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BTECH NOTES SERIES

Material Science and Metallurgy (Engineering Materials and Applications)

(As Per AICTE/Technical Universities Syllabus)

CONTENT

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ELECTRICAL, MAGNETIC AND ELECTRONIC PROPERTIES OF MATERIALS

ELECTRICAL CONDUCTION

One of the most important characteristics of a solid material is the ease with which it transmits an electric current. **Ohm's law** relates the current I to the applied voltage V as follows:

$$V = I R$$

where R is the resistance of the material through which the current I is passing. The units of V, I and R, are Volt, ampere and Ohm respectively.

Resistivity of a material is given as

$$\rho = \frac{RA}{l} \ \Omega\text{-m}$$

Electrical conductivity is simply the reciprocal of resistivity (ρ), i.e.

$$\sigma = \frac{1}{\rho} \ (\Omega\text{-m})^{-1} \text{ or mho/m.}$$

When an electric field E is applied to a conductor an electric current begins to flow and the **current density** by Ohm's law is

$$J = \sigma E$$

The **conductivity** may be defined as the movement of electrical charge from one point to another and it depends on the number of charge carriers (n), the charge per carrier (e) and the mobility of carriers (μ), i.e.

$$\sigma = ne\mu$$

The unit of mobility (μ) is $m^2 \ V^{-1}s^{-1}$.

This equation is of immense importance for solid materials. From this equation, we note that the electrical conductivity depends on two factors: (i) the number n of charge carriers per unit volume and (ii) their mobility μ.

Let E be the electric field applied to a conductor, e be the charge on the electron and m the mass of the electron. The electrons move in a specific direction under the influence of the electric field. The directional motion of a free electron is called a *drift*. The average velocity gained during this drift motion is termed as *drift velocity*.

Example

Calculate the drift velocity of free electrons in a metal of area of cross-section 2 x 10^{-4} m^2 in which a current of 100 A is flowing. The density of free electrons in the metal is 7.23 x 10^{28} m^{-3}

Solution

Given that A = 2 x 10^{-4} m^2, I = 100 A, n = 7.23 x 10^{28} m^{-1}

Current density

$$J = nev_d$$

$$\therefore \qquad v_d = \frac{J}{ne} = \frac{I/A}{ne} = \frac{I}{neA}$$

$$= \frac{100}{(7.23x10^{28})(1.6x10^{-19})(2x10^{-4})} = 4.32\,\mu m/s$$

Example

A potential difference of 3 V is applied across a uniform wire of length 30 m. Calculate the drift velocity of electrons through the copper. Given that the relaxation time is 10^{-14} s.

Solution

Electric field $E = \frac{V}{L} = \frac{3}{30} = 0.1Vm^{-1}$

Drift velocity $v_d = \frac{eE\tau}{m} = \frac{1.6x10^{-19}x0.1x10^{-14}}{9.1x10^{-31}} = 0.176x10^{-3}ms^{-1}$

DIELECTRICS

These are the materials or insulators which have the unique characteristic of being able to store electric charge. Examples are mica, asbestos, ceramics, glass etc.

Most common properties of dielectric materials are:

- dielectric constant
- dielectric strength
- insulation resistance
- surface resistivity
- loss factor
- tangent of loss factor in terms of a capacitor or phase difference
- polar and non-polar materials.

Dielectric constant

In an electric field, the charge density D is directly proportional to the applied field, i.e.

$$D = \varepsilon E \qquad (1)$$

Where ε is the dielectric constant or permittivity of the material placed between the electrodes.

For vacuum,

$$D = \varepsilon_0 E \qquad (2)$$

where $\varepsilon_o = 8.854 \times 10^{-12}$ farad/m is called the absolute permittivity.

One can define the relative permittivity (ε_r) of a dielectric as the ratio of electric field density produced in the dielectric medium (E_0) to that produced in vacuum (E) by the same electric field strength, i.e.

$$E_r = E_0/E$$

Or $$\varepsilon_r = \varepsilon_0/\varepsilon$$

In general, $$D = \varepsilon_r\varepsilon_0 E \qquad (3)$$

Polarization

When an electric field is applied to a solid containing positive and negative charges, the positive charges are displaced in the direction of the field towards the negative end, while the negative charges are displaced in the opposite direction. This displacement produces local dipoles throughout the solid. The dipole moment per unit volume of the solid is the sum of all the individual dipole moments within that volume and is called the polarization P of the solid. As the polarization measures the additional flux density arising from the presence of the material as compared to free space, it has the same units as D and is related to it as follows:

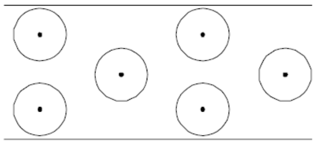
$$D = \varepsilon_0 E + P \qquad (4)$$

From (1) and (4)

$$P = \varepsilon_0(\varepsilon_r - 1)E \qquad (5)$$

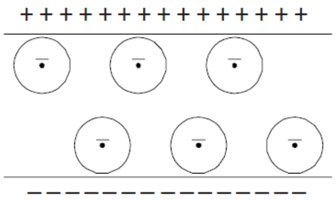
Electronic polarization

Electronic polarization is the result of the displacement of the positively charged nucleus and the (negative) electrons of an atom in opposite directions on application of an electric field.



No field

On applying a field, the electron cloud around the nucleus readily shifts towards the positive end of the field. Such a shift results in a dipole moment within the atom, as a certain distance now separates the nucleus and the centre of the electron cloud.



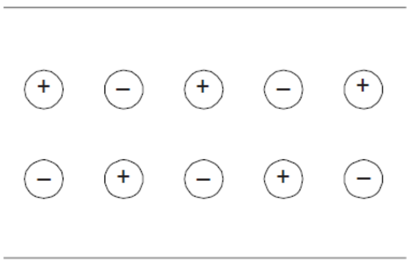
Field applied

The extent of this shift is proportional to the field strength. As the dipole moment is defined as the product of the charge and the shift distance, it is also proportional to the field strength.

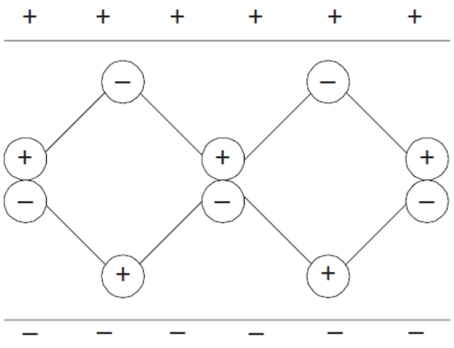
Ionic polarization

The ionic polarizability is due to this shift of the ions relative to other oppositely-charged neighbours. It should be distinguished from electronic polarization, where the electron cloud of an atom shifts with reference to its own nucleus.

In an ionic crystal, for e.g. the negative ions are attracted towards the positive side and vice versa as illustrated in given figure.



No field applied



Field applied

NaCl is a good example of ionic polarization.

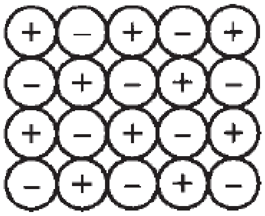
Orientation polarization

There are many molecular structures which have permanent electronic dipoles due to symmetric nature of their atomic structures. Few examples of such molecules are: H_2O, HCl etc.

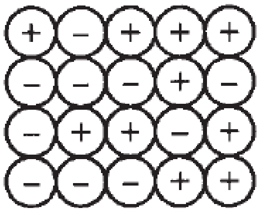
The permanent molecular dipoles in such materials can rotate about their axis of symmetry to align with an applied field which exert a torque in them. This is known as orientation polarization. This type of polarization is |rarely perfect as thermal fluctuations do not permit all the dipoles to align with the applied field. With the rise in temperature the degree of polarization decreases.

Space-Charge polarization

It occurs due to the accumulation of charges at the electrodes or at the interfaces in a multiphase material.



No field



Field applied

The ions diffuse over appreciable distances in response to the applied field, giving rise to a redistribution of charges in the dielectric medium.

Dielectric Loss

A dipole tends to align itself along the direction of applied electric field and for ac fields tends to follow the field and be in a phase with it. However, the interaction of this dipole with other dipoles in the medium prevents this and this leads to dielectric loss. This loss appears as heat.

Usually the dielectric loss is expressed in terms of a quantity called ‘the loss tangent’, tan δ.

$$\tan\delta = \frac{1}{\omega\varepsilon_0\varepsilon'\rho}$$

Where ρ is resistivity.

The energy losses in a dielectric material are due to:

- ionization,
- leakage current,
- polarization, and
- structural inhomogeneity

Dielectric strength

As the voltage applied across a dielectric is increased, dielectric loses its insulation property at a certain voltage called the breakdown voltage (V_{br}). The corresponding field strength (E_{br}) is given by

$$E_{br} = \frac{V_{br}}{t}$$

Here t is the thickness of the material. This voltage, V_{br} per unit thickness of the material is called the dielectric strength and usually expressed in Volts/mil or kV/millimetre or mega Volt/m.

Electric breakdown

The **breakdown of a dielectric** is due to the collision of accelerated electrons or ions with molecules. At relatively high fields, the electrons in the dielectric gain enough energy to knock other charged particles and make them available for conduction.

Dielectric failure involves deterioration and electric breakdown or cascading. Resistance to electronic breakdown in a dielectric is **intrinsic dielectric strength** of the material. Intrinsic breakdown in a dielectric is caused by imperfection. When the applied potential across the dielectric becomes high enough, a few electrons are broken loose at points where their bonds are strained by the presence of imperfections. Upon being freed, these electrons are accelerated rapidly through the material. The dielectric material loses completely its insulating capacity as a result of this process.

Intrinsic breakdown

The intrinsic breakdown of a dielectric material is due to the excitation of electrons into the conduction band across the energy gap under conditions of excessive voltage. The excited electrons moving under a high accelerating force can excite more electrons in turn, resulting in an avalanche of conducting electrons and consequent physical breakdown. It is difficult to see how this can occur in an ideal dielectric, where the energy gap is large. However, impurities in the dielectric can create additional energy levels that lie in the energy gap and can help in the excitation of electrons into the conduction band. An increase in temperature aids the thermal excitation of electrons and can bring about the intrinsic breakdown.

Thermal breakdown

Thermal breakdown is due to the attainment of an excessive temperature in the dielectric. The energy loss referred to earlier has to be dissipated as heat. If the heat dissipated is less than the heat generated, there is a progressive increase in the temperature of the dielectric, which may melt eventually.

Defect breakdown

Defect breakdown is due to cracks and pores at the surface. To decrease the possibility of surface shorting, insulators are designed with lengthened surface paths. Moisture from the atmosphere can collect on the surface discontinuities and result in breakdown. Glazing is done on ceramic insulators to make the surface non-absorbent. Gases can collect at pores and cracks and the breakdown can occur due to a gas discharge.

Example (BPUT 2020, 5 marks)

The polarizability of argon gas is 1.8 x 10^{-40} C^2m/N. Calculate the dielectric constant and electric super susceptibility of argon at NTP.

Solution

Polarization $P = \varepsilon_0(\varepsilon_r - 1)E = N\alpha E$

Or $(\varepsilon_r - 1) = \dfrac{N\alpha}{\varepsilon_0}$

Where N is the number of argon atoms per unit volume at NTP.

$$N = \frac{N_A}{V} = \frac{6.023x10^{23}}{22.4x10^3} = 2.689x10^{19}\,cm^3 = 2.689x10^{25}/m^3$$

Now $\varepsilon_r - 1 = \dfrac{2.689x10^{25}(1.8x10^{-40})}{8.85x10^{-12}}$

∴ $\varepsilon_r = 1.0005469$

Now electric super susceptibility

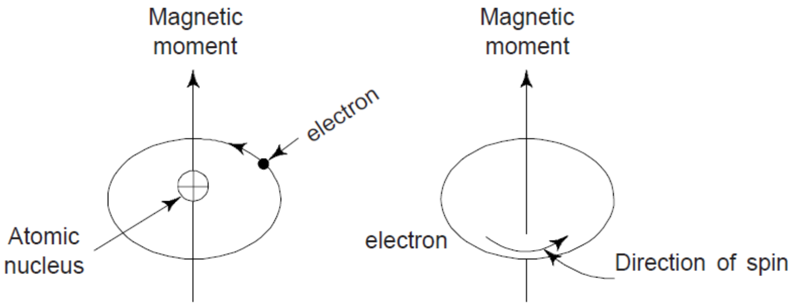
$$X_e = \varepsilon_r - 1 = 1.0005469 - 1 = 0.0005469$$

MAGNETIC MOMENTS

Magnetism is dipolar, i.e. magnetism is characterized by having two opposite poles: north (N) and south (S). The strength of a magnetic dipole is measured by the product of the pole strength and the distance between the poles. This is called magnetic moment. Magnetic dipoles are influenced by magnetic fields and within a magnetic field, the force of the field itself exerts a torque that tends to orient the dipoles with the magnetic field.

The macroscopic magnetic properties of a substance are a consequence of magnetic moments associated with individual electrons. Each electron in an atom has magnetic moments that originate from the following two sources:

- orbital magnetic moment of electrons
- spin magnetic moment of electrons



Magnetic moment associated with (a) an orbiting electron and (b) a spinning electron

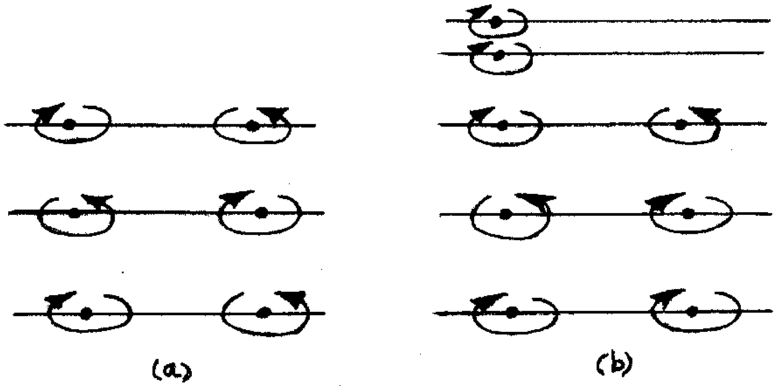
Magnetic properties of a material originate due to the *imbalance* of spin orientation in atoms. A number of atoms or molecules have paired and unpaired electrons. We may note that there is one electron in the outermost s-shell which is unpaired and align itself in an applied field, which gives rise to magnetism. This reveals that the magnetic moment of an atom in the solid state is due only to an incomplete inner shell.

FERROMAGNETISM

Ferromagnetism is a result of the electron structure around atoms. We recall that at most two electrons can occupy each energy level of an isolated atom. These two electrons have “spins” in opposite directions and since each spinning electron is equivalent to a moving charge, each electron acts as an extremely small magnet, with accompanying north and south poles.

Generally speaking, a material with an even number of electrons has as many electrons spinning in one direction as in the other (Following Figure a), and the net effect is a magnetically insensitive structure.

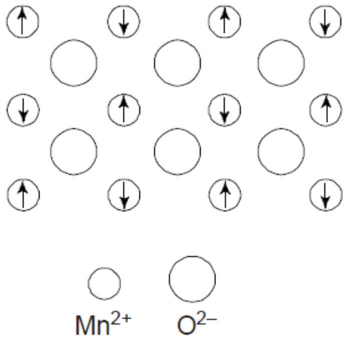
In iron, cobalt, nickel and gadolinium, however, more electrons spin in one direction than in the opposite direction (Fig. b), and therefore the whole atom acts as a small magnet.



In a ferromagnetic material, as in all other substances, the atoms are influenced by their neighbours. Adjacent atoms may align the selves so that their magnetic orientations are in the same direction. Such an area (actually a volume) of magnetic alignment is called a magnetic domain. In an unmagnetized ferromagnetic material, domains are randomly oriented, and consequently their effects are cancelled out. However, if the domains are aligned by a magnetic field, the material becomes magnetic. The alignment of all the domains in one direction provides an additive effect with may or may not be permanent after the external magnetic field is removed. The terms magnetically “hard” and “soft” are used to indicate whether the magnetic alignment is permanently retained.

ANTIFERROMAGNETISM

This originates when the spin moments of the neighbouring atoms are ordered in an antiparallel arrangement (see figure) or when the exchange integral is negative.



This property is exhibited by some metals, alloys and salts of transition elements in which the atomic magnetic moments, at sufficiently low temperatures, form an ordered array which alternates or spirals so as to give no net total moment in zero applied field.

The most direct way of detecting such arrangements is by means of neutron diffraction. A crystal exhibiting antiferromagnetism may be considered to be consisting of two independent sublattices A and B, one of which is spontaneously magnetized in the opposite direction. This type of magnetism was first observed in the crystals of MnO. Manganese oxide (MnO) is a ceramic material that is ionic in character having both Mn^{2+} and O^{2-} ions. No net magnetic moment is associated with the O^{2-} ions, since there is a total cancellation of both spin and orbital moments. However, the Mn^{2+} ions possess a net magnetic moment that is predominantly of spin origin. These Mn^{2+} ions are arrayed in the crystal structure of MnO crystal such that the moments of adjacent Mn^{2+} ions are antiparallel (see figure). This is why that the opposing magnetic moments cancel one another, and as a consequence, the solid as a whole possess no net magnetic moment.

FERRIMAGNETISM

In some compounds, e.g. in some ceramics, etc., the constituent atoms may be antiferromagnetically coupled but with different magnetic moments. This would give rise to a net magnetic moment in each coupling and the some of the moments of all the coupling could result in magnetization which is comparable in order of magnitude to ferromagnets. This phenomenon is termed as *ferrimagnetism*.

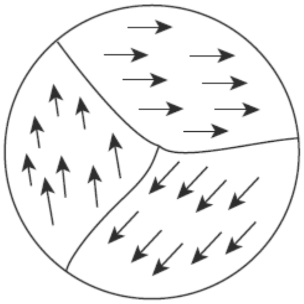
The distinction between the two lies in the source of the net magnetic moments. This type of magnetism occurs in materials such as ferrites which are basically the oxides of various metal elements.

These ionic materials may be represented by the chemical formula MFe_2O_4 in which M represents any one of several metallic elements. The prototype ferrite is Fe_3O_4 or $FeO.Fe_2O_3$ the mineral magnetite, sometimes also called as lodestone.

Ferromagnetic materials which finds wide applications in electrical engineering have a disadvantage, that they have *low electrical resistivity*. The laminations used for electrical machines have a resistivity 14 x 10^{-4} ohm m whereas the highest value obtainable in ferromagnetic alloys is less than 10^{-2} ohm m. Obviously, this disadvantage of the ferromagnetic materials limit their application in high frequency alternating current applications, high eddy current losses and poor magnetic utilization of metals occur in sheets even at low frequencies. The saturation magnetization for ferrimagnetic materials are not as high as for ferromagnets. Moreover, ferrites being ceramic materials, are good electrical insulators. For some magnetic applications, such as high-frequency transformers, a low electrical conductivity is most desirable, because this prevents eddy currents in cores of coils.

DOMAINS AND HYSTERESIS

At temperatures below Curie point, T_c, in ferromagnetic and ferrimagnetic materials, there exist domains, i.e. small volume regions in each of which there is mutual alignment of all magnetic dipoles in the same direction as shown in the figure.

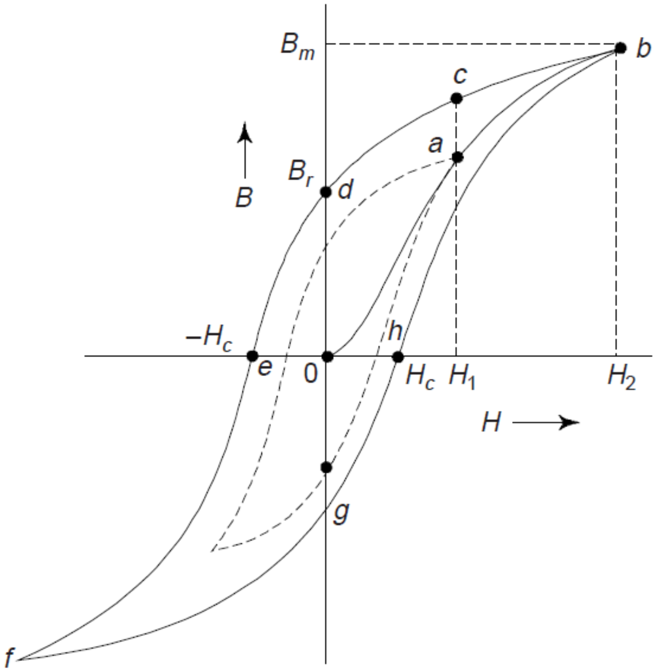


There is magnetization in each domain. For a solid piece, the overall magnetization is the vector sum of magnetizations in all the domains.

Flux density, B and field density, H are not proportional to each other in ferromagnetic and ferrimagnetic materials.

As the field H is applied, domains change shape and size by the movement of domain boundaries. As the field H increases, the domains, which are favourably oriented grow at the expense of other domains that are not favourably oriented. As the process of magnetization continues, at saturation point in all the domains dipole moments are aligned with the external field, H as shown in hysteresis loop. The magnetic dipoles in all domains are aligned with external field, H.

When the ferromagnetic sample that is initially demagnetized is subjected to a continuously increasing magnetizing force H, the relation between H and flux density B is shown by the normal magnetization curve *Oab*.



The point a indicates the magnetic condition as the increasing magnetic intensity has reached H_1. If H is increased to a maximum value H_2 and then decreased again to H_1, the decreasing flux density does not follow the path of increase, but decrease at a rate less than that at which it rose.

The lag in the change of B behind the change of H is called **hysteresis**.

If the value of H is further reduced from H_1 to zero, B is not reduced to zero but to a value B_r. The specimen has retained a permanent magnetism. This ordinate B_r is called the **retentivity** or **remanence**.

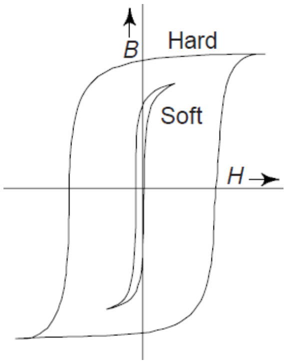
The value of B may be reduced to zero at *e* by reversing the direction of H and increasing its value of H_c. This value of H_c is called the **coercive force** or **coercivity**.

As H is increased in the negative direction, the magnetization proceeds along the curve until at f the values of B and H are the same as those at b, but opposite in direction. When reverse changes in H are made, the magnetization changes along the curve *fghb*. This entire loop *bdefghb* is called a **hysteresis loop**.

If the hysteresis loop starts from another point on the nor mal magnetization curve, such as a, there will be a smaller hysteresis loop entirely within the larger, such as the dotted loop. These curves sometimes called **B-H curves** and are used to describe magnetic materials.

Hysteresis Loop of Soft and Hard Magnets

The difference between hard magnets and soft magnets are best shown by hysteresis loops.



In a soft magnet, there is a near perfect backtrack as the magnetic field is removed. A reversed magnetic field provides a symmetrical curve in the third quadrant.

The hysteresis curve of a permanent (hard) magnet differs significantly. When the magnetic field is removed, most of the induction is retained to give a permanent induction, B_r. A reversed field, called the coercive field, - H_c, is necessary before the induction drops to zero. The completed loop of a permanent magnet possesses 180^0 symmetry.

The integrated area within the hysteresis loop is the energy required to complete one magnetization cycle from 0 to +H to -H to 0. Soft magnets require negligible energy; hard magnets require sufficient energy.

The maximum energy product BH_{max} for pure iron (soft magnet) is about 50 J/m^3.

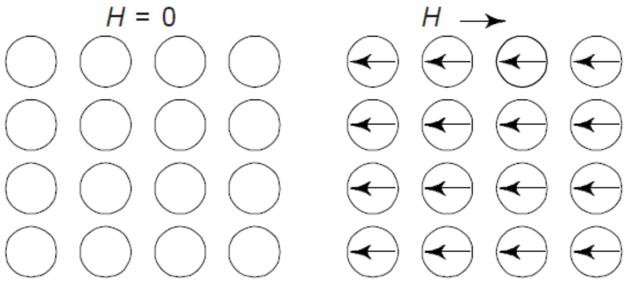
The maximum energy product BH_{max} for plain carbon steel (hard magnet) is about 1000 J/m^3.

DIAMAGNETISM

Diamagnetism is a very weak form of magnetism exhibited by substances with a negative magnetic susceptibility i.e., by substances which magnetize in a direction opposite to that of an applied magnetic field. A diamagnetic substance has a magnetic permeability less than 1, and is repelled when placed near a magnet. Examples are silver, gold, copper etc.

When a magnetic field is applied to an atom, the motion of the orbital electrons gets modified in such a way that a weak magnetic moment opposing the field is induced. Diamagnetism is the result of this interaction. In a diamagnetic solids, the magnetic lines of forces due to an applied field are repelled.

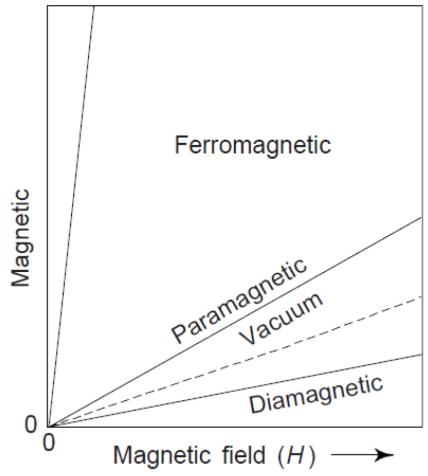
The atomic magnetic dipole configuration for a diamagnetic material with and without an external field is shown in given figure.



The arrows in the figure represent atomic dipole moments.

Diamagnetism is found in all materials; but because it is so weak, it can be observed only when other types of magnetism, i.e. para or ferromagnetism are totally absent. The condition for pure diamagnetism is that all electronic spins be paired and all orbital moments either be zero or effectively cancel one another.

A schematic B-H curve for a magnetic, ferromagnetic, diamagnetic and paramagnetic substances is also shown in below.



BH curve

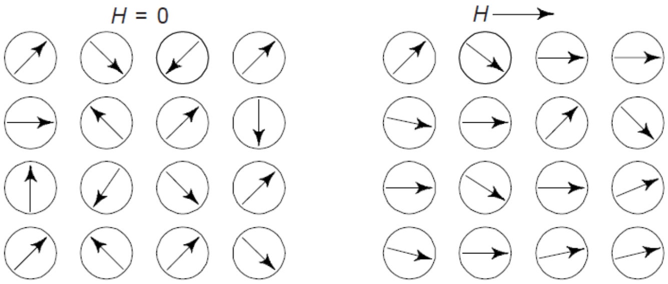
PARAMAGNETISM

Some atoms and molecules possess intrinsic permanent magnetic moments.

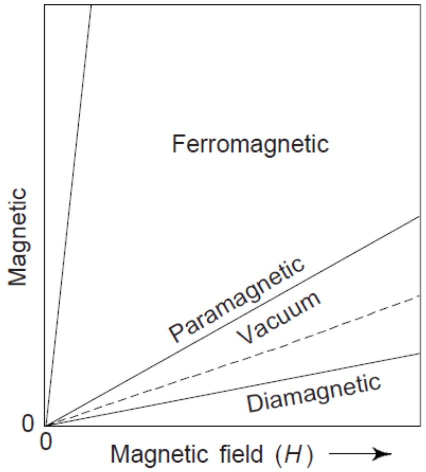
In the absence of an externally applied field, the moments of the atoms in a solid are randomly oriented with respect to one another and the solid as a whole has no net magnetic moment.

If an external field is applied, the magnetic moments tend to align themselves parallel to the applied field, so as to *lower their potential energy*. It is well known that a suspended magnetic needle aligns itself spontaneously with the earth's magnetic field. Similarly, there is a spontaneous tendency for the permanent moment of the atoms of the solid to align themselves in the direction of the field, theory intensifying the lines of force in the field direction. This phenomenon is called Paramagnetism.

The atomic magnetic dipole configuration for a paramagnetic material with and without an external field is shown in given figure. The arrows in the figure represent atomic dipole moments.



A BH curve is shown below.



Example (AU 2020, 2022, 4 marks)

A paramagnetic material has a magnetic field intensity of 10^4 *Am*$^{-1}$*. If the susceptibility of the material at room temperature 1s 3. 7 x* 10^{-3}*, calculate the magnetization and flux density of the material.*

Solution

Susceptibility = I/H

Intensity of magnetisation

$$I = \text{Susceptibility} \times H$$

Intensity of magnetisation = $3.7 \times 10^{-3} \times 10^4 = 37$ A/m

MAGNETIC PERMEABILITY

Some materials become magnetized when placed in a magnetic field; the ability of a material to become magnetized is called magnetic permeability. An example of this is rubbing a piece of iron with a magnet: the iron will become magnetized and have its own magnetic field, meaning it has some degree of magnetic permeability.

Many substances, even water, have a degree of magnetic permeability. When a material is placed in a magnetic field, it interacts with the field in one manner or another. The permeability of a substance describes the way the material responds and the effects of the field on the material. A substance with magnetic permeability will either magnetize itself in the direction of the field or in opposition to it. Thus, depending on the permeability, the substance will either be attracted to or repelled by the field.

Scientists represent magnetic permeability with the Greek letter, mu (μ). The International System of Units (SI) measures permeability in henrys per meter (H/m) or in Newton per ampere squared (N/A^2).

Example

A transformer core is wound with a coil carrying an alternating current at a frequency of 50 Hz. Assuming the magnetization to be uniform throughout the core volume of 0.01 m^3*, calculate the hysteresis loss. The hysteresis loop has an area of 60,000 units, when the axes are drawn in unit of* 10^{-4} $Wb\ m^{-2}$ *and* 10^2*,* Am^{-1}*.*

Solution

Energy lost during each cycle

$$= \text{Area of loop} = 10^{-4} \times 10^2 \times 60{,}000 = 600\ Jm^{-3}$$

Volume of the transformer = $0.01\ m^3$

Energy lost in the core in each cycle = 600 x 0.01 = 6 J

Power loss due to hysteresis = 6J x 50 Hz = 300 W.

Example

In a 440 V, 50 Hz transformer, the total iron loss is 2300 W. When the applied voltage is 220 V at 25 Hz, the total iron loss 750 W. Calculate the eddy current loss at the normal voltage and frequency.

Solution

The hysteresis loss and the induced emf are proportional to the frequency. The eddy current loss is proportional to the square of the induced emf. Let W_e and W_h be the eddy current and the hysteresis losses at 25 Hz. Then,

$$W_e + W_h = 750\ W$$

At 440 V and so Hz, we have

$$4\ W_e + 2\ W_h = 2300\ W$$

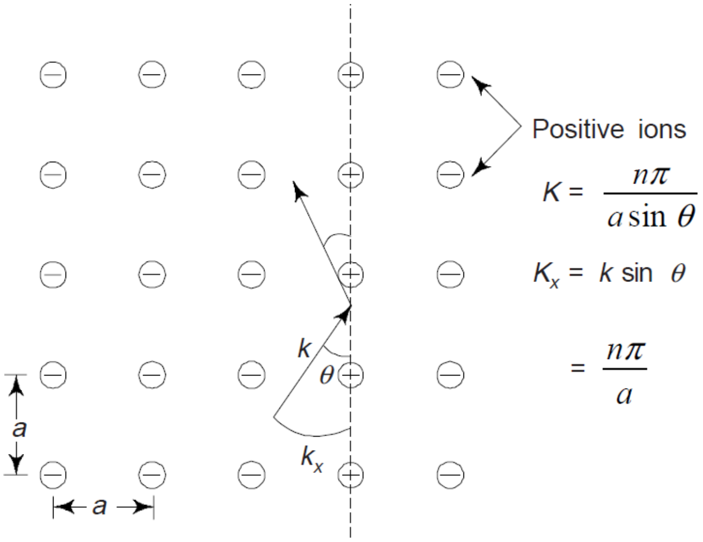
or $$2\ W_e = 800\ W$$

So, the eddy current loss at the normal voltage and frequency = $4\ W_e$ = 1600 W.

ZONE (BAND) THEORY

Electron in a real metal, move in a region of periodic potential (contrary to Somerfield assumption), and are not capable of possessing those energies and directions of movement that produce internal reflections (as per **Bragg's law**). This condition divides electrons in different zone's (Brillouin zone) separated from one another. The differences between the consecutive zones are termed as energy gaps.

In any real metal electrons move in a region of periodic potential.



One of the important conclusions arrived by a wave mechanical treatment of electrons in a periodic potential is that the movement of electron in a crystal can occur under conditions which satisfy the Bragg's Diffraction law.

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

or

$$\lambda = \frac{2a\sin\theta}{n}$$

Where n is an integer, λ is the wave length of the electrons, d is the spacing of a given lattice plane, and θ is the angle of incidence of the electrons relative to the given lattice plane.

From Bragg's law, we are able to derive a relation

$$k\sin\theta = \frac{n\pi}{a}$$

Where, k is a vector the direction of which is the same that in which electron moves, and the magnitude of which is directly proportional to the momentum of the electron.

The above expression tells us that wherever component k resolved normal to the lattice plane equals $\frac{n\pi}{a}$, Bragg's condition of interval reflection of the electron will be satisfied.

Since the critical values of this normal component of the wave number k vary inversely with the inter planer spacing d, it is evident that the first planes to have an influence on the motion of the electrons will be those with the largest value of d, with the lowest miller indices.

In case of simple cubic lattice, Bragg condition is first satisfied by (100) planes of the lattice. After this, the nest set of planes for which Bragg condition will satisfied is (110), the second most widely spaced planes in a simple crystal structure.

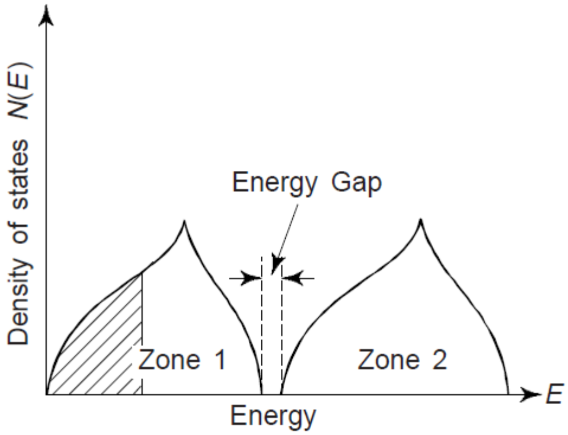
The zones obtained with the help of these sets of planes are generally termed as first Brillouin zones, second Brillouin zone and so on.

A Brillouin zone may be defined as the area in a wave number space enclosed by planes which gives the values of the normal component of the wave number k as $\frac{\pi}{a}$.

Application Of Zone Theory

Conductors

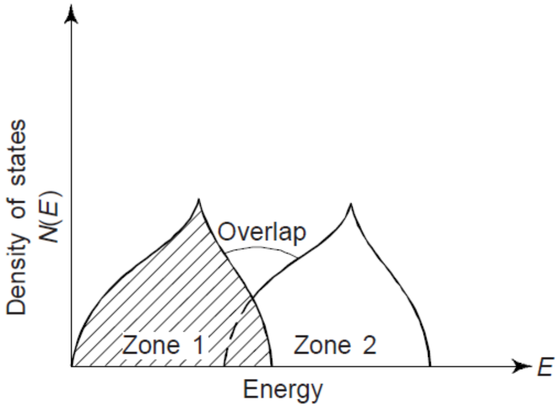
Case I : Let us consider the case where energy gap between the first and second zones is larger enough so that there is no overlapping of energy levels in the first two zones.



Now assume we are concerned with a mono-valent metal with cubic lattice and that each zone metal is capable of holding, two electrons per atom. Since the atoms of the metal contain only a single valence electron per atom, there are enough electrons to fill half of the first zone. At absolute zero, it can be assumed that the electrons will occupy the bottom half of the energy levels of the first zone.

When a zone is partly fined, the solid is a normal metal or electrical conductor. In order that an electrical current can more through a solid, electrons, must be capable of moving into higher energy levels. This is possible in the above case, because energy levels in a zone are vacant and any small applied electrical potential can cause electron to be accelerated into higher energy levels.

Case 2: When a solid contains enough electrons to fill a Brillouin zone completely it may still possess the properties of metallic conductor provided there is an overlapping of zones.

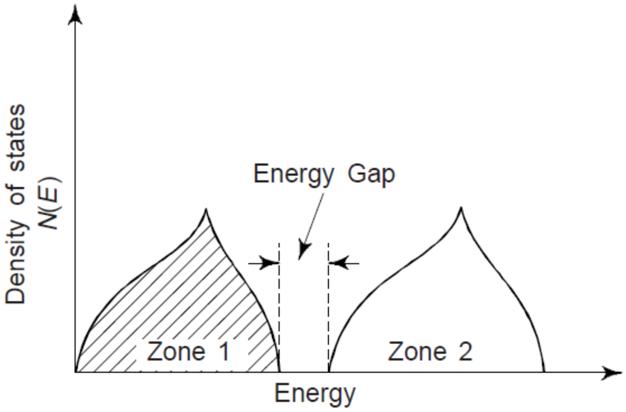


Now, let us assume there are just enough electrons to fill the first zone. Because of overlap in the energy levels. some of the electrons will overflow into the second zone, with the result that both zones will be filled to the same level of energy.

Electrical conduction is possible in a solid of this type because there are empty energy states in both zones directly above the electrons in the Fermi level (highest filled states).

Insulators

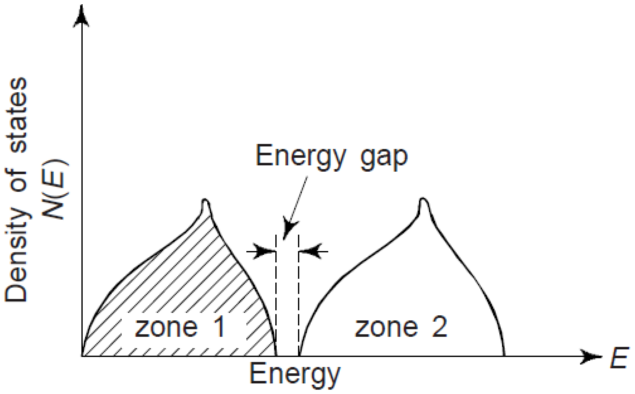
Now consider a solid which contains just enough electrons to fill the first band completely, but where the energy gap between the first and second zone is large enough so that there is no overlapping of energy levels in the first two zones. In the present case, there would be two valence electrons per atoms in a metal with simple cubic structure. The solid behaves as an insulator. Electrons cannot move into higher levels in the first zone core bands, because all of the states are filled. In addition, no normal electrical potential is capable of raising them across the energy gap from first to second zone.



In general, insulator are those materials which have electrical completely filling a Brillouin zone and, the same time, have wide energy gaps between the fined zones and zones lying directly above them.

Semiconductors

These are a group of materials in which the energy gap between the filled and unfilled zones is very small and zones do not overlap.

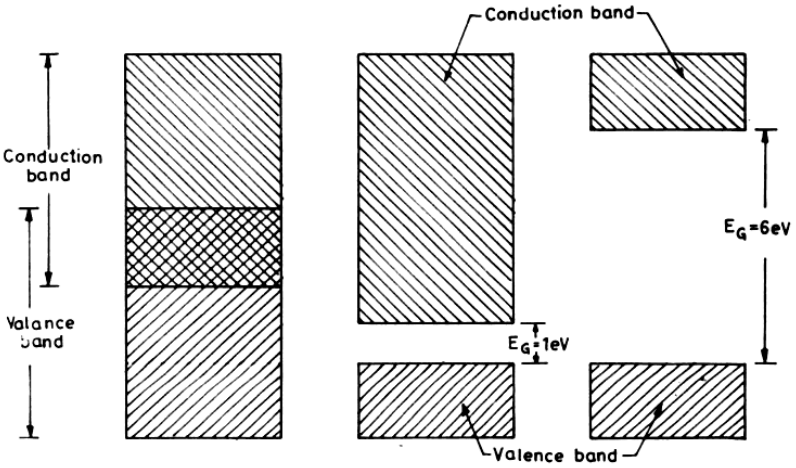


Due to small energy gap between the two zones, no electron can jump from the first zone to the second zone (which is empty) at absolute zero temperature (i.e., at 0°K).

When temperature is raised, say, at room temperature, electrons get sufficient thermal energy which makes electron to jump across the small gap into the empty zone 2. Obviously, in semiconductors, the electrical conductivity (or flow of electron, i.e., current) increases with the increase in temperature. At 0°K, a semiconductor behaves as an insulator since the thermal energy available to cross the energy is zero. The electrical conductivity of semiconductors lies in between those of conductors and insulators.

Energy Band Diagrams of Conductors, Semiconductors and Insulators

On the basis of the energy band structure, a material may be called a conductor, insulator, or semiconductor.



(a) Conductor (b) semiconductor (c) insulator

Conductors

A crystalline solid is called a conductor or metal if the uppermost energy band is *partly filled* or the uppermost filled band and the next unoccupied band overlap in energy.

Here, the electrons in the uppermost band find neighbouring vacant states to move in, and thus behave as free particles. When an electric field is applied, these electrons gain energy from the field and produce an electric current, so that a metal is a good conductor of electricity. The partially filled band is called the **conduction band**. The electrons in the conduction are known as free electrons or conduction electrons. Silver, copper, aluminium, etc. are few examples of good conductors.

Insulators

In some crystalline solids, the forbidden energy gap between the uppermost filled band, called the **valence band**, and the lowermost empty band, called the **conduction band**, is *very large*,

In such solids at ordinary temperatures only a few electrons can acquire enough thermal energy to move from the valence band into the conduction band. Such solids are known as insulators. Since only a few free electrons are available in the conduction band, an insulator is a bad conductor of electricity. It has been observed that if the temperature of an insulator is increased, some electrons do jump to the conduction band. Therefore a small electrical conduction may take place. Rubber, Bakelite, mica etc. are good examples of insulators.

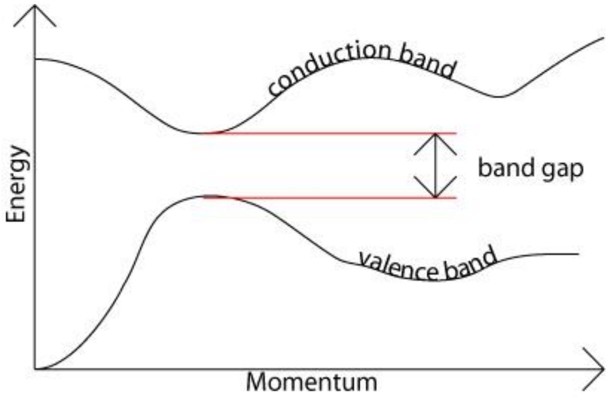
Semiconductors

A material for which the width of the **forbidden energy gap** between the valence and the conduction band is relatively small (about 1 eV) is referred as semiconductor. Germanium and Silicon having forbidden energy gaps of 0.78 and 1.2 eV respectively at 0 K are typical semiconductors. As the forbidden gap is not very wide, some of the valence electrons acquire enough thermal energy to go into the conduction band. These electrons then become free and can move about under the action of an applied electric field. The absence of an electron in the valence band is referred to as a **hole**. The holes also serve as carriers of electricity. The electrical conductivity of a semiconductor is less than that of a metal but greater than that of an insulator.

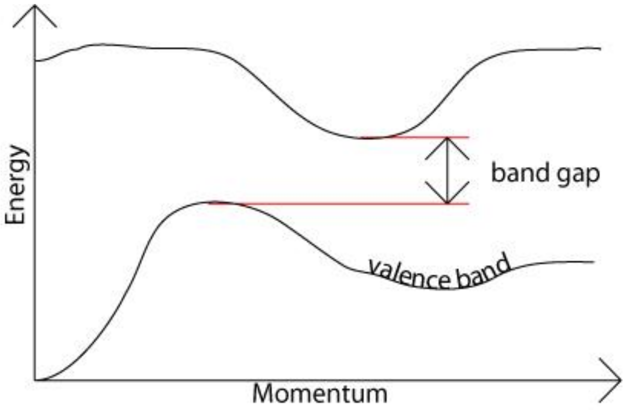
The electrical conduction in semiconductors which we have described is called **intrinsic conductivity**. The conductivity of a semiconductor can also be enhanced by the addition of certain impurities.

Direct and Indirect Band Gap Semiconductors

The band gap represents the minimum energy difference between the top of the valence band and the bottom of the conduction band, However, the top of the valence band and the bottom of the conduction band are not generally at the same value of the electron momentum. In a direct band gap semiconductor, the top of the valence band and the bottom of the conduction band occur at the same value of momentum, as in the schematic below.



n an indirect band gap semiconductor, the maximum energy of the valence band occurs at a different value of momentum to the minimum in the conduction band energy:



The indirect process proceeds at a much slower rate, as it requires three entities to intersect in order to proceed: an electron, a photon and a phonon.

PROPERTIES OF SEMI-CONDUCTORS

- The resistivity of a semi-conductor is more than that of a conductor but less that of an insulator.
- Semi-conductors have negative temperature co-efficient of resistance i.e., the resistance of semi-conductor decreases with the increase in temperature and vice-versa.
- When some suitable impurity (e.g.., arsenic gallium) is added to a semi-conductor, its conduction properties change appreciably.

COMMONLY USED SEMI-CONDUCTOR MATERIALS

There are many varieties of semi-conductor materials used such as germanium, silicon, selenium, boron etc, but **germanium** & **silicon** are the two most frequently used semi-conductor material in electronics. Both elements have the same crystal structure and similar characteristics.

Germanium and silicon are tetravalent elements having four electrons in their outer shells. In pure form, these four valence electrons are covalent bonded with the electrons of neighbouring four atoms. Hence, there are no free electrons available for electrical conduction in these semi-conductor materials. It is due to this fact that germanium and silicon act as insulators under ordinary conditions and at very low temperature (say 0^oK). However, at higher temperatures, some electrons may succeed to liberate themselves and get transferred to the conduction band.

It may be noted here that semi conductive materials are never used in their pure form as such but are used in doped form, where some trivalent or pentavalent element is added in them so as to obtain desired properties. this would become clear from the following articles.

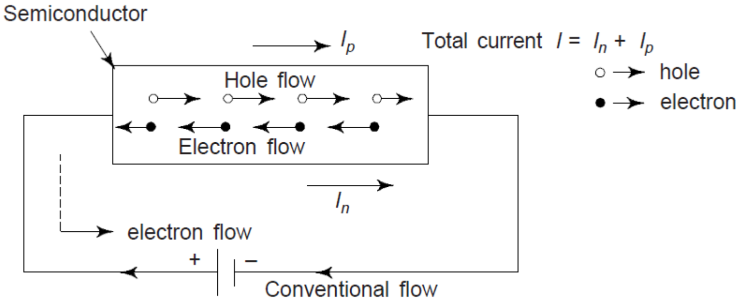
Intrinsic Semiconductors

A pure semiconductor or a semiconductor in its *purest form* is called “intrinsic semiconductor”.

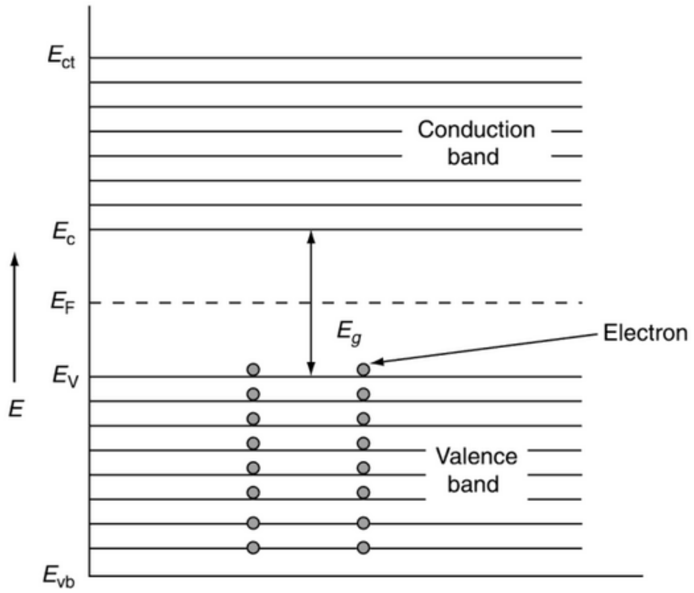
At absolute zero temperature, a pure (or intrinsic) semiconductor behaves as an insulator. If its temperature is raised, the covalent bonds are broken. Whenever a free electron is generated, a hole is created simultaneously. In other words, free electrons and holes are always generated in pairs. Therefore, concentration of electrons and holes in an intrinsic semiconductor will always be equal. This type of generation of electron/hole pairs is called “ thermal generation”.

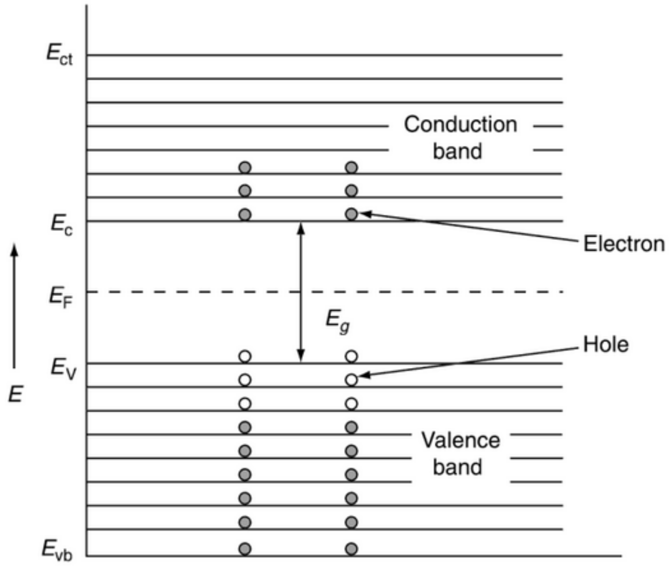
The energy required for lifting an electron from valence band to the conduction band is equal to the forbidden gap. In case of Ge, it is 0.72 eV, and in case of Si, it is 1.12 eV. Due to more gap, less number of electron/hole pairs will be generated in silicon than in germanium at room temperature. In other words at room temperature conductivity of pure silicon will be less than that of germanium.

An electron carries a negative charge and a hole is assumed to carry an equivalent positive charge. Both are called charge carriers and can constitute “**electron current**” and **hole current** respectively.



Both the charge carriers(electrons and holes) move at random or haphazardly within the crystal. When an electron during thermal generation leaves the valence band and enters the conduction band, a hole is created in the valence band. Now this free electron moves at random in the conduction band and the hole(created) moves at random in the valence band.





Since there are two types of charge carriers (free electrons and holes) in the intrinsic semiconductor, its specific conductance is the sum of the conductivities σ_n due to free electrons and σ_p due to holes. Thus the electric conductivity of an intrinsic semiconductor is

$$\sigma_i = \sigma_n + \sigma_p = ne\mu_n + pe\mu_p$$

where μ_e and μ_n are electron and **hole mobilities** respectively. The mobility μ is defined as the **drift velocity** per unit electric field. The magnitude of μ_n is always less than μ_e for semiconductors, n and p are concentrations (number of charge carrier per cubic meter) of electrons and holes respectively in a semiconductor.

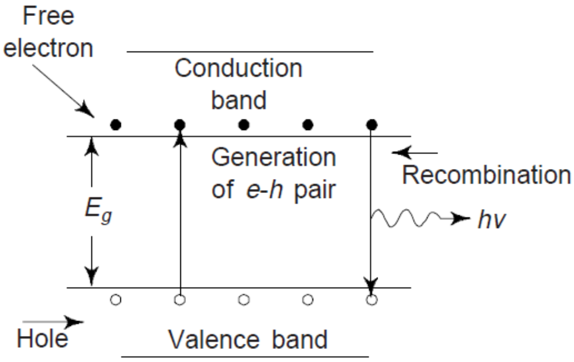
Since for an intrinsic semiconductor

$$n = p = n_i$$

one obtains $\sigma_i = n_i e(\mu_e + \mu_p)$

Recombination of Electrons and Holes

This is the process in which the free electrons in the conduction band jump into the valence band to combine with holes. In this process of recombination the electron-hole (e-h) pair is destroyed.



In this process the minimum energy released in the form of electromagnetic radiation is equal to the band gap (Eg).

We have, E_g = hv. Where h is Planck’s constant and v is the frequency of the radiation.

While some electron-hole pairs are lost due to recombination, new e-h pairs are generated due to thermal excitation. For an intrinsic semiconductor at a constant temperature the rate of combination and the rate of generation of e-h pairs are equal and hence the electron and hole concentrations remain constant at their thermal equilibrium value. With the rise in temperature, the thermal equilibrium value of the electron and the hole concentrations also increases.

Example

The resistivity of pure silicon at room temperature is 3000 ohm m. Calculate the intrinsic carrier density. Given the electron and hole mobilities are 0.14 m^2/Vs and 0.05 m^2/Vs, respectively.

Solution

The intrinsic charge carriers in pure silicon are electrons and holes in equal numbers.

$$n = n_e = n_h = \frac{\sigma}{(\mu_e + \mu_h)e}$$

$$= \frac{1}{(0.14 + 0.05)x3000x1.62x10^{-19}} = 1.095x10^{16}\ m^{-3}$$

Example

Find the conductivity and resistivity of a pure silicon crystal at temperature 300°K. The density of electron hole pair per cc at 300°K for a pure silicon crystal is 1.072 x 10^{10} and the mobility of electron μ_n = 1350 cm^2/volt-sec and hole mobility μ_h = 480 cm^2/volt-sec.

Solution

Conductivity of pure silicon

Conductivity of pure silicon crystal is given by

$$\sigma = n_i e(\mu_e + \mu_n) n_i = 1.072x10^{10}$$

$$\sigma_i = 1.072x10^{10} x1.6x10^{-19}(1350+480) = 3.14x10^{-6}\, mho/cm$$

$$\mu_n = 1350\ cm^2/volt\text{-}sec$$

$$\mu_h = 480\ cm^2/volt\text{-}sec$$

$$e = 1.6x10^{-19}$$

Resistivity of silicon crystal

Resistivity of silicon crystal is given by

$$\rho_i = \frac{1}{\sigma_i} = \frac{1}{3.14x10^{-6}} = 3.18x10^{5}\, ohm - cm$$

Example (AU 2022, 4 marks)

The intrinsic carrier concentration of Ge at 300 K is 2.37 x 10^{19} m^{-3}. Calculate the electrical conductivity, if electron and hole mobilities are 0.38 m^2 v^{-1}s^{-1} and 0.18 m^2 v^{-1}s^{-1}. Also find resistivity.

Solution

$$\sigma_i = n_i e(\mu_e + \mu_h)$$

Given n_i = 2.37 x 10^{19} m^{-3}

μ_e = 0.38 m^{2}V^{-1}s^{-1}

μ_n = 0.18 m^{2}V^{-1}s^{-1}

now $$\sigma_i = n_i e(\mu_e + \mu_n) = 2.37x10^{19} x1.6x10^{-19}(0.38+0.18)$$

= 2.12 Ω^{-1}m^{-1}

Resistivity = 1/σ_i = 1/2.12 = 0.47 Ωm

Example (AU 2022, 2 marks)

Calculate the wavelength emission of GaAs semiconductor which has a band gap of 1.44 eV.

Solution

Energy gap of semiconductor

$$E_g = h\nu$$

Here h= Planck's constant = 6.63 x 10^{-34} J-s

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

∴ $$\lambda = \frac{hc}{E_g}$$

Now $E_g = 1.44 \text{ eV} = 1.44 \text{ x } 1.6 \text{ x } 10^{-19}$ J

∴ $$\lambda = \frac{6.63x10^{-34}x3x10^{8}}{1.44x1.6x10^{-19}} = 8633x10^{-10}m$$

$$= 8633 \text{ Å}$$

Example (AU 2022, 4 marks)

If silicon has energy gap of 1.07 eV at 27°C, what is the probability of an electron being thermally promoted to conduction band?

Solution

$$E - E_f = \frac{1.107}{2} = 0.5535eV$$

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

$$= \frac{1}{e^{(0.5535)/(86.2x10^{-6})(298)}+1} = 4.39x10^{-10}$$

Extrinsic Semiconductor

The number of free electrons and holes produced by thermal energy in a pure semi-conductor is generally too small at room temperature. The number of free electrons and holes may, however, be increased by adding a few atoms of another elements to semi-conductor (known as **doping**).

Depending upon the type of impurity added, the extrinsic semi-conductors are divided into the following two types;

- N-type semi-conductor, and
- P-type semi-conductor

N-Type Extrinsic Semi-Conductor

When the type of impurity added to a semi-conductor is such that there exist a large number of free electrons in the semi-conductor, it is called an N-type semi-conductor. Examples of impurities for this type of semi-conductor are pentavalent impurities like arsenic, antimony and phosphorous. Such impurities which produce N-type semi-conductors are known as donor impurities which produce N-type semi-conductors are known as donor impurities because they provide or donate excess electrons in the semi-conductor crystal.

Consider a pure germanium crystal which has four valence electrons. When a small amount of any pentavalent impurity like arsenic is added to such a crystal, a large number of free electrons exist in the crystal. Arsenic has five valence electrons. An arsenic atom fits in the germanium crystal in such a way that its four valence electrons form covalent bonds with four germanium atoms. The fifth valence electron of arsenic atom finds no place in the covalent bonds and is thus free.

Therefore, for each arsenic atom added one free electron will be available in the germanium crystal. Though each arsenic atom provides only one free electron yet an extremely small amount of arsenic impurity provides enough atoms to supply millions of free electrons.

N-Type conductivity. The current conduction in an N-Type semi-conductor is by electrons i.e. negative charges and is called N-Type conductivity. Electrons are the **majority carries** in N-type semi-conductors, while holes are **minority carries**.

P-Type Extrinsic Semi-Conductor

When the type of impurity added to a semi-conductor is such that there exists a large number of holes in the semi-conductor, it is called P-type semi-conductor. Typical examples are trivalent impurities like gallium, indium or boron. Such impurities are called acceptor impurities because the holes created can accept electrons.

Consider a pure germanium semi-conductor. When a small amount of trivalent impurity like gallium is added to germanium, there exist a large number of holes in the crystal Gallium is trivalent i.e. its atom has three valence electrons. Each atom of gallium impurity fits into the germanium crystal but only three covalent bonds can be formed.

In the fourth covalent bond only germanium atom contributes one valence electron while gallium has no valence electron to contribute as all its three valence electrons are already engaged in covalent bonds with germanium atoms. In other words, fourth bon is incomplete, being short of one electron. This missing electron in the fourth bond is called a hole.

Thus one hole is created in the crystal by the addition of one atom. The number of holes in the germanium semi-conductor depends on the amount of gallium added. The hole is a positive charge equal to charge of one electron with opposite polarity. It acts as a virtual positive charge although there is no physical charge. It follows that in P-type semi-conductor, there exist a large number of holes.

P-type conductivity. The current conduction in a P-type semi-conductor is by holes and is called P-type or hole-type conductivity. Holes are referred to as **majority carries**.

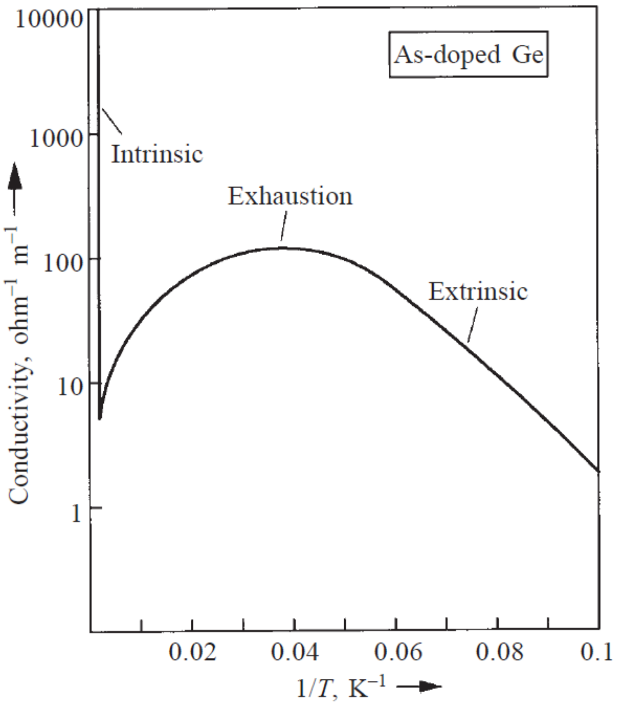
Consider a P-type semi-conductor. Under the influence of potential difference the electrons of the crystal will tend to move towards the positive terminal and jump into available holes of gallium atoms. Since free electrons are not available in P-type germanium the electrons which are moving towards the positive terminal come from covalent bonds. The tendency of electrons to leave the covalent bonds is due to the fact that holes are available in front of them. An electron from one covalent and jumps into the hole in front of it thus leaving the hole in the bond it has left. This electron now jumps into the next available hole and so on. As this process continues it is clear that holes are shifted towards the negative terminal of the battery. It should be noted that in P-type conductivity electrons are simply transferred from one atom to a neighbouring atom.

Difference between n-type and p-type semiconductors

n-type semiconductor	p-type semiconductor
Electrons are majority charge carriers and holes are minority charge carriers.	Holes are majority charge carriers and electrons are minority charge carriers.
The majority of charge carriers move from low potential to high potential.	The majority of charge carriers move from high potential to low potential.
An donor is a doping atom that can produce an n-type semiconductor whenever introduced to a semiconductor.	An acceptor is a contaminating atom that could produce a p-type semiconductor whenever introduced to a semiconductor.
Pentavalent impurities are added.	Trivalent impurities are added.
It has donor energy levels that are very close to the conduction band.	It has acceptor energy levels that are very close to the valence band.

Effect of Temperature on Semiconductors

A typical plot of the logarithm of conductivity against temperature is shown for an extrinsic semiconductor in given figure.



The plot can be divided into three distinct regions. In the low temperature range (corresponding to large values of 1/T), the conductivity is an exponential function of temperature. The electrons excited from the donor level to the conduction band (or the holes created by excitation to the acceptor level) become available in increasing numbers with increasing temperature. So, this region is called the **extrinsic region**.

From the slope of the **straight line** in this region, the ionization energy of the impurity can be calculated.

At higher temperatures, there is the second region called the **exhaustion region**. Here, the excitation of charge carriers due to impurities is nearing completion, due to the exhaustion of unexcited impurity electrons or holes. This is indicated by the flat region of almost zero slope.

Increasing temperature results in decreasing mean free path of the conduction electrons or holes. So, the mobility decreases with increasing temperature.

Above room temperature, there is another linear region with a negative slope of large magnitude, which corresponds to intrinsic conduction. The slope difference between the extrinsic and intrinsic regions reflects the difference in magnitude between the impurity ionization energy and the energy gap E_g.

For stability of operation of a semiconductor device, a relatively flat region is desirable.

FACTORS AFFECTING ELECTRICAL RESISTANCE OF MATERIALS

- **Length**: Electrical resistance is directly proportional to the length of the conductor, more the length, more is the resistance.
- **Area of cross Section:** Electrical resistance is inversely proportional to the area of cross section.
- **Impurities**: impurities in a metal always increase the resistivity of the metal due to their influence on deflecting and scattering of electrons. More the impurities more is the resistivity.
- **Temperature**: Resistivity of a metal increases with temperature according to the relationship, $P_{t2}=P_{t1}[1+\alpha(t_2-t_1)]$, where t_1 and t_2 are the initial and final temperatures, P_{t1} and P_{t2} are the corresponding resistivity and α is the temperature coefficient of resistance. As the temperature of metal rises, atoms vibrate more vigorously and electrons move more randomly. This causes increased collision between electrons and the atoms thereby increasing the resistivity.
- **Plastic deformation**: Cold working like forging, rolling or wire drawing introduces crystal distortions and increase in dislocations. These tend to d3eflect and scatter the moving electrons. This causes an increase in the resistivity.
- **Heat treatment**: Hardening by quenching or precipitation increases resistivity. This is because of increased grain boundaries which hinder the flow of electrons. Annealing has the reverse influence and decreased resistivity.

Doping

Under ordinary conditions, a pure semiconductor behaves like an insulator. But when an extremely small amount of impurity(trivalent or pentavalent atom) is added, it starts behaving like a conductor. The process of adding impurity to a pure semi-conductor to make it an extrinsic semi-conductor, is called *doping*.

In one process, the surface of silicon wafers is exposed to the vapour of an appropriate impurity at a temperature above 1100°C in a quartz tube furnace. The part of the surface not to be exposed to the impurity diffusion must be masked off so that the impurities diffuse into the portion selected by the designer for conductivity change.

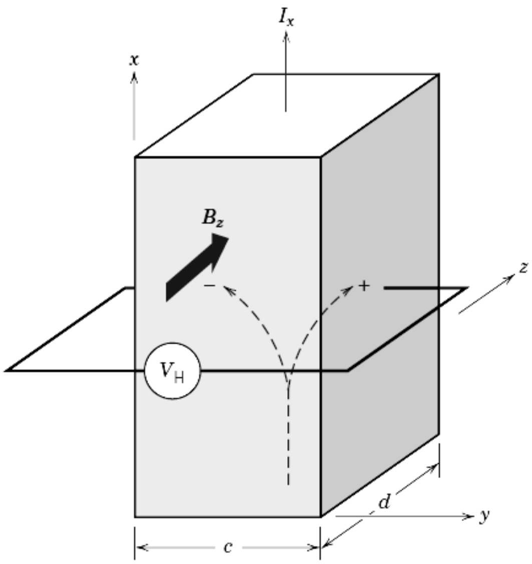
In another technique, p-type silicon wafer is coated with phosphorus and heated to permit the phosphorus to diffuse into the silicon.

HALL EFFECT

he principle of the Hall effect states that when a current-carrying conductor or a semiconductor is introduced to a perpendicular magnetic field, a voltage can be measured at the right angle to the current path. This effect of obtaining a measurable voltage is known as the **Hall effect**.

For some materials, it is on occasion desired to determine the material's majority charge carrier type, concentration, and mobility. Such determinations are not possible from a simple electrical conductivity measurement; a Hall effect experiment must also be conducted. This Hall effect is a result of the phenomenon whereby a magnetic field applied perpendicular to the direction of motion of a charged particle exerts a force on the particle perpendicular to both the magnetic field and the particle motion directions.

In demonstrating the Hall effect, consider the specimen geometry shown in following figure, a parallelepiped specimen having one corner situated at the origin of a Cartesian coordinate system.



In response to an externally applied electric field, the electrons and/or holes move in the x direction and give rise to a current I_x. When a magnetic field is imposed in the positive z direction (denoted as B_z), the resulting force brought to bear on the charge carriers will cause them to be deflected in the y direction—holes (positively charged carriers) to the right specimen face and electrons (negatively charged carriers) to the left face, as indicated in the figure. Thus, a voltage, termed the Hall voltage V_H, will be established in the y direction. The magnitude of V_H will depend on I_x, B_z, and the specimen thickness d as follows:

$$V_H = \frac{R_H I_x B_z}{d} \qquad (1)$$

In this expression R_H is termed the **Hall coefficient**, which is a constant for a given material. For metals, wherein conduction is by electrons, R_H is negative and equal to

$$R_H = \frac{1}{n|e|} \tag{2}$$

Thus, n may be determined, inasmuch as R_H may be measured using Equation 1 and the magnitude of e, the charge on an electron, is known.

Furthermore, the **electron mobility μ_e** is just

$$\mu_e = \frac{\sigma}{n|e|} \tag{3}$$

or, using Equation 2,

$$\mu_e = |R_H|\sigma \tag{4}$$

Thus, the magnitude of μ_e may also be determined if the conductivity has also been measured.

Applications of Hall Effect

The Hall effect is utilized in various applications across different fields. Here are some notable applications:

- **Magnetic Field Sensing:** Hall effect sensors are widely used to measure magnetic fields. They are employed in compasses and navigation systems.
- **Current Sensing:** These sensors can measure the current flowing through a conductor without direct contact, making them essential in power management and electrical systems.
- **Position Sensing:** Hall effect sensors are used in automotive applications, such as determining the position of the crankshaft and camshaft in engines.
- **Speed Detection:** They are used in tachometers to measure the rotational speed of wheels or motors, providing feedback for control systems.
- **Flow Measurement:** In liquid flow meters, Hall effect sensors can measure the flow of conductive fluids by detecting the induced voltage.
- **Data Storage:** In hard drives, Hall effect sensors are used for reading data, detecting the magnetic states of storage media.
- **Proximity Sensing:** These sensors detect the presence of nearby magnetic objects, enabling applications like door sensors and security systems.

Example (AU 2023, 2 marks)

In an N-type semiconductor, the concentration of electron is 2 x 10^{22} m^{-3}. Its electrical conductivity is 112^{-1} m^{-1}. Calculate the mobility of electrons.

Solution

Conductivity $\sigma = 112\ \Omega^{-1}m^{-1}$

Carrier concentration of electrons

$N_i = 2 \times 10^{22}\ m^{-3}$

Hall coefficient

$$R_H = \frac{1}{ne} = \frac{1}{2x10^{22}x1.6x10^{-19}} = 3.125x10^{-4}\ m^{-3}C^{-1}$$

Mobility $\mu = \sigma R_H = 112x3.125x10^{-4} = 0.035\, m^2v^{-1}s^{-1}$

Example (AU 2022, 4 marks)

A n-type semiconductor has Hall coefficient of 4.16 x 10^{-4} m^3 C^{-1}. The conductivity is 108 ohm^{-1}m^{-1}. Calculate its charge earner density n_e and electron mobility (μ_e) at room temperature.

Solution

Hall coefficient $R_H = 4.16 \times 10^{-4}\ m^3C^1$

Conductivity $\sigma = 108\ \Omega m^{-1}$

For “n” type, the charge carrier density

$$n_e = \frac{3\pi}{8}\frac{1}{R_H e} = \frac{3x3.14}{8}.\frac{1}{1.6x10^{-19}x4.6x10^{-4}}$$

$= 1.7690 \times 10^{22}\ m^{-3}$

Electron mobility

$$\mu_e = \frac{\sigma_e}{n_e e} = \frac{108}{1.7690x10^{22}x1.6x10^{-19}}$$

$= 0.0381\ m^2v^{-1}s^{-1}$

ASSIGNMENT

Q.1. (AU 2020, 2 marks): Explain dielectric breakdown in materials.

Answer: Described in this module.

Q.2. (AU 2020, 7 marks): Formulate expressions for electronic, ionic and orientational Polarization and obtain Langevin-Debye Equation for dielectric materials.

Answer: Solved in this module.

Q.3. (BPUT 2020, 5 marks): The polarizability of argon gas is 1.8 x 10^{-40} C^2m/N. Calculate the dielectric constant and electric super susceptibility of argon at NTP.

Answer: Solved in this module.

Q.4. (BPUT 2020, 2 marks): What do you meant by magnetic moment?

Answer: Described in this module.

Q.5. (BPUT 2020, 5 marks): Explain ferromagnetic materials with suitable examples.

Answer: Described in this module.

Q.6. (UTU 2019, 5 marks): Explain: (i) diamagnetism (ii) Paramagnetism (iii) ferromagnetism (iv) antiferromagnetism

Answer: Described in this module.

Q.7. (AU 2020, 2022, 7 marks): Explain the Domain Theory of Ferromagnetism and the types of energy involved in Ferromagnetic materials.

Answer: Described in this module.

Q.8. (UTU 2019, 5 marks): Explain Ferromagnetism and hysteresis curve & loop.

Answer: Described in this module.

Q.9. (BPUT 2020, 5 marks): Write a short note on hysteresis curve.

Answer: Described in this module.

Q.10. (AU 2020, 2022, 4 marks): A paramagnetic material has a magnetic field intensity of 10^4 Am^{-1}. If the susceptibility of the material at room temperature 1s 3. 7 x 10^{-3}, calculate the magnetization and flux density of the material.

Answer: Solved in this module.

Q.11. (AU 2020, BPUT 2020, 2 marks): Differentiate hard and soft magnetic materials.

Answer: Described in this module.

Q.12. (AU 2023, 2 marks): Mention the failures of classical free electron theory.

Answer: The free electron theory of Sommerfeld was successful in explaining the various electronic and thermal properties of metals such as specific heat, Paramagnetism, electrical conductivity, electron emission, etc. However, there are various other properties which could not be explained by this theory.

- The theory could not explain why certain solids have a large number of free electrons and thus behave as good conductors while certain others have hardly any electrons and are, therefore, insulators.
- It also could not account for the variation of resistivity with temperature for the latter type of materials.
- The properties of semiconductors also could not be explained on the basis of this theory.

Q.13. (BPUT 2020, 5 marks): Differentiate between p- and n-type semiconductors with suitable examples.

Answer: Described in this module.

Q.14. (BPUT 2020, 2 marks): Why the conductivities of semiconductor material increases on increasing with temperature?

Answer: Described in this module.

Q.15. (AU 2022, 2 marks): What is electron effective mass?

Answer: When an external field is applied to a semiconductor, the charge carriers, i.e., the electrons and the holes, experience forces due to the external applied field and also due to the internal periodic field produced by the crystal. If the external applied is much weaker than the internal field, the effect of the latter is to modify the mass of the carriers in such a way that the carriers respond to the applied field with this modified mass obeying the laws of classical mechanics. This modified mass of the carriers is termed the effective mass of the carriers.

Q.16. (AU 2022, 2 marks): What is an indirect band gap semiconductor? Give example.

Answer: Described in this module.

Q.17. (AU 2022, 2 marks): Distinguish drift current and diffusion current.

Answer: Diffusion current: The diffusion current is composed of majority charge carrier electrons in N region and holes in P region, overcoming the potential barrier to diffuse electrons into P region and holes into N region. In unbiased junction, the majority charge carriers have just insufficient energy to cross the potential barrier. With forward biasing, the height of contact potential gets lowered. The majority charge carriers having energy more than that required overcoming the potential barrier of forward biased junction start diffusing across the junction and diffusion current starts flowing. With increase in forward bias voltage, the magnitude of potential barrier decreases. Thus the diffusion current increases with increase of forward bias voltage.

Drift current: The drift current is given by I = neAv. The drift velocity v is directly proportional to electric field. Thus it seems that, if the drift current depends on potential barrier. But the drift current is relatively insensitive to the height of the potential barrier. This is due to the fact that the drift current is limited not only by how fast carriers arc swept down the barrier, but rather also depends on how often and how many.

Q.18. (AU 2022, 2023, 2 marks): What is known as recombination in semiconductor?

Answer: Described in this module.

Q.19. (AU 2022, BPUT 2020, 12 marks): Explain Hall effect phenomena and obtain an expression for Hall coefficient.

Answer: Described in this module.

Q.20. (BPUT 2020, 2 marks): What are the application of Hall Effect?

Answer: Described in this module.

Q.21. (AU 2022, 2 marks): Calculate the electrical conductivity of copper, which has electron density 2 x 10^{28}/cm^3 and $\tau = 10^{-4}$ second.

Q.22. (AU 2022, 2 marks): Calculate the wavelength emission of GaAs semiconductor which has a band gap of 1.44 eV.

Answer: Solved in this module.

Q.23. (AU 2022, 4 marks): The intrinsic carrier concentration of Ge at 300 K is 2.37 x 10^{19} m^{-3}. Calculate the electrical conductivity, if electron and hole mobilities are 0.38 m^2 $v^{-1}s^{-1}$ and 0.18 m^2 $v^{-1}s^{-1}$.

Answer: Solved in this module.

Q.24. (AU 2023, 2 marks): In an N-type semiconductor, the concentration of electron is 2 x 10^{22} m^{-3}. Its electrical conductivity is 112^{-1} m^{-1}. Calculate the mobility of electrons.

Answer: Solved in this module.

Q.25. (AU 2022, 4 marks): If silicon has energy gap of 1.07 eV at 27°C, what is the probability of an electron being thermally promoted to conduction band?

Answer: Solved in this module.

Q.26. (AU 2022, 4 marks): A n-type semiconductor has Hall coefficient of 4.16 x 10^{-4} m^3 C^{-1}. The conductivity is 108 $ohm^{-1}m^{-1}$. Calculate its charge earner density n_e and electron mobility (μ_e) at room temperature.

Answer: Solved in this module.