Chapter 10

Semiconductor and Superconductivity

Semiconductor

Semiconductors are materials having four valence electrons and whose electrical conductivity lies between the conductivities of good conductors and insulators. ex: Ge, Si.

At absolute zero, a semiconductor acts as an insulator when temperature increases some of the valence electron are able to cross the small forbidden gap and reach the conduction band. Hence conductivity increases as temperature increases. Therefore it has negative temperature coefficient of resistance [R decreases with T].

The forbidden band gap does not exist in metal, it is narrow in semiconductor and wide in insulator.

Currents in Semiconductor

Current in semiconductor is due to motion of both electron in conduction band and motion of holes in valance band.

1. **Electron current:**

At room temperature conduction electrons are present in semiconductor. They move at random manner. Under the action of external field these electron acquire an additional force in the direction of electric field, and move towards anode thus forming the electron current. The electron current is same as that in pure conductor.

2. **Hole current:**

When a semiconductor is at normal temperature, some of the electrons in valence band jump to conduction band and create holes in valence band, when an external field's applied, the valence electron move from the end at negative potential to the end of positive potential. The electron jump forward to the succeeding hole by creating a hole behind. Again the later electron jump to succeeding hole by creating a hole behind. In this way there occurs a movement of electron from one hole to another. It seems as a movement of hole in the direction opposite to that of electron. This movement of hole constitutes a current called hole current.

- electron current is due to the flow of electron in conduction band.
- hole current is due to the flow of electron in valence band.
- The charge of hole can be considered as a positive charge having equal magnitude as the charge of an electron.

- The hole current and electron current have opposite direction.

Type of Semiconductors

1. **Intrinsic Semiconductor**

A pure semiconductor is called an intrinsic semiconductor. In any intrinsic semiconductor, the thermally generated electrons and holes are so few that we can not get any useful current. So it's conductivity is poor. The thermally generated electron and holes are so few that it can be considered as an insulator.

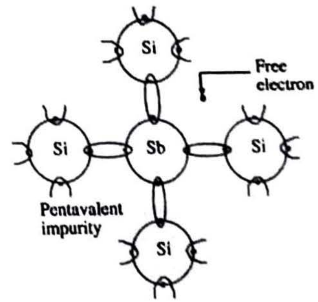
2. **Extrinsic Semiconductor**

The conductivity of semiconductor rises when some impurities are added on it. The addition of impurity causes to increase either electron concentration or hole concentration. Such semiconductors which are doped with some impurity and having higher conductivity are called an extrinsic semiconductor.

Extrinsic semiconductors are of two types.

a. **N-type Semiconductor**

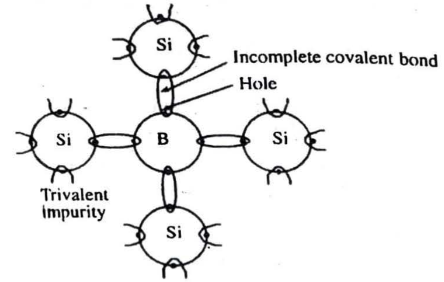
When a pentavalent impurity like arsenic (As), phosphorus (P) or antimony (Sb) is added to pure semiconductor, a N-type semiconductor is formed. The four electrons out of five valence electron of these impurity make covalent bond with four valance electron of Silicon or Germanium. So one electrons remains free on every add of impurity. Since the concentration of electron (negative charge carries) increases in this semiconductor so it is called N-type semiconductor. Since the pentavalent atom donate an electron for conduction so it is called donor.



In N-type semiconductor electrons are majority charge carriers and holes are minority charge carrier. In this semiconductor each Germanium have four covalent bonds with impurity atom. But each impurity atom have four covalent bonds with Germanium atoms leaving behind one free electron. So, pentavalent impurity is called donor.

b. **P-type Semiconductor**

When a trivalent impurity such as Boron (B), Aluminum (Al) or Gallium (Ga) is added to pure Silicon or Germanium, a p-type semiconductor is formed.



The three valence electron of those impurity can form only three complete covalent bonds with silicon which has four valence electron. There is deficiency of one electron to form fourth bond. This means an electron vacancy is left in the fourth bond. This give rise to a hole. So one hole is created on every add of trivalent impurity. In this way concentration of hole can be raised to desire level without increasing the concentration of electron.

In this semiconductor holes are majority charge carrier and electrons are minority charge carrier. Hence it is named P-type semiconductor.

In this semiconductor three silicon atom have covalent bond with Boron. Since Boron has only three valence electron so fourth bond can not be formed. Which creates a hole as shown in figure above.

When a trivalent impurity is doped in a pure silicon, a hole is created. This hole has tendency to accept an electron so trivalent impurities are called acceptor.

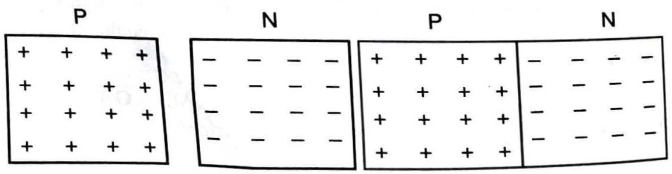
P-N Junction

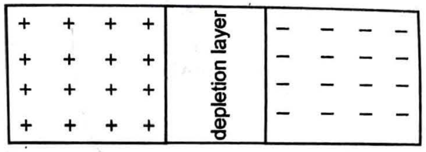
When one P – type semiconductor and one N-type semiconductor are placed in contact as shown in figure below, the resulting semiconductor device is called P–N junction diode, the plane of contact is called junction of diode.

When P-type and N-type crystals are placed in contact the recombination of electrons and holes takes place at the junction. This continues till a potential barriers is developed at the junction of diode. This region of potential barrier is called depletion layer.

The value of voltage developed at the junction is called junction voltage.

The two surface of the depletion layer act like two plates of the capacitor. The capacitance between these two surfaces is called junction capacitance.





Biasing of a P-N Junction

There are two possible ways of an external voltage can be applied to the P-N junction.

1. **Forward Biasing**

   A P-N junction is said to be forward biased if the positive terminal of a battery is connected to P-region and negative terminal of the battery is connected to the N-region.

   In forward biased, electrons from N-side and holes from P-side are pushed toward the junction. The depletion layer decreases which results the decrease in junction potential.

   On increasing the applied potential, the current through the diode also increases. The potential at which the current suddenly attains a high value is called Knee voltage (V_K). The value of knee voltage for Si and Ge are 0.7 V and 0.3 V respectively. If the applied voltage is greater than knee voltage a continuous current flows in the diode. Thus, semiconductor diode acts as conductor.

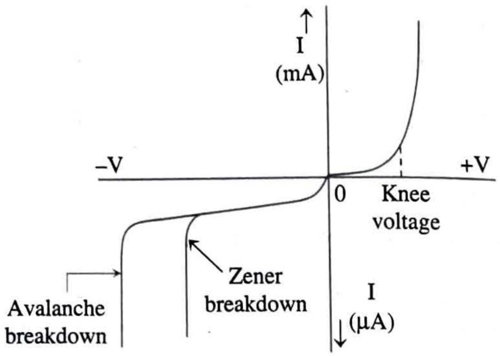
2. **Reverse Biasing**

   A P-N junction is said to be reverse biased if the negative terminal of a battery is connected to P-region and positive terminal of the battery is connected to N-region. In reverse biased, the holes on the P-region are attracted towards the cathode of the battery. While the electrons in the N-region are attracted towards anode of the battery. As result, the depletion layer widens. As the voltage increases small current flows through the diode. On increasing the voltage, at a definite value of reverse voltage $V_r = V_{br}$ the reverse current goes up abruptly. This phenomenon is known as pn junction breakdown and the reverse voltage Vr at which the junction break down is known as breakdown voltage V_{br}. There are two types of break down in reverse biased P-N junction.

Types of Breakdown

1. **Zener breakdown:** This form of break down occurs in junctions which, being heavily doped, have narrow depletion layer. The break down voltage can set up a very strong electric field across this narrow layer This field is strong enough to break the covalent bonds there by generating electron hole pairs. Even a small further increase in reverse voltage is capable of producing large number of current carriers.

2. **Avalanche break down:** This form of break down occurs in junctions which being lightly doped, have wide depletion layers where the electric field is not strong enough to produce zener break down. The minority carriers acclerated by applied field collide with the atoms in the depletion region. Upon collision with valence electrons, covalent bonds are broken and electron hole pairs are generated. These newly generated charge carries are also accelerated by the electric field resulting in more collisions and hence further production of charge carriers. This leads to an avalanche of charge carriers producing large current and hence break down.



Mobility

The magnitude of drift velocity (average velocity of electron) per unit applied electric field is called mobility of electron.

i.e. $\mu = \frac{v_d}{E}$ .... (1)

since, $J = n\,e\,v_d$

Also, $J = \sigma E$

Comparing these two equations

$$ne\,v_d = \sigma E \text{ or } \frac{v_d}{E} = \frac{\sigma}{n\,e} \Rightarrow \mu = \frac{\sigma}{n\,e}$$

Therefore, $\sigma = ne\mu$ .... (2)

Also, $\sigma = \frac{ne^2\tau}{m}$ ..... (3)

From (2) and (3) we can write,

$$n\,e\mu = \frac{ne^2\tau}{m}$$

$\mu = \frac{e\,\tau}{m}$ ..... (4) where τ is relaxation time.

Conductivity of Semiconductor:

In case of semiconductor, the current is due to flow of both electrons and holes. If σ_e and σ_h are conductivity of a semiconductor due to electrons and holes respectively, the total conductivity is given by.

$$\sigma = \sigma_e + \sigma_h$$

We know, $\sigma = ne\,\mu$

For electron, $\sigma_e = n_e\,e\,\mu_e$, where, n_e = number of electrons per unit volume, μ_e = mobility of electron

and for holes, $\sigma_h = n_h e\,\mu_h$, where, n_h = number of holes, μ_h = mobility of holes

Substituting σ_e and σ_h for σ

$$\sigma = (n_e\,e\mu_e + n_h\,e\,\mu_h)$$

$$\text{or, } \sigma = e\,(n_e\mu_e + n_h\,\mu_h)$$

The resistivity is given by the expression,

$$\sigma = \frac{1}{\rho} = e\,(n_e\mu_e + n_h\mu_h)$$

For an intrinsic semiconductor, $n_e = n_h = n$ (say)

$$\sigma = ne\,(\mu_e + \mu_h)$$

According this equation, conductivity increases with 'n'. As temperature increases the free charge carriers (n) increase in semiconductor. So conductivity of semiconductor increases with temperature.

Junction Capacitance

P-N junction exhibit capacitive effects when they are either forward biased or reverse biased.

Diffusion or Storage Capacitance (C_D)

When the pn junction is forward biased we get diffusion capacitance. If the forward voltage across the pn junction is increased, the more holes will diffuse towards n-region and more electrons will diffuse towards p-side. Electrons are minority carriers in p-region and holes are minority carriers in n-region. *The rate of increase of diffused minority charge with applied potential difference is defined as diffusion capacitance.*

i.e. $C_D = \frac{dQ}{dV}$

Depletion Layer or Transition Capacitance (C_T)

When the pn junction is reverse biased we get depletion layer capacitance. For reverse biased, the depletion region acts like an insulator or as a dielectric material. The p and n-regions on either side have low resistance and acts as plates of parallel plate capacitor. *This junction capacitance is called transition capacitance or depletion layer capacitance.* It is also termed as space charge layer capacitance or barrier capacitance.

It is given by,

$$C_T = \frac{\epsilon A}{W}$$

Where,

ϵ = Permittivity of depletion region

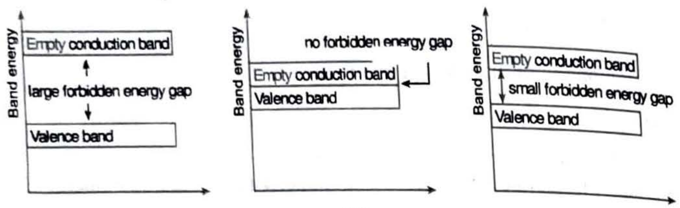
A = Cross - sectional area of p or n-region

W = Width of transition region.

When the reverse biased is increased, it will increase W and C_T will decreases.

Electrical conduction in metals, insulators and semiconductor according to band theory of solids:

The electrical conduction properties of different elements and compounds can be explained in terms of number of electrons present in conduction band. The electrons lying in the valence band play no part in the conduction process.



(a) (b) (c)

Fig. Energy band model for (a) insulator (b) metal (c) semiconductor

a. **Conductor (metals):**

Metals are those in which plenty of electrons are available for electrical conduction. Therefore metals are excellent conductors.

In terms of energy bands, conductors are those which have overlapping valence and conduction bands or no forbidden band. So valence electron also take part in conduction process. Due to the absence of forbidden energy gap, there is no possibility to establish holes. The total current is simply a flow of electrons.

b. **Insulators:**

An insulator has wide forbidden energy gap. The valence band is completely filled with electrons and the conduction band is completely empty. The valence electrons are bound very tightly to their parent atom thus requiring very large electric field to remove them from attraction of their nucei. For conduction to take place, electrons must be given sufficient energy to jump from the valence band to conduction band. Increase in temperature enables some electrons to go to conduction band which accounts for the negative temperature coefficient of resistance of insulators.

c. **Semiconductors:**

The electrical property of semiconductor lies in between those of insulators and conductors. At room temperature, they have partially filled conduction band and partially filled valence band. The valence band is very narrow in the order of nearly about 1 eV. At absolute zero, there are no electrons in conduction band and valence band is completely filled. With increase in temperature, some of electrons get excited to conduction band from valence band. This means the conductivity of semiconductor increases with temperature. So they have negative temperature coefficient of resistance.

Metal-Semi conductor Junction

In solid state physics, a metal semiconductor junction is a type of junction in which a metal comes in close contact with a semiconductor material. M-S Junction can either be rectifying or non rectifying. The rectifying metal semiconductor Junction forms a Schottky Junction, making a device known as a Schottky diode while the non rectifying junction is called Ohmic contact.

1. Schottky Junction

A Schottky Junction is rectifying in the sense that it allows flow of current in one direction and opposes the flow of current in opposite direction. When the work function of metal (ϕ_m) is greater than that of n-type semiconductor (ϕ_n), a Schottky Junction is formed. In this case the Fermi level of n- type semiconductor lies above that of metal. The more energetic electrons in the conduction band of the semiconductor can easily tunnel into metal, leaving behind a net positive space charge. A potential V_o, therefore develops between the metal and semiconductor. Eventually, at equilibrium this built in potential reaches a value that prevents further accumulation of electrons at the metal surface. At equilibrium, the Fermi level through out the solid is uniform. Thus E_{Fm} and E_{Fn} line up.

In case of Schottky junction the flow of electrons takes place from semiconductor side to metal side. The electrons will accumulate in metal and the positive charges were left in the region of semiconductor near to contact region. So the gap E_c - E_F increases in that region. The Fermi level is at equilibrium position or at constant position. So to maintain the increase in E_c - E_F gap the conduction band of semiconductor near to contact region bends upward as shown in figure. This phenomenon is called *band bending*.

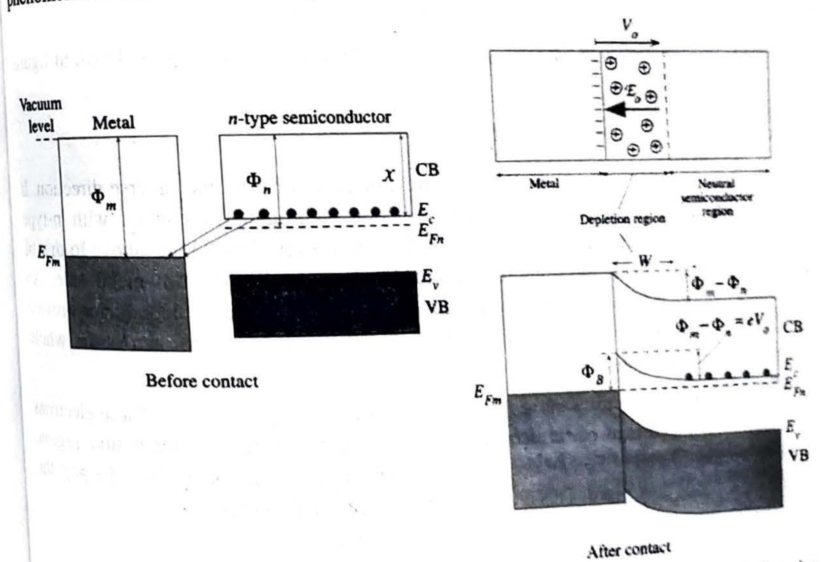


Figure (1): *Formation of a Schottky junction between metal and an n-type semiconductor when $\phi_m > \phi_n$*

Case - I:

Under forward biased condition the semiconductor side is connected to negative terminal of supply. It assists the flow of electron from semiconductor to metal. The applied potential (V) reduces the built in potential (V_o) to V_o-V.

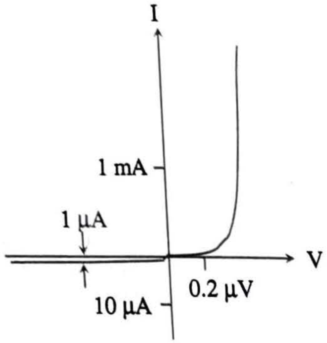


Figure 2: I - V characteristics of Schottky Junction exhibits rectifying properties.

Case II:

When the Schottky junction is reverse biased, that is the positive terminal is connected to the semiconductor, It resists (opposes) the flow of electron from semi conductor to metal. The applied potential (V_r) increases the built in potential V_o to $V_o + V_r$.

Thus the I - V characteristics of Schottky junction exhibit rectifying property as shown in figure (2).

2. Ohmic Contact

An Ohmic contact means, it allows the flow of current in both forward and reverse direction. It is formed when a metal having smaller work function is brought in contact with n-type semiconductor having larger work function. That is the Fermi level of metal lies above to that of semiconductor, which means electrons tunnel into the semi conductor from metal side. An equilibrium is reached when the accumulated electrons in the CB of the semiconductor prevent further electrons tunneling from the metal that is the Fermi level is uniform across the whole system from one end to another.

In case of Ohmic contact, electrons move from metal side to semiconductor side. These electrons will accumulate in the region of semiconductor near to contact called accumulation region. Hence in this region the E_C - E_F gap decreases. To maintain the decrease in E_C - E_F gap the conduction band bends downward. This phenomenon is called *band bending.*

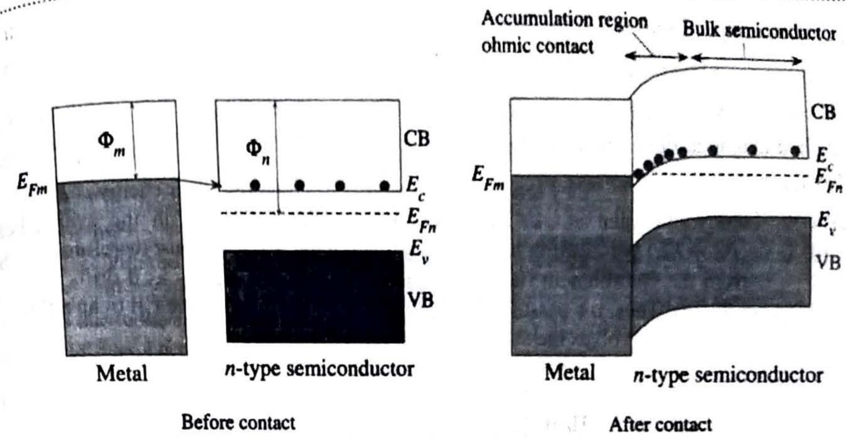


Figure 3: When a metal with a smaller work function than an n-type semiconductor is put into contact with the n-type semiconductor, the resulting junction is an Ohmic contact in the sense that it does not limit the current flow.

The semi conductor region near the Junction in which there are excess of electron is called the accumulation region. It can be seen from figure (3) that the conduction electrons on either side of contact region have about the same energy and therefore there is no barrier involved to cross the junction by electrons in either direction under applied field.

The Ohmic contact is a junction between a metal and a semiconductor that does not limit current flow in either direction. The current is limited by the resistance of semiconductor outside the contact region rather than the thermal emission of carriers across the potential barrier at contact. Both the metal and the accumulation region have comparatively high concentrations of electrons compared with the bulk of semiconductor. The current is therefore determined by the resistance of the bulk region. The current density is simply $J = \sigma E$

Where,

σ = conductivity of semiconductor

E = applied field.

Superconductors

Kammerlingh Onnes discovered that the resistivity of mercury (Hg) becomes zero below the temperature of 4K. This property of material being of zero resistivity below certain temperature is called superconductivity. Such materials are called superconductor. And this temperature is called critical temperature. Below the critical temperature the material is in superconductive state and above the critical temperature the material is in normal state.

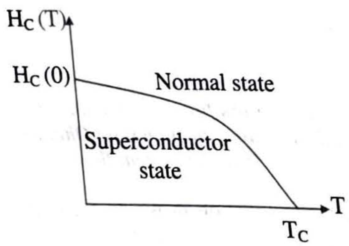
In superconductor current once created persist for several years without diminution because there is no thermal energy loss.

Property of superconductor

1. Critical magnetic field:

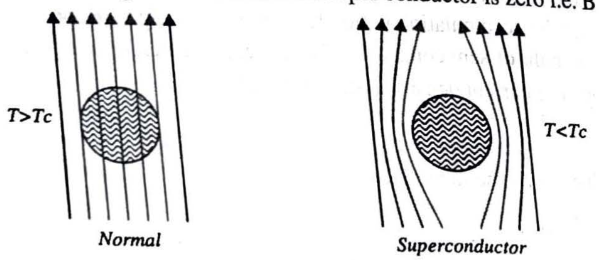
A sufficiently strong magnetic field can destroy superconductivity. The critical value of applied magnetic field which can destroy superconductivity is called critical magnetic field Hc(T).

At critical temperature, the critical field is zero, i.e. Hc (T) = 0. The veriation of critical field with temperature is as shown in figure The nature of curve is parabolic and can be represented by the relation. $H_c(T) = H_c(0)\left(1-\frac{T^2}{T_c^2}\right)$, where Hc(0) is critical field at 0 K.



2. Meissner Effect:

Meissner in 1935, found that if a superconductor is cooled in a magnetic field down to critical temperature, the lines of induction of magnetic field (B) are pushed out. This phenomenon is called Meissner effect. This means superconductor shows perfect diamagnetic effect i.e. magnetic field inside the super conductor is zero i.e. B = 0.



We have, $B = \mu_o(H+M) \Rightarrow 0 = \mu_o(H+M)$

$$\Rightarrow H + M = 0 \Rightarrow H = -M \Rightarrow \frac{m}{H} = -1$$

Therefore, susceptibility $\chi = \frac{M}{H} = -1$

Since χ is –ve, so superconductor exhibit perfect diamagnetism.

We thus conclude that the conditions defining superconducting state are,

E = 0 (Since $\rho = 0$, from the absence of resistivity)

B = 0 (from meissner effect)

BCS Theory

The microscopic theory put forward by Bardeen, Cooper and Schrieffer (BCS) provides the better quantum explanation of superconductivity. It accounts very well for all the properties exhibited by the superconductor. This theory is called BCS theory.

According to this theory the superconductivity occur when a strong interaction between two electrons takes place to distort the lattice. This interaction is strongest when the two electrons have equal and opposite moment and spin. Such an interaction occurs by means of phonon exchange. The superconductivity occurs when this attractive interaction overcome the usual repulsive coulomb interaction. Two such electrons which interact attractively in the phonon field are called a Cooper pair.

The paired elections (Cooper pairs) can maintain their coupled motion up to a certain distance called coherence length. The coherence length is given by $L_g = \frac{\hbar v_F}{B_E}$

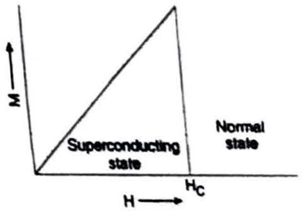
Here, v_F is called Fermi velocity and B_E is binding energy of the pairs.

Classification of Superconductors

On the basis of magnetizing behaviour, superconductors can be classified as type – I (or soft) and type – II (or hard) superconductors.

Type – I superconductor

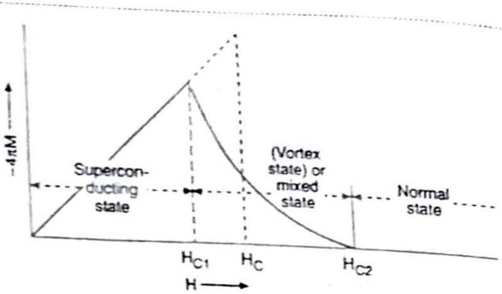
This type of superconductor obeys complete Meissner's effect up to critical field. They are completely diamagnetic. The magnetization curve for Type - I materials is as shown in figure. At the critical magnetizing field, the magnetization decreases abruptly and the material becomes normal.



Type I

Type – II Super Conductor

This type of superconductor losses magnetization gradually as shown in figure. For applied field below H_{C1} the material is diamagnetic and hence the field is completely excluded.



Type II

Here H_{C1} is called lower critical field. Above H_{C1}, the field starts penetrating into the material until the upper critical field H_{C2} is reached. Between the two critical magnetic fields H_{C2} and H_{C1}, the material is said to be in mixed state or vortex state. Above the magnetic field H_{C2}, the material becomes normal conductor.

Solved Example

1. Calculate the coherence length of aluminum, if the size of the energy gap is 3.4×10^{-4} eV and Fermi velocity is $2.02\times10^{6}ms^{-1}$.

Solution:

Given,

$$B_E = 3.4\times10^{-4}eV = 3.4\times10^{-4}\times1.6\times10^{-19}\ J$$

$$V_F = 2.02\times10^{6}\ ms^{-1}$$

We have coherence length $L_\xi = \frac{\hbar v_F}{B_E} = \frac{hv_F}{2\pi B_E}$

$$\Rightarrow L_\xi = \frac{6.62\times10^{-34}\times2.02\times10^{6}}{2\times3.14\times3.4\times10^{-4}\times1.6\times10^{-19}} = 3.92\times10^{-6}m$$

$\therefore$ Coherence length $L_\xi = 3.92\times10^{-6}m$

Exercise

1. What are intrinsic and extrinsic semiconductors?
2. Explain the classification of solids. What are metals, insulators and semiconductors.
3. Discuss the energy band structure of solids and explain electrons and holes conduction.
4. What do you mean by semiconductors? Explain the term intrinsic and extrinsic semiconductor.
5. How will you prepare a p–n junction from p – type and n–type materials. How do the free carriers behave at the junction? Explain the terms (i) Depletion layer (ii) Junction break down (iii) Junction capacitance.
6. Write short notes on types of break down in pn-Junction diode.

7. Write short notes on metal - semiconductor Junction. Derive an expression for electrical conductivity of semiconductor.
8. Define P-type and N-type semiconductor. Derive an expression for electrical conductivity of semiconductor.
9. Explain the mechanism of conduction in metal and semiconductor.
10. Classify solids on the basis of band theory of solids.
11. What is superconductor. Explain superconductivity with reference to BCS theory.
12. Write short notes on types of superconductor.
13. What are super conductors? Explain the various properties of super conductor.
14. Explain the distinction between type -I (soft) and type II (hard) super conductors using Meissner effect.
15. Write short notes on critical magnetic field and Meissner effect.
16. Mobilities of electrons and holes in a sample of intrinsic germanium at room temperature are 36000 cm^2/Volt-sec and 1700 cm^2/Volt-sec respectively. If the electron and hole densities are each equal to 2.5×10^{13} per cm^3, calculate the conductivity.

    [Hint: $\sigma = \sigma_n + \sigma_p = (ne\mu_e + ne\mu_h) = 2.12$ mho]
17. The super conducting state of a lead specimen has critical temperature 6.2K at zero magnetic field and the critical field is 0.64×10^{6} A/m at 0°K. Estimate the critical field at 5K.

    [Hint: $T_c = 6.2K$, $H_c(0) = 0.64\times10^{6}$ A/m, T = 5K, $H_c(T) = ?$

    $H_c(T) = H_c(0)\,[1-\frac{T^2}{T_c^2}] = 2.22\times10^{4}$ A/m]
18. Critical temperature of a superconductor when no magnetic field present is 6.65 K. Find the temperature at which critical field becomes one half of its value at 0°k. [Ans: T = 4]
19. Experiments on a sample show that at 12 K a critical field of 15T exist and at 10 K the critical field is 18 T. Calculate (i) Critical temperature (T_c) ii) Critical field at 0°K [$H_c(O)$]

    [Hint: $H_c(12) = H_C(0)\,[1-\left(\frac{12}{T_c}\right)^2]$ and $H_c(10) = H_c(0)\,[1-\left(\frac{10}{T_c}\right)^2]$

    divide these two equations to get, T_c then substitute T_c in one of above equations to get H_c (0)]
7. What are Superconductors? How they differ from perfect conductors? Give basic properties and uses of super conductors.

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