conductors (Temperature Dependent)
  - Extrinsic Semi Conductors
    - N-Type Semi Conductors
    - P- Type Semi Conductors
- Conductors

N- Type Semi Conductor

Majority Carriers are Electrons & Minority Carriers are holes

P- Type Semi Conductor

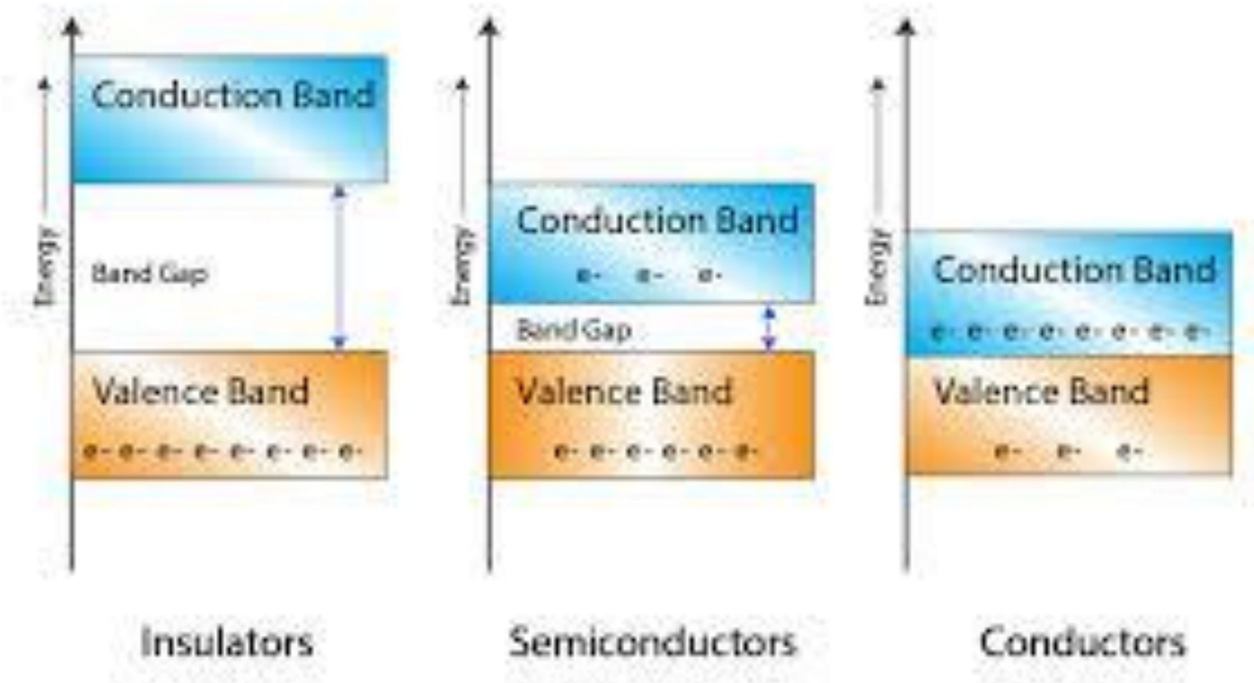
Majority Carriers are Holes & Minority Carriers are Electrons

- The **valence band** is simply the outermost electron orbital of an atom of any specific material that electrons actually occupy

- The **conduction band** is the band of electron orbitals that electrons can jump up into from the valence band when excited. When the electrons are in these orbitals, they have enough energy to move freely in the material

- The energy difference between the highest occupied energy state of the valence band and the lowest unoccupied state of the conduction band is called the **band gap**

- A large band gap means that a lot of energy is required to excite valence electrons to the conduction band. Conversely, when the valence band and conduction band overlap as they do in metals, electrons can readily jump between the two bands meaning the material is highly conductive



In case of Insulators the E_G = 6 eV (Approximate)
In case of Semi Conductors the E_G = 1 eV (Approximate)
In case of Conductors E_G = 0 eV (Approximate)

Examples for Semi Conductor Materials

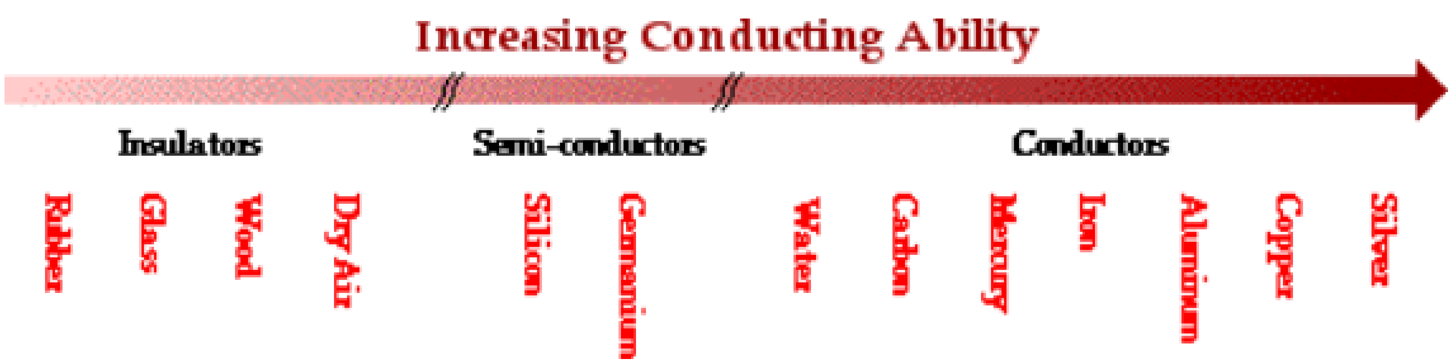
Material	Chemical symbol	Details
Germanium	Ge	❖ Radar detection diodes to the first transistors. ❖ Offers a better charge carrier mobility than silicon and is therefore used for some RF devices.
Silicon	Si	❖ Silicon is the most widely used type of semiconductor material. ❖ Easy to fabricate and provides and good general electrical and mechanical properties. ❖ Advantage for integrated circuits as it forms high quality silicon oxide that is used for insulation layers between different active elements of the IC.
Gallium arsenide	GaAs	❖ Gallium arsenide is the second most widely used type of semiconductor after silicon. ❖ Used in high performance RF devices where its high electron mobility is utilised. ❖ Costly for fabrication
Silicon carbide	SiC	❖ Used in power devices ❖ Used with some early forms of yellow and blue LEDs.
Gallium Nitride	GaN	❖ Used in microwave transistors where high temperatures and powers are needed. It is also being used in some microwave ICs. Used in some blue LEDs.
Gallium phosphide	GaP	❖ Used within LED technology. ❖ Used in many early low to medium brightness LEDs producing a variety of colours dependent upon the addition of other dopants.
Cadmium sulphide	CdS	❖ Used in photo resistors and also solar cells.
Lead sulphide	PbS	❖ Used as the mineral galena, this semiconductor material was used in the very early radio detectors known as 'Cat's Whiskers' where a point contact was made with the tin wire onto the galena to provide rectification of the sign

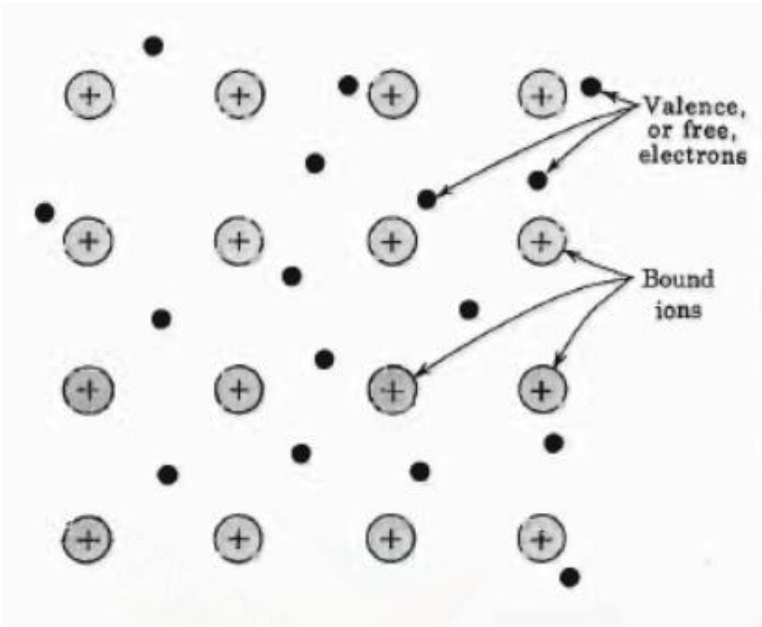
Examples for Metals / Conductors

- Copper and Silver
- Aluminum
- Gold
- Steel and Brass Alloys

Examples for Insulators

- Rubber
- Glass
- Wood
- Dry Air





Schematic arrangement of the atoms in one plane in a metal, drawn for monovalent atoms

Free electron gas theory:

Free electron gas theory assumes the positive ion cores are embedded in the gas of negative free electrons. The free electrons do not attach permanently with any of the core, hence always free to move through whole crystal.

If a constant Electric field ε (volts/meter) is applied, results electrostatic force and accelerates the electrons. The average drift velocity (v) (meter / sec) of electrons is given by

$$v = \mu\varepsilon$$

The units of μ are square meters per volt-sec

In case of Semi Conductors, the mobility of electron μ_n is more than mobility of the hole μ_p

Property	Ge	Si
Atomic number	32	14
μ_n cm^2 / V-Sec at 300° K	3800	1300
μ_p cm^2 / V-Sec at 300° K	1800	500

The free electron gas theory explains conduction in

A . Metals only

B . Semiconductors only

C . Insulators only

D . All of these

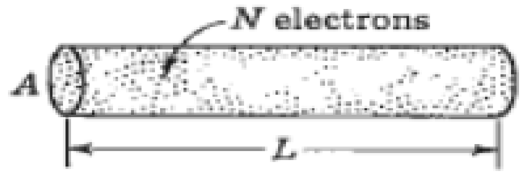
Answer: Metals Only (A)

Important Definitions

❖ Current density	Amperes/ Sq meter
❖ Carrier Concentration	Carriers/Cubic volume
❖ Charge density	Coulombs per cubic meter
❖ Mobility	Square meters per volt-sec
❖ Conductivity	Siemens / Meter
❖ Diffusion constant	Sq. Meters/ Sec

Current Density:

If N electrons are contained in a length L of conductor (Fig.) and if it takes an electron a time T second to travel a distance of L meters 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 area, which, by definition, is the current in amperes, is

$$I = \frac{Nq}{T} = \frac{Nqv}{L}$$

because L/T is the average, or drift, speed **v m/s** of the electrons. By definition, the current density, denoted by the symbol **J,** is the current per unit area of the conducting medium. That is assuming a uniform current distribution

$$J = \frac{I}{A}$$

where J is in amperes per square meter, and A is the cross-sectional area (in meters) of the conductor. This becomes by equation

$$J = \frac{Nqv}{LA}$$

from the figure 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).**

.

$$n = \frac{N}{LA}$$

and equation reduces to $J = \ nqv = \ \rho v$

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

Conductivity:

$$J = nqv = nq\mu\varepsilon = \sigma\varepsilon$$

where $\sigma = nq\mu$

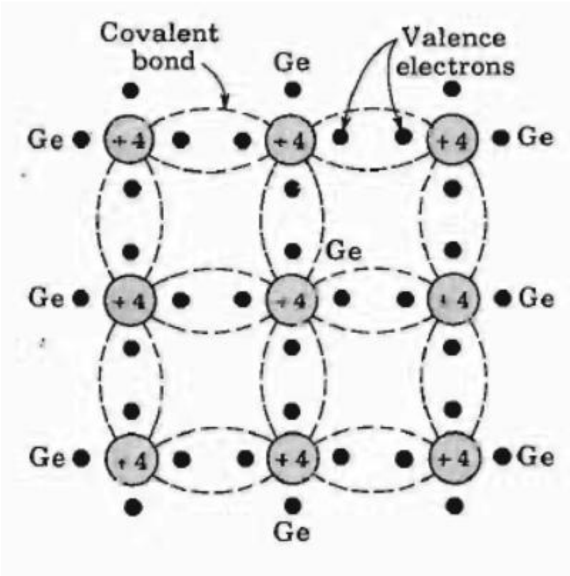
is the conductivity of the metal in (ohm-meter)$^{-1}$

Power is dissipated within the metal by the electronics, and the power density (Joule heat) is given by

$$J\varepsilon = \sigma\varepsilon^2$$

Units are given as Watts per cubic meter

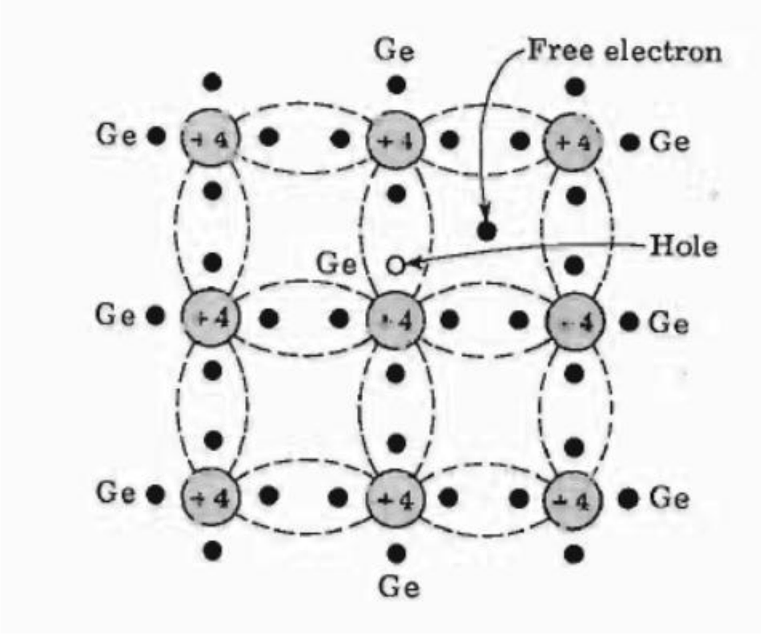
Electronics and Holes in an Intrinsic Semiconductor:



Crystal structure of germanium

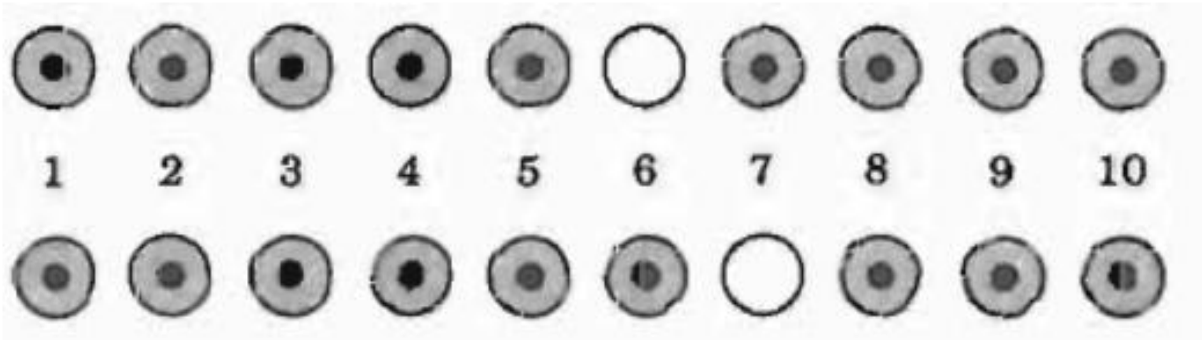
Element	Atomic number	Configuration
C	6	$1s^2 2s^2 2p^2$
Si	14	$1s^2 2s^2 2p^6 3s^2 3p^2$
Ge	32	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$
Sn	50	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^2$

The inert ionic core of the germanium atom carries a positive charges of +4 measured in units of the electronic charge.



Germanium crystal with a broken covalent bond

The energy E_G required to break such a covalent bond is about 0.72 eV for germanium and 1.1 eV for silicon at room temperature.



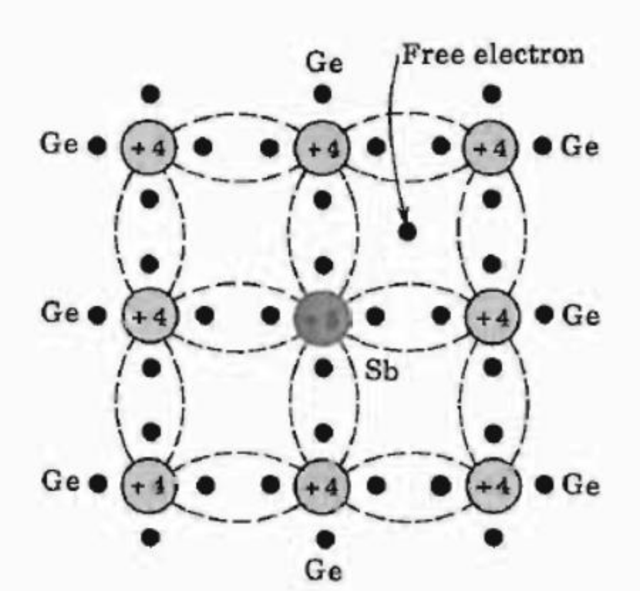
The mechanism by which a hole contributes to the conductivity

$$n = p = n_i$$

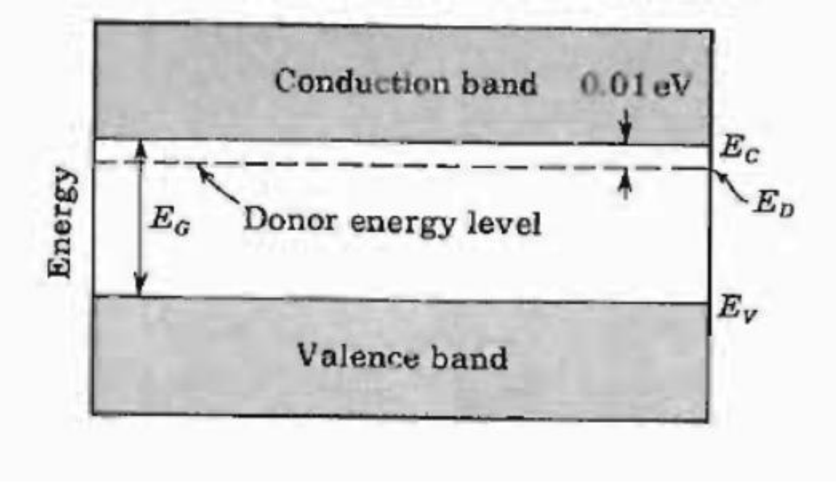
where n_i is called the intrinsic concentration.

n_i at 300° K , (per sq. cm) is 2.5×10^{13} for Ge, 1.5×10^{10} for Si

Extrinsic Semiconductor (n type)



Crystal lattice with a germanium atom displaced by a pentavalent impurity atom



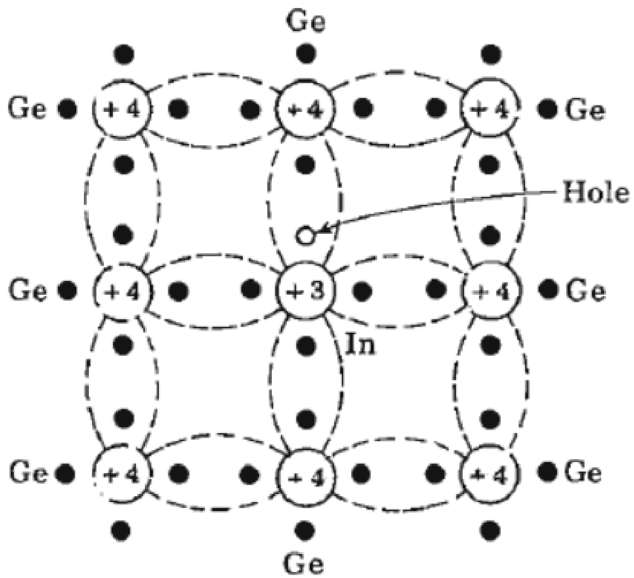
Energy band diagram of n-type semiconductor

Donor Impurity atoms: Antimony, Arsenic , Phosperous

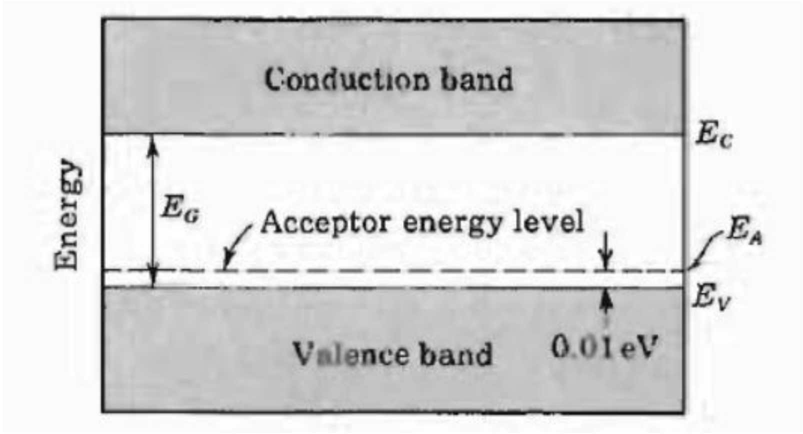
The energy required to detach this fifth electron from the atom is of the order of only 0.01 eV fro Ge or 0.05 eV for Si.

Minority carriers are Holes and Majority carriers are Electrons

Extrinsic Semiconductor (p type)



Crystal lattice with a germanium atom displaced by atom of a trivalent impurity



Energy-band diagram of p-type semiconductor

Donor Impurity atoms: Boron, Gallium, Indium

Minority carriers are Electrons and Majority carriers are Holes

Mass action law

Under thermal equilibrium, the relationship between free electrons and holes is called the mass action law

$$np = n_i^2$$

Where n_i is intrinsic concentration and it is function of temperature

Charge Densities in a Semiconductor

Consider pure semi conductor, with hole concentration as '**p**', and electron concentration '**n**'.

Let N_D equal the concentration of donor atoms. They are practically all ionized. N_D positive charges per cubic meter are contributed by the donor ions. Hence the total positive charge density is $N_D + p$.

Similarly, if N_A is the concentration of acceptor ions, these contribute N_A negative charges per cubic meter. the total negative charge density is $N_A + n$.

Since the semiconductor is electrically neutral the magnitude of the positive charge density must equal that of the negative concentration, or $N_D + p = N_A + n$

Consider an n-type material having $N_A = 0$. Since the number of electrons is much grater than the number of holes in an n-type semiconductor (n>>p) , then

$$n \approx N_D$$

The concentration 'p_n' of holes in the n-type semiconductor is obtained from which is now written $n_n\, p_n = n_i^{\,2}$.

$$n_n \approx N_D$$

Similarly for p-type semiconductor

$$n_p p_p = n_i^2$$

$$p_p \approx N_A \qquad\qquad n_p = \frac{n_i^2}{N_A}$$

Conductivity

One carrier is negative (the free electron), of mobility μ_n , and the other is positive (the hole) , of mobility μ_p .

These particles move in opposite directions in an electric field ε , but since they are of opposite sign, the current of each is in the same direction. Hence the current density J is given by

$$J = (n\mu_n + p\mu_p)\, q\varepsilon = \sigma\varepsilon$$

where n = magnitude of free-electron (negative) concentration

p = magnitude of hole (positive) concentration

σ = conductivity

Hence, $\sigma = (n\mu_n + p\mu_p)q$

for the pure semiconductor, n = p = n_i where n_i is the intrinsic concentration.

Intrinsic Concentration

Increase in temperature, the density of hole-electron pairs increases and, correspondingly, the conductivity increases.

The intrinsic concentration n_i varies with T as

$$n_i^2 = A_o\, T^3\, \varepsilon^{-E_{GO}/kT}$$

where, E_{GO} is the energy gap at 0^ok in electron volts, k is the Boltzman constant in eV/ ^{o}k , and A_o is a constant independent of T.

Energy Gap

The forbidden region E_G in a semiconductor depends upon temperature, as pointed our . Experimentally it is found that , for silicon

$$E_G\,(T) = 1.21 - 3.60 \times 10^{-4}T$$

and at room temperature (300^oK), $E_G = 1.1eV$.

Similarly, for germanium,

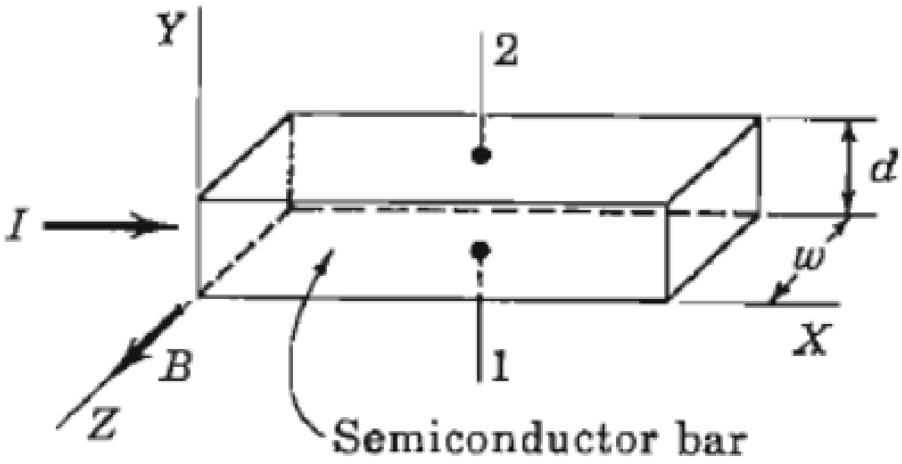
$$E_G\,(T) = 0.785 - 2.23 \times 10^{-4}T$$

and at room temperature, $E_G = 0.72$ eV

Hall effect

If a specimen (metal or semiconductor) carrying a current I is placed in a transverse magnetic field B, an electric field $\mathcal{E}$ is induced in the direction perpendicular to both I and B.

This phenomenon, known as the Hall effect. It is used to determine whether a semiconductor is n- or p-type. and also to find carrier concentration, conductivity and mobility.



I is in the positive X direction and B is in the positive Z direction, a force will be exerted in the negative Y direction on the current carriers.

The current I may be due to holes moving from left to right or to free electrons traveling from right to left in the semiconductor specimen.

Hence, independently of whether the carriers are holes or electrons, they will be forced downward to ward side 1.

If the semiconductor is n-type material, so that the current is carried by electrons, these electrons will accumulate on side 1, and this surface becomes negatively charged with respect to side 2. Hence a potential, called the Hall voltage, appears between surfaces 1 and 2.

If the polarity of V_H is positive at terminal 2, then, as explained above, the carriers must be electrons. If, on the other hand, terminal 1 becomes charged positively with respect to terminal 2, the semiconductor must be p-type.

In the equilibrium state the electric filed intercity ε due to the Hall effect must exert a force on the carrier which just balances the magnetic force, or

$$q\varepsilon = Bqv$$

Where, q is the magnitude of the charge on the carrier, and v is the drift speed. $\varepsilon = V_H/d$, where d is the distance between surfaces 1 and 2.

J = ρv = Current(I)/wd, where J is the current density, ρ is the charge density, and w is the width of the specimen in the direction of the magnetic field. Combining these relationships, we find

$$V_H = \varepsilon d = Bvd = \frac{BJd}{\rho} = \frac{BI}{\rho\omega}$$

If V_H, B, I and ω are measured, the charge density ρ can be determined from above eq.

It is customary to introduce the Hall coefficient R_H defined by

Hence,
$$R_H = \frac{1}{\rho}$$

$$R_H = \frac{V_H W}{BI}$$

If conduction is due primarily to charges of one sign, the conductivity is related to the mobility μ by

$$\sigma = \rho\mu$$

If the conductivity is measured together with the Hall coefficient, the mobility can be determined from

$$\mu = \sigma R_H$$

Assume that all particles travel with the mean drift speed v. Actually, the current carriers have a random thermal distribution in speed.

If this distribution is taken into account, it is found that Eq. remains valid provided that R_H is defined by $3\pi/8\rho$. Also Eq. must be modified to $\mu = (8/3\pi)\, R_H$

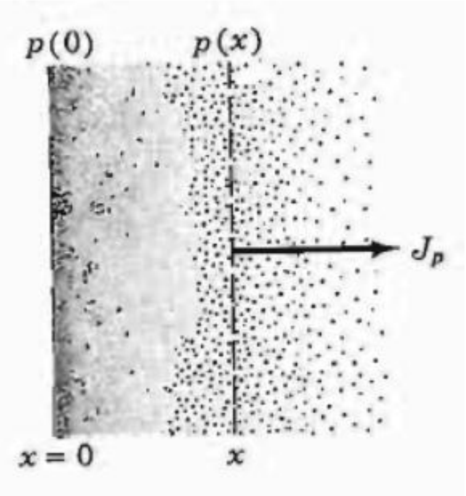
Applications

Since V_H is proportional to B (for a given current I), then the Hall effect has been incorporated into a magnetic field meter. Another instrument called a Hall-effect multiplier.

It is available to give an output proportional to the product of two signals.

If I is made proportional to one of the inputs and if B is linearly related to the second signal, then from , V_H is proportional to the product of the two inputs.

Diffusion



x1 x2

p1 p2

(p2<p1)

$$\frac{dp}{dx} = \frac{p2 - p1}{x2 - x1}$$

This value is negative

x1 x2

n1 n2

$$\frac{dn}{dx} = \frac{n2 - n1}{x2 - x1}$$

This value is also negative

$(n2 < n1)$

Hole diffusion current density is

$$J_p = -qD_p \frac{dp}{dx}$$

Electron diffusion curent density is

$$J_n = qD_n \frac{dn}{dx}$$

'-' sign is not included as q is negative

Total currents in Semi-conductor

1. Hole diffusion current
2. Electron diffusion current
3. Hole drift current
4. Electron drift current

Total Hole current is given as $J_p = q\mu_p p\varepsilon - qD_p \frac{dp}{dx}$

Total Electron current is given as $J_n = q\mu_n n\varepsilon + qD_n \frac{dn}{dx}$

Einstein relationship

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T$$

Where V_T is the “volt-equivalent of temperature”

$$V_T = \frac{\bar{k}\,T}{q} = \frac{T}{11{,}600}$$

Where $\bar{k}$ is the Boltzmann constant in joules per degree Kelvin.

$\bar{k}$ = 1.60 x 10^{-19} k

The value of k is given as 8.620 x 10^{-5} ev/^{o}Kelvin

The value of $\bar{k}$ is given as 1.381 x 10^{-23} J/^{o}Kelvin

Objective type questions

1. In intrinsic semiconductors, number of electrons ___________ to number of holes.

   (a) Equal (b) Greater than (c) Less than (d) Can not define

2. In n-type semiconductors, number of holes ___________ number of electrons.

   (a) Equal (b) Greater than (c) Less than (d) Can not define

3. In p-type semiconductors, number of holes ___________ number of electrons.

   (a) Equal (b) Greater than (c) Less than (d) Twice

Objective questions

4. Mobility of holes is ___________ mobility of electrons

   (a) Equal (b) Greater than (c) Less than (d) Can not define

5. Electrical conductivity of insulators is the range _____________.

   (a) $10^{-10}(\Omega\text{-mm})^{-1}$ (b) $10^{-10}(\Omega\text{-cm})^{-1}$ (c) $10^{-10}(\Omega\text{-m})^{-1}$ (d) $10^{-8}(\Omega\text{-m})^{-1}$

6. Units for electric field strength

   (a) A/cm^2 (b) mho/meter (c) cm^2 /V-sec (d) V/cm

7. Energy band gap size for semiconductors is in the range ___ eV.

(a)1-2 (b) 2-3 (c) 3-4 (d) > 4

8.Energy band gap for insulators is in the range _______ eV.

(a)1-2 (b) 2-3 (c) 3-4 (d) > 4

9.One of the following element is not an example of semiconductor

(a) Si (b) Al (c) Ge (d) Sn

10. Which of the following semiconductor is used in LED

(a) Ge (b) Si (c) Cadmium Sulphide (d) Gallium Phosphide

11. The unit of conductivity is given as

(a) Siemens/meter (b) Siemens-meter (c) $(\Omega)^{-1}$ – meter

(d) Ω/meter

12. The mass-action law is given by

(a) $np = n_i$ (b) $np = n_i^2$ (c) $n+p = n_i^2$ (d) $n/p = n_i$

13. Calculate the diffusion current density when the concentration of electron varies from the 10^{18} to $7*10^{17}$ cm^{-3} over a distance of 0.10 cm $D=225 cm^2/s$

(a) 100 A/cm^2

(b) 108 A/cm^2

(c) 0.01A/cm^2

d) None

Explanation:

$J = e\,D\,(dn/dx) = 1.6*10^{-19}*225*(10^{18} - (7*10^{17}))\,/\,0.1$

$= 108\ A/cm^2$

14. The relation between energy gap in semi- conductor

(a) Increases with temperature

(b) Decreases with temperature

(c) Independent of temperature

(d) None of the above

15. Calculate the diffusion constant for the holes when the mobility of the holes is $400cm^2/V\text{-}s$ and temperature is 300K?

a) $1.035m\ m^2/s$ (b) $0.035m\ m^2/s$ (c) $1.5m\ m^2/s$ (d) $1.9m\ m^2/s$

Explanation: $D_p = V_T * \mu_p$

$= (1.38*10^{-23}*300*400*10^{-2})/(1.6*10^{-19})$

$= 1.035m\ m^2/s$

16. Which of the last orbit is having valence electrons in Germanium semiconductor

(a) 5 (b) 4 (c) 6 (d) 3

17. Which of the last orbit is having valence electrons in Silicon semiconductor

(a) 5 (b) 4 (c) 6 (d) 3

18. The condition for the validity of Ohm's law is that the

(a) Temperature should remain constant

(b) Current should be proportional to voltage

(c) Resistance must be wire wound type

(d) All of the above

19. In a *p*-type silicon sample, the hole concentration is $2.25 \times 10^{15}/cm^3$. If the intrinsic carrier concentration $1.5 \times 10^{10}/cm^3$, the electron concentration is

(a) $10^{21}/cm^3$

(b) $10^{10}/cm^3$

(c) $10^{16}/cm^3$

(d) None of the above

20. For a particular material the Hall coefficient was found to be zero. The material is

(a) insulator

(b) metal

(c) intrinsic semiconductor

(d) none of the above

21. The band gap of Silicon at 300^oK is

(a) 1.36 eV

(b) 1.10 ev

(c) 0.80 eV

(d) 0.67 ev

22.The electron and hole concentration in a intrinsic semiconductor are n_i and p_i respectively. When doped with p-type material, these changes to n and p. Then

(a) $n+p = n_i + p_i$

(b) $n+n_i=p+p_i$

(c) $np_i = n_i p$

(d) $np = n_i p_i$

23. The intrinsic semiconductor carrier concentration of silicon sample at 300° K is 1.5×10^{16} m^{-3}. If after doping, the number of majority carriers is 5×10^{20} m^{-3}. The minority carrier density is

(a) 4.5×10^{11} m^{-3} (b) 3.33×10^{4} m^{-3} (c) 5.00×10^{20} m^{-3}

(d) 3.00×10^{-5} m^{-3}

24. Hall Voltage is dependent on

(a) Current

(b) Charge density

(c) Magnetic field

(d) All of the above

25. Calculate the hall voltage when the electric field is 5v/m and height of semiconductor is 2 cm

(a) 10 V

(B) 1 V

(c) 0.1 V

(d) 0.01 V

Thermal Equilibrium

The condition under which two substances in physical contact with each other exchange no heat energy. Two substances in **thermal equilibrium** are said to be at the same temperature.

Conductivity, Resistivity of Metals

Material	Resistivity p(Ω•m) at 20°C	Conductivity σ(S/m) at 20°C
Copper	1.68×10^{-8}	5.98×10^{7}
Gold	2.44×10^{-8}	4.52×10^{7}
Aluminum	2.82×10^{-8}	3.5×10^{7}

Conductivity of **semiconductors range** from 10^{-6} to 10^{4} $(\Omega\text{-m})^{-1}$

Conductivity of insulators ranges between 10^{-10} to 10^{-20} $(\Omega\text{-m})^{-1}$

Conductivity ranges of Metals between 10^{4} to 10^{7} $\text{ohm}^{-1}\ \text{m}^{-1}$