

B.E. 2nd Semester Examination May-2008
Paper : PHY-102-E

Time allowed : 3 hours]

[Maximum marks : 100

Before answering the question, candidates should ensure that they have been supplied the correct and complete question paper. No complaint in this regard will be entertained after examination.

Note : Attempt any **five** questions, selecting at least two questions from each part.

PART-A

1. (a) What are Miller indices? Give their significance. How would you determine the Miller indices of a plane in a crystal? 10
(b) What are point defects in solids? Derive an expression for the concentration of Schottky defects at equilibrium temperature. 10
2. (a) What is Plank's constant? Discuss its importance? 8
(b) Derive time independent Schrodinger wave equation for a free particle. 12
3. (a) Discuss the motion of a free electron in a periodic potential and discuss Fermi-Dirac distribution function. 14
(b) What is density of states? Discuss briefly. 6
4. Write notes on any two : 10+10
(i) X-ray diffraction powder method for crystal structure analysis.
(ii) Thermionic Emmission,
(ii) Drude theory of conduction.

PART - B

5. (a) Discuss briefly : 15
(i) Origin of energy bands,
(ii) E-k diagrams, and
(iii) Brillouin zones
(b) What is fermi energy? Discuss its variation with temperature. 5
6. (a) What is photo-conductivity? Discuss a simple model of a photo-conductor. Show that sensitive photo-conductors should have long response time. 15
(b) Write a short note on photovoltaic cells. 5
7. (a) What is superconductivity? Give salient features and uses of superconductors. 12
(b) Describe London theory of superconductivity. 8
8. Write notes on any two : 10+10
(i) Classical theory of ferromagnetism
(ii) Effective mass

Ans. 1. (a) Miller Indices

Miller indices are the set of smallest integers (hkl) required to specify the set of parallel planes in a crystal lattice.

For a particular lattice the sets of lattice planes may be chosen in different ways for example (a), (b), (c), (d) etc., see fig. The spacing between the successive planes and the density of lattice points vary accordingly.

Determination of the Miller indices of a plane in a crystal :

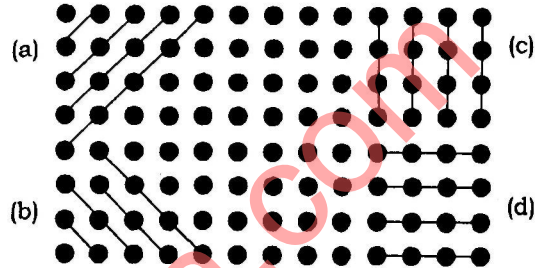
(i) Let us consider that the intercepts by the given lattice plane on the three crystal axes X , Y and Z are in the ratio $pa : qb : rc$ where a , b and c may be either small integers or simple fractions.

(ii) Take the reciprocal of p, q, r , i.e., $\frac{1}{p}, \frac{1}{q}, \frac{1}{r}$

(iii) Finally determine the smallest possible

integers h, k, l such that $h:k:l = \frac{1}{p}, \frac{1}{q}, \frac{1}{r}$

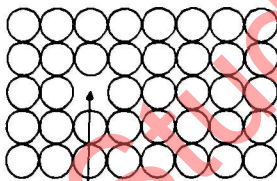
The numbers h, k, l are called the *Miller indices* of a given set of planes and the plane is specified as (hkl).

**Ans. 1. (b) Point Defects :**

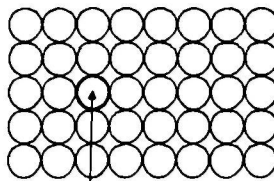
Point defects are irregularities of crystal lattice at some isolated lattice points. As the name implies point defects are the point like regions in the crystal and therefore may also be referred as zero-dimensional imperfections. Point defect may have its extension upto a few atom diameters.

The most common point defects in a crystal of a pure element are as follows :

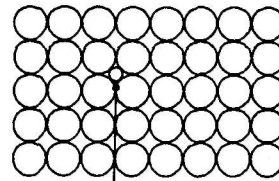
(i) **Vacancies** : A vacancy is the simplest point defect in a crystal. A vacancy refers to a missing atom or vacant atomic site in a crystal. (Fig.a) This defect may either arise from imperfect packing during the original crystallisation or from thermal vibrations of atoms at high temperatures.



Vacancy
(a)



Substitutional Impurity
(b)



Interstitial Impurity
(c)

(ii) **Substitutional impurity** : It is the impurity in which a foreign atom replace a parent atom in the crystal. Pentavalent or trivalent impurity atoms doped in pure semiconductor crystal (Germanium or silicon) refer substitutional impurity in the crystal (Fig.b).

(iii) **Interstitial Impurity** : In crystals the packing factor is always less than 1. In crystals in which packing factor is low, an extra small sized atom can enter the interstitial space in the parent crystal without disturbing the regularly positioned atoms. Such an impurity is called interstitial impurity.

Expression for the Concentration of Schottky Defects at equilibrium temperature:

We consider a pure crystal composed of equal number of positively and negatively charged ions and suppose that it contains a total of N ions and n Schottky defects, i.e. n cation vacancies and n anion vacancies in its interior. To calculate its free energy F , we first calculate S and U . We calculate S by using the result that the number of different ways in which each kind of vacancies can be produced is given by

$$\frac{N!}{(N-n)!n!} \quad \dots (1)$$

and that the different ways W in which n vacancy pairs can be produced is obtained by squaring the expression (1), since the number of cation and anion vacancies are equal. We thus use

$$W = \left[\frac{N!}{(N-n)!n!} \right]^2 \quad \dots (2)$$

Finally, we use also the Boltzmann relation

$$W = k_B \log W, \text{ where } k_B \text{ is Boltzmann's constant } \dots (3)$$

and obtain for S as

$$S = k_B \log \left[\frac{N!}{(N-n)!n!} \right]^2 \quad \dots (4)$$

U is expressed as

$$u = nE_p \quad \dots (5)$$

where E_p is the energy required to produce a pair of vacancies in the crystal's interior, U the internal energy of the crystal. Thus, the Helmholtz free energy F of the crystal is

$$F = U - TS = nE_p - k_B T \log \left[\frac{N!}{(N-n)!n!} \right]^2 \quad \dots (6)$$

The logarithmic term in (6) containing factorials can be simplified by using Stirling's approximation :

$$\log x! \cong x \log x - x \quad \text{for } x > 1$$

so that

$$\begin{aligned} \log \left[\frac{N!}{(N-n)!n!} \right]^2 &= 2[\log N! - \log(N-n)! - \log n!] \\ &= 2[N \log N - N - (N-n) \log(N-n) + (N-n) - n \log n + n] \\ &= 2[N \log N - (N-n) \log(N-n) - n \log n] \quad \dots (7) \end{aligned}$$

We thus have in place of (6) :

$$F = nE_p - 2k_B T [N \log N - (N-n) \log(N-n) - n \log n] \quad \dots (8)$$

Now, when the equilibrium is attained at a given temperature T , the free energy F is minimum. This means that

$$\left(\frac{\partial F}{\partial n} \right)_T = 0 = E_p - 2k_B T [\log(N-n) - \log n] \quad \dots (9)$$

since the total number of atomic positions in the crystal, N , is not altered. We thus have, after rearranging the term in (9),

or
$$\frac{N-n}{n} = -e^{E_p/2k_B T} \quad \dots(10)$$

As the number of vacancies in a crystal is much smaller than the number of ions; that is $n \ll N$ and $N - n \approx N$, we have may approximate (10) as

$$n \approx N e^{-E_p/2k_B T} \quad \dots(11)$$

This gives the concentration of Schottky defects when the equilibrium is attained at a temperature T .

Ans. 2. (a) Plank's Constant:

The Plank's constant ' h ' was introduced by Plank to explain the characteristics of black body radiation. At that time the Plank's idea of "*discrete change of energy* between radiation and matter" was revolutionary and infact this idea gave birth to quantum theory.

The value of Plank's constant $h = 6.62 \times 10^{-34}$ joule-second.

Importance : The discovery of Plank's constant led to the origin of quantum theory. Due to smallness of h the quantum theory is applicale only where energy changes and dimensions of particles are very small.

Ans. 2. (b) Time Independent Schrödinger Equation:

Consider a system of stationary waves to be associated with the particle. Let $\psi(\mathbf{r}, t)$ be the wave characteristic for the de-Broglie wave at the any location $\mathbf{r} = ix + jy + kz$ at time t . Then the differential equation of the wave motion in three dimension in accordance with Maxwell wave-equation can be written as

$$\nabla^2 \psi = \frac{1}{u^2} \frac{\partial^2 \psi}{\partial t^2} \quad \text{or} \quad \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} + \frac{1}{u^2} \frac{\partial^2 \psi}{\partial t^2} \quad \dots(1)$$

where u is the wave velocity.

The solution of equation (1) gives ψ as a periodic displacement in term of time i.e.

$$\psi(\mathbf{r}, t) = \psi_0 e^{-i\omega t} \quad \dots(2)$$

where ψ_0 is the amplitude at the point considered. It is function of position \mathbf{r} i.e. of co-ordinates (x, y, z) and not of time t .

The equation (2) may be expressed as

$$\psi(\mathbf{r}, t) = \psi_0(\mathbf{r}) e^{-i\omega t} \quad \dots(3)$$

Differentiating equation (3) twice with respect to t , we get

$$\frac{\partial \psi}{\partial t} = -i\omega \psi_0(\mathbf{r}) e^{-i\omega t} \quad \text{and} \quad \frac{\partial^2 \psi}{\partial t^2} = -\omega^2 \psi_0(\mathbf{r}) e^{-i\omega t}$$

Substitute this in equation (1), we get

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} = -\frac{\omega^2}{u^2} \psi \quad \dots(4)$$

$$\text{But } \omega = 2\pi\nu = \frac{2\pi u}{\lambda} \Rightarrow \frac{\omega}{u} = \frac{2\pi}{\lambda} \quad \dots(5)$$

$$\text{Also } \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} = \nabla^2 \psi \quad \dots(6)$$

Using equations (5) and (6), equation (4) becomes

$$\nabla^2 \psi + \frac{4\pi^2}{\lambda^2} \psi = 0 \quad \dots(7)$$

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So far we have not introduced wave mechanical concept and so that treatment is general. For introducing the concept of wave mechanics, we must put for De-Broglie equation.

$$\lambda = \frac{h}{mv} \quad \dots(8)$$

Sub. in equation (7), we get

$$\nabla^2\psi + \frac{4\pi^2m^2v^2}{h^2}\psi = 0 \quad \dots(9)$$

If E and v are the total and potential energies of the particle respectively then its K.E. $\frac{1}{2}mv^2$ is given by $\frac{1}{2}mv^2 = E - V$ which gives $m^2v^2 = 2m(E - V)$

Substituting this in equation (9), we get

$$\nabla^2\psi + \frac{8\pi^2m}{h^2}(E - V)\psi = 0 \quad \dots(10)$$

The above equation is called Schrodinger time independent wave equation. The quantity ψ is usually referred as wave function.

Let us now substitute in equation (10)

$$h = \frac{h}{2\pi} \quad \dots(11)$$

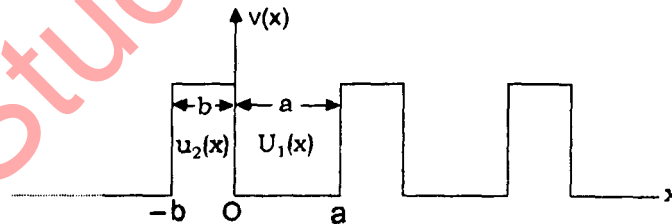
Then Schrodinger time-independent wave equation in usually used form may be written as

$$\nabla^2\psi + \frac{2m}{h^2}(E - V)\psi = 0 \quad \dots(12)$$

This is Schrodinger's time independent wave equation.

Ans. 3. (a) Motion of a free electron in a periodic potential :

Ans. For the motion of an electron in a periodic potential, it assumes that the potential energy of an electron in a linear array of positive nuclei has the form of a periodic square potentials of periods $a + b$ such that in regions such as $0 < x < a$, the potential energy is equal to zero and in region such as $-b < x < 0$; the potential energy is V_0 . The potential function is shown in fig. This model, although idealised, is very useful because it explains many useful periodic features of the behaviour of electron-lattices.



Fermi Dirac Distribution Function :

The assembly of electrons may be regarded as a Fermi-Dirac gas obeying Fermi-Dirac statistics.

The probability $f(\epsilon)$ of an electron occupying an energy level ϵ given by

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

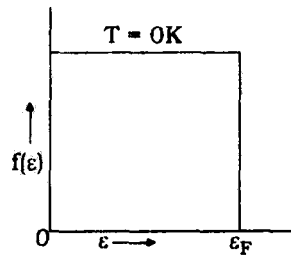
where ϵ_F is the Fermi energy and is a constant for a given system.

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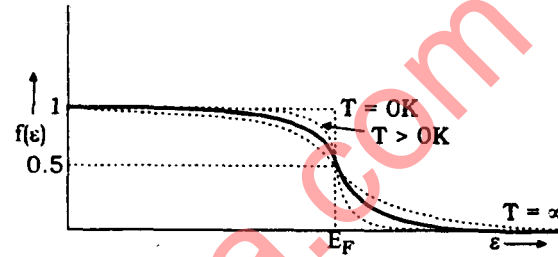
Following figures represents the shape of Fermi-function at different temperatures.

$$f(\epsilon) = \begin{cases} 1 & \text{for } \epsilon < \epsilon_F \\ 0 & \text{for } \epsilon > \epsilon_F \end{cases}$$

This means that at absolute zero, all the quantum states below ϵ_F are completely occupied while all the quantum states above ϵ_F are completely unoccupied, so ϵ_F is the maximum energy of the filled state. With increase of temperature the Fermi-function plot shows deviation.



(a) At absolute zero



(b) At different temperature

At any temperature above 0 K if $\epsilon = \epsilon_F$

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

Thus Fermi level is that level at which probability of electrons occupation is $\frac{1}{2}$.

At any finite temperature (say $T = 300$ K), the Fermi function differs from Fermi plot at 0 K in the searing of the drop from 1 to 0. In actual case the extent of searing is very small except at very high temperatures.

Ans. 3. (b) Density of states :

We have seen that the energy levels of a particle in a region constant potential are quantised. The number of energy levels per unit energy range at given energy is called the density of states, i.e.

$$\text{density of states} = \frac{dn}{dE_n}$$

$$\text{We have } E_n = V_0 + \frac{n^2 \pi^2 \hbar^2}{2mL^2} \quad \dots(1)$$

Differentiate w.r.t. n , we get ($V_0 = \text{constant}$)

$$dE_n = \frac{\pi^2 \hbar^2}{2mL^2} 2n dn$$

\therefore Density of states

$$\therefore \frac{dn}{dE_n} = \frac{mL^2}{\pi^2 \hbar^2 n}$$

$$\text{From (1), } n = \left[\frac{2mL^2(E_n - V_0)}{\pi^2 \hbar^2} \right]^{1/2}$$

$$\therefore \text{Density of states } D(E_n) = \frac{dn}{dE_n} = \frac{mL^2}{\pi^2 \hbar^2 \cdot [2mL^2(E_n - V_0)/\pi^2 \hbar^2]^{1/2}}$$

$$= \frac{L}{n\hbar} \left[\frac{m}{2(E_n - V_0)} \right]^{1/2}$$

Ans. 4. (i) X-Ray diffraction powder method for crystal structure analysis :

Please see answer 4(b), Paper December 2008

Ans. 4. (ii) Thermionic Emission :

Thermionic Emission : The phenomenon of emission of electrons from the surface of the metal, when it is heated, is called thermionic emission. In vacuum tubes, the metallic cathode is heated which supplies the electrons for the operation of the tube. Thermionic emission from pure metals depend upon the temperature of the metal, the nature and surface of the metal and the surrounding of the metal. We shall discuss the condition which allows the electron to escape the metal surface.

According to free electron model, at absolute zero, all levels upto Fermi level E_F are filled. The electron at E_F cannot escape the metal surface because of an energy barrier at the surface. The height of this barrier is ϕ and is called work function. As the temperature is raised, the electrons from below E_F occupy the levels above it. At energies higher than $(E_F + \phi)$, the levels above the barrier become populated. Electrons in these levels have enough energy and escape from metal surface of metals, this results in thermionic emission, as shown in the fig.

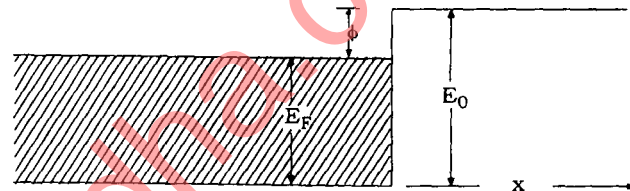


Fig. Model of Thermionic Emission

Ans. 4. (iii) Drude Theory of Conduction :

The basic assumptions of **Lorentz-Drude theory** are :

1. There are a large number of free electrons in a metal. These electrons are free to move about the whole volume of the metal like the molecules of a perfect gas in a container.
2. The motion of free electrons in a metal is similar to the thermal agitation of a perfect gas. The assembly of free electrons in a metal is called electron gas. The electrical or thermal conductivity of metals is solely due to these free electrons.
3. The free electrons in metals move randomly in all possible directions with widely different velocities like the molecules of a perfect gas. The distribution of velocities is in accordance with Maxwellian distribution for a gas. The random speed is a function of temperature, the average kinetic energy of a free electron is equal to that of a gas molecule

at the same temperature. Thus the average kinetic energy of an electron is $\left(\frac{3}{2}\right)kT$ where k is Boltzmann's constant and T is absolute temperature.

4. The free electrons make collisions from time to time with fixed positive ions in the lattice and also among themselves. The collisions among the electrons themselves have no practical contribution to the conductivity of metals.

5. In the absence of a external electric field, the random motion of free electrons is equally probable along all directions. As a result the current density vector is zero in the absence of electric field.

6. When an external electric field is applied, the electrons drift slowly with some average velocity; known as average drift velocity, in the direction opposite to that of electric

field. The drift velocity of free electrons is superimposed over their random velocity. Thus the random motion of free electrons is modified by the application of external electric field.

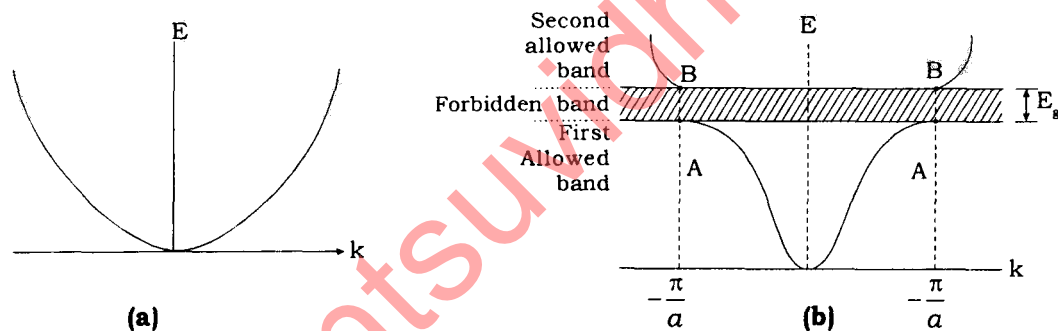
7. In the presence of external electric field, the process of inelastic collision of free electrons with the positive ions of the lattice continues.

8. The average distance traversed by a free electron between two successive collisions with the positive ions is known as mean free path represented by λ .

Ans. 5. (a) (i) Origin of Energy Bands :

Bragg reflection, as discussed in diffraction of x-rays in crystals, is an important feature of wave propagation in periodic structures. The important consequence of Bragg reflection is that it leads to the existence of an energy gap in the distribution in energy of the states of conduction electrons. These energy gaps are also called forbidden energy bands.

In order to understand the origin of forbidden bands, consider first the simple problem of a linear lattice of lattice constant ' a '. The low energy portion of the band structure are shown in [Fig. (a)] for entirely free electrons and in [Fig. (b)] for electrons which are nearly free but have an energy discontinuity at $k = \pi/a$ giving rise to a forbidden energy band. In one dimension the Bragg equation $2d \sin \theta = n\lambda$ becomes $k = n\pi/a$ so that the first reflections occur at $k = \pm\pi/a$ and the first energy gap also occurs at these points. Other energy gaps occur for the other positive and negative integral values of n .



Ans. 5. (a) (ii) E-K Diagrams :

Please see answer 5 (a), Paper December 2008.

5. (a) (iii) Brillouin Zones

(i) **One dimensional :** In one dimensional periodic potential lattice, the energy discontinuities occur when wave number k satisfies the condition $k = n\pi/a$, n is a positive or negative integer. If we consider a line, in the following fig. representing k values divided into energy discontinuities into segments of length $\pm\pi/a$, then these line segments are known as Brillouin zones. The first segment $-\pi/a < k < \pi/a$ is called first Brillouin zone, the two segments $-\pi/a < k < -2\pi/a$ and $\pi/a < k < 2\pi/a$ correspond to the second Brillouin zone and so on.

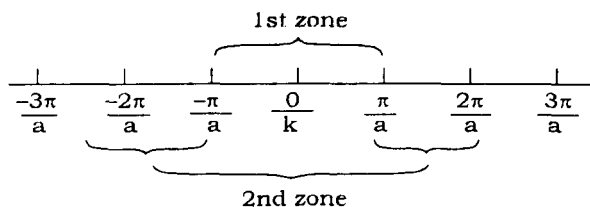


Fig. The first two Brillouin zones for one -dimensional lattice.

(ii) Two dimensional :

Let us consider the motion of an electron in the field of two-dimensional square lattice. The motion of electron in two dimensions can be discussed using a wave number k which is measured in the direction of propagation of the wave.

The wave number k has components k_x and k_y along x and y -axes respectively.

To sketch the first Brillouin zone, the k_x axis in the following fig. having values of $\pm \pi/a$ represent the limits of the zone. Similarly, along k_y axis the values $\pm \pi/a$ also represent the limits of the zone. The condition for any discontinuity is

$$k = \pm n \pi / a$$

For two dimensions this condition will become

$$k_x n_1 + k_y n_2 = \pi / a (n_1^2 + n_2^2)$$

where n_1 and n_2 are integers corresponding to the single integer n and referring to each of the axes. For the first zone n_1 and n_2 are made equal to 0, ± 1 in turn, which give following two equations of the lines bordering the first zone,

$$n_1 = \pm 1, n_2 = 0 \text{ giving } k_x = \pm \pi / a$$

$$n_1 = 0, n_2 = \pm 1 \text{ giving } k_y = \pm \pi / a$$

Thus a square passing through the points A, B, C, D gives the first Brillouin zone. The second zone is obtained by taking n_1 and n_2 as next integers in the series. These are $n_1 = \pm 1$ and $n_2 = \pm 1$. This gives four equations for four lines with boundaries $2\pi/a$ and $-2\pi/a$.

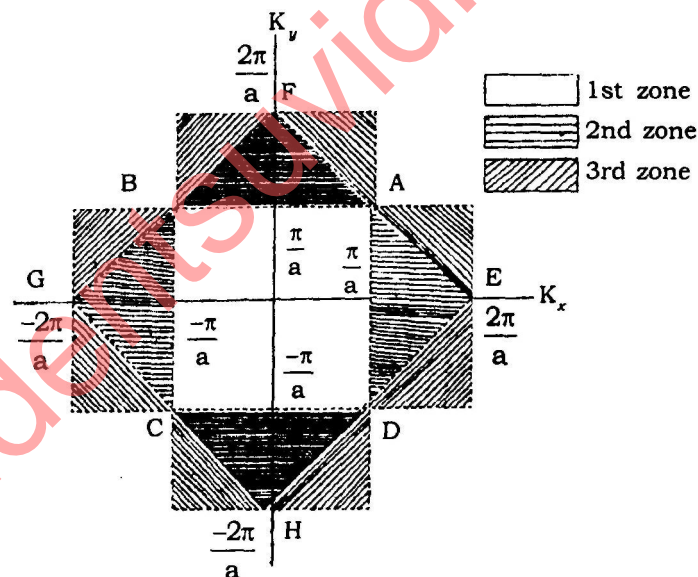


Fig. The first three Brillouin zones for a two-dimensional square lattice.

These four lines enclose a region EFGH. The region enclosed between the first Brillouin zone ABCD and square EFGH, contain all states in the second energy band. It is called second Brillouin zone. Similarly the third Brillouin zone is obtained giving n_1 and n_2 values of 0, ± 1 and ± 2 .

Ans. 5. (b) Fermi-Energy

Let us consider N -non-interacting electrons contained in a box at absolute zero temperature. using Pauli's exclusion principle on the energy distribution of conduction electrons, it can be shown that all the energy levels below a certain level will be filled with electrons and all the levels above it will be empty. The level which divides the filled and empty levels is

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called the Fermi-level at absolute zero and the corresponding energy or that level is called the Fermi-energy and the denoted by $\epsilon_F(0)$. We note that according to quantum theory, even at absolute zero, all the electrons are not condensed into a state of zero energy as happens in classical theory, but they occupy states between energy values 0 and $\epsilon_F(0)$.

Effect of Temperature : With rise of temperature, the Fermi energy decreases. The Fermi energy at absolute temperature T given by

$$\epsilon_F(T) = \epsilon_F(0) \left[1 - \frac{1}{12} \left(\frac{\pi k T}{\epsilon_F(0)} \right)^2 \right]$$

Ans. 6. (a) Photoconductivity :

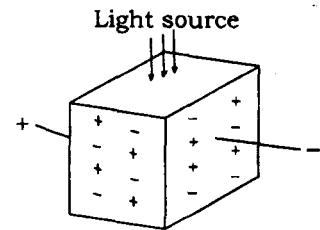
When light radiation falls on an insulating crystal, its electrical conductivity increases. this phenomenon is called photoconductivity.

The expression for photoconductivity is given by

$$\sigma = \left(\frac{L}{A} \right)^{1/2} e\mu$$

where L = number of photons absorbed per unit volume per second or L represents light-level, μ = electron mobility, A = constant

Simple Model of a Photoconductor : We shall consider the simplest possible model of a photoconductor. This model (shown in the figure) suppose that the electron-hole pairs are produced uniformly throughout the volume of the crystal by irradiation with an external light source, that recombination occurs by direct annihilation of electrons with holes, and that electrons leaving the crystal at one electrode are replaced by electrons flowing in from the opposite electrode. Further, it is convenient to neglect the mobility of the holes in comparison with the mobility of the electrons; this is not a drastic assumption.



Long response time for sensitive photo conductors : The rate of change of the electron concentration n is now expressed as

$$\frac{dn}{dt} = L - Anp = L - An^2 \quad (\text{using } n = p) \quad \dots(1)$$

Here L is the number of photons, absorbed per unit volume of the specimen per unit time and Anp represents the recombination rate. In the steady state $\frac{dn}{dt} = 0$, so that $L - An^2 = 0$. Thus in the steady-state electron concentration is given by

$$n_0 = \left(\frac{L}{A} \right)^{1/2} \quad \dots(2)$$

and

$$\sigma = n_0 e\mu = \left(\frac{L}{A} \right)^{1/2} e\mu \quad \dots(3)$$

For the photoconductivity, μ is here the electron mobility. Note that this relation predicts that at a given voltage the photoconductivity will vary with light level L as $L^{0.5}$; the actual exponent observed however ranges between 0.5 and 1.0 or even higher, see fig.

The decay of photoelectrons (hence of photoconductivity) after the light has been switch off suddenly is evidently described by

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$$\frac{dn}{dt} = -An^2 \quad \dots(4)$$

which has the solution $\frac{1}{n} = At + \frac{1}{n_0} \quad \dots(5)$

where n_0 is the carrier concentration at $t = 0$ when the light was turned off. It is now easy to conclude

from (5) that the electron concentration drops to $\frac{1}{2}n_0$ in the time

$$t_0 = \frac{1}{An_0} = (LA)^{-1/2} = \frac{n_0}{L} \quad \dots(6)$$

Combining this with (4), we get $t_0 = \frac{\sigma}{e\mu L}$

...(7)

t_0 is called the response time. Thus, theory predicts that the response time should be directly proportional to the photoconductivity at a given light level L ; sensitive photoconductors should have long response times. This prediction is, however, rarely observed in practice.

Ans. 6. (b) Photo-Voltaic Cells

Becquerel in 1839 discovered that when a pair of electrodes is immersed in an electrolyte and light is allowed to incident on one of them, a potential difference is created between the electrodes. This phenomenon is called **photo-voltaic effect**. Devices based on this effect are known as **photo-voltaic cells**. Thus photovoltaic cells are the devices in which light energy is used to create a potential difference. The potential differences so developed is directly proportional to the frequency and intensity of incident light.

Construction and working : A basic photovoltaic cell consists of a piece of semiconducting material bonded to a metal plate. Materials like selenium and silicon are mostly used for preparing photovoltaic cells.

When light is made to fall on semiconducting material, valence electrons and holes are liberated from its crystal structure. The electrons so liberated move towards the metal plate whereas holes flow in opposite direction. Thus a potential difference is created between the semiconducting material and the metal plate. Consequently a conventional current flows in the external circuit through a load resistor R as shown by an arrows in fig.

In an actual form of photo-voltaic cell a thin metallic film of silver, gold or platinum is deposited on a semiconducting layer like cuprous oxide (Cu_2O) or iron selenide. The whole arrangement is then attached to a metal base plate (say, copper), as shown in fig.

When external light is allowed to fall on metallic film F , it penetrates easily and at the barrier layer between the metallic film and the semiconductor, photo-electric emission occurs. The photoelectrons so emitted from the layer, move towards the mataltic film.

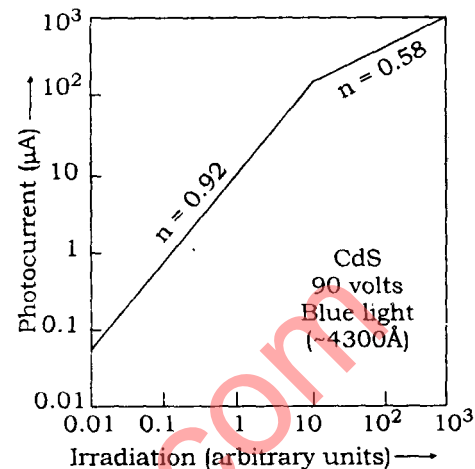
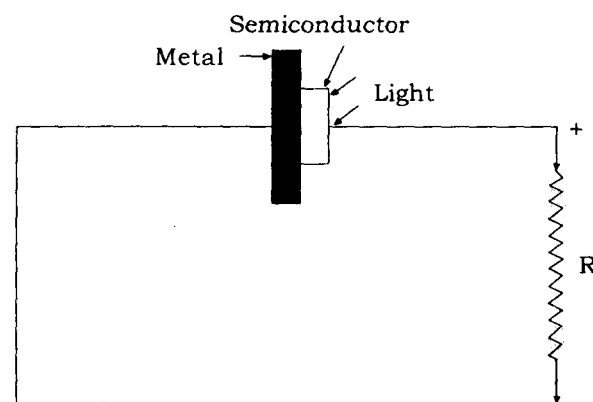


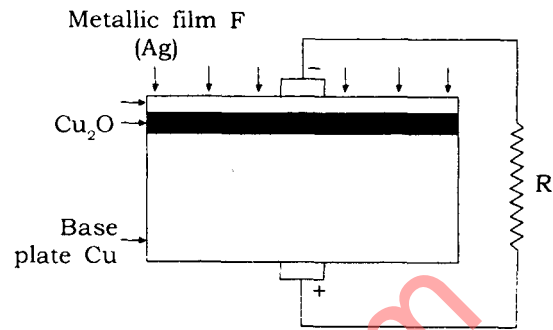
Fig. Photoconductive response vs. illumination level for a CdS crystal.



Consequently, the metallic film F becomes negatively charged and the copper base plate positively charged. Hence a potential difference is developed between the two and a current flows in the external circuit. The strength of the current is proportional to the intensity of light and flows without any bias, i.e. without any external source of e.m.f.

Uses : These cells are used in devices like:

1. Photographic exposure metre.
2. Direct reading illumination metre.
3. Operation of relays.



Ans. 7. (a) Superconductivity

In 1911, Kammerlingh Onnes found that the electrical resistance of some metals, alloys and compounds drops suddenly to zero when the specimen is cooled below a certain temperature. This phenomenon is called "superconductivity" and the cooled specimen is said to be a "superconductor".

Salient features and uses of superconductors :

1. Electrical properties : The superconducting state of a material is characterised by zero electrical resistance. On superconductivity state $E = 0$, so $\rho = 0$. That is in superconducting state the resistivity of material disappears. Hence a superconductor can conduct electric current even in the absence of an applied voltage, and the current can persist for year without any detectable decay.

2. Magnetic Properties : The superconductivity state of a material mainly depends on temperature and magnetic field. It exists only in a particular range of temperature and field strength. The superconducting state disappears if the temperature of the specimen is raised above its critical temperature T_c or if a sufficiently strong magnetic field is applied. The minimum value of magnetic field at a given temperature at which superconductivity disappears is called the critical magnetic field (H_c).

3. Thermal Properties : The thermal properties like entropy, heat capacity thermal conductivity etc. of a metal change sharply at transition temperature (T_c) of superconductivity as the temperature is lowered.

4. Optical properties : The photons of energy $h\nu < \text{energy gap } \Delta$ are not absorbed by superconductors. nearly all the photons incident on metal are reflected back, but for a thin film of the order 20\AA more photons are transmitted in the superconducting state than the normal state. This is due to the effect of photon-energies on resistivity of a superconductor.

Ans. 7. (b) London Theory of Superconductivity :

According to London's theory, "It was assumed that there are two types of conduction electrons in superconductors i.e. the normal electrons and super electrons. The variation of the entropy with temperature suggests that the number of normal conducting electrons decreases below transition temperature while that of superconducting electrons increases. "At OK all electrons are superconducting and above the transition temperatures all the electrons are normal. Thus the total current density J , consists of normal current density J_n and super current density J_s i.e.

$$J = J_n + J_s$$

If n_s and n_n are the number of super and normal electrons per unit volume respectively and v_s and v_n be the respective velocities then

$$J = en_s v_s + en_n v_n$$

If a constant electric field E is applied to the superconducting material, the superconducting electrons face no resistance and the electric field gives the electrons and acceleration. In other words the superconducting electrons are assumed to behave in the electric field just as free electrons. The equation of motion of superconducting electrons is

$$m \frac{dv_s}{dt} = eE$$

Below the transition temperature T_c it can be assumed that the total current density is due to superconducting electrons. Therefore

$$J_s = e n_s v_s$$

and
$$\frac{dJ_s}{dt} = e n_s \frac{dv_s}{dt}$$

or
$$\frac{dJ_s}{dt} = e^2 n_s E / m \quad \dots(1)$$

This is the basic relation describing the absence of resistance and known as first London equation. This states that no electric field is necessary unless the current changes, steady currents may be set up in the absence of electric field. This is the phenomenon of superconductivity.

The equation for normal current density is

$$J_n = \sigma_n E = \frac{n_n e^2 E}{m} \tau$$

which states that the electric field is necessary for a steady current. If $E = 0$, J_n becomes zero unlike superconducting state.

We write Maxwell's equations

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}$$

and
$$\nabla \times \mathbf{H} = \mathbf{J}_s + \frac{\partial \mathbf{D}}{\partial t} \quad \text{or} \quad \nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J}_s + \frac{\partial \mathbf{D}}{\partial t} \right)$$

where \mathbf{J}_s is the current density of superconducting electrons. Further, unless the fields are varying very rapidly with time the displacement current density $\frac{\partial \mathbf{D}}{\partial t}$ is negligible in comparison with \mathbf{J}_s . Thus inside the superconductors, Maxwell's equations are

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{B}}{\partial t} \quad \dots(2)$$

and
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}_s \quad \dots(3)$$

Putting the value of E from eqn. (1) into eqn. (2), we get

$$-\frac{\partial \mathbf{B}}{\partial t} = \left(\frac{m}{n_s e^2} \right) \nabla \times \mathbf{J} \quad \left(\mathbf{J}_s = \frac{\partial \mathbf{J}_s}{\partial t} \right)$$

or
$$\nabla \times \mathbf{J}_s = -\left(\frac{n_s e^2}{m} \right) \frac{\partial \mathbf{B}}{\partial t}$$

Integrating with time

$$\nabla \times \mathbf{J}_s = - \left(\frac{n_s e^2}{m} \right) (\mathbf{B} - \mathbf{B}_0)$$

where \mathbf{B}_0 is the constant of integration. As Meissner effect prohibits magnetic fields in the superconductors, the constant of \mathbf{B}_0 must be zero. Thus

$$\nabla \times \mathbf{J}_s = - \frac{n_s e^2}{m} \mathbf{B} \quad \dots(4)$$

This is second London equation. Eqns. (1) and (4) are together known as London equations.

Ans. 8. (i) Classical Theory of Ferromagnetism :

Please see answer 8 (a), Paper December 2008

8. (ii) Effective Mass of Electron

A free electron has well defined mass and obey's Newton's laws when accelerated by an external electric field but when electron is in a periodic potential of the crystal lattice, its behaviour in external electric field is different from that of a free electron. The deviation of the actual electron behaviour than free electron behaviour may be accounted simply considering the electron to have effective mass m^* rather than free electron mass m .

According to de Broglie an electron with which velocity v is equivalent to a wave packet moving with group velocity v_g , the group velocity v_g being equal to particle velocity v , i.e.,

$$v_g = v = \frac{d\omega}{dk} \quad \dots(1)$$

where ω is angular frequency of de broglie wave and $k = \frac{2\pi}{\lambda}$ is propagation constant.

$$\text{The energy of particle } E = \hbar\omega \Rightarrow \frac{dE}{dk} = \hbar \frac{d\omega}{dk} \Rightarrow \frac{d\omega}{dk} = \frac{1}{\hbar} \frac{dE}{dk}.$$

$$\text{In view of this, equatin (1) gives } v = \frac{1}{\hbar} \frac{dE}{dk}. \quad \dots(2)$$

When an electric field \vec{X}_e is applied on the electron, then force on electron $\vec{F} = -e\vec{X}_e$. Work

done by electric field over a small distance dx traversed in time dt is $dW = -eX_e dx$

This is the gain in kinetic energy of the particle.

Gain in energy of electron in time dt is

$$dE = -eX_e v dt \quad \left(\text{Since } \frac{dx}{dt} = v \right)$$

Substituting value of v from equation 92), we get

$$dE = -eX_e \left(\frac{1}{\hbar} \frac{dE}{dk} \right) dt$$

$$\Rightarrow \frac{dE}{dt} dk = - \frac{eX_e}{\hbar} \frac{dE}{dk} dt \Rightarrow \frac{dk}{dt} = - \frac{eX_e}{\hbar} \quad \dots(3)$$

8. (iii) Hall Effect :

Please see answer 5 (b), Paper December 2008

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