Reg No..... (17PHU102)

KARPAGAM ACADEMY OF HIGHER EDUCATION **COIMBATORE-21** (Under Section3 of UGC Act 1956) **DEPARTMENT OF PHYSICS I B.Sc PHYSICS First Semester II-Internal Examination Solid State Physics** Time:2 hours Maximum:50 marks PART-A(20x1=20Marks) Answer all questions 1. In some materials, the electrical resistance becomes zero, when they are cooled to a. High temperature b. low temperaturec. Very High temperature d very low temperature

- Superconductivity was observed by

 a.Bardeen b. Ginzburg landau c. H Kamerclingh onnes
 d. Schrieffer
- 3. The temperature at which a normal conductor loses its resistivity and becomes a superconductors in known as

- 4. If the transition temperature is low , then the superconductors are known asa.High temperature b .low temperature c. Very High temperature d very low temperature
- If the transition temperature is high, then the superconductors are known as a.High temperature b .low temperature c. Very High temperature d very low temperature
- 6. Which of the following is an example for type II superconductors ?
 - a. Pb b.Zn c. Ga d. Vanadium
- 7. At low temperature, cooper pairs move a. with scatteringb. without scattering c. without any resistance theory the lattice points d. both b and c
- Conductivity of semiconductor is less than
 a. conductor b. insulator c. liquid d. gases
- Majority charge carriers of p type semiconductor is
 a. electron b. hole c. ions d.None of these
- 10. Minority charge carriers of n type semiconductor isa. electron b. hole c. ions d. None of these
- 11. Susceptibility of dia magnetic materials is ______a. zero b. <0 c. >0 d. equal to zero
- 12. Susceptibility of Para magnetic materials is _________a. Zero b. positive c. negative d. neutral

a.constant temperature b. transition temperature c.

Critical temperature d. zero temperature

- 13. The unit of electrical conductivity isa mho / metre b. mho / sq.m c. ohm / metre d. ohm / sq.m
- 14. Which of the following materials has highest electrical conductivity ?

a. Steel b. Aluminium c. silver d. carbon

15. Magnetic order exits only belw certain temperature called

a. curie temperature b. constant temperature c.critical temperature d. all the above

- 16. Ferromagnetic material exhibits----- magnetic momenta. spontaneousb. Stimulatedc. absorptiond. none of these
- 17. The field required to destroy the super conducting property is called as _____
- a. Magnetic field b. critical magnetic fieldc. critical field d. constant field
- a. High temperature b. low temperaturec. very high temperature d. very low temperature

a. High temperature b. low temperature
c. very high temperature d. very low temperature
20. Optical phonons have a non-zero frequency at the
a. molecular zone center b. Atomic zone center
c. Brillouin zone center d. miller zone center

PART-B (2x3=6 Marks)

Answer all the questions

- 21. Give an example for Dia-, Para- magnetic materials?
- 22. Write a note on magnetic materials?
- 23. Give an explanation for T^3 law.

PART-C (3x8=24 Marks)

Answer all the questions

24. a. Explain classical Langevin Theory of Diamagnetism.

OR

- b. Draw B-H curve and explain the hysteresis and energy loss
- 25. (a) Explain classical Langevin Theory of paramagnetism. (or)
 - (b) Write a short note on four types of magnetic Materials.

26. a. Explain in detail about N type and P type semiconductors

OR

b. Explain in detail about Hall Effect.

Reg No.....

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KARPAGAM ACADEMY OF HIGHER EDUCATION

COIMBATORE-21

(Under Section3 of UGC Act 1956)

DEPARTMENT OF PHYSICS

I B.Sc PHYSICS

First Semester

II-Internal Examination

Solid State Physics

Time:2 hours

Maximum:50 marks

PART-A(20x1=20Marks)

Answer all questions

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 - a. constant temperature b. transition temperature c. Critical temperature d. zero temperature
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- If the transition temperature is high, then the superconductors are known as a.High temperature b .low temperature c.
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 - a. Steel b. Aluminium **c. silver** d. carbon
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16. Ferromagnetic material exhibits----- magnetic moment a. **spontaneou**s b. Stimulated c. absorption d. none of these 17. The field required to destroy the super conducting property is called as a. Magnetic field b. critical magnetic field c. critical field d. constant field a. High temperature b. low temperature c. very high temperature d. very low temperature 19. If the transition temperature is high, then the superconductors are known as _______ superconductors High temperature b. low temperature c. very high temperature d. very low temperature a. 20. Optical phonons have a non-zero frequency at the a. molecular zone center b. Atomic zone center c. **Brillouin zone center** d. miller zone center

PART-B (2x3=6 Marks)

Answer all the questions

21. Give an example for Dia-, Para- magnetic materials?

Some examples of diamagnetic substances are antimony, bismuth, copper, lead, gold, silver, zinc, quartz, mercury, alcohol, sodium chloride, water, hydrogen, air, argon etc.,

Some examples include aluminium, chromium, manganese, oxygen, platinum, alkali and alkaline earth metals.

22. Write a note on magnetic materials?

In most atoms, electrons occur in pairs. Electrons in a pair spin in opposite directions. So, when electrons are paired together, their opposite spins cause their magnetic fields to cancel each other. Therefore, no net magnetic field exists.

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Alternately, materials with some unpaired electrons will have a net magnetic field and will react more to an external field. Most materials can be classified as diamagnetic, paramagnetic or ferromagnetic.

23. Give an explanation for T^3 law.

At room temperature this is a very small contribution to the overall heat capacity (on the order of a few percent). However, at very low temperatures the electronic heat capacity dominates, since it is linear in temperature while the lattice heat capacity is proportional to T^3 .

PART-C (3x8=24 Marks)

Answer all the questions

24. a. Explain classical Langevin Theory of Diamagnetism.

Diamagnetism, kind of magnetism characteristic of materials that line up at right angles to a non-uniform magnetic field and that partly expel from their interior the magnetic field in which they are placed. First observed by S.J. Brugmans (1778) in bismuth and antimony, diamagnetism was named and studied by Michael Faraday(beginning in 1845). He and subsequent experimenters found that some elements and most compounds exhibit this "negative" magnetism. Indeed, all substances are diamagnetic: the strong external magnetic field speeds up or slows down the electrons orbiting in atoms in such a way as to oppose the action of the external field in accordance with Lenz's law.

The diamagnetism of some materials, however, is masked either by a weak magnetic attraction (paramagnetism) or a very strong attraction (ferromagnetism). Diamagnetism is observable in substances with symmetric electronic structure (as ionic crystals and rare gases) and no permanent magnetic moment. Diamagnetism is not affected by changes in temperature. For diamagnetic materials the value of the susceptibility (a measure of the relative amount of induced magnetism) is always negative and typically near negative one-millionth.

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b. Draw B-H curve and explain the hysteresis and energy loss

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Magnetic Hysteresis Loop



The **Magnetic Hysteresis** loop above, shows the behaviour of a ferromagnetic core graphically as the relationship between B and H is non-linear. Starting with an unmagnetised core both B and H will be at zero, point 0 on the magnetisation curve.

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If the magnetisation current, i is increased in a positive direction to some value the magnetic field strength H increases linearly with i and the flux density B will also increase as shown by the curve from point 0to point a as it heads towards saturation.

Now if the magnetising current in the coil is reduced to zero, the magnetic field circulating around the core also reduces to zero. However, the coils magnetic flux will not reach zero due to the residual magnetism present within the core and this is shown on the curve from point a to point b.

To reduce the flux density at point b to zero we need to reverse the current flowing through the coil. The magnetising force which must be applied to null the residual flux density is called a "Coercive Force". This coercive force reverses the magnetic field re-arranging the molecular magnets until the core becomes unmagnetised at point c.

An increase in this reverse current causes the core to be magnetised in the opposite direction and increasing this magnetisation current further will cause the core to reach its saturation point but in the opposite direction, point d on the curve. This point is symmetrical to point b. If the magnetising current is reduced again to zero the residual magnetism present in the core will be equal to the previous value but in reverse at point e.

Again reversing the magnetising current flowing through the coil this time into a positive direction will cause the magnetic flux to reach zero, point f on the curve and as before increasing the magnetisation current further in a positive direction will cause the core to reach saturation at point a.

Then the B-H curve follows the path of a-b-c-d-e-f-a as the magnetising current flowing through the coil alternates between a positive and negative value such as the cycle of an AC voltage. This path is called a **Magnetic Hysteresis Loop**. The effect of magnetic hysteresis shows that the magnetisation process of a ferromagnetic core and therefore the flux density depends on which part of the curve the ferromagnetic core is magnetised on as this depends upon the circuits past history giving the core a form of "memory". Then ferromagnetic materials have memory because they remain magnetised after the external magnetic field has been removed.

However, soft ferromagnetic materials such as iron or silicon steel have very narrow magnetic hysteresis loops resulting in very small amounts of residual magnetism making them ideal for use in relays, solenoids and transformers as they can be easily magnetised and demagnetised.

Since a coercive force must be applied to overcome this residual magnetism, work must be done in closing the hysteresis loop with the energy being used being dissipated as heat in the magnetic material. This heat is known as hysteresis loss, the amount of loss depends on the material's value of coercive force.

By adding additive's to the iron metal such as silicon, materials with a very small coercive force can be made that have a very narrow hysteresis loop. Materials with narrow hysteresis loops are easily magnetised and demagnetised and known as soft magnetic materials.

25. (a) Explain classical Langevin Theory of paramagnetism.

Paramagnetism, kind of magnetism characteristic of materials weakly attracted by a strong magnet, named and extensively investigated by the British scientist Michael Faraday beginning in 1845. Most elements and some compounds are paramagnetic. Strong paramagnetism (not to be confused with the ferromagnetism of the elements iron, cobalt, nickel, and other alloys) is exhibited by compounds containing iron, palladium, platinum, and the rare-earth elements. In such compounds atoms of these elements have some inner electron shells that are incomplete, causing their unpaired electrons to spin like tops and orbit like satellites, thus making the atoms a permanent magnet tending to align with and hence strengthen an applied magnetic field.

Strong paramagnetism decreases with rising temperature because of the de-alignment produced by the greater random motion of the atomic magnets. Weak paramagnetism, independent of temperature, is found in many metallic elements in the solid state, such as sodium and the other alkali metals, because an applied magnetic field affects the spin of some of the loosely

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bound conduction electrons. The value of susceptibility (a measure of the relative amount of induced magnetism) for paramagnetic materials is always positive and at room temperature is typically about 1/100,000 to 1/10,000 for weakly paramagnetic substances and about 1/10,000 to 1/100 for strongly paramagnetic substances.

(b) Write a short note on four types of magnetic Materials.

Diamagnetism

Diamagnetism, kind of magnetism characteristic of materials that line up at right angles to a non-uniform magnetic field and that partly expel from their interior the magnetic field in which they are placed. First observed by S.J. Brugmans (1778) in bismuth and antimony, diamagnetism was named and studied by Michael Faraday(beginning in 1845). He and subsequent experimenters found that some elements and most compounds exhibit this "negative" magnetism. Indeed, all substances are diamagnetic: the strong external magnetic field speeds up or slows down the electrons orbiting in atoms in such a way as to oppose the action of the external field in accordance with Lenz's law.

The diamagnetism of some materials, however, is masked either by a weak magnetic attraction (paramagnetism) or a very strong attraction (ferromagnetism). Diamagnetism is observable in substances with symmetric electronic structure (as ionic crystals and rare gases) and no permanent magnetic moment. Diamagnetism is not affected by changes in temperature. For diamagnetic materials the value of the susceptibility (a measure of the relative amount of induced magnetism) is always negative and typically near negative one-millionth.

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Magnetism: Magnetic properties of matter

Phenomenon associated with magnetic fields, which arise from the motion of electric charges. This motion can take many forms. It can be an electric current in a conductor or charged particles moving through space, or it can be the motion of an electron in an atomic orbital. Magnetism is also...

Ferrimagnetism, type of permanent magnetism that occurs in solids in which the magnetic fields associated with individual atoms spontaneously align themselves, some parallel, or in the same direction (as in ferromagnetism), and others generally antiparallel, or paired off in opposite directions (as in antiferro magnetism). The magnetic behaviour of single crystals of ferrimagnetic materials may be attributed to the parallel alignment; the diluting effect of those atoms in the antiparallel arrangement keeps the magnetic strength of these materials generally less than that of purely ferromagnetic solids such as metalliciron.

Ferrimagnetism occurs chiefly in magnetic oxides known as ferrites. The natural magnetism exhibited by lodestones, recorded as early as the 6th century BC, is that of a ferrite, the mineral magnetite, a compound containing negative oxygen ions

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 O^{2-} and positive iron ions in two states, iron(II) ions, Fe^{2+} , and iron(III) ions, Fe^{3+} . The oxygen ions are not magnetic, but both iron ions are. In magnetite crystals, chemically formulated as Fe_3O_4 , for every four oxygen ions, there are two iron(III) ions and one iron(II) ion. The iron(III) ions are paired off in opposite directions, producing no external magnetic field, but the iron(II) ions are all aligned in the same direction, accounting for the external magnetism.

The spontaneous alignment that produces ferrimagnetism is entirely disrupted above a temperature called the Curie point, characteristic of each ferrimagnetic material. When the temperature of the material is brought below the Curie point, ferrimagnetism revives.

Ferromagnetism, physical phenomenon in which certain electrically uncharged materials strongly attract others. Two materials found in nature, lodestone (ormagnetite, an oxide of iron, Fe_3O_4) and iron, have the ability to acquire such attractive powers, and they are often called natural ferromagnets. They were discovered more than 2,000 years ago, and all early scientific studies of magnetism were conducted on these materials. Today, ferromagnetic materials are used in a wide variety of devices essential to everyday life. *e.g.*, electric motors and generators, transformers, telephones, and loudspeakers.

Ferromagnetism is a kind of magnetism that is associated with iron, cobalt,nickel, and some alloys or compounds containing one or more of these elements. It also occurs in gadolinium and a few other rare-earth elements. In contrast to other substances, ferromagnetic materials are magnetized easily, and in strong magnetic fields the magnetization approaches a definite limit called saturation. When a field is applied and then removed, the magnetization does not return to its original value—this phenomenon is referred to as hysteresis. When heated to a certain temperature called the Curie point, which is different for each substance, ferromagnetic materials lose their characteristic properties and cease to be magnetic; however, they become ferromagnetic again on cooling.

The magnetism in ferromagnetic materials is caused by the alignment patterns of their constituent atoms, which act as elementary electromagnets. Ferromagnetism is explained by the concept that some species of atoms possess a magnetic

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moment—that is, that such an atom itself is an elementary electromagnet produced by the motion of electrons about its nucleus and by the spin of its electrons on their own axes. Below the Curie point, atoms that behave as tiny magnets in ferromagnetic materials spontaneously align themselves. They become oriented in the same direction, so that their magnetic fields reinforce each other.

One requirement of a ferromagnetic material is that its atoms or ions have permanent magnetic moments. The magnetic moment of an atom comes from its electrons, since the nuclear contribution is negligible. Another requirement for ferromagnetism is some kind of interatomic force that keeps the magnetic moments of many atoms parallel to each other. Without such a force the atoms would be disordered by thermal agitation, the moments of neighboring atoms would neutralize each other, and the large magnetic moment characteristic of ferromagnetic materials would not exist.

There is ample evidence that some atoms or ions have a permanent magnetic moment that may be pictured as a dipole consisting of a positive, or north, pole separated from a negative, or south, pole. In ferromagnets, the large coupling between the atomic magnetic moments leads to some degree of dipole alignment and hence to a net magnetization.

The French physicist Pierre-Ernest Weiss postulated a large-scale type of magnetic order for ferromagnets called domain structure. According to his theory, a ferromagnetic solid consists of a large number of small regions, or domains, in each of which all of the atomic or ionic magnetic moments are aligned. If the resultant moments of these domains are randomly oriented, the object as a whole will not display magnetism, but an externally applied magnetizing field will, depending on its strength, rotate one after another of the domains into alignment with the external field and cause aligned domains to grow at the expense of nonaligned ones. In the limiting state called saturation, the entire object will comprise a single domain.

Domain structure can be observed directly. In one technique, a colloidal solution of small magnetic particles, usually magnetite, is placed on the surface of a ferromagnet. When surface poles are present, the particles tend to concentrate in certain

regions to form a pattern that is readily observed with an optical microscope. Domain patterns have also been observed with polarized light, polarized neutrons, electron beams, and X rays.

In many ferromagnets the dipole moments are aligned parallel by the strong coupling. This is the magnetic arrangement found for the elemental metals iron (Fe), nickel (Ni), and cobalt (Co) and for their alloys with one another and with some other elements. These materials still constitute the largest group of ferromagnets commonly used. The other elements that possess a collinear ordering are the rare-earth metals gadolinium (Gd), terbium (Tb), and dysprosium (Dy), but the last two become ferromagnets only well below room temperature. Some alloys, although not composed of any of the elements just mentioned, nevertheless have a parallel moment arrangement. An example of this is the Heusler alloy CuAlMn₃, in which the manganese(Mn) atoms have magnetic moments, though manganese metal itself is not ferromagnetic.

Since 1950, and particularly since 1960, several ionically bound compounds have been discovered to be ferromagnetic. Some of these compounds are electrical insulators; others have a conductivity of magnitude typical of semiconductors. Such compounds include chalcogenides (compounds of oxygen, sulfur, selenium, or tellurium), halides (compounds of fluorine, chlorine, bromine, or iodine), and their combinations. The ions with permanent dipole moments in these materials are manganese, chromium (Cr), andeuropium (Eu); the others are diamagnetic. At low temperatures, the rare-earth metals holmium (Ho) and erbium (Er) have a nonparallel moment arrangement that gives rise to a substantial spontaneous magnetization. Some ionic compounds with the spinel crystal structure also possess ferromagnetic ordering. A different structure leads to a spontaneous magnetization in thulium (Tm) below 32 kelvins (K).

Above the Curie point (also called the Curie temperature), the spontaneous magnetization of the ferromagnetic material vanishes and it becomesparamagnetic (*i.e.*, it remains weakly magnetic). This occurs because the thermal energy becomes sufficient to overcome the internal aligning forces of the material. The Curie temperatures for some important ferromagnets are: iron, 1,043 K; cobalt, 1,394 K; nickel, 631 K; and gadolinium, 293 K.

26. a. Explain in detail about N type and P type semiconductors

P and N type Semiconductors

p-n junction diodes are made up of two adjacent pieces of p-type and n-type semiconducting materials. p-type and n-type materials are simply semiconductors, such as silicon (Si) or germanium (Ge), with atomic impurities; the type of impurity present determines the type of the semiconductor. The process of purposefully adding impurities to materials is called doping; semiconductors with impurities are referred to as "doped semiconductors".

p-type

In a pure (intrinsic) Si or Ge semiconductor, each nucleus uses its four valence electrons to form four covalent bonds with its neighbors (see figure below). Each ionic core, consisting of the nucleus and non-valent electrons, has a net charge of +4, and is surrounded by 4 valence electrons. Since there are no excess electrons or holes In this case, the number of electrons and holes present at any given time will always be equal.



An intrinsic semiconductor. Note each +4 ion is surrounded by four electrons.

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Now, if one of the atoms in the semiconductor lattice is replaced by an element with three valence electrons, such as a Group 3 element like Boron (B) or Gallium (Ga), the electron-hole balance will be changed. This impurity will only be able to contribute three valence electrons to the lattice, therefore leaving one excess hole (see figure below). Since holes will "accept" free electrons, a Group 3 impurity is also called an acceptor.



A semiconductor doped with an acceptor. An excess hole is now present.

Because an acceptor donates excess holes, which are considered to be positively charged, a semiconductor that has been doped with an acceptor is called a p-type semiconductor; "p" stands for positive. Notice that the material as a whole remains electrically neutral. In a p-type semiconductor, current is largely carried by the holes, which outnumber the free electrons. In this case, the holes are the majority carriers, while the electrons are the minority carriers.

n-type

In addition to replacing one of the lattice atoms with a Group 3 atom, we can also replace it by an atom with five valence electrons, such as the Group 5 atoms arsenic (As) or phosphorus (P). In this case, the impurity adds five valence electrons to the lattice where it can only hold four. This means that there is now one excess electron in the lattice (see figure below). Because it donates an electron, a Group 5 impurity is called a donor. Note that the material remains electrically neutral.

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A semiconductor doped with a donor. A free electron is now present.

Donor impurities donate negatively charged electrons to the lattice, so a semiconductor that has been doped with a donor is called an n-type semiconductor; "n" stands for negative. Free electrons outnumber holes in an n-type material, so the electrons are the majority carriers and holes are the minority carriers.

b. Explain in detail about Hall Effect.

The Hall Effect is a physical effect named after Edwin Hall, an American physicist who discovered that when the path of electrons running through a semiconductor was deflected by a magnetic field, a potential difference was induced perpendicular to the direction of the current. In 1985 (over 100 years after Hall's discovery), a German physicist, Klaus von Klitzing was awarded a Nobel Prize for his work with the quantized Hall Effect. The Hall Effect is the working mechanism in a wide range of devices and applications including the gauss meter, ammeters, tachometers, spectrum analyzers, paintball guns, and many more electronic devices.

The following diagram shows the basic theoretical description of the Hall Effect. If a current I in a slab of conducting material runs in the x direction through an applied magnetic field B, it will be deflected due to the magnetic force on the

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moving charges. Depending on whether the charge is positive or negative, the charges will build up on either face 3 or face 4 of the slab. This charge buildup causes an electrostatic potential difference between faces 3 and 4, and is referred to as the Hall voltage, VH. The Hall resistance is the ratio of VH / I, and is observed to increase as the applied magnetic field is increased.



Figure 1. Geometry for measuring the Hall voltage for a semiconductor in a magnetic field.

Measuring the Hall effect is useful in determining many things, including the type of the semiconductor (p-type or n-type), the charge of the carriers, the concentration, mobility, and band structure of the material.

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Date:

Time:2 hours Maximum:50 marks

PART-A(20×1=20Marks) Answer all questions

1.	The process of producing electric dipoles inside the dielectrics by an external electric field is
	A. polarisation B. Interference C. diffraction D. coherence
2.	If the strength of the electric field is increased, the strength of the induced dipole
	A. decrease B. increase C. remains constant D. zero
3.	The induced dipole moment is proportional to of the electric field
	A. Intensity B. resistance
	C. capacitance D. none of these
4.	is the quantity which is used for analyzing electrostatic fields
	A. Electric vector B. Electric displacement vector C. electric induction D. both a
	and c
5.	The dielectric constant determines the share of the which is absorbed
	by the material A. Tensile stress B. dielectric stress C.electric stress
~	D. magnetic stress
6.	is the ratio between the absolute permittivity and the permittivity
	of free space
7	A. Susceptionity B. dielectric constant C. permeability D.none of these
7.	B flux lines C electric induction
	D flux density
8	is a measure of polarisation in the dielectric A. Dipole
0.	moment B. electric dipole C. dielectric constant D.entropy
9.	The dielectric constant for silicon is A. 6 B. 8 C.9 D. 12
10.	The dielectric constant for glass is A. 7 B. 4 C. 4to7 D. 8
11.	Schering bridge (resonance method) is not applicable at frequencies of region
	A. ultraviolet B. microwave C. visible D. Infra red
12.	The example for active dielectrics are A. glass B. silica
	C. piezo electrics D. mica
13.	The example for passive dielectrics is
	A. glass B. mica C. all insulating materials D. all of these

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14.		molec	ules wil	l not have	centre of symmetry		A. pola	ar
	B. non pol	ar C.d	lipolar	D. mono	polar			
15.	The examp	le for pola	ar molec	ules is				
	A. H ₂ O	B. N ₂	0	C. CH ₃	D. both A and B			
16.	The examp	le for non	polar m	olecules is	S			
	A. N ₂ O	B. CH ₃	C.CH	I 4	D. CO			
17.		m	olecules	s posses ce	entre of symmetry	A. pola	r	B. non polar
	C. dipolar	D. mo	nopolar	-		-		-
18.		r	nolecule	es posses d	ipole moment	A. pola	ır	B. non polar
	C. dipolar	D. mo	nopolar					
19.		molect	ules do 1	not posses	dipole moment	A. pola	r	
	B. non po	lar C.	dipolar	-	-	-		
	D. monopo	olar	-					
20.	Monoatom	ic gases e	xhibit		_kind of polarizatio	on	A.	Electronic B.
	Ionic C.	orientation	n D.s	space char	ge			

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PART-B (3×2=6 Marks)

Answer all the questions

21. Give an example for dielectric materials.

Porcelain (ceramic), mica, glass, plastics, and the oxides of various metals.

22. What is the polarization?

If a material contains polar molecules, they will generally be in random orientations when no electric field is applied. An applied electric field will polarize the material by orienting the dipole moments of polar molecules. This decreases the effective electric field between the plates and will increase the capacitance of the parallel plate structure. The dielectric must be a good electric insulator so as to minimize any DC leakage current through a capacitor.

23. List out the difference between P and N type Semiconductors

	Р Туре	N Туре
Type of	Extrinsic semiconductor	Extrinsic semiconductor
Description	A type of extrinsic semiconductor that carries a positive charge	A type of extrinsic semiconductor that carries a negative

Comparison between P Type and N Type Semiconductor:

	and has an improved conductivity.	charge and has an improved conductivity.
Hole concentration	Larger hole concentration	Less hole concentration
Electron concentration	Less electron concentration	Larger electron concentration
Charge	Positive charge of the hole	Negative charge of the electron
Carriers	Holes are the majority carriers and electrons are the minority carriers	Electrons are the majority carriers and holes are the minority carriers
Creation	Created by doping an intrinsic semiconductor with acceptor impurities	Created by doping an intrinsic semiconductor with donor impurities
Dopant	Common p-type dopant for silicon is boron. Others include aluminum or gallium.	Common dopant for n-type silicon is phosphorus. Others include antimony and arsenic.

PART-C (3×8=24 Marks)

Answer all the questions

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24. A) Deduce the Claussius - Mossotti equation.

The polarization (P) of the dielectric is given by

$$P = \sum_{j} N_{j} p_{j} = \sum_{j} N_{j \in \text{Ibc}(j)}$$

Here, N_j is the concentration and j is the polarizability of atom j and E_{loc} (j) is the local field at atom sites j. p_j is the dipole moment of the jth atom.

The total local field at a cubic site is given by Lorentz relation

Here E is the macroscopic electric field.

P=(N_{j j})(
$$E + 1/(3\varepsilon_1 0) P$$
)
P(($1 - \Sigma N_j \alpha_j$)/3 ε_0) = E N_{j j}

Thus, the dielectric susceptibility is given by,

$$= \frac{P}{\varepsilon_0 E} = \frac{\Sigma N_j \alpha_j}{\varepsilon_0} \left(\mathbf{1} - \frac{N_j \alpha_j}{3\varepsilon_0} \right)$$

Further, the dielectric constant,

$$\varepsilon_r = \mathbf{1} + \chi_e = 1 + \frac{\Sigma N_j \alpha_j}{\varepsilon_0} \left(\mathbf{1} - \frac{N_j \alpha_j}{\mathbf{3}\varepsilon_0} \right) = \frac{\mathbf{3}\Sigma N_j \alpha_j}{\mathbf{3}\varepsilon_0 - \Sigma N_j \alpha_j}$$

$$(\varepsilon_{\downarrow}r - 1))/(\varepsilon_{\downarrow}r + 2) = 1/(3\varepsilon_{\downarrow}0) [\Sigma N]_{\downarrow}j \alpha_{\downarrow}j$$

Equ.(5) is called clausius-Mossotti relation

It relates the dielectric constant to the atomic polarizability provided the condition of cubic symmetry holds.

B) Discuss in detail about Electronic polarization

Let us consider a single atom of atomic number Z. Say, +e coulomb is the charge of each proton in the nucleus and -e coulomb is the charge of each electron surrounds the

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nucleus. All orbiting electrons in the atom form a spherical cloud of negative charge surrounds the positively charged nucleus. The charge of nucleus is +Ze coulombs and charge of the negative cloud of electrons is -Ze coulombs. Let us also assume that the negative charge of the electrons cloud is homogeneously distributed on a sphere of radius R. When there is no influence of any external electric field, the center of this sphere and center of nucleus of the atom coincide. Now, say an external electric field of intensity E volt per meter is applied on the atom. Because of this external electric field the nucleus of the atom is shifted towards negative intensity of the field and the electron cloud is shifted towards the positive intensity of the field.

As due to influence of external electric field the center of nucleus and center of electrons cloud are separated, there will be an attraction force developed between them according to <u>Coulomb's law</u>. Say, at the distance of separation of center of nucleus and electron cloud, x, the equilibrium is established. That means at distance of separation x, the forces acting on the nucleus or electron cloud due to external electric field and due to Coulomb law become same and opposite. It is obvious that the radius of nucleus is much much more than that of electron cloud. So in respect of electron cloud the nucleus can be considered as point charge. Hence, the electrostatic force acting on the nucleus would be +E.Z.e. Now the nucleus has been shifted from the center of electrons cloud by a distance x. According to Gauss's theorem, the force due to negative electron cloud acting upon the positive nucleus would only be due to the portion of the cloud enclosed by the sphere of radius x. The portion of the cloud outside the sphere of radius x does not apply any force on the nucleus. Now, the volume of the sphere of radius x is (4/3) x^3 and the volume of the sphere of radius R is (4/3) R^3 .

Now total negative charge of the electron cloud is -Ze and we have already considered that it is uniformly distributed throughout the volume of the cloud. Hence, the quantity of negative charge enclosed by the sphere of radius x is,

$$\left[rac{-Ze}{\left(rac{4}{3}
ight)\pi R^3}
ight] imes \left(rac{4}{3}
ight)\pi x^3=rac{-Zex^3}{R^3}$$

Only this much charge will apply coulombic force on the nucleus. So, according to Coulomb's law, the force would be

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$$\frac{\left(\frac{Ze \times Zex^3}{R^3}\right)}{4\pi\epsilon_0 x^2} = \frac{Z^2 e^2 x}{4\pi\epsilon_0 R^3}$$

At equilibrium condition,

$$EZe = rac{Z^2 e^2 x}{4\pi\epsilon_0 R^3}$$
 $E = rac{Zex}{4\pi\epsilon_0 R^3} \Rightarrow x = \left(rac{4\pi\epsilon_0 R^3}{Ze}
ight)E$

Now the dipole moment of the nucleus is Zex as dipole moment is the product of charge of the nucleus and the distance of displacement. Now, putting the expression of x in the expression of dipole moment, we get,

$$Ze(rac{4\pi\epsilon_0R^3}{Ze})E = 4\pi\epsilon_0R^3E$$

The polarization is defined as the number of dipole moments per unit volume of the material. If N is the number of dipole moments per unit volume, the polarization would be,

$$P = 4\pi\varepsilon_0 R^3 EN$$

From the above expression it is found that the **electronic polarization** or atomic polarization is dependent upon the radius (or volume) of the atom and the number of atoms presents in unit volume of the material.

25. A) Explain the concept of Complex Dielectric Constant.

A complex dielectric constant is used to describe the dielectric constant during a periodic variation of the electric field, where the field variation is described by a sine-shaped waveform. It is written in the form

$\epsilon \epsilon = \epsilon' + i * \epsilon'' = \epsilon' + i * \epsilon''$

where the real part, $\epsilon'\epsilon'$, is the permittivity component quantifying the stored energy (i.e. the part directly proportional to the field amplitude) and the imaginary part, $\epsilon''\epsilon''$ is the dielectric loss factor, which describes the part of the electric energy that is lost through movement of molecules/ions as a result of the continually changing field (the contribution from this component is proportional to the rate of the electric field change, or the first derivative of the electrical field function). This component also gives rise to a phase difference between the field function and the resulting polarization. Without this component both would be perfectly in phase. Both components depend on the frequency of the field variation.

B) Discuss in detail about orientation polarization

Before discussing Orientational polarization, let us examine the structural details of some molecules. Let us take an oxygen molecule. A single oxygen atom has only 6 electrons on its outermost cell. One oxygen atom creates the double covalent bond with another oxygen atom and creates an oxygen molecule. In an oxygen molecule, the distance between the centers of the nucleus of two atoms is 121 Pico-metre. But there is no permanent or resultant dipole moment as both ends of the molecules are equally charged. There is no net charge transfer between the atoms in the molecule. Similarly, if we take the pictures of hydrogen, nitrogen etc we will find there is also no net dipole moment for the same reasons. Now, let us consider the molecular structure of water.

A water molecule is bent structured. Here, oxygen atom has the covalent bond with two hydrogen atoms. Oxygen portion of the water molecule is slightly negative whereas hydrogen portions are slightly positive. These negative positive portions of the molecules form two dipole moments pointed from the center of oxygen atom to center of hydrogen atoms.

The angle between these two dipole moments is 105°. There would be a resultant of these two dipole moments. This resultant dipole moment is present in each of the water molecule even in the absence of any externally applied field. So, the water molecule has a permanent dipole moment. Nitrogen dioxide or similar types of molecules have same permanent dipole moment for same reason. When an electric field is applied externally, the molecules with permanent dipole moment orient themselves according to the direction of applied electric field. This is because external electric field exerts a torque on the permanent dipole moment of each molecule. The process of orientation of permanent dipole moments along the axis of applied electric field is called orientational polarization.

26. A) Explain about superconductivity and give some applications.

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Superconductivity was first observed in 1911 by the Dutch physicist H.K. Onnes in the course of his experiments on the electrical conductivities of metals at low temperatures. He observed that as purified mercury is cooled its resistivity vanished abruptly at 4.2 K. Above this temperature, the resistivity is small but finite, while the resistivity below this point is so small it is essentially zero. The temperature at which the transition takes place is called the critical temperature (T_c). The temperature (T_c) which marks the transition of a normal conductor to the superconducting state, is defined as the transition temperature. Above the critical temperature (T_c), the substance is in the familiar *normal state*, but below (T_c) it enters an entirely different *superconducting state*. The superconducting state is marked by a sudden fall of the electrical resistivity of the material to nearly zero, when it is cooled to a sufficiently low temperature.



The resistivity of a metal may be written as $p = \frac{m}{ne^2 \tau}$ where m= mass of the electron, e= charge of the electron n=No. of electrons per unit volume and = collision time. The vibration of the ions in a crystal decreases with decreasing temperature. This has the effect of decreasing the probability of an electron-ion collision or of increasing the collision time τ . Thus decreases as the temperature is lowered. According to the above equation, this implies that the resistivity of a metal should tend towards zero, as the temperature zero. If τ becomes infinite at sufficient low temperatures, then the resistivity vanishes entirely, which is what is observed in superconductivity. As the temperature is lowered below T_c , fraction of the electron becomes superconducting, in the sense that they have infinite collisions. These electrons undergo no scattering whats oever,

eventhough the substance may contain some impurities and defects. It is these electrons which are responsible for superconductivity.

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APPLICATIONS OF SUPERCONDUCTORS

When heated the superconducting sample, its normal resistivity at the Temperature $T_{\rm c}.$

Superconductivity appears in metallic elements (silver, lead, etc) of the periodic system and also in alloys and semiconductors. The range of transition temperature at present extends from 23.2K for the alloy Nb₃, Ge₂ to 0.01 K for some semiconductors. There are many applications of superconductivity.

- i) One is in the construction of superconducting electromagnets that carry large resistance less currents and, therefore produce large magnetic fields (5-10 Tesla). If superconducting wire for magnet windings are used, currents of the order of 100 amperes can be carried by very fine wires. Thus small-size magnets can be constructed. In which a superconducting coil immersed in liquid helium (4K). Starting from zero, the current is increased until the magnetic field B reaches the desired value. At that point the switch is closed. The current now flows through the switch. The power supply is then turned off. The current will continue to flow through the coil indefinitely without resistive losses.
- Superconducting cables can be used to transmit electric power over long distance without resistive losses. This is possible only if the cost of keeping the cable below its critical temperature is less than the value of the power lost using ordinary cables.
- iii) Superconductors are used for amplifying very small direct currents and voltages.
- iv) Superconductors are employed in switching devices.
- v) Because superconductors are diamagnetic, they can be used to shield out unwanted magnetic flux, as in shaping the magnetic lens system of an electron microscope.

B) Explain in detail about Type I and type II Superconductors

The superconductors can be classified into two distinct groups according to their behavior in external magnetic field.

Type I Superconductors

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The superconductors, in which the magnetic field is totally excluded from the interior of superconductors below a certain magnetizing field H_c , and at H_c the material loses superconductivity and the magnetizing field penetrates fully are termed as type I or soft superconductors.

Ex: Tin, lead, Aluminum, Mercury, Zinc, Magnesium, Etc. The magnetization curve for type I super-conducting material is given below:



The important characteristics of type I superconductors are:

i) They exhibit complete Meissner effect.

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ii) The critical values of magnetic field H_c at which magnetization drops are very low. The maximum known critical field for type I superconductor is of the order of 0.1T. The low value of H_c makes these materials unsuitable for use in high field superconducting magnets.

The magnetization curve shows that transition at H_c is reversible. This means that if the magnetic field is reduced below H_c , the material again acquires superconducting property and the field is expelled.

iii) Below H_c the material is superconductor and above H_c it becomes a conductor.

Type II superconductors

The superconductors in which the material loses magnetization gradually rather than suddenly are termed as type II or hard superconductors.



The important characteristics are:

- i) They donot show complete Meissner effect.
- ii) These superconductors have two critical fields: H_{c1} and H_{c2} . The specimen is diamagnetic below H_{c1} i.e., the magnetic field is completely excluded below H_{c1} . At H_{c1} the flux begins to penetrate the specimen, and the penetration of flux increases until the upper critical field H_{C2} is reached. At H_{C2} the magnetization vanishes and specimen returns to normal conducting state. The value of critical field for type II materials may be 100 times or more higher than the values of H_c for type I superconductors. Critical fields H_{c2} upto 30 T have been observed.

The materials which display type II behavior are essentially inhomogeneous and include Nb-Zr, Nb-Ti alloys and Va-Ga and Nb-Sn inter-metallic compounds. These are technically more useful than type I superconductors due to tolerating high magnetic fields.

Reg No.....

ITPHU102] KARPAGAM ACADEMY OF HIGHER EDUCATION COIMBATORE-21 (Under Section3 of UGC Act 1956) DEPARTMENT OF PHYSICS I B.Sc PHYSICS First Semester III-Internal Examination Solid State Physics

Date:

Time:2 hours Maximum:50 marks

PART-A(20×1=20Marks) Answer all questions

1.	The process of producing electric dipoles inside the dielectrics by an external electric field is
	A. polarisation B. Interference C. diffraction D. coherence
2.	If the strength of the electric field is increased, the strength of the induced dipole
	A. decrease B. increase C. remains constant D. zero
3.	The induced dipole moment is proportional to of the electric field
	A. Intensity B. resistance
	C. capacitance D. none of these
4.	is the quantity which is used for analyzing electrostatic fields
	A. Electric vector B. Electric displacement vector C. electric induction D. both a
	and c
5.	The dielectric constant determines the share of the which is absorbed
	by the material A. Tensile stress B. dielectric stress C.electric stress
~	D. magnetic stress
6.	is the ratio between the absolute permittivity and the permittivity
	of free space
7	A. Susceptionity B. dielectric constant C. permeability D.none of these
7.	B flux lines C electric induction
	D flux density
8	is a measure of polarisation in the dielectric A. Dipole
0.	moment B. electric dipole C. dielectric constant D.entropy
9.	The dielectric constant for silicon is A. 6 B. 8 C.9 D. 12
10.	The dielectric constant for glass is A. 7 B. 4 C. 4to7 D. 8
11.	Schering bridge (resonance method) is not applicable at frequencies of region
	A. ultraviolet B. microwave C. visible D. Infra red
12.	The example for active dielectrics are A. glass B. silica
	C. piezo electrics D. mica
13.	The example for passive dielectrics is
	A. glass B. mica C. all insulating materials D. all of these

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14.	molecules will not have centre of symmetry		A. polar					
	B. non pol	ar C.d	lipolar	D. mono	polar			
15.	The examp	le for pola	ar molec	ules is				
	A. H ₂ O	B. N ₂	0	C. CH ₃	D. both A and B			
16.	The examp	The example for non polar molecules is						
	A. N ₂ O	B. CH ₃	C.CH	4	D. CO			
17.		m	olecules	s posses ce	entre of symmetry	A. pola	ır	B. non polar
	C. dipolar	D. mo	nopolar	-		-		-
18.		r	nolecule	s posses d	ipole moment	A. pola	ar	B. non polar
	C. dipolar	D. mo	nopolar					
19.		molect	ules do 1	not posses	dipole moment	A. pola	ar	
	B. non po	lar C.	dipolar	-	-	_		
	D. monopo	olar	-					
20.	Monoatom	ic gases e	xhibit		_kind of polarization	on	A.	Electronic B.
	Ionic C.	orientation	n D.s	space char	ge			

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PART-B (3×2=6 Marks)

Answer all the questions

21. Give an example for dielectric materials.

Porcelain (ceramic), mica, glass, plastics, and the oxides of various metals.

22. What is the polarization?

If a material contains polar molecules, they will generally be in random orientations when no electric field is applied. An applied electric field will polarize the material by orienting the dipole moments of polar molecules. This decreases the effective electric field between the plates and will increase the capacitance of the parallel plate structure. The dielectric must be a good electric insulator so as to minimize any DC leakage current through a capacitor.

23. List out the difference between P and N type Semiconductors

	Р Туре	N Туре
Type of	Extrinsic semiconductor	Extrinsic semiconductor
Description	A type of extrinsic semiconductor that carries a positive charge	A type of extrinsic semiconductor that carries a negative

Comparison between P Type and N Type Semiconductor:

	and has an improved conductivity.	charge and has an improved conductivity.
Hole concentration	Larger hole concentration	Less hole concentration
Electron concentration	Less electron concentration	Larger electron concentration
Charge	Positive charge of the hole	Negative charge of the electron
Carriers	Holes are the majority carriers and electrons are the minority carriers	Electrons are the majority carriers and holes are the minority carriers
Creation	Created by doping an intrinsic semiconductor with acceptor impurities	Created by doping an intrinsic semiconductor with donor impurities
Dopant	Common p-type dopant for silicon is boron. Others include aluminum or gallium.	Common dopant for n-type silicon is phosphorus. Others include antimony and arsenic.

PART-C (3×8=24 Marks)

Answer all the questions

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24. A) Deduce the Claussius - Mossotti equation.

The polarization (P) of the dielectric is given by

$$P = \sum_{j} N_{j} p_{j} = \sum_{j} N_{j \in \text{Ibc}(j)}$$

Here, N_j is the concentration and j is the polarizability of atom j and E_{loc} (j) is the local field at atom sites j. p_j is the dipole moment of the jth atom.

The total local field at a cubic site is given by Lorentz relation

Here E is the macroscopic electric field.

P=(N_{j j})(
$$E + 1/(3\varepsilon_1 0) P$$
)
P(($1 - \Sigma N_j \alpha_j$)/3 ε_0) = E N_{j j}

Thus, the dielectric susceptibility is given by,

$$= \frac{P}{\varepsilon_0 E} = \frac{\Sigma N_j \alpha_j}{\varepsilon_0} \left(\mathbf{1} - \frac{N_j \alpha_j}{3\varepsilon_0} \right)$$

Further, the dielectric constant,

$$\varepsilon_r = \mathbf{1} + \chi_e = 1 + \frac{\Sigma N_j \alpha_j}{\varepsilon_0} \left(\mathbf{1} - \frac{N_j \alpha_j}{\mathbf{3}\varepsilon_0} \right) = \frac{\mathbf{3}\Sigma N_j \alpha_j}{\mathbf{3}\varepsilon_0 - \Sigma N_j \alpha_j}$$

$$(\varepsilon_{\downarrow}r - 1))/(\varepsilon_{\downarrow}r + 2) = 1/(3\varepsilon_{\downarrow}0) [\Sigma N]_{\downarrow}j \alpha_{\downarrow}j$$

Equ.(5) is called clausius-Mossotti relation

It relates the dielectric constant to the atomic polarizability provided the condition of cubic symmetry holds.

B) Discuss in detail about Electronic polarization

Let us consider a single atom of atomic number Z. Say, +e coulomb is the charge of each proton in the nucleus and -e coulomb is the charge of each electron surrounds the

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nucleus. All orbiting electrons in the atom form a spherical cloud of negative charge surrounds the positively charged nucleus. The charge of nucleus is +Ze coulombs and charge of the negative cloud of electrons is -Ze coulombs. Let us also assume that the negative charge of the electrons cloud is homogeneously distributed on a sphere of radius R. When there is no influence of any external electric field, the center of this sphere and center of nucleus of the atom coincide. Now, say an external electric field of intensity E volt per meter is applied on the atom. Because of this external electric field the nucleus of the atom is shifted towards negative intensity of the field and the electron cloud is shifted towards the positive intensity of the field.

As due to influence of external electric field the center of nucleus and center of electrons cloud are separated, there will be an attraction force developed between them according to <u>Coulomb's law</u>. Say, at the distance of separation of center of nucleus and electron cloud, x, the equilibrium is established. That means at distance of separation x, the forces acting on the nucleus or electron cloud due to external electric field and due to Coulomb law become same and opposite. It is obvious that the radius of nucleus is much much more than that of electron cloud. So in respect of electron cloud the nucleus can be considered as point charge. Hence, the electrostatic force acting on the nucleus would be +E.Z.e. Now the nucleus has been shifted from the center of electrons cloud by a distance x. According to Gauss's theorem, the force due to negative electron cloud acting upon the positive nucleus would only be due to the portion of the cloud enclosed by the sphere of radius x. The portion of the cloud outside the sphere of radius x does not apply any force on the nucleus. Now, the volume of the sphere of radius x is (4/3) x^3 and the volume of the sphere of radius R is (4/3) R^3 .

Now total negative charge of the electron cloud is -Ze and we have already considered that it is uniformly distributed throughout the volume of the cloud. Hence, the quantity of negative charge enclosed by the sphere of radius x is,

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Only this much charge will apply coulombic force on the nucleus. So, according to Coulomb's law, the force would be

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$$\frac{\left(\frac{Ze \times Zex^3}{R^3}\right)}{4\pi\epsilon_0 x^2} = \frac{Z^2 e^2 x}{4\pi\epsilon_0 R^3}$$

At equilibrium condition,

$$EZe = rac{Z^2 e^2 x}{4\pi\epsilon_0 R^3}$$
 $E = rac{Zex}{4\pi\epsilon_0 R^3} \Rightarrow x = \left(rac{4\pi\epsilon_0 R^3}{Ze}
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Now the dipole moment of the nucleus is Zex as dipole moment is the product of charge of the nucleus and the distance of displacement. Now, putting the expression of x in the expression of dipole moment, we get,

$$Ze(rac{4\pi\epsilon_0R^3}{Ze})E = 4\pi\epsilon_0R^3E$$

The polarization is defined as the number of dipole moments per unit volume of the material. If N is the number of dipole moments per unit volume, the polarization would be,

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From the above expression it is found that the **electronic polarization** or atomic polarization is dependent upon the radius (or volume) of the atom and the number of atoms presents in unit volume of the material.

25. A) Explain the concept of Complex Dielectric Constant.

A complex dielectric constant is used to describe the dielectric constant during a periodic variation of the electric field, where the field variation is described by a sine-shaped waveform. It is written in the form

$\epsilon \epsilon = \epsilon' + i * \epsilon'' = \epsilon' + i * \epsilon''$

where the real part, $\epsilon'\epsilon'$, is the permittivity component quantifying the stored energy (i.e. the part directly proportional to the field amplitude) and the imaginary part, $\epsilon''\epsilon''$ is the dielectric loss factor, which describes the part of the electric energy that is lost through movement of molecules/ions as a result of the continually changing field (the
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B) Discuss in detail about orientation polarization

Before discussing Orientational polarization, let us examine the structural details of some molecules. Let us take an oxygen molecule. A single oxygen atom has only 6 electrons on its outermost cell. One oxygen atom creates the double covalent bond with another oxygen atom and creates an oxygen molecule. In an oxygen molecule, the distance between the centers of the nucleus of two atoms is 121 Pico-metre. But there is no permanent or resultant dipole moment as both ends of the molecules are equally charged. There is no net charge transfer between the atoms in the molecule. Similarly, if we take the pictures of hydrogen, nitrogen etc we will find there is also no net dipole moment for the same reasons. Now, let us consider the molecular structure of water.

A water molecule is bent structured. Here, oxygen atom has the covalent bond with two hydrogen atoms. Oxygen portion of the water molecule is slightly negative whereas hydrogen portions are slightly positive. These negative positive portions of the molecules form two dipole moments pointed from the center of oxygen atom to center of hydrogen atoms.

The angle between these two dipole moments is 105°. There would be a resultant of these two dipole moments. This resultant dipole moment is present in each of the water molecule even in the absence of any externally applied field. So, the water molecule has a permanent dipole moment. Nitrogen dioxide or similar types of molecules have same permanent dipole moment for same reason. When an electric field is applied externally, the molecules with permanent dipole moment orient themselves according to the direction of applied electric field. This is because external electric field exerts a torque on the permanent dipole moment of each molecule. The process of orientation of permanent dipole moments along the axis of applied electric field is called orientational polarization.

26. A) Explain about superconductivity and give some applications.

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Superconductivity was first observed in 1911 by the Dutch physicist H.K. Onnes in the course of his experiments on the electrical conductivities of metals at low temperatures. He observed that as purified mercury is cooled its resistivity vanished abruptly at 4.2 K. Above this temperature, the resistivity is small but finite, while the resistivity below this point is so small it is essentially zero. The temperature at which the transition takes place is called the critical temperature (T_c). The temperature (T_c) which marks the transition of a normal conductor to the superconducting state, is defined as the transition temperature. Above the critical temperature (T_c), the substance is in the familiar *normal state*, but below (T_c) it enters an entirely different *superconducting state*. The superconducting state is marked by a sudden fall of the electrical resistivity of the material to nearly zero, when it is cooled to a sufficiently low temperature.



The resistivity of a metal may be written as $p = \frac{m}{ne^2 \tau}$ where m= mass of the electron, e= charge of the electron n=No. of electrons per unit volume and = collision time. The vibration of the ions in a crystal decreases with decreasing temperature. This has the effect of decreasing the probability of an electron-ion collision or of increasing the collision time τ . Thus decreases as the temperature is lowered. According to the above equation, this implies that the resistivity of a metal should tend towards zero, as the temperature zero. If τ becomes infinite at sufficient low temperatures, then the resistivity vanishes entirely, which is what is observed in superconductivity. As the temperature is lowered below T_c , fraction of the electron becomes superconducting, in the sense that they have infinite collisions. These electrons undergo no scattering whats oever,

eventhough the substance may contain some impurities and defects. It is these electrons which are responsible for superconductivity.

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APPLICATIONS OF SUPERCONDUCTORS

When heated the superconducting sample, its normal resistivity at the Temperature $T_{\rm c}.$

Superconductivity appears in metallic elements (silver, lead, etc) of the periodic system and also in alloys and semiconductors. The range of transition temperature at present extends from 23.2K for the alloy Nb₃, Ge₂ to 0.01 K for some semiconductors. There are many applications of superconductivity.

- i) One is in the construction of superconducting electromagnets that carry large resistance less currents and, therefore produce large magnetic fields (5-10 Tesla). If superconducting wire for magnet windings are used, currents of the order of 100 amperes can be carried by very fine wires. Thus small-size magnets can be constructed. In which a superconducting coil immersed in liquid helium (4K). Starting from zero, the current is increased until the magnetic field B reaches the desired value. At that point the switch is closed. The current now flows through the switch. The power supply is then turned off. The current will continue to flow through the coil indefinitely without resistive losses.
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- v) Because superconductors are diamagnetic, they can be used to shield out unwanted magnetic flux, as in shaping the magnetic lens system of an electron microscope.

B) Explain in detail about Type I and type II Superconductors

The superconductors can be classified into two distinct groups according to their behavior in external magnetic field.

Type I Superconductors

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The superconductors, in which the magnetic field is totally excluded from the interior of superconductors below a certain magnetizing field H_c , and at H_c the material loses superconductivity and the magnetizing field penetrates fully are termed as type I or soft superconductors.

Ex: Tin, lead, Aluminum, Mercury, Zinc, Magnesium, Etc. The magnetization curve for type I super-conducting material is given below:



The important characteristics of type I superconductors are:

i) They exhibit complete Meissner effect.

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ii) The critical values of magnetic field H_c at which magnetization drops are very low. The maximum known critical field for type I superconductor is of the order of 0.1T. The low value of H_c makes these materials unsuitable for use in high field superconducting magnets.

The magnetization curve shows that transition at H_c is reversible. This means that if the magnetic field is reduced below H_c , the material again acquires superconducting property and the field is expelled.

iii) Below H_c the material is superconductor and above H_c it becomes a conductor.

Type II superconductors

The superconductors in which the material loses magnetization gradually rather than suddenly are termed as type II or hard superconductors.



The important characteristics are:

- i) They donot show complete Meissner effect.
- ii) These superconductors have two critical fields: H_{c1} and H_{c2} . The specimen is diamagnetic below H_{c1} i.e., the magnetic field is completely excluded below H_{c1} . At H_{c1} the flux begins to penetrate the specimen, and the penetration of flux increases until the upper critical field H_{C2} is reached. At H_{C2} the magnetization vanishes and specimen returns to normal conducting state. The value of critical field for type II materials may be 100 times or more higher than the values of H_c for type I superconductors. Critical fields H_{c2} upto 30 T have been observed.

The materials which display type II behavior are essentially inhomogeneous and include Nb-Zr, Nb-Ti alloys and Va-Ga and Nb-Sn inter-metallic compounds. These are technically more useful than type I superconductors due to tolerating high magnetic fields.

Reg No	8.	is a measure
[17PHI]102]		of polarisation in the dielectric A.
		Dipole moment B. electric
KARPAGAM ACADEMY OF HIGHER		dipole C. dielectric constant D.entropy
		The dielectric constant for silicon is
EDUCATION COMPATORE 11		A. 6 B. 8 C.9 D. 12
COIMBATORE-21	10.	The dielectric constant for glass is
(Under Section3 of UGC Act 1956)		A. 7 B. 4 C. 4to7
DEPARTMENT OF PHYSICS		D. 8
I B.Sc PHYSICS	11.	Schering bridge (resonance method) is
First Semester		not applicable at frequencies
III Internal Examination		of region A ultraviolet B
		microwaye C, visible D. Infra red
Solid State Physics	12	The example for active dielectrics are
	12.	A glass B silica
Date: Time:2 hours		<u>C niezo electrics</u> D mica
Maximum:50 marks	13	The example for passive dielectrics is
	15.	A glass B mica C all insulating
PART-A(20×1=20Marks)		materials D all of these
Answer all questions	1/	molecules will not have
	14.	$\underline{\qquad} \qquad $
1. The process of producing electric dipoles		B non polar C dipolar D mono
inside the dielectrics by an external		nolar
electric field is	15	The example for poler molecules is
A. polarisation B. Interference	15.	The example for polar molecules is
C. diffraction D. coherence		
2. If the strength of the electric field is		A. $\Pi_2 O$ D. $N_2 O$ C. $C\Pi_3$ D. both A and D.
increased, the strength of the induced	16	D. DOULA allu D The exemple for non-noise molecules is
dipoleA. decrease B. increase	10.	A N O P CH C CH
C. remains constant D. zero		A. N_2O B. CH_3 C. CH_4
3. The induced dipole moment is	17	D.CO
proportional to of the	17.	molecules posses
electric field		centre of symmetry A. polar B.
A. Intensity B. resistance		non polar C. dipolar D.
C. capacitance D. none of these	10	monopolar
4. is the quantity which	18.	molecules posses
is used for analyzing electrostatic fields		dipole moment A. polar B.
A. Electric vector B Electric	10	non polar C. dipolar D. monopolar
displacement vector C. electric	19.	molecules do not posses
induction D. both a and c		apole moment A. polar
5. The dielectric constant determines the		Б. non polar U.dipolar
share of the which is	20	D. monopolar
absorbed by the material A. Tensile	20.	wonoatomic gases exhibit
stress B. dielectric stress		Kind of polarization
C.electric stress D. magnetic stress		A. Electronic B. Ionic
6. is the ratio		C. orientation D. space charge
between the absolute permittivity and the		
permittivity of free space		
A. Susceptibility B. dielectric constant		PART-B (3×2=6 Marks)
C. permeability D. none of these		Answer all the questions
7. is a		
dimensionless quantity A Dielectric	21.	Give an example for dielectric materials.
constant R flux lines C electric	22.	What is the polarization?
induction	23.	List out the difference between P and N
D flux density		type Semiconductors
D. Hux density		

PART-C (3×8=24 Marks)

Answer all the questions

24. A) Deduce the Claussius - Mossotti equation.

(OR)

B) Discuss in detail about Electronic polarization

25. A) Explain the concept of Complex Dielectric Constant.

(OR)

B) Discuss in detail about orientation polarization

26. A) Explain about superconductivity and give some applications.

(OR)

B) Explain in detail about Type I and type II Superconductors

Reg. No.....[17PHU102]

KARPAGAM ACADEMY OF HIGHER EDUCATION COIMBATORE -641 021 I B.Sc PHYSICS, Test - I SOLID STATE PHYSICS

Max Marks: 50

PART – A (20 $\hat{1}$ 1 = 10 Marks)

Answer all questions. Each question carries 1 mark.

1. The example for amorphous materials are			
a) Glass b) calcite c) quartz d) Diamond			
2. The example for crystalline solid materials are			
a) Rubber b) Wood c) Plastic d) Calcite			
3. Space lattice is arrangement of crystal point in			
a) One dimension b) Two dimension c) Three dimension c)			
Zero dimension			
4. A group of atom attached to each lattice point is called			
a) Space lattice b) Basis c) Unit cell			
d) Crystal lattice			
5. The interfacial angle for cubic structure are			
a) $= = b$) $= c$) $= d$)			
6. Primitive unit cell are present isa) Centre position b)			
Corner position c) Top position d) Bottom position			
7. The sharp melting point in meansa) 50-75°C b) 80-			
$85^{\circ}C$ c) $80-84^{\circ}C$ d) $80-82^{\circ}C$			
8. Broad melting point in means a) 50-85°C			
b) $80-85^{\circ}C$ c) $80-84^{\circ}C$ d) $80-82^{\circ}C$			
9. Bragg's law is a) $2dsin = n$			
b) $2\sin = n$ c) $2d = n$ d) $d\sin = n$			
10. Example for face-centred cubic lattice is			
a) NaCl b) CsCl c) HCl d) MgCl			

11. The inter-facial angle for hexagonal structure are ----a) = $= 120^{\circ}$, $= 90^{\circ}$ b) $= = 90^{\circ}$, 120° c) = =90°, =120° =90°. d) $=120^{\circ}$ 12. Which of the following has the least packing fraction c) Diamond structure a) Bcc b) Scc d) Fcc 13. The metal which has hexagonal close packed structure is _____ a) silver b) iron c) magnesium d) Aluminium 14.Collective excitation in а periodic, elastic arrangement of atoms or molecules in condensed like solids and matter. some liquids is called a) Phonons b) photons c) Proton d) Neutron 15. The concept of phonons was introduced in 1932 by a) Igor Tamm b) Thmson c) Einstein d) Newton 16. phonon energy E= a) hv b) hc c) hv^2 d) All the above 17. The metal which has hexagonal close packed structure is a) silver b) iron c) magnesium d) Aluminium can be carried out from highly 18._____ supersaturated solutions. a) Nucleation b) Agitation c) Cooling rate d) None of these 19. The actual structure of the crystalline solids is determined by a) X-rays b) Neutron beams c) Electron beams d) All the above 20. Solids are classified in to types based on the arrangement of atoms. d) Five a) Three c) One b) Two

PART – B

(3 X 2 = 6)

ANSWER THE OUESTIONS

21. What is know primitive unit cel.

22. Define lattice basis.

23. What is meant by unit cell.

Part – C (3 x 8 = 24) 24. a. Write a note on lattice translation vector and Miller indices. OR b. Derive Bragg's law for X-ray diffraction 25. a. Differentiate between amorphous and crystalline solid. OR b. What are the types of lattices? 26. a. Write a note on reciprocal lattice? OR

b. Describe one-dimensional monoatomic lattice vibrations.

KARPAGAM ACADEMY OF HIGHER EDUCATION,COIMBATORE -641 021
B.Sc. DEGREE EXAMINATIONS
III INTERNAL
MATHEMATICAL PHYSICS-I
Answer key
Part-A $(20 \text{ x } 1 = 20)$
Choose the correct answer:
1. The sum of nth roots of unity are
a) 3 b) 2 c) 1 d) 0
2. The value of $i^2 + i^3 + i^4$ is
a) (-i) b) I c) 1 d)-1
3. The exponential form of a complex number is
a) $\mathbf{z} = \mathbf{r} \mathbf{e}^{\mathbf{i} \mathbf{\theta}}$ b) $\mathbf{z} = \mathbf{e}^{\mathbf{i} \mathbf{q}}$ c) $\mathbf{z} = \cos \mathbf{q} / \mathbf{r}$
d) $z = r / \cos q$
4. A single valued function $f(z)$ which is differentiable at $z = zo$ it is said to be
a) irregular function b) analytic function
c) periodic function d) all the above
5. If a given number is wholly real, it is found in/on
a) a real axis b) imaginary c) x-y plane d) space
6. The symbol i with the property i 2 = -1 was introduced by
a) Euler b) Gauss . c) Cauchy d) Reimann
7. The Conjugate of 1/i is
a) -1 b)1 c)1 d)-i
8. In the Argand diagram, the fourth roots of unity forms a
a) square b) rectangle c) circle d) rhombus
9. A number of the form a+1b is called a
a) Complex number b) imaginary numbers c) real numbers d) all the above
10. Any function which satisfies the Laplace equation is known as
a) analytic function b) single function
c) conjugate function a) narmonic function
11. The value of $P_1(x)$ is
a) $x / 2$ b) x c) 1 d) $\frac{7}{2}(x - 1)$ 12 The identical roots of the Legendre's functions are
12. The identical roots of the Legendre's functions are
a) $m = 1$ b) $m = 1$ c) $m = 0$ or $m = -1$
13 If Io and I, are Bessel's functions then $L'(x)$ is given by
a) $I_0(x) = 1/x I_1(x)$ b) $= I_0 = c I_0(x) + 1/x I_1(x)$
d) $I_0(x) = 1/x I_1(x)$
14 If $I_{n+1}(x) = (2/x) I_n(x) - I_0(x)$ where In is the Bessel function of first kind order 'n' Then
'n' is
a) $(0 \ b) \ 2 \ c) \ 1 \ d) \ -1$
15. The function $1/(Z-1)(Z+1)$ is analytic
a) at all points $y=x$ b) at all points.except $Z=1$
c) at all points, except $Z=-1$ d) both b and c
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16. If Z=a+ib, then real part of Z-1 is \overline{c} -b/ a^2 +b² a) $-b/\sqrt{a^2+b^2}$ b) $a/\sqrt{a^2+b^2}$ d) a/ a^2+b^2 17. The conjugate of (1+i)(3+4i) is d (-1-7i) a) 1+7i b) **1-7i** c) 7-i 18. A connected open set is called a) an open set b) a closed set c) a banded set d) domain 19. Which is the analytic function of complex variable z=x+iy _____. d) e sinz b) Re Z c) Log Z a) |Z| 20. For a unit circle around the origin, the value of sin q is a) $\frac{z^2 + 1}{2iz}$ b) $\frac{z^2 - 1}{2iz}$ c) $\frac{z^2 + 1}{2z}$ d) $\frac{z^2 - 1}{2z}$

Answer all the questions

21. Define Analytic function.

A function f(z) is said to be analytic in a region R of the complex plane if f(z) has a derivative at each point of R and if f(z) is single valued.

 $(3 \times 2 = 6)$

22. Define complex number

A combination of a real and an imaginary number in the form $\mathbf{a} + \mathbf{b}\mathbf{i}$

a and **b** are real numbers, and **i** is the "unit imaginary number" $\sqrt{(-1)}$

The values **a** and **b** can be zero.

These are all complex numbers: 1 + i, 2 - 6i, -5.2i, 4

23. Why Laplace equation is most commonly used in differential equation?

The solutions of Laplace's equation are the harmonic functions, which are important in many fields of science, notably the fields of electromagnetism, astronomy, and fluid dynamics, because they can be used to accurately describe the behavior of electric, gravitational, and fluid potentials. In the study of heat conduction, the Laplace equation is the steady-state heat equation.

24. a) Derive the solution for Laplace's Equation in cylindrical co-ordinates. Suppose that we wish to solve Laplace's equation,

$$\nabla^2 \phi = 0, \tag{1}$$

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а within a cylindrical volume of radius L and height L. Let us adopt the standard cylindrical coordinates, r, , . Suppose that the curved portion of the bounding surface corresponds z = 0r = az = L, while the two flat portions correspond to and , respectively. Suppose, to finally, that the boundary conditions that are imposed at the bounding surface are $\phi(r,\theta,0)=0,$ (2) $\phi(a, A, z) = 0$

$$\phi(a,\theta,z) = 0,\tag{3}$$

$$\phi(r,\theta,L) = \Phi(r,\theta), \tag{4}$$

 $\Phi(r,\theta)$

is a given function. In other words, the potential is zero on the curved and bottom where surfaces of the cylinder, and specified on the top surface.

In cylindrical coordinates, Laplace's equation is written

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\phi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2\phi}{\partial\theta^2} + \frac{\partial^2\phi}{\partial z^2} = 0.$$
(5)

Let us try a separable solution of the form

$$\phi(r,\theta,z) = R(r) Q(\theta) Z(z).$$
(6)

Proceeding in the usual manner, we obtain

$$\frac{d^2 Z}{dz^2} - k^2 Z = 0, (7)$$

$$\frac{d^2Q}{d\theta^2} + m^2 Q = 0, \tag{8}$$

$$\frac{d^2R}{dr^2} + \frac{1}{r}\frac{dR}{dr} + \left(k^2 - \frac{m^2}{r^2}\right)R = 0.$$
(9)

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Note that we have selected exponential, rather than oscillating, solutions in the -direction [by $-k^2 Z$ $+k^2 Z$ writing , instead of , in Equation (9)]. As will become clear, this implies that the radial solutions oscillate, which is the appropriate choice for the particular set of boundary conditions under consideration. The solution to Equation (9), subject to the constraint Z(0) = 0 that [which follows from the first boundary condition, (4)] is $Z(z) = \sinh(k z).$ (10)

The most general solution to Equation (10) is

$$Q(\theta) = \sum_{m=0,\infty} \left[A_m \cos(m\theta) + B_m \sin(m\theta) \right].$$
(11)

Note that, to ensure that the potential is single-valued in $\stackrel{\theta}{}$, the constant $\stackrel{m}{}$ is constrained to be an integer. Finally, if we write then Equation (11) becomes $d^2R = 1 dR (m^2)$

$$\frac{d^2R}{dp^2} + \frac{1}{p}\frac{dR}{dp} + \left(1 - \frac{m^2}{p^2}\right)R = 0.$$
(12)

This equation is known as *Bessel's equation*. The standard solution of this equation that is well r = 0 behaved at is \sqrt{r}

$$J_m(p) = \frac{1}{\pi} \int_0^{\pi} \cos(p \, \sin \theta - m \, \theta) \, d\theta. \tag{13}$$

This solution, which is known as a Bessel function, has the properties that

$$J_m(p) \to \frac{1}{m!} \left(\frac{p}{2}\right)^m \qquad \text{as } p \to 0 , \qquad (14)$$

$$J_m(p) \to \left(\frac{2}{\pi p}\right)^{1/2} \cos\left(p - m\frac{\pi}{2} - \frac{\pi}{4}\right) \qquad \text{as } p \to \infty .$$
(15)

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In other words, at small arguments the function has a power-law behavior, whereas at large arguments it takes the form of an oscillation of slowly decaying amplitude. It follows that $R(r) = J_m(kr).$ (16)

Let j_{mn} n th zero of the Bessel function $J_m(p)$. In other words, j_{mn} is the n th root p $J_m(p) = 0$ j_{mn} can be looked up in (in order, as increases from zero) of . The values of the can be looked up in standard reference books. (For example, and .) We can satisfy our $k = k_{mn}$, where i

$$k_{mn} = \frac{J_{mn}}{a}.$$
 (17)

Thus, our separable solution becomes

$$\phi(r,\theta,z) = \sum_{m=0,\infty} \sum_{n=1,\infty} \sinh(j_{mn} z/a) J_m(j_{mn} r/a) \left[A_{mn} \cos(m\theta) + B_{mn} \sin(m\theta) \right].$$
(18)

 $\Phi(r, \theta)$

It is convenient to express the specified function in the form of a Fourier series: that is,

$$\Phi(r,\theta) = \sum_{m=0,\infty} \left[C_m(r) \cos(m\theta) + S_m(r) \sin(m\theta) \right].$$
(19)

Our final boundary condition, then yields

$$C_m(r) = \sum_{n=1,\infty} A_{mn} \sinh(j_{mn} L/a) J_m(j_{mn} r/a),$$
(20)

$$S_m(r) = \sum_{n=1,\infty} B_{mn} \sinh(j_{mn} L/a) J_m(j_{mn} r/a).$$
(21)

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It remains to invert the previous two expressions to obtain the coefficients $A_{mn} = B_{mn}$. In fact, it is possible to demonstrate that if

$$f(p) = \sum_{n=1,\infty} a_{mn} J_m(j_{mn} p)$$
(22)

then

$$a_{mn} = \frac{2}{J_{m+1}^2(j_{mn})} \int_0^1 p f(p) J_m(j_{mn} p) dp.$$
(23)

Hence,

$$A_{mn} = \frac{2}{a^2 J_{m+1}^2(j_{mn}) \sinh(j_{mn} L/a)} \int_0^a r C_m(r) J_m(j_{mn} r/a) dr,$$
(24)

$$B_{mn} = \frac{2}{a^2 J_{m+1}^2(j_{mn}) \sinh(j_{mn} L/a)} \int_0^a r S_m(r) J_m(j_{mn} r/a) dr,$$
(25)

and our solution is fully determined.

 $a \rightarrow \infty$. In this case, according to Equation (409), the allowed values Consider the limit that of become more and more closely spaced. Consequently, the sum over discrete k-values in k (10) morphs into an integral over a continuous range of values. For instance, suppose that we $z \ge 0$, subject to the boundary condition wish to solve Laplace's equation in the region $\phi(r,\theta,0) = \Phi(r,\theta)$ $\phi \rightarrow 0$ $\Phi(r,\theta)$ $z \rightarrow \infty$ and $r \to \infty$, with that , where is specified. In this as $Z(z) = e^{-kz}$ in order to satisfy the boundary condition at large ⁶. The case, we would choose r = 0 $R(r) = J_m(kr)$ ensures that the potential is well behaved at choice , and automatically satisfies the boundary condition at large r. Hence, our general solution becomes

$$\phi(r,\theta,z) = \sum_{m=0,\infty} \int_0^\infty e^{-kz} J_m(kr) \left[A_m(k) \cos(m\theta) + B_m(k) \sin(m\theta) \right] dk.$$
(26)

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If we write

$$\Phi(r,\theta) = \sum_{m=0,\infty} \left[C_m(r) \cos(m\,\theta) + S_m(r) \sin(m\,\theta) \right]$$
(27)

then the final boundary condition implies that

$$C_m(r) = \int_0^\infty J_m(k\,r)\,A_m(k)\,dk,$$
(28)

$$S_m(r) = \int_0^\infty J_m(k\,r)\,B_m(k)\,dk.$$
(29)

We can invert the previous two expressions by means of the identity

$$\int_{0}^{\infty} r J_{m}(kr) J_{m}(k'r) dr = \frac{1}{k} \delta(k-k').$$
(30)

Hence, we obtain

$$A_m(k) = \int_0^\infty k \, r \, J_m(k \, r) \, C_m(r) \, dr, \tag{31}$$

$$B_m(k) = \int_0^\infty k \, r \, J_m(k \, r) \, S_m(r) \, dr, \tag{32}$$

and our solution is fully defined.

Suppose that we wish to solve Laplace's equation in a cylindrical volume of radius f and height L, subject to the boundary conditions

$$\phi(r,\theta,0) = 0, \tag{33}$$

$$\phi(r,\theta,L) = 0, \tag{34}$$

$$\phi(a,\theta,z) = \Phi(\theta,z), \tag{35}$$

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 $\Phi(\theta, z)$

where is specified. In other words, the potential is zero on the two flat portions of the bounding surface, and given on the curved portion. We can again look for a separable solution of the form.. Proceeding in the usual manner, we obtain

$$\frac{d^2 Z}{dz^2} + k^2 Z = 0, (36)$$

$$\frac{d^2Q}{d\theta^2} + m^2 Q = 0, \tag{37}$$

$$\frac{d^2R}{dr^2} + \frac{1}{r}\frac{dR}{dr} - \left(k^2 + \frac{m^2}{r^2}\right)R = 0.$$
(38)

Note that we have selected oscillating, rather than exponential solutions in the z -direction [by $+k^{2}Z$ $-k^{2}Z$ writing , instead of , in Equation (37]. This is the appropriate choice for the particular set of boundary conditions under consideration. The solution to Equation (38), subject Z(0) = Z(L) = 0to the constraints that [which follow from the boundary conditions (35) and (36)] is

$$Z(k) = \sin(k_n z), \tag{39}$$

where

$$k_n = n \frac{\pi}{L}.\tag{40}$$

Here, is a positive integer. The single-valued solution to Equation (429) is again

$$Q(\theta) = \sum_{m=0,\infty} \left[A_m \cos(m\theta) + B_m \sin(m\theta) \right].$$
(41)

Finally, writing
$$p = k_n r$$
, Equation (40) takes the form

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CIA II-ANSWER KEY

$$\frac{d^2R}{dp^2} + \frac{1}{p}\frac{dR}{dp} - \left(1 + \frac{m^2}{p^2}\right)R = 0.$$
(42)

This equation is known as the *modified Bessel equation*. The standard solution of this equation r = 0 that is well behaved at is $\sqrt[n]{r}$

$$I_m(p) = \frac{1}{\pi} \int_0^{\pi} e^{p \cos \theta} \cos(m\theta) \, d\theta.$$
(43)

This solution, which is known as a modified Bessel function, has the properties that

$$I_m(p) \to \frac{1}{m!} \left(\frac{p}{2}\right)^m$$
 as $p \to 0$, (44)

$$I_m(p) \to \frac{e^p}{\sqrt{2\pi p}}$$
 as $p \to \infty$. (45)

In other words, at small arguments the function has a power-law behavior, whereas at large arguments it grows exponentially. It follows that

$$R(r) = I_m(k_n r). \tag{46}$$

Thus, our separable solution becomes

$$\phi(r,\theta,z) = \sum_{m=0,\infty} \sum_{n=1,\infty} \sin(k_n z) I_m(k_n z) \left[A_{mn} \cos(m\theta) + B_{mn} \sin(m\theta) \right].$$
(47)

If we express the function $\Phi(\theta, z)$ as a Fourier series in θ and z, so that

$$\Phi(\theta, z) = \sum_{m=0,\infty} \sum_{n=1,\infty} \sin(k_n z) \left[C_{mn} \cos(m\theta) + S_{mn} \sin(m\theta) \right], \tag{48}$$

then the boundary condition (427) yields

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$$A_{mn} = \frac{C_{mn}}{I_m(k_n a)},\tag{49}$$

$$B_{mn} = \frac{S_{mn}}{I_m(k_n a)}.$$
(50)

Hence, our solution is fully specified.

(Or)

b)Derive the solution for Laplace's Equation in Cartesian co-ordinates.

We first develop a general method for finding solutions $\Phi = \Phi(x, y)$ to Laplace's equation inside a rectangular domain, with given boundary conditions for Φ on all four edges of the rectangle. In Cartesian coordinates, as we saw above, Laplace's equation is

$$\nabla^2 \Phi = \nabla \cdot (\nabla \Phi) = \frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0 \quad . \tag{7.3}$$

and in two dimensions we just drop the last term.

We will now try looking for a solution of the form

$$\Phi(x,y) = X(x)Y(y).$$

where X(x) is some function of x only, and Y(y) is some function of y only. Such a solution is called a separable solution. We cannot justify this in advance, but if it works then the uniqueness theorem tells us we are OK. It is possible to prove that any solution can be written as a sum (possibly an infinite sum) of separable solutions, but this is beyond the scope of this course.

Substituting the above Φ into (7.3) gives

$$\frac{\mathrm{d}^2 X}{\mathrm{d}x^2}Y + X\frac{\mathrm{d}^2 Y}{\mathrm{d}y^2} = 0.$$

Dividing this by XY gives

$$\frac{1}{X}\frac{\mathrm{d}^2 X}{\mathrm{d} x^2} = -\frac{1}{Y}\frac{\mathrm{d}^2 Y}{\mathrm{d} y^2}.$$

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Now, the left-hand side is a function of x only, and the right-hand side is a function of y only. This can only be satisfied if both sides are the same unknown constant.

Note: to prove the constant, X(x) and Y(y) must satisfy the above at any x, y inside our rectangle: so consider the above equation along a line (x_0, y) with fixed $x = x_0$ and varying y. The LHS is fixed, so the RHS must therefore be independent of y, i.e. constant. The same argument with y_0 fixed and x varying shows the LHS is constant, and it must be the same constant.

Now we call that constant $-\lambda$ with the minus sign for convenience, and both sides above equal $-\lambda$. Thus we have

$$\frac{\mathrm{d}^2 X}{\mathrm{d} x^2} + \lambda X = 0 \quad \text{and} \quad \frac{\mathrm{d}^2 Y}{\mathrm{d} y^2} - \lambda Y = 0 \; .$$

If $\lambda \neq 0$, these equations are the differential equations for trigonometric and hyperbolic functions, which we met in chapter 1, so we know their general solutions as follows:

If λ is positive, define $k = \sqrt{\lambda}$ and the solution is

$$X = A\cos kx + B\sin kx, \quad Y = C\cosh ky + D\sinh ky,$$

where A, B, C, D are any constants. Multiplying these together,

$$\Phi = (A\cos kx + B\sin kx)(C\cosh ky + D\sinh ky) .$$
(7.4)

If λ is negative, define $k = \sqrt{-\lambda}$ and then the solution is

$$X = \hat{A}\cosh kx + \hat{B}\sinh kx, \quad Y = \hat{C}\cos ky + \hat{D}\sin ky.$$

where $\hat{A}, \hat{B}, \hat{C}, \hat{D}$ are different constants. Then

$$\Phi = (\hat{A}\cosh kx + \hat{B}\sinh kx) (\hat{C}\cos ky + \hat{D}\sin ky) .$$
(7.5)

Note: in each of these solutions there is usually one more constant than we really need. For example if in (7.4) $AC \neq 0$ we can write

$$\Phi = AC(\cos kx + B/A\sin kx)(\cosh ky + D/C\sinh ky)$$

using just three constants AC, B/A and D/C: this means that in examples, one of the four constants can usually be set to 1. One way to do this is to write (7.4) as

$$\Phi = L\sin(kx + M)\sinh(ky + N)$$

for some constants L, M, and N. Usually this works fine, except it does not cover the case where D = 0.

Finally, we need to deal separately with the case $\lambda = 0$: hat easily gives us solutions $X = A_0x + B_0$ and $Y = C_0y + D_0$ so

$$\Phi = (A_0 x + B_0)(C_0 y + D_0) ,$$

with more constants A0, B0, C0 and D0. It is usually convenient to multiply this out and re-write it as

$$\Phi = \alpha + \beta x + \gamma y + \delta x y \tag{7.6}$$

with $\alpha, \beta, \gamma, \delta$ as alternative constants.

Remember, from linearity, any sum of any of the above functions with any k and any constants is also a solution of Laplace's equation. So, if we are given a boundary condition, solving Laplace's equation basically

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25. a) Find the value of the intergral $\int_c^{(x + y)dx + x^2y dy} (i)$ Along y=x², having (0,0)(3,9) end points

(ii)Along y=3x between the same points. Do the

values depend upon path.

oln. $\int (\pi + y) d\pi + x^2 y dy - 0$ Let P=x+y ; Q=22y $\frac{\partial P}{\partial y} = 1$; $\frac{\partial Q}{\partial n} = 2\pi y$ (or) $\frac{\partial P}{\partial y} \neq \frac{\partial Q}{\partial x}$ Then integrals are not independent of path (a) Along $y = x^2$; dy = 2xdx putting of values of y and dy in (), we get $\int (x + x^2) dx + x^2 x^2 (2x dx) = \int (x + x^2 + 2x^5) dx = \int \frac{x^2}{2} + \frac{x^3}{3} + \frac{x^6}{3} \int (x + x^2 + 2x^5) dx = \int \frac{x^2}{2} + \frac{x^3}{3} + \frac{x^6}{3} \int \frac{x^6}{3} + \frac{x^6}{3} \int \frac{x^6}{3} + \frac{x$ = 9 + 9 + 243 = 256/2 (b) Along $y=3\pi$; $dy=3d\pi$ Sub these values in O we get $\int_{-\infty}^{3} (\pi+3\pi) d\pi + \pi^{2}(3\pi) \lfloor 3d\pi \rfloor$ $= \int_{-\infty}^{3} (4\pi + 9\pi^{3}) d\pi = \left[2\pi^{2} + \frac{9\pi^{4}}{4} \right]_{-\infty}^{3}$ 0(0,0) $= 18 + \frac{729}{4} = 200'4$

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(Or)

b)State and prove the Cauchy's integral theorem.



Cauchy's integral formula states that

$$f(z_0) = \frac{1}{2\pi i} \oint_{y} \frac{f(z) dz}{z - z_0},$$
(1)

where the integral is a contour integral along the contour γ enclosing the point z_0 .

It can be derived by considering the contour integral

$$\oint_{\gamma} \frac{f(z) dz}{z - z_0},\tag{2}$$

defining a path $\frac{1}{2}$ as an infinitesimal counterclockwise circle around the point $\frac{20}{20}$, and defining the path $\frac{1}{20}$ as an arbitrary loop with a cut line (on which the forward and reverse contributions cancel each other out) so as to go around $\frac{20}{20}$. The total path is then

$$\gamma = \gamma_0 + \gamma_r, \tag{3}$$

so

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CIA II-ANSWER KEY MATHEMA

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$$\oint_{\gamma} \frac{f(z) dz}{z - z_0} = \oint_{\gamma_0} \frac{f(z) dz}{z - z_0} + \oint_{\gamma_r} \frac{f(z) dz}{z - z_0}.$$
(4)

From the Cauchy integral theorem, the contour integral along any path not enclosing a pole is 0. Therefore, the first term in the above equation is 0 since ∞ does not enclose the pole, and we are left with

$$\oint_{\gamma} \frac{f(z) dz}{z - z_0} = \oint_{\gamma_r} \frac{f(z) dz}{z - z_0}.$$
(5)

Now, let $z \equiv z_0 + r e^{i\theta}$, so $dz = i r e^{i\theta} d\theta$. Then

$$\oint_{\gamma} \frac{f(z) dz}{z - z_0} = \oint_{\gamma_r} \frac{f\left(z_0 + r e^{i\theta}\right)}{r e^{i\theta}} i r e^{i\theta} d\theta$$
(6)

$$= \oint_{\gamma_r} f\left(z_0 + r e^{i\theta}\right) i d\theta.$$
⁽⁷⁾

But we are free to allow the radius *r* to shrink to 0, so

$$\oint_{\gamma} \frac{f(z) dz}{z - z_0} = \lim_{r \to 0} \oint_{\gamma_r} f\left(z_0 + r e^{i\theta}\right) i d\theta$$
(8)

$$\oint_{\gamma_r} f(z_0) i d\theta \tag{9}$$

$$= i f(z_0) \oint_{\gamma_r} d\theta$$
(10)

$$=2\pi i f(z_0),$$
 (11)

giving (1).

If multiple loops are made around the point 20, then equation (11) becomes

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$$n(\gamma, z_0) f(z_0) = \frac{1}{2\pi i} \oint_{\gamma} \frac{f(z) dz}{z - z_0},$$
(12)

where $n(\gamma, z_0)$ is the contour winding number.

A similar formula holds for the derivatives of f(z),

$$f'(z_0) = \lim_{h \to 0} \frac{f(z_0 + h) - f(z_0)}{h}$$
(13)

$$= \lim_{h \to 0} \frac{1}{2 \pi i h} \left[\oint_{\gamma} \frac{f(z) dz}{z - z_0 - h} - \oint_{\gamma} \frac{f(z) dz}{z - z_0} \right]$$
(14)

$$= \lim_{h \to 0} \frac{1}{2\pi i h} \oint_{\gamma} \frac{f(z) [(z - z_0) - (z - z_0 - h)] dz}{(z - z_0 - h) (z - z_0)}$$
(15)

$$= \lim_{h \to 0} \frac{1}{2\pi i h} \oint_{\gamma} \frac{h f(z) dz}{(z - z_0 - h) (z - z_0)}$$
(16)

$$= \frac{1}{2\pi i} \oint_{y} \frac{f(z) dz}{(z-z_0)^2}.$$
 (17)

Iterating again,

$$f''(z_0) = \frac{2}{2\pi i} \oint_{\gamma} \frac{f(z) dz}{(z - z_0)^3}.$$
(18)

Continuing the process and adding the contour winding number n,

$$n(\gamma, z_0) f^{(r)}(z_0) = \frac{r!}{2\pi i} \oint_{\gamma} \frac{f(z) dz}{(z - z_0)^{\gamma + 1}}.$$
(19)

26. a) Test the analyticity of the function w=sinz and hence derive that $\frac{dy}{dx}$ (sin z)=cosz

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CIA II-ANSWER KEY

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Solution:

$$W = \sin z = \sin(z + iy) \qquad (\cdot, z = x + iy) \\
= \sin z \cos iy + \cos z \sin iy \\
= \sin z \cosh y + i\cos z \sinh y \\
\frac{\partial u}{\partial x} = \cos z \cosh y + \frac{\partial u}{\partial y} = \sin z \sinh y \\
\frac{\partial u}{\partial z} = -\sin z \sinh y + \frac{\partial u}{\partial y} = \sin z \sinh y \\
\frac{\partial u}{\partial z} = -\sin z \sinh y + \frac{\partial u}{\partial y} = \cos z \cosh y$$
Thus $\xi - R$ coditions,

$$\left[\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y} + \frac{\partial u}{\partial y} = -\frac{\partial v}{\partial x}\right]$$
. Cauchy Riemann Conditions are satisfied. Hence $\sin z$ is an analytical function

$$\frac{d}{dz} (\sin z) = \frac{d}{dz} [\sin z \cosh y + i\cos z \sinh y] \qquad (.by 0)$$

$$= \frac{\partial}{\partial x} [\sin z \cosh y + i\sin z \sinh y]$$

$$= \cos z \cosh y - i\sin z \sinh y$$

$$= \cos z \cosh y - i\sin z \sinh y$$

$$= \cos (x + iy)$$

$$= \cos z \cdot$$

(Or) b)Derive the Cauchy's Riemann differential equation. N.GEETHA KAHE,COIMBATORE-21 ASSISTANT PROFESSOR DEPARTMENT OF PHYSICS Suppose that we consider $f(z) = z^2$ and substitute into this z = x+iy. We can therefore write this function again in the following way:

$$f(z) = z^2 = F(x,y) = (x+iy)^2 = (x^2 - y^2) + i2xy = u(x,y) + iv(x,y)$$

where $u(x,y) = (x^2 - y^2)$ and where v(x,y) = 2xy. Now since z = x+iy, we know that

$$x = \frac{z + \overline{z}}{2}$$
 and $y = \frac{z - \overline{z}}{2i}$

from which it follows that $\frac{\partial x}{\partial z} = \frac{1}{2}$ and $\frac{\partial y}{\partial z} = \frac{1}{2i}$. Now consider the complex derivative f'(z).

$$f'(z) = \frac{\partial F}{\partial x}\frac{\partial x}{\partial z} + \frac{\partial F}{\partial y}\frac{\partial y}{\partial z} = (2x - 2yi)(\frac{1}{2}) + (-2y + 2xi)(\frac{1}{2i})$$

This of course reduces to f'(z) = 2z and the result agrees with the derivative computed in the previous section using limits.

Now suppose that F(x,y) = u(x,y) + iv(x,y) is <u>any</u> differentiable complex function. What must be true about the functions u and v? This is the subject of the Cauchy - Riemann equations.

First, suppose that z changes by x changing alone. Then, assume that z changes by y changing alone. This would give us two expressions for the derivative of

 $\mathbf{f}(\mathbf{z}) = \mathbf{F}(\mathbf{x}, \mathbf{y}).$

The first (holding y constant) can be written as

$$f'(z)|_{y \ cons \ tan \ t} = \frac{\partial F}{\partial x} \frac{\partial x}{\partial z} = \frac{\partial u}{\partial x} \frac{\partial x}{\partial z} + i \frac{\partial v}{\partial x} \frac{\partial x}{\partial z} = \frac{1}{2} \left\{ \frac{\partial u}{\partial x} + i \frac{\partial v}{\partial x} \right\}$$

while the second (*holding x constant*) can be written as

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CIA II-ANSWER KEY

EY MATHEMATICAL PHYSICS-I(17PHU103)

$$f'(z)|_{x \text{ constant}} = \frac{\partial F}{\partial y} \frac{\partial y}{\partial z} = \frac{\partial u}{\partial y} \frac{\partial y}{\partial z} + i \frac{\partial v}{\partial y} \frac{\partial y}{\partial z} = \frac{1}{2} \left\{ -i \frac{\partial u}{\partial y} + \frac{\partial v}{\partial y} \right\}.$$

Now, the derivative of f(z) cannot depend on which way that z is changing (either by x changing alone or alternatively by y changing alone) and so the two expressions for f'(z) must be equal if the derivative exists. This implies that

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y}$$
 and that $-\frac{\partial u}{\partial y} = \frac{\partial v}{\partial x}$

These two equalities are known as the Cauchy-Riemann Equations.

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KARPAGAM ACADEMY OF HIGHER EDUCATION, COIMBATORE DEPARTMENT OF PHYSICS I B.Sc., PHYSICS SOLID STATE PHYSICS - LECTURE PLAN (17PHU102)

Unit	Topics to be covered	P.No.	No. of hours
No.			
	Amorphous and Crystalline Materials. Lattice Translation Vectors.	T1(87-88)	1
	Lattice with a Basis. Unit Cell.	T1(88)	1
	Miller Indices	T1(89,112)	1
	Reciprocal Lattice	T1(138-144)	1
Ι	Types of Lattices	T1(303)	1
	Brillouin Zones	T1(303-305)	1
	Diffraction of X-rays by Crystals	T1(165-166)	1
	Bragg's Law	T1(166)	1
	Atomic and Geometrical Factor.	T1(139-140)	1
	Revision		1

Textbooks:

T 1- Solid state Physics by S.O.Pillai, The new age publishers

UG Programme 2017-2018 Odd

Unit No.	Topics to be covered	P.No.	No. of hours
	Lattice Vibrations and Phonons: Linear Monoatomic and Diatomic Chains.	T2(169-172, 176-178)	1
п	Acoustical and Optical Phonons	T2(174-176)	1
	Qualitative Description of the Phonon Spectrum in Solids.	T2(178-180)	1
	Dulong and Petit's Law	T1(334-340)	1
	Einstein and Debye theories of specific heat of solids	T1(340-343)	1
	T ³ law	T1(343-349)	1
	Revision		1

Textbooks:

- T 1- Solid state Physics by S.O.Pillai, The new age publishers T 2- Introduction to solid state Physics By Charles Kittel, 8th edi.

Unit No.	Topics to be covered	P.No.	No. of hours
	Dia-, Para-, Ferri- and Ferromagnetic Materials	T1(426,439-444)	1
	Classical Langevin Theory of diamagnetic Domains	T1(440-444)	1
	Quantum Mechanical Treatment of Paramagnetism	T1(459-465)	1
	Curie's law, Weiss's Theory of Ferromagnetism and Ferromagnetic Domains	T1(446-450, 454-455)	1
ш	Classical Langevin Theory of Paramagnetism	T1(446-450)	1
111	Discussion of B-H Curve	T1(493-500)	1
	Hysteresis and Energy Loss	T1(493)	1
	Revision		1

Textbooks:

T 1- Solid state Physics by S.O.Pillai, The new age publishers

Unit No.	Topics to be covered	P.No.	No. of hours
	Dielectric Properties of Materials	T1(623-632)	1
	Polarization And Depolarization Field.	T1(623-632) T2(512)	1
	Local Electric Field at an Atom	T1(641-643)	1
	Electric Susceptibility. Polarizability	T2(509)	1
IV	Clausius Mosotti Equation. Classical Theory of Electric Polarizability	T1(645-648) T2(509)	1
	Normal and Anomalous Dispersion Cauchy and Sellmeir relations.	T2(635-640,515)	1
	Langevin-Debye equation. Complex Dielectric Constant	T1(663)	1
	Optical Phenomena	T2(526)	1
	Application: Plasma Oscillations	T2(529)	1
	Plasma Frequency, Plasmons	T2(529)	1
	Revision		1

Textbooks:

T 1- Solid state Physics by S.O.Pillai, The new age publishers T 2- Introduction to solid state Physics By Charles Kittel, 8th edi.

Unit No.	Topics to be covered	P.No.	No. of hours
	Elementary band theory	T1(292)	1
	Kronig Penny model. Band Gaps	T1(292-303,520)	1
	Conductors, Semiconductors and insulators	T1(520-539)	1
	P and N type Semiconductors	T1(539-543)	1
N7	Conductivity of Semiconductors, mobility	T1(273-276)	1
	Hall Effect, Hall coefficient	T1(357-359)	1
	Superconductivity: Experimental Results	T1(359)	1
	Critical Temperature. Critical magnetic field	T1(364-366)	1
	Meissner effect.	T1(370)	1
	Type I and type II Superconductors.	T1(371-373)	1
	Revision		1
	Old Question Paper Discussion		1
	Old Question Paper Discussion		1
	Old Question Paper Discussion		1

Textbooks:

T 1- Solid state Physics by S.O.Pillai, The new age publishers.

KARPAGAM ACADEMY OF HIGHER EDUCATION, COIMBATORE. DEPARTMENT OF PHYSICS I B.Sc., PHYSICS SOLID STATE PHYSICS (17PHU102)

PROGRAMME OUTCOME

Solid state physics is a very wide field, and it includes many branches. It concerned with the physical properties of solids, particularly the special properties exhibited by atoms and molecules because of their association in the solid phase. The existence of powerful theoretical methods and concepts applicable to a wide range of problems has been an important unifying influence in the field. It is quite natural therefore that an introductory textbook should emphasize theoretical models of solids, rather than the details of experimental techniques or the results of measurements on complicated systems which may have great industrial importance.

LEARNING OUTCOME

On successful completion of the course students will be able to:

- 1. To acquire knowledge of the fundamental physics underpinning solid state physics
- 2. To understand the concepts and potential applications of solid state physics
- 3. To develop analytical, laboratory and computing skills through problem solving, and laboratory and computer based exercises, which involve the application of physics to various model solid state physics systems
- 4. To successfully apply the theoretical techniques presented in the course to practical problems
- 5. To develop good writing and communication skills through working with peers and writing up the results of the assigned laboratory and computer exercises as reports
- 6. To learn how to prepare publications by casting the reports in the form of a scientific paper.

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SEMESTER – I SOLID STATE PHYSICS

17PHU102

L T P C 5 - - 5

Objective:

This course integrates theory of Solid State Physics with experimental demonstrations in the Physics Lab. The course will provide a valuable theoretical introduction and an overview of the fundamental applications of the physics of solids. This course includes theoretical description of crystal and electronic structure, lattice dynamics, and optical properties of different materials (metals, semiconductors, dielectrics, magnetic materials and superconductors), based on the classical and quantum physics principles.

UNIT - I

Crystal Structure: Solids: Amorphous and Crystalline Materials. Lattice Translation Vectors. Lattice with a Basis. Unit Cell. Miller Indices. Reciprocal Lattice. Types of Lattices. Brillouin Zones. Diffraction of X-rays by Crystals. Bragg's Law. Atomic and Geometrical Factor.

UNIT - II

Elementary Lattice Dynamics: Lattice Vibrations and Phonons: Linear Monoatomic and Diatomic Chains. Acoustical and Optical Phonons.Qualitative Description of the Phonon Spectrum in Solids.Dulong and Petit's Law, Einstein and Debye theories of specific heat of solids (qualitative only). T³ law

UNIT - III

Magnetic Properties of Matter: Dia-, Para-, Ferri- and Ferromagnetic Materials. Classical Langevin Theory of dia– and Paramagnetic Domains. Quantum Mechanical Treatment of Paramagnetism. Curie's law, Weiss's Theory of Ferromagnetism and Ferromagnetic Domains. Discussion of B-H Curve. Hysteresis and Energy Loss.

UNIT - IV

Dielectric Properties of Materials: Polarization. Local Electric Field at an Atom. Depolarization Field. Electric Susceptibility. Polarizability. Clausius Mosotti Equation. Classical Theory of Electric Polarizability. Normal and Anomalous Dispersion. Cauchy and Sellmeir relations. Langevin-Debye equation. Complex Dielectric Constant. Optical Phenomena. Application: Plasma Oscillations, Plasma Frequency, Plasmons.

UNIT - V

Elementary band theory: Kronig Penny model. Band Gaps. Conductors, Semiconductors and insulators. P and N type Semiconductors. Conductivity of Semiconductors, mobility, Hall Effect, Hall coefficient. Superconductivity: Experimental Results. Critical Temperature. Critical magnetic field. Meissner effect. Type I and type II Superconductors.

TEXT BOOKS

- 1. Solid State Physics by S. O. Pillai, New Age Science Publisher, 2010, ISBN 1906574103, 9781906574109.
- 2. Introduction to Solid State Physics, Charles Kittel, 8th Ed., 2004, Wiley India Pvt. Ltd.

REFERENCE BOOKS:

- 1. Solid State Physics by R. J. Singh, Dorling Kindersley (India) Publisher, 2012, ISPN-978-81-317-5401-6.
- 2. Solid State Physics by J. R. Hook, H. E. Hall, John Wiley & Sons, Ltd, 2010, ISBN 9780471928041.
- 3. Solid State Physics, Rita John, 2014, McGraw Hill
- 4. Solid State Physics, M.A. Wahab, 2011, Narosa Publications
KARPAGAM ACADEMY OF HIGHER EDUCATION DEPARTMENT OF PHYSICS I BSC PHYSICS

SOLID STATE PHYSICS (17PHU102)

2017-2020 MULTIPLE CHOICE QUESTIONS

QUESTION

UNIT - II	OPTION 1	OPTION 2	OPTION 3	OPTION 4	ANSWERS
Debug feature is agual to	1.33	1 22 × 1042	22 × 10+2	6 x 1042	1 22 × 1042
Debye nequency is equal to	1.23	1.25 X 10-5	.23 x 10+3	0 x 10 - 5	1.23 x 10-3
concerve excitation in a periodic, etastic arrangement of atoms or molecules in condensed matter, incessing and some inductions is a molecules in condensed matter, incessing and some inductions or molecules in condensed matter, incessing and some inductions of the automation of the	i Phonons	photons	nuetron	proton	Phonons
In represents an excited state in the quantum mechanical quantization of the modes of violations of elastic students of interacting [electronics	condensed matter physics	chamistry	mathematics	condoncod
The concent of bhomons was introduced in 1932 by	Soviet obysicist loor Tar	Thomson	C V Raman		Soviet nhv
In concept of photons was included in 1952 by	velocity	single frequency	multiple frequency	speed	single from
A photon is a quantum mechanical description of an elementary viorational motion in which a fautice of atoms of molecules unito	E-ha	$E = h(x_1 + x_2)$	E-has	E-hy/2	E-b-
phonon energy	E-IIC	$E = n(v_1 + v_2)$	E-IIV	E-IIV/2	E-IIV
The specific heat at constant volume should be just the rate of change with	pressure of that energy	volume of that energy.	temperature of that energy	density of that energy.	temperatu
The quantity nu/k is sometimes called the	I nomson temperature	C v Raman temperature	Einstein temperature	debye remperature	Einstein te
Debye advanced the treatment by treating as collective modes in the solid which are now called "phonons".	quantum oscillators	electronics oscillators	oscillators	caissical oscillators	quantum o
. term phonon is used to draw an analogy between photon representing a quantum of electromagnetic radiation and	quanta of lattice vibrati	quanta of lattice space	quanta of lattice constant	lattice vibration	quanta of la
The energy of a phonon can be derived by considering the lattice as a	collection of protons.	collection ofmolecules.	conection of oscillators.	collection of atoms.	conection o
I unere are no phonons, an materiais would be	acousticsemiconductor	infrared radiation	acoustic insulators.	opticalitisulators.	infrared rat
Typical provide energies are comparable with	UV			Ri tua abasasa	inirareu rac
A transverse optical photon created by the photon decays into two photons.	phonons and photons	multiple phonons	one priorioris	two phonons.	two phone
A-rays can be scattered by	TAA		TAC	TAD	phonons
At low temperatures specific near varies as	174	1***	1~8	1~2 ii	1/13
rinonon ampitude increases with.	Accustic abarration	entirel abarrar	temperature	increasing pressure	Increasing Accustic ab
concrete movements of atoms of the fattice out of their equilibrium positions is called	Acoustic phonons	optical phonons	phonons	photons	Acoustic pr
Out-of-phase movements of the atoms in the fattee, one atom moving to the feft, and its neighbour to the right	Acoustic priorions	optical priorions	priorioris	photons	information
opical phonons that interact with right is canced	mirared active	Atomic control	RF active	visible active	Deillewin act
Optical phonons nave a non-zero frequency at the	molecular zone center	Atomic zone center	Britouin zone center	infiner zone center	Brillouin 20
Optical photonisoccurs in the fattice basis consists of	one atom	two or more atoms	Person contraction	ininite atom	alestresie a
Optical pronons that are <i>Raman active</i> can also interact indirectly with right, through	Growth accident	thormal strossor	nhara transformation	all the above	all the abov
The impurity stemp in the lattice which gives characteristic selever to the courted is called	colour contro	E contro	V contro	Elcontro	colour cont
The impurity atoms in the factore which gives characteristic colours to the crystal is called		r centre	fort conline rote	r centre	colour certi
is essential for the growth of large crystals	Reideomon tochnique	slow cooling rate	vanor decomposition	cipilo spirital tochnology	Slow Coolin
is used to grow crystals of materials containing volatile constituents	8901 kgm 2	0002kgm 2	801 kgm 2	000kgm 2	2201 kgm
Calculate the density of ion. Atomic weight = 55.6. Avagadinointimite = .0254102/K mol. Atomic radius of PCL non is 0.125mm to shore used for anywing courted from mol.	czochrulskile	vapor decomposition	Norpouil technique	all the above	czochrulcki
imperfections are also called OD imperfections	noint	line	surface	volume	noint
Imperies are simply atom sites	Interdtitialcies	Impurities	vacancies	electronic defects	vacancies
de sinply empty actin sites	schottlar	frackla	Intrincic	overingia	schottlar
In indicatives are called under the provided from lattice in to an interstitial site is called	schottky	frenkel	Intrinsic	extrinsic	frankal
Importe a ystal, an for a spayed non-instance in to an interstatial site is called	Intrinsic	extrinsic	lonic	compositional	compositio
Impurities defects are of types	two	three	four	five	two
Point deferts are created by Construction of the Construction of t	annlying electric fields	guring thermal energy	mechanical stress	two	two
An edge dislocation lies to its hurger vector	narallel	perpendicular	above	below	nernendici
An screw dislocation lies to its burger vector	narallel	perpendicular	above	below	narallel
Sneed of movement of an edge dislocation is	smaller	greater	remains constant	zero	greater
Speed of movement of an screw dislocation is	smaller	greater	remains constant	zero	smaller
surface defects are imperfections	OD	1D	2d	3d	2d
Surface defects are also called defects	dislocation	plane	boundary	orientation	plane
The change in the stacking of atomic planes acress a boundary gives rise to imperfections	external surface	internal surface	grain boundaries	twin boundaries	internal sur
I we angular misorientation is of the order of few degree but	less than 10°	greater than 10°	equal to 10°	20°	less than 10
Hiph angel boundaries have misorientation of order	10° to 20°	even greater than this amount	10° to 30°	both c and b	both c and
Tilt boundary. 0 =	h/b	b/h	b	h	b/h
Imperfectiona which separate two orientations that are mirror images of one another are called	grain boundaries	twin boundaries	tilt boundaries	turst boundaries	twin bound
Stacking faults are more frequently found is	deformed metals	annealed metals	non metals	none of these	deformed r
Line defects are imperfections	OD	1d	2d	3d	1d
Inserting the extra plane in the top of the crystal is called	edge dislocation	positive edge dislocation	negative edge dislocation	dislocation	positive ed
Inserting the extra plane in the bottom of the crystal is called	edge dislocation	positive edge dislocation	negative edge dislocation	dislocation	negative e
Any deviation from this perfect atomic periodicity is an imperfection called as	space defect	lattice defect	electrical defect	none of these	lattice defe
The plane separating the two incorrectly juxtaposed layers is called	stacking fault	tilt boundaries	twist boundaries	twin boundaries	stacking fau
The plane of atoms glider over another by integral multiples of an inter atomic distance is called	slip	axis	plane	all the above	slip
The row of atoms about which a normal crystal allographic plane appears to spiral ramping is called	dislocation	edge dislocation	screw dislocation	Frenkel dislocation	, screw dislo
What are the two basic modes of plastic deformation	slip	turnning	shear stress	both a and b	both a and
Foreign particle inclusions, large voids or non crystalline regions which have the dimensions of atleart 10 to 30 A' are called	point	surface	line	volume	volume
A boundary separates crystals of different orientations in a poly crystalline solid	Grain	turn	twist	tilt	Grain
Both screw and edge dislocations may occur together in the forming a dislocations	spherical	curved	circular	planar	curved

ANSWERS

ed matter physics. Hysicist Igor Tamm quency ture of that energy. emperature oscillators lattice vibration quanta of lattice vibration of oscillators. nsulators. adiation nons. g temperature phonons ionons ctive zone center atoms c defects two or more atoms ove ntre ling rate n technique 1 -3 kils ional cular rface 10° d b ndaries l metals edge dislocation edge dislocation fect fault location d b

KARPAGAM ACADEMY OF HIGHER EDUCATION DEPARTMENT OF PHYSICS

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2017-2020

MULTIPLE CHOICE QUESTIONS					
UNIT III					
QUESTION	OPTION 1	OPTION 2	OPTION 3	OPTION 4	ANSWERS
When south of a landstand many density to a te	when for the	when the w	share (an abas	alter factor	when the states
The unit of electrical conductivity is	mno / metre	mno / sq.m	onm / metre	onm / sq.m	mno / metre
The branch of physics that deals with the study and properties of solids is called	Nuclear physics	Chemistry	solid state physics	Particle physics	solid state physics
Cooking utensis are a good example or	Conduction	Convection	Radiation	Both aand c	Conduction
Electrical resistance of a piece of metal changes with	Change in pressure	Change in temperature	Change in density	Change in heat capacity	Change in temperature
electrical conductivity of insulators in the range	10 ⁻ 10 (Ω-mm) ⁻	10 ⁻ 10(Ω-cm) ⁻	10 ⁻ 10(Ω-m) ⁻ '	10 ⁻ 8(Ω-m) ⁻¹	10 ⁻ 10 (Ω-mm) ⁻ '
Units for electric field strength	A/CM ²	mho/meter	cm²/V.S	V/CM	cm²/V.S
Energy band gap size for semiconductors is in the rangeev.	1-2	2-3	3-4	>4	2-3
Energy band size for insulators is in the rangeev.	1-2	2-3	3-4	>4	3-4
Flow of electrons is affected by the following	Thermal vibrations	Impurity atoms	Crystal defects	All	All
Conductance of any conductors is expressed as	ampere / watt	mho	volt ² / watt	watt / ampere ²	mho
Three elements having conductance G1,G2 and G3 are connected in parallel, their combined conductance will be	(G1+G2+G3)=1	G1+G2+G3	1/G ₁ +1/G ₂ +1/G ₃	(1/G ₁ +1/G ₂ +1/G ₃) ⁻¹	G1+G2+G3
Which of the following materials has highest electrical conductivity ?	Steel	Aluminium	Copper	Silver	Silver
The electrical conductivity of metal is typically of the order of (in ohm ⁻¹ m ⁻¹)	107	10 ⁵	10-4	10 ⁻⁶	10'
Pure metal generally have	High conductivity and lo	High conductivity and large temperature	Low conductivity and zero te	 Low conductivity and high temperature co efficient 	High conductivity and large temperature co efficient
Poorest conductor of electricity is	Aluminium	Carbon	Steel	Silver	Carbon
Which of the following has positive temperature coefficient ?	Ge	Au	Paper	Rubber	Au
Thermal conductivity of metal with addition of alloying element	Increases	Decreases	Remains constant	None	Decreases
Thermal conductivity of metal with increases of hardnesss	Increases	Decreases	Remains constant	None	Decreases
Thermal conductivity of a material with dampness	Increases	Decreases	Remains constant	None	Increases
Thermal conductivity of non metals with increases of density	Increases	Decreases	Remains constant	None	Increases
Thermal conductivity of metals with increases of pressure	Increases	Decreases	Remains constant	None	Remains constant
Metal possess	High electrical and therr	Obey ohm's law	At high temperatures, Rand T	all of above	all of above
According to classical free electron theory	There is no interaction b	The interaction of free election with ion	The free election find uniform	all of above	all of above
In a drude metal, collisions with collision time Z ? Have a damping effect in the equation of motion for the momentum of an elec	Proportional to Z	Proportinal to 1/Z	Proportional to Z ²	Proportional to 1/z ²	Proportinal to 1/Z
The widemann-Franz law states that the thermal to electrical conductivity ratio (K/σ) is	proportional to T	proportional to 1/T	proportional to T ²	proportional to 1/T ²	proportional to T
The hall voltage is directly proportional to	Current	Electric field	Magnetic flux density	all of above	Magnetic flux density
Electic field stength related to hall voltage is given by	VHD	Vh/d	VhE	ED	Vh/d
Hall probe is made of	Metals	Non metals	Semi conductor	Radioactive material	Semi conductor
In hall effect, the voltage across the probe is nown as	Hall voltage	Fmf	P otential diffeence	None of above	Hall voltage
The band gap of a condcto is given by	~3ev	~13ev	~7ev	0	0
Init of themal conditivity in MKS units is	Kcal/Kg m ² °c	Kcal - m/h m ² °c	Kcal/h m ² °c	Kcal - m/ h°c	Kcal - m/h m ² °c
Unit of themal conditivity in SL units is	I/m ² sex	l/m [°] k sec	W/m°k	Both a and c	Both a and c
nick the wrong case. Heat flowing for one side to othe deends diectly on	surface aea	Time	Thickness	Temperature diffeence	Thickness
Heat is closely related with	Liquids	Energy	Temperature	Entropy	Temperature
Metals is a good conditors of heat herause	Their atoms collide frequ	Their atoms are relatively to aat	They contains fee electons	All the above	Their atoms collide frequently
Themal conditivity of water in general with rise in temperature	Increase	Decrease	May increase or decreasa der	remainis constant	May increase or decreasa depending on temperature
Temperature of steam at 540° can be measured by	Themometer	Themistor	Themocounle	Themonile	Themocouple
Heat flows from one body to other when they have	Different heat contents	Different specific heat	Different atomic strate	Different temperature	Different temperature
Which of the following have least value of conductivity	Glass	Water	plastic	Air	Air
Which of the following is exected to have bighest thanal conductivity	Steam	Solidice	Melting ice	Water	Solid ice
What there is not a singly dependence	Its tomporature	Rate of the body	Kind and external of its sface	all of the above	all of the above
Themal conductivity of wood docender on	Moisturo	Density	Tomporature	all the above	all the above
There are used a begin to use and use this large a use the same when the personal used difference between and the face is used.	Themal Desistence	Thermal conductivity	Thermel coefficient	Tomosoture andient	Themel conductivity
read conducted through unit area and unit thickness per unit time when temperature difference between opposite faces is unity	Conduction	Convertion	Dediction	remperature gradient	adiation
Steran boltmann aw is able to near tarister by (at 202 K)	1 44 vi 10 ⁻⁸ webb elimite	2 44 v 40 ⁻⁸ wett shark ⁻²	2 44 v 40 ⁻⁸ ····································		2 44 v 40 ⁻⁸ wetter ber b ⁻²
The value of lorentz nmber is equal to (at 293 K)	1.44 × 10 ° watt onmk	2.44 × 10 ° watt onmk *	3.44 × 10 ° watt onmk *	4.44 × 10° watt ohmk ⁻²	2.44 × 10 ° watt onmk *
The micoscopic form of onm's law is	J=2e	E = J	J = neva		
The value of boltzmann constant is	1.56U × 10 J/K	1.500 × 10 *** J/ K	1.500 × 10 *** JK	1.500 × 10 JK	1.500 × 10 - J/K
The average distance tavelied between two consective collision is called	Drift velocity	wean tree path	Relaxation time	Collision time	Mean free path
The velocity acquired by the free electron after steady state is reached, due to the application of applied electric field is	Drift velocity	Constant vélocity	Average velocity	None of these	Diff velocity
Collision time =	٨v	N/ V	٨	V	N/ V
The electronic charge is	1.021 × 10 ⁻¹⁹ J	1.021 × 10 ¹⁰ J	1.4021 × 10 ⁻¹⁹ J	1.4021 × 10 ⁻¹⁹ J	1.021 × 10 ⁻¹⁹ J
The Relaxation time is approximately	10 ⁻ * S	10'* s	10 ⁻¹³ s	10 ¹³ s	10 ⁻¹⁴ S
The drift velocity acquired by the free electron in a unit electric field is	Mobility	Mean free path	Relaxation time	Collision time	Mobility

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Crystal Structure: Solids: Amorphous and Crystalline Materials. Lattice Translation Vectors. Lattice with a Basis. Unit Cell. Miller Indices. Reciprocal Lattice. Types of Lattices. Brillouin Zones. Diffraction of X-rays by Crystals. Bragg's Law. Atomic and Geometrical Factor.

CRYSTAL STRUCTURE

There are two main forms of solid substance, characterizing different atoms arrangement in their microstructures: amorphous and crystalline.

Amorphous solid

Amorphous solid substance does not possess long-range order of atoms positions. Some liquids when cooled become more and more viscous and then rigid, retaining random atom characteristic distribution. This state is called under cooled liquid or amorphous solid. Common glass, most of Polymers, glues and some of Ceramics are amorphous solids. Some of the Metals may be prepared in amorphous solid form by rapid cooling from molten state.

Crystalline solid

Crystalline solid substance is characterized by atoms arranged in a regular pattern,

of crystal lattice, which is a lattice with atoms or ions attached to the lattice points. The smallest possible part of crystal lattice, determining the structure, is called primitive unit cell.

Crystal structure and specific metal properties are determined by **metallic bonding** – force, holding together the atoms of a metal. Each of the atoms of the metal contributes its **valence electrons** to the crystal lattice, forming an electron cloud or electron "gas", surrounding positive metal ions. These **free electrons** belong to the whole metal crystal.

Ability of the valence free electrons to travel throughout the solid explains both the high electrical conductivity and thermal conductivity of metals. Dr. S. KARUPPUSAMY Karpagam Academy of Higher Education Page **1** of **20** Department of Physics Coimbatore-21

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Other specific metal features are: luster or shine of their surface (when polished), their malleability (ability to be hammered) and ductility (ability to be drawn). These properties are also associated with the metallic bonding and presence of free electrons in the crystal lattice.

Examples of typical crystal lattice are presented in the picture:

Crystal lattice examples



Crystal lattice is the periodic and systematic arrangement of atoms that are found in crystals with the exception of amorphous solids and gases. In the simplest of terms, the crystal lattice can be considered as the points of intersection between straight lines in a three-dimensional network. The physical properties of crystals like cleavage, electronic band structure and optical transparency are predominantly governed by the crystal lattice. A unit cell is the smallest component of the crystal lattice and describes the arrangement of atoms in a crystal. The unit cell is characterized by its lattice parameters which consist of the length of the cell edges and the angles between them.

There are seven crystal lattice systems namely monoclinic, triclinic, orthorhombic, rhombohedral, tetragonal, hexagonal and cubic. All these seven crystal lattice have their own variants giving rise to a total of 14 Bravais Lattices. Among these seven lattice systems, the cubic system exhibits the symmetry of a cube is considered to be the simplest and also the most symmetric of all crystal lattices. There are three different types of cubical crystal lattice systems namely Simple Cubic (SC), Body-Centered Cubic (CBC) and the Face Centered Cubic (FCC). As the name indicates, Dr. S. KARUPPUSAMY Karpagam Academy of Higher Education Page 2 of 20 Department of Physics Coimbatore-21

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Simple Cubic is the simplest form of the structure. The simple cubic unit cell has one lattice point at each of the eight corners of the cube. The number of lattice points is usually denoted by Z and for a SC, the value of Z is 1. The packing efficiency of a lattice is defined as the ratio of total volume of the cell occupied by the host atom to the volume of the cell. Usually, crystals with higher packing efficiency are preferred because of their favorable properties. This packing efficiency for SC works has been reported to be around 52%.

The unit cell of a BBC crystal lattice contains one host atom in the center of the cube and one each at the corner of the cube. In a BCC, the corner atoms do not overlap with one another and the value of Z is 2. The packing efficiency of BCC is higher than the SC and works out to be 68%. The unit cells in FCC have one host atom at each corner and one host atom on each face. The value of Z for FCC is 4 and has a very high packing efficiency of 74%. The FCC crystal lattice is also known as the Cubic Closest Packing (CCP) because it has the maximum efficiency for spheres of equal radius. The structure of cesium chloride (CsCl) is that of a Simple Cubic whereas Zinc Sulfide is said to have a Face Centered Cubic arrangement.

Many of the electrical and mechanical properties of these crystals are controlled by the defects and irregularities arising in the ideal geometry of the crystal lattice. It has been reported that the presence of magnetic impurities can cause severe alteration of properties such as specific heat of the substance. Certain dislocations in the crystal could lead to a substance which allows shear at lower stress than that deserved for an ideal crystal.

It should be noted that the stability of a crystal structure cannot be predicted solely based on the chemical composition of the substance. Even the prediction of medium sized structures, an enormous computational power is required to run sophisticated algorithms such as evolutionary algorithms, random sampling and principles of metadynamics. Based on possible combinations of symmetry, there are a total of 32 crystal classes of which 20 are piezoelectric as they are devoid of a center of Dr. S. KARUPPUSAMY Karpagam Academy of Higher Education Page **3** of **20**

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symmetry. Ten of these 32 groups are polar and hence pyroelectric too. Certain solid substances exhibit the phenomenon of Polymorphism wherein the same substance can exist in more than one crystalline form and have different sets of properties.

UNIT CELL

The crystal structure of a material or the arrangement of atoms within a given type of crystal structure can be described in terms of its unit cell. The unit cell is a small box containing one or more atoms, a spatial arrangement of atoms. The unit cells stacked in three-dimensional space describes the bulk arrangement of atoms of the crystal. The crystal structure has a three-dimensional shape. The unit cell is given by its lattice parameters, which are the length of the cell edges and the angles between them, while the positions of the atoms inside the unit cell are described by the set of atomic positions (x_i , y_i , z_i) measured from a lattice point.

BRAVAIS LATTICE

In geometry and crystallography, a **Bravais lattice**, studied by Auguste Bravais (1850) is an infinite array of discrete points generated by a set of discrete translation operations described by:

$\mathbf{R} = n_1 \mathbf{a}_1 + n_2 \mathbf{a}_2 + n_3 \mathbf{a}_3$

where n_i are any integers and \mathbf{a}_i are known as the primitive vectors which lie in different directions and span the lattice. This discrete set of vectors must be closed under vector addition and subtraction. For any choice of position vector \mathbf{R} , the lattice looks exactly the same.

A crystal is made up of a periodic arrangement of one or more atoms (the *basis*) repeated at each lattice point. Consequently, the crystal looks the same when viewed from any of the lattice points.

Two Bravais lattices are often considered equivalent if they have isomorphic symmetry groups. In this sense, there are 14 possible Bravais lattices in threedimensional space. The 14 possible symmetry groups of Bravais lattices are 14 of the 230 space groups.

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Bravais lattices in 2D

In two dimensions, there are five Bravais lattices. They are oblique, rectangular, centered rectangular, hexagonal, and square.



Bravais lattices in 3D

Name of crystal system Length of Base vectors	Angles between axes	Bravais Lattices		
Cubic a ₁ = a ₂ = a ₃	r = s = x = 90 ⁰			
		cubic	cubic body	cubic face centered (<i>fcc</i>)

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				Orthorhombic face centered
Monoclinic a1 Ó a2Ó a3	r1N1s1N1J A ^a =1x1 Ó1 90 º	Monocline primitive		Monocline base face centered
Tricline a 1 Ól a 2 Ó a 3	r1Ó1s1Ó1x1 Ó1JA ^A 1	Tricline		

The **simple cubic unit cell** is the simplest repeating unit in a simple cubic structure. Each corner of the unit cell is defined by a lattice point at which an atom, ion, or molecule can be found in the crystal. By convention, the edge of a unit cell always connects equivalent points. Each of the eight corners of the unit cell therefore must contain an identical particle. Other particles can be present on the edges or faces of the

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unit cell, or within the body of the unit cell. But the minimum that must be present for the unit cell to be classified as simple cubic is eight equivalent particles on the eight corners. The **body-centered cubic unit cell** is the simplest repeating unit in a body-centered cubic structure. Once again, there are eight identical particles on the eight corners of the unit cell. However, this time there is a ninth identical particle in the center of the body of the unit cell.

The **face-centered cubic unit cell** also starts with identical particles on the eight corners of the cube. But this structure also contains the same particles in the centers of the six faces of the unit cell, for a total of 14 identical lattice points.

The face-centered cubic unit cell is the simplest repeating unit in a cubic closest-packed structure. In fact, the presence of face-centered cubic unit cells in this structure explains why the structure is known as *cubic* closed-packed.

Determining the Unit Cell of a Crystal

Atoms on the corners, edges, and faces of a unit cell are shared by more than one unit cell, as shown in the figure below. An atom on a face is shared by two unit cells, so only half of the atom belongs to each of these cells. An atom on an edge is shared by four unit cells, and an atom on a corner is shared by eight unit cells. Thus, only one-quarter of an atom on an edge and one-eighth of an atom on a corner can be assigned to each of the unit cells that share these atoms.



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If nickel crystallized in a simple cubic unit cell, there would be a nickel atom on each of the eight corners of the cell. Because only one-eighth of these atoms can be assigned to a given unit cell, each unit cell in a simple cubic structure would have one net nickel atom.

Simple cubic structure:

 $\frac{9.746 \times 10^{-23} \text{ g/unit cell}}{4.376 \times 10^{-23} \text{ cm}^3/\text{unit cell}} = 2.23 \text{ g/cm}^3$

Because there would be twice as many atoms per unit cell if nickel crystallized in a body-centered cubic structure, the density of nickel in this structure would be twice as large.

Body-centered cubic structure:

(8 corners x 1/8) + 1 body = 2 atoms

If nickel crystallized in a face-centered cubic structure, the six atoms on the faces of the unit cell would contribute three net nickel atoms, for a total of four atoms per unit cell.

Face-centered cubic structure:

 $(8 \text{ corners } x \ 1/8) + (6 \text{ faces } x \ 1/2) = 4 \text{ atoms}$

Because they have different numbers of atoms in a unit cell, each of these structures would have a different density. Let's therefore calculate the density for nickel based on each of these structures and the unit cell edge length for nickel given in the previous section: 0.3524 nm. In order to do this, we need to know the volume of the unit cell in cubic centimeters and the mass of a single nickel atom.

The volume (V) of the unit cell is equal to the cell-edge length (a) cubed.

$$V = a^3 = (0.3524 \text{ nm})^3 = 0.04376 \text{ nm}^3$$

Since there are 10^9 nm in a meter and 100 cm in a meter, there must be 10^7 nm in a cm.

$$\frac{10^9}{1 m} \times \frac{1 m}{100 \ cm} = 10^7 \ nm/cm$$

We can therefore convert the volume of the unit cell to cm^3 as follows.

$$4.376 \times 10^{-2} \ nm^3 \times \left[\frac{1 \ cm}{10^7 \ nm}\right]^3 = 4.376 \times 10^{-23} \ cm^3$$

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The mass of a nickel atom can be calculated from the atomic weight of this metal and Avogadro's number.

$$\frac{58.69 \text{ g Ni}}{1 \text{ mol}} \propto \frac{1 \text{ mol}}{6.022 \times 10^{23} \text{ atoms}} = 9.746 \times 10^{-23} \text{ g/atom}$$

The density of nickel, if it crystallized in a simple cubic structure, would therefore be 2.23 g/cm^3 , to three significant figures.

Unit Cell of Simple cubic structure:

8 corners x 1/8 = 1 atom

If nickel formed a body-centered cubic structure, there would be two atoms per unit cell, because the nickel atom in the center of the body wouldn't be shared with any other unit cells.

Body-centered cubic structure:

 $\frac{2(9.746 \times 10^{-23} \text{ g/unit cell})}{4.376 \times 10^{-23} \text{ cm}^3/\text{unit cell}} = 4.45 \text{ g/cm}^3$

There would be four atoms per unit cell in a face-centered cubic structure and the density of nickel in this structure would be four times as large.

Face-centered cubic structure:

$$\frac{4(9.746 \times 10^{-23} \text{ g/unit cell}}{4.376 \times 10^{-23} \text{ cm}^3/\text{unit cell}} = 8.91 \text{ g/cm}^3$$

The experimental value for the density of nickel is 8.90 g/cm³. The obvious conclusion is that nickel crystallizes in a face-centered cubic unit cell and therefore has a cubic closest-packed structure.

Atomic packing factor

In crystallography, **atomic packing factor** (APF) or **packing fraction** is the fraction of volume in a crystal structure that is occupied by atoms. It is dimensionless and always less than unity. For practical purposes, the APF of a crystal structure is determined by assuming that atoms are rigid spheres. The radius of the spheres is taken to be the maximal value such that the atoms do not overlap. For one-component crystals (those that contain only one type of atom), the APF is represented mathematically by

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$$APF = \frac{N_{atoms}V_{atom}}{V_{unitcell}}$$

where N_{atoms} is the number of atoms in the unit cell, V_{atom} is the volume of an atom, and $V_{unit \ cell}$ is the volume occupied by the unit cell. It can be proven mathematically that for one-component structures, the more dense arrangement of atoms has an APF of about 0.74. In reality, this number can be higher due to specific intermolecular factors. For multiple-component structures, the APF can exceed 0.74.

Body-centered cubic crystal structure



The primitive unit cell for the body-centered cubic (BCC) crystal structure contains several fractions taken from nine atoms: one on each corner of the cube and one atom in the center. Because the volume of each corner atom is shared between adjacent cells, each BCC cell contains two atoms.

Each corner atom touches the center atom. A line that is drawn from one corner of the cube through the center and to the other corner passes through 4r, where r is the radius of an atom. By geometry, the length of the diagonal is a 3. Therefore, the length of each side of the BCC structure can be related to the radius of the atom by

$$a = \frac{4r}{\sqrt{3}}$$
.

Knowing this and the formula for the volume of a sphere $((4/3)_{pi} r^3)$, it becomes possible to calculate the APF as follows:

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$$APF = \frac{N_{\text{atoms}}V_{\text{atom}}}{V_{\text{crystal}}} = \frac{2(4/3)\pi r^3}{(4r/\sqrt{3})^3}$$
$$= \frac{\pi\sqrt{3}}{8} \approx 0.68.$$

Hexagonal close-packed crystal structure



For the hexagonal close-packed (HCP) structure the derivation is similar. The side length of the hexagon will be denoted as a while the height of the hexagon will be denoted as c. Then:

$$a = 2r$$
$$c = \sqrt{\frac{2}{3}}(4r).$$

It is then possible to calculate the APF as follows:

$$\begin{aligned} \text{APF} &= \frac{N_{\text{atoms}} V_{\text{atom}}}{V_{\text{crystal}}} = \frac{6(4/3)\pi r^3}{[(3\sqrt{3})/2](a^2)(c)} \\ &= \frac{6(4/3)\pi r^3}{[(3\sqrt{3})/2](2r)^2(\sqrt{\frac{2}{3}})(4r)} = \frac{6(4/3)\pi r^3}{[(3\sqrt{3})/2](\sqrt{\frac{2}{3}})(16r^3)} \\ &= \frac{\pi}{\sqrt{18}} \approx 0.74. \end{aligned}$$

APF of common structures

By similar procedures, the ideal atomic packing factors of all crystal structures can be found. The common ones are collected here as reference, rounded to the nearest hundredth.

• Simple cubic: 0.52

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- Body-centered cubic: 0.68
- Hexagonal close-packed: 0.74
- Face-centered cubic: 0.74
- Diamond cubic: 0.34

ATOMIC RADIUS

The **atomic radius** of a chemical element is a measure of the size of its atoms, usually the mean or typical distance from the nucleus to the boundary of the surrounding cloud of electrons. Since the boundary is not a well-defined physical entity, there are various non-equivalent definitions of atomic radius.

Unit Cell: The Simplest Repeating Unit in a Crystal

The structure of solids can be described as if they were three-dimensional analogs of a piece of wallpaper. Wallpaper has a regular repeating design that extends from one edge to the other. Crystals have a similar repeating design, but in this case the design extends in three dimensions from one edge of the solid to the other.

We can unambiguously describe a piece of wallpaper by specifying the size, shape, and contents of the simplest repeating unit in the design. We can describe a three-dimensional crystal by specifying the size, shape, and contents of the simplest repeating unit and the way these repeating units stack to form the crystal.

The simplest repeating unit in a crystal is called a **unit cell**. Each unit cell is defined in terms of **lattice points** — the points in space about which the particles are free to vibrate in a crystal.

The structures of the unit cell for a variety of salts are shown below.



Unit I

Measuring the Distance Between Particles

Nickel is one of the metals that crystallize in a cubic closest-packed structure. Consider that a nickel atom has a mass of only 9.75×10^{-23} g and an ionic radius of only 1.24×10^{-10} m, it is a remarkable achievement to be able to describe the structure of this metal. The only way to determine the structure of matter on an atomic scale is to use a probe that is even smaller. One of the most useful probes for studying matter on this scale is electromagnetic radiation.

In 1912, Max van Laue found that x-rays that struck the surface of a crystal were diffracted into patterns that resembled the patterns produced when light passes through a very narrow slit. Shortly thereafter, William Lawrence Bragg, who was just completing his undergraduate degree in physics at Cambridge, explained van Laue's results with an equation known as the **Bragg equation**, which allows us to calculate the distance Dr. S. KARUPPUSAMY Karpagam Academy of Higher Education Page **14** of **20** Department of Physics Coimbatore-21

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between planes of atoms in a crystal from the pattern of diffraction of x-rays of known wavelength.

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

The pattern by which x-rays are diffracted by nickel metal suggests that this metal packs in a cubic unit cell with a distance between planes of atoms of 0.3524 nm. Thus, the cell-edge length in this crystal must be 0.3524 nm. Knowing that nickel crystallizes in a cubic unit cell is not enough. We still have to decide whether it is a simple cubic, body-centered cubic, or face-centered cubic unit cell. This can be done by measuring the density of the metal.

STRUCTURE OF NACLAND ZnS

NaCl should crystallize in a cubic closest-packed array of Cl⁻ ions with Na⁺ ions in the octahedral holes between planes of Cl⁻ ions. We can translate this information into a unit-cell model for NaCl by remembering that the face-centered cubic unit cell is the simplest repeating unit in a cubic closest-packed structure.

There are four unique positions in a face-centered cubic unit cell. These positions are defined by the coordinates: 0,0,0; 0,1/2,1/2; 1/2,0,1/2; and 1/2,1/2,0. The presence of an particle at one corner of the unit cell (0,0,0) requires the presence of an equivalent particle on each of the eight corners of the unit cell. Because the unit-cell edge connects equivalent points, the presence of a particle in the center of the bottom face (0,1/2,1/2) implies the presence of an equivalent particle in the center of the top face (1,1/2,1/2). Similarly, the presence of particles in the center of the 1/2,0,1/2 and 1/2,1/2,0 faces of the unit cell implies equivalent particles in the centers of the 1/2,1,1/2 and 1/2,1/2,1 faces. The figure below shows that there is an octahedral hole in the center of a face-centered cubic unit cell, at the coordinates 1/2,1/2,1/2. Any particle at this point touches the particles in the centers of the unit cell.

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The other octahedral holes in a face-centered cubic unit cell are on the edges of the cell, as shown in the figure below.



If Cl^- ions occupy the lattice points of a face-centered cubic unit cell and all of the octahedral holes are filled with Na⁺ ions, we get the unit cell shown in the figure below.



We can therefore describe the structure of NaCl in terms of the following information.

- NaCl crystallizes in a cubic unit cell.
- The cell-edge length is 0.5641 nm.
- There are Cl^- ions at the positions 0,0,0; 1/2,1/2,0; 1/2,0,1/2; and 0,1/2,1/2.
- There are Na⁺ ions at the positions 1/2, 1/2, 1/2; 1/2, 0, 0; 0, 1/2, 0; and 0, 0, 1/2.

Placing a $\mbox{Cl}^{\mbox{-}}$ ion at these four positions implies the presence of a $\mbox{Cl}^{\mbox{-}}$ ion on each

of the 14 lattice points that define a face-centered cubic unit. Placing a Na+ ion in theDr. S. KARUPPUSAMYKarpagam Academy of Higher EducationPage 16 of 20Department of PhysicsCoimbatore-21

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center of the unit cell (1/2, 1/2, 1/2) and on the three unique edges of the unit cell (1/2, 0, 0; 0, 1/2, 0; and 0, 0, 1/2) requires an equivalent Na⁺ ion in every octahedral hole in the unit cell.

ZnS crystallizes as cubic closest-packed array of S^{2-} ions with Zn^{2+} ions in tetrahedral holes. The S^{2-} ions in this crystal occupy the same positions as the Cl⁻ ions in NaCl. The only difference between these crystals is the location of the positive ions. The figure below shows that the tetrahedral holes in a face-centered cubic unit cell are in the corners of the unit cell, at coordinates such as 1/4, 1/4, 1/4. An atom with these coordinates would touch the atom at this corner as well as the atoms in the centers of the three faces that form this corner. Although it is difficult to see without a three-dimensional model, the four atoms that surround this hole are arranged toward the corners of a tetrahedron.



Because the corners of a cubic unit cell are identical, there must be a tetrahedral hole in each of the eight corners of the face-centered cubic unit cell. If S^{2-} ions occupy the lattice points of a face-centered cubic unit cell and Zn^{2+} ions are packed into every other tetrahedral hole, we get the unit cell of ZnS shown in the figure below.



The structure of ZnS can therefore be described as follows.

• ZnS crystallizes in a cubic unit cell.

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The cell-edge length is 0.5411 nm.

There are S^{2-} ions at the positions 0,0,0; 1/2,1/2,0; 1/2,0,1/2; and 0,1/2,1/2.

There are Zn^{2+} ions at the positions 1/4, 1/4, 1/4; 1/4, 3/4, 3/4; 3/4, 1/4, 3/4; and 3/4,3/4,1/4.

Note that only half of the tetrahedral holes are occupied in this crystal because there are two tetrahedral holes for every S²⁻ ion in a closest-packed array of these ions.

Lattice constant



Unit cell definition using parallelepiped with lengths a, b, c and angles between the sides given by , , .

The **lattice constant** [or lattice parameter] refers to the constant distance between unit cells in a crystal lattice. Lattices in three dimensions generally have three lattice constants, referred to as a, b, and c. However, in the special case of cubic crystal structures, all of the constants are equal and we only refer to a. Similarly, in hexagonal crystal structures, the a and b constants are equal, and we only refer to the a and cconstants. A group of lattice constants could be referred to as lattice parameters. However, the full set of lattice parameters consist of the three lattice constants and the three angles between them.

For example the lattice constant for a common carbon diamond is a = 3.57Å at 300 K. The structure is equilateral although its actual shape can not be determined from only the lattice constant. Furthermore, in real applications, typically the average lattice constant is given. As lattice constants have the dimension of length, their SI unit is the

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meter. Lattice constants are typically on the order of several angstroms (i.e. tenths of a nanometre). Lattice constants can be determined using techniques such as X-ray diffraction or with an atomic force microscope.

In epitaxial growth, the lattice constant is a measure of the structural compatibility between different materials. Lattice constant matching is important for the growth of thin layers of materials on other materials; when the constants differ, strains are introduced into the layer, which prevents epitaxial growth of thicker layers without defects.

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POSSIBLE QUESTIONS

2 MARKS

- 1. Write the difference between crystalline and amorphous solid.
- 2. Define: Basis, Crystal lattice, Unit cell.
- 3. Define Unit Cell and Miller Indices.
- 4. State lattice and Unit cell?
- 5. What is reciprocal lattice?
- 6. Define Bragg's law
- 7. What is Amorphous and Crystalline Materials?

6 MARKS

- 8. Explain Bravais lattice in different dimension.
- 9. Explain the structure of KCl and NaCl.
- 10. Describe the seven crystal system with suitable diagram.
- 11. Explain the concept of Bragg's law.
- 12. Explain the Bragg diffraction and derive the equation.
- 13. Write the differences of Crystals and amorphous and give an examples.
- 14. Explain the Bravais lattices of seven crystal systems with neat sketch.
- 15. Explain miller indices and obtain the procedure and features of miller indices of crystal planes.
- 16. Write a short note on following crystal structures: a)Diamond b)NaCl
- 17. Describe the seven systems of crystals with suitable diagrams.
- 18. Einstein and Debye theories of specific heat of solids

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Elementary Lattice Dynamics: Lattice Vibrations and Phonons: Linear Monoatomic and Diatomic Chains. Acoustical and Optical Phonons.Qualitative Description of the Phonon Spectrum in Solids.Dulong and Petit's Law, Einstein and Debye theories of specific heat of solids (qualitative only). T³ law

Lattice vibrations

The oscillations of atoms in a solid about their equilibrium positions. In a crystal, these positions form a regular lattice. Because the atoms are bound not to their average positions but to the neighboring atoms, vibrations of neighbors are not independent of each other. In a regular lattice with harmonic forces between atoms, the normal modes of vibrations are lattice waves. These are progressive waves, and at low frequencies they are the elastic waves in the corresponding anisotropic continuum. The spectrum of lattice waves ranges from these low frequencies to frequencies of the order of 1013 Hz, and sometimes even higher. The wavelengths at these highest frequencies are of the order of interatomic spacing. At room temperature and above, most of the thermal energy resides in the waves of highest frequency.

Because of the short wavelength, the motion of neighboring atoms is essentially uncorrelated, so that for many purposes the vibrations can be regarded as those of independently vibrating atoms, each moving about its average position in three dimensions with average vibrational energy of 3kT, where k is the Boltzmann constant and T the absolute temperature.

The wave character of the vibrations is needed, however, to describe heat transport by lattice waves. Also, lattice vibrations interact with free electrons in a conducting solid and give rise to electrical resistance. The temperature variation at low temperatures provides evidence that this interaction is with waves. Scattering of lattice waves by defects increases with increasing frequency (f); its variation depends on the nature of the defect. Scattering by external and internal boundaries is almost independent of frequency, thus dominating at low frequencies and hence at low temperatures.

A study of the thermal conductivity of nonmetallic crystals as function of temperature yields information about the defects present, and about the harmonic nature of the inter-atomic forces in the crystal lattice. One of the main types of internal motion of a solid, in which the constituent particles (atoms or Dr. S. KARUPPUSAMY Karpagam Academy of Higher Education Page 1 of 19 Department of Physics Coimbatore-21

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molecules) oscillate about equilibrium positions lattice points.

For example, lattice vibrations in the form of standing or traveling sound waves arise whenever a crystal is acted upon by an external force that varies over time. However, even in the absence of external influences a steady state of vibrations is established in a crystal that is in thermal equilibrium with its environment, just as a fixed distribution of atoms or molecules is established in a gas according to their rate of translatory motion. The nature of lattice vibrations depends on the symmetry of the crystal, the number of atoms in its unit cell, the type of chemical bond, and the type and concentration of the crystal defects. The higher the temperature, the greater will be the displacement u of atoms in the process of oscillation, but even up to the melting point, at which a solid becomes a liquid, it is much smaller than the lattice constant.

The forces that tend to hold the atoms in equilibrium positions are proportional to their relative displacements as if they were interconnected to each other by springs (Figure 1). The representation of a crystal as a set of particles connected by dually elastic forces is called a harmonic approximation.

In a crystal consisting of N unit cells of n atoms each there exist 3nN - 6 types of the simplest vibrations in the form of standing waves, which are called normal (or natural) oscillations, or modes. Their number is equal to the number of degrees of freedom of the set of particles in the crystal, less the three degrees of freedom that correspond to the translator motion and the three that correspond to the rotary motion of the crystal as a whole. The number 6 may be disregarded, since 3nN is a quantity of the order of 1022-1023 per cubic centimeter of the crystal.

In the course of normal vibration all particles of the crystal oscillate about their own equilibrium positions with the same constant frequency _, like simple harmonic oscillators. All possible normal vibrations may be present simultaneously in a crystal, and each occurs as if the others were not present. Any motion of atoms in a crystal that does not disrupt its microstructure maybe represented as a superposition of the normal vibrations of the crystal.



Figure 1. Representation of a body-centered cubic crystal in the form of a set of particles of mass m that are interconnected by springs with stiffness's r1, and r2 Every standing wave of a normal vibration may in turn be represented as two elastic plane traveling waves that are propagating in opposite directions (normal waves). In addition to the frequency , a plane traveling wave is characterized by the wave vector k, which defines the direction of motion of the wave front and the wavelength = 2 /k, and also by the polarization, which determines the nature of the individual particle motion. In the general case elliptical polarization takes place. Here each atom describes an ellipse about its own equilibrium position (Figure 2), and the normal to the plane of the ellipse does not coincide in direction with k. The elliptical orbits are identical for identical atoms that occupy equivalent positions in the lattice. In crystals where every point is a center of symmetry, all normal waves are plane-polarized: the atoms in any normal vibration perform reciprocating motions about their equilibrium positions.



Equilibrium position

Figure 2. Elliptical polarization of elastic waves in a crystal; k is a wave vector Dispersion of normal waves. For every value of k there exist 3n of normal waves with different polarization. They are numerated by the integral variable = 1, 2,3n and are called branches of normal vibrations. For waves of a given type of the quantities and k

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B.Sc., 2017-2018 Odd cannot be arbitrary but are interconnected by a specific relationship = (k,), called the dispersion law. For example, if a crystal is represented in the form of a set of identical

atoms of mass m that lie at equal distances a from each other and are joined in pairs by in such a way that they form an infinite chain and can be springs having stiffness displaced only along its axis (Figure 3a), the unit cell consists of one particle and one branch of the normal vibration frequency exists, with the dispersion law. In a diatomic linear chain (Figure 3b) the cell contains two particles with masses m and M and has two branches with a more intricate dispersion law (Figure 4). The elastic waves in a crystal always have dispersion. In particular, their phase velocity usually differs from the group velocity at which the vibratory energy is transmitted through the crystal. Although the of elastic waves propagated in a continuous medium increases indefinitely frequency with an increase in k, some maximum vibration frequency max, usually about 1013 hertz (Hz), exists in a crystal because of the periodic location of the atoms and the finite magnitude of the force binding.



Figure 3. The simplest models of a crystal: (a) linear monatomic chain, (b) linear diatomic chain; (m) and (M) masses of the two particles that make up a unit cell them. Natural frequencies may not entirely fill the interval between = 0 and $= \max$ and may contain vacant areas (forbidden bands) that separate two successive branches (Figure 4). There is no forbidden band between adjacent branches if the branches overlap.

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Vibrations that correspond to the forbidden band or have frequency $> \max$ cannot propagate in a crystal and attenuate rapidly.



Dispersion law of a diatomic linear chain: (1) acoustical branch, (2) optical branch, Acoustical and optical branches. The first three branches of vibrations, with = 1, 2, 3, are called acoustical branches. If the wavelength greatly exceeds the longest period of a space lattice (that is, k is small), the branches are characterized by the linear dispersion law = c.k. These are ordinary sound waves, and c is the phase velocity of their propagation, which depends on the direction of propagation and on polarization.

They are plane-polarized in one of the three mutually perpendicular directions according to the three values of = 1, 2, 3, and correspond to vibrations of the crystal as a continuous medium. In an anisotropic crystal it usually is the case that none of these directions coincides with the direction of wave propagation, that is, with k. Only in an elastic isotropic medium do sound waves have purely longitudinal and purely cross polarization. The acoustical branches cover the band from zero to about 1013 Hz. However, as the wavelength decreases the dispersion law becomes more complex.

For the other 3(n - 1) branches of the frequency, the displacements of the atoms in the course of the vibrations corresponding to a long wavelength take place in such a way that the center of mass of an individual unit cell is at rest. In ionic crystals, whose unit cell consists of ions of opposite sign, motion of this type can be initiated by an alternating electric field, such as a light wave, usually one whose frequency lies in the infrared region. Therefore, these branches are said to be optical. The acoustical branch was named after the initial zone (Figure 4), since the initial zone of the acoustical branch is ordinary sound. Phonons.

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A set of moving quasiparticles with momentum p = hk and energy = h, where his Planck's constant, may be placed in correspondence with every traveling plane wave with vector k and frequency . These quasiparticles are the field quanta of crystal lattice vibrations and are called phonons by analogy with photons, the quanta of the electromagnetic field. Influence of Lattice Vibrations on Crystal Properties. The higher the temperature of a crystal, the more intensively its atoms oscillate about their equilibrium position. When the amplitude of the vibrations exceeds some critical value, melting begins and the crystal structure is destroyed.

As the temperature drops, the amplitude decreases, and it reaches a minimum when $T = 0^{\circ}K$. According to the laws of quantum mechanics it is impossible for atoms to stop completely and for their energy to become zero; when $T = 0^{\circ}K$ they perform zero-point oscillations. Since the energy of zero-point oscillations is usually insufficient to cause melting of solid, all liquids eventually solidify as the temperature decreases. The only exception is helium, which remains a liquid all the way down to $0^{\circ}K$ and solidifies only under pressure. The lattice heat capacity is a quantitative characteristic of a crystal's ability to store heat in the form of oscillatory energy. The heat capacity per atom is found to be approximately equal to3kB, where kB is the Boltzmann constant, at high temperatures (Dulong and Petit's law) and proportional to T^3 when T approaches $0^{\circ}K$.

In metals and semiconductors there are in addition to atoms or ions free electrons, which create an electric current in the presence of an electric field. The laws governing their motion are such that they pass unhindered through an ideal crystal consisting of atoms in a state of zero-point oscillations. Therefore, resistance of an electric current when T -> 0° K arises only to the extent that crystals always contain defects that scatter electrons. However, at temperatures T > 0° K the oscillations randomly disrupt the ideally periodic nature of the lattice and create supplementary electric resistance, called lattice, or phonon, electric resistance. Upon collision with oscillating atoms, electrons transmit to the crystal skeleton part of the energy of their own directed translator motion, which is released as Joule heat.

An harmonicity. In reality restoring forces are not strictly proportional to the displacements of atoms from equilibrium positions, and the vibrations of a crystal are not strictly harmonic (an harmonicity). The nonlinearity of inter atomic forces is small, since

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the amplitudes of the oscillations are small. However, by virtue of this nonlinearity individual normal vibrations are not independent but rather are interconnected, and resonance between them is possible, as in a system of coupled pendulums.

Hormonicity plays the same role in the process of establishing thermodynamic equilibrium in crystals as do the collisions of particles in a gas. In particular, this explains the thermal expansion of crystals, the deviation from Dulong and Petit's law in the high-temperature region, and the difference between the isothermic and adiabatic elastic constants of a solid and their dependence on temperature and pressure.

When a solid is heated non uniformly, heat fluxes arise in it. In metals most of this heat is transferred by electrons; in dielectrics, by normal waves (phonons). Therefore if we have in mind dielectrics or the lattice part of the thermal conductivity of metals, in the absence of an harmonicity the heat flux would propagate with the velocity of normal waves-that is, at approximately the speed of sound. Because of an harmonicity the waves in a heat flux exchange energy and interfere with each other. In the process of interference of loss of the total momentum of the heat flux takes place. As a result, thermal resistance arises, and the thermal energy is transferred at the diffusion rate, which is much slower than the rate or propagation of elastic energy such as a sound wave. An harmonicity is also one reason for the attenuation of ultrasound in crystals.

Local and quasi-local vibrations. The nature of lattice vibrations is significantly affected by defects in the crystal lattice. The stiffness of inter atomic bonds and the masses of particles in the region of a defect differ from those of an ideal crystal, which is called the standard or the matrix. As a result, the normal waves are not plane. For example, if a defect is an impurity atom of mass m₀, coupled with its neighbors by "springs" of stiffness ₀, its natural frequency may fall within the forbidden band of matrix frequencies. Only the impurity atom takes an active part in such vibration; therefore, it is called a local vibration. Since there a real ways many defects in a real crystal, local vibration, having been excited at one defect, may extend to another, as in the resonance of identical, weakly coupled pendulums. Therefore, local vibrations have an entire spectrum of frequencies that form the impurity zone of the lattice vibration frequencies.

In addition to local vibrations, so-called quasi-local vibrations may exist in the lowfrequency region. In particular, such vibrations can be found in a crystal with heavy

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impurity atoms. At low temperatures quasi-local vibrations sharply increase the lattice heat capacity, the coefficient of thermal expansion, and thermal and electric resistance. For example, 2–3 percent impurity atoms that are 10 times heavier than the matrix atoms is sufficient at low T to double the lattice heat capacity and coefficient of thermal expansion. Local vibrations of extended defects, such as dislocations, propagate along the defects in the form of waves but do not penetrate into the matrix, as in the case of point defects. The frequency of these vibrations may fall within either the forbidden or permitted bands of matrix frequencies, differing from them by their dispersion law. Such, for example, are the surface sound waves that occur near the flat boundary of a solid (Rayleigh waves). There are various experimental methods for studying lattice vibrations.

Excitation by means of infrared radiation is one method of studying local and quasilocal vibrations. It is accompanie by a resonance decrease in the transparency of the crystal and makes possible not only the detection of the vibrations but also the determination of their frequencies. Studies of inelastic scattering of neutrons in crystals make possible determination of the dispersion law and polarization of normal vibrations. The dispersion law may also be reconstructed by using the diffusion scattering of X rays. The Mössbauer effect makes possible direct determination of the mean square displacements and momenta of atoms in the process of lattice vibrations. Acoustic and optical modes. Now, let us examine the allowed vibration modes in a lattice. The most rudimentary lattice we can consider is a linear chain of identical atoms.

Figure 4.4: A simple chain lattice of identical atoms. If we displace the nth atom from its equilibrium position by a small amount n parallel to the chain, the neighboring atoms $((n-1)^{th} \text{ and } (n+1)^{th})$ will also be displaced by n - n-1 and n - n+1 respectively. Therefore the nth atom is actually displaced by an amount n - n-1 with respect to the (n-1th) atom, and by n - n+1 with respect to the (n+1)th atom. According to the Lorentz model, these atoms can be considered to be connected by springs. Therefore the n th atom will experience a restoring force F equivalent to that of Hooke's Law. Because the n th atom is connected to two springs (one to each neighboring atom) there will be two contributions to this force, which is given by:

F = - [(n - n - 1) - (n + 1 - n)]

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Where, is the spring constant. Applying Newton's second law we also get: $F = m \cdot d^2 n/dt^2$

Where, m is the mass of the oscillator. Thus,

 $d^2 n/dt^2 = (/m) [(n - n - 1) - (n + 1 - n)] \dots (4.1)$

Solutions to equation (4.1) have the form:

 $n = _{0}e i(kna-ut) \dots (4.2)$

Where, ω is the angular frequency of the wave, k is the wave number and o is the amplitude of oscillation. If we now substitute equation (4.2) into equation (4.1) we get:

 $\begin{aligned} \omega 2 &= 2(/m) [1 - \cos(ka)] \\ \omega 2 &= 4(/m) \sin 2(ka/2) \\ \omega &= \pm 2 (/m) \frac{1}{2} \sin(ka/2)....(4.3) \end{aligned}$

This equation gives the allowed vibration modes in this simple lattice. From equation (4.3) it is obvious that $\omega > 2(/m) \frac{1}{2}$ is not possible. Frequencies above $\omega = 2(/m) \frac{1}{2}$ cannot propagate through the lattice. In this model the displacement of the oscillator is along the chain, therefore the wave motion is longitudinal. This is the longitudinal acoustic mode.

Now consider a chain in which there are two different atoms of type X and Y, with masses mX and mY respectively (mX > mY), placed alternately along the chain. Again we displace the nth atom, of type X, by a small amount n. The nearest neighboring atoms, both of type Y, are displaced by n-1 and n+1 as before; the next nearest atoms, both of type X, are displaced by n-2 and n+2 and so on. We have two different atom types in the chain, so we require two equations for the restoring force: one for the nth atom of type X and one for the (n+1)th atom of type Y. Hence we get:

FX = -X[(n - n - 1) - (n + 1 - n)] FY = -Y[(n - n + 1) - (n + 1 - n + 2)]For simplicity, let X = Y = . Again we can use Newton's second law and get: $FX = mX \cdot d^2 n/dt^2$ $FY = mY \cdot d^2 n + 1/dt^2$ And again, analogous to the monatomic chain we get solutions of the form:

- n = Xe i(kna-iit)
- $n = Ye i(k(n+1)a-\omega t)$

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From which we get:

 $\omega 2 = [(1/mX) + (1/mY)] \pm [\{(1/mX) + (1/mY)\}^2 - \{4\sin^2(ka)\}/mXmY].....(4.4)$

If we take the negative sign in equation (4.4), we get the acoustic mode already encountered, with the maximum allowed frequency at $\omega = 2(/mX)\frac{1}{2}$ again. However, if we take the positive sign in equation (4.4), we get the optical mode, so called because this mode is easily excited by radiation of the appropriate frequency in ionic solids. In this case we find that there is a range of permitted frequencies with both a maximum and a minimum which correspond to the longitudinal and transverse optical (LO and TO) modes. The minimum frequency (TO) is given by: $\omega TO = 2(/mY)\frac{1}{2}$

The maximum frequency (LO) is given by:

 $\omega LO = 2[/{(1/mX)+(1/mY)}]^{1/2}$

The transverse and longitudinal optical modes represent the onset and cutoff of an absorption band.

It is generally thought that absorptivity measurements only involve the TO component, however, in reality the LO component can play an important role (Berreman 1963). The contribution from the LO mode depends on the constituents of the molecule/solid under consideration as well as the crystal structure, grain size/sample thickness etc. The conditions under which the spectrum is taken and the nature of the spectrometer also affect the relative contributions from the TO and LO modes. It is therefore necessary to understand the contributions from all these factors in order to interpret spectra correctly.

SPECIFIC HEAT OF GASES

When a gas is heated, there is in general, an increase in volume as well as pressure in addition to the rise in temperature. For simplicity either the pressure or volume may be kept constant while temperature rises. Therefore, a gas has two specific heats. (i) Specific heat at constant volume, and (ii) Specific heat at constant pressure. The specific heat of a gas at constant volume is the amount of heat required to raise the temperature of 1 gm of the gas through 1°C, the volume being kept constant. It is denoted by c_v. The specific heat of a gas at constant pressure is the amount of heat required to raise the temperature of 1 gm

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of the gas through 1°C, the pressure being kept constant. It is denoted by c_p . In the former case, the whole heat supplied increases the internal energy of the gas. As a result the temperature rises by 1°C.

In the latter case the gas is allowed to expand against a constant pressure and in doing s it does external work in addition to the work done in increasing the temperature by 1° C; i.e., the internal energy, as in the former case. Hence the specific heat at constant pressure c_p is greater than the specific heat at constant volume c_v by an amount equal to the thermal equivalent of the external work done by the gas, i.e., by the amount of heat that must be used up to do this external work.

Therefore, $c_p - c_v = Q = W$,

Where, Q s the amount of heat used to do the extra work and W the external work done in the same units as of Q.

Difference between cp and cv:

If C_p and C_v are the molar heats at constant pressure and constant volume, respectively, (i.e., $C_p = M.c_p$ and $C_v = M.c_v$, where M is the molecular weight of the gas) we have $C_p - C_v = R$.

Variation of Specific heat of diatomic gases with temperature:

It has been observed experimentally that the specific heat of diatomic gases like H_2 , N_2 , Cl_2 , HCl etc. increases with increase of temperature and decreases with decreases of temperature, finally approaching the limiting value (3/2) R (= 2.98 calories), which is the value of specific heat of monoatomic gases at al temperatures. This leads us to a conclusion that at sufficiently low temperatures al diatomic gases have the same value of specific heat at constant volume, i.e., C_v , as that of monoatomic gas.

Explanation for the variation of specific heat of diatomic gases with temperature: Classical theory:

The molecule of a diatomic gas may be supposed to consist of two atoms at a certain distance from each other, the atoms being held together by force of attraction, forming a dumb-bell. Such a system cannot be stable unless the particles execute a rotatory motion about the common centre of gravity, the necessary centripetal force for rotation

being provided by the force of attraction between the molecules. Thus, every diatomic molecule not only move as a whole, but also rotates about an axis passing through the centre of gravity of the molecule. Besides the translatory and rotatory motion of the molecule, the atoms in molecule can vibrate or oscillate along the line joining them. Thus in general the diatomic molecules may have three types of motion – translation, rotation and vibration of its atoms with respect to each other. If these motions are independent of each other, the total energy of a gram molecule of a gas is the sum of three kinds of energies of individual molecules. The total energy W_m of a gram molecule at temperature T should be given by,

$$\mathbf{W}_{\mathrm{m}} = \mathbf{W}_{\mathrm{t}} + \mathbf{W}_{\mathrm{r}} + \mathbf{W}_{\mathrm{v}}$$

where W_t , W_r , and W_v are respectively, the energies per gram molecule associated with translational, rotational and vibrational motions of the molecules. The translational motion of the diatomic molecule may be described by the translational motion of the centre of mass, which will have three degrees of freedom. According to classical theory the kinetic theory, the kinetic energy associated with each degree of freedom is $\frac{1}{2}$ kT, therefore, the kinetic energy of translational motion of one gram molecule is given by

 $W_t = N \times 3 \times \frac{1}{2} kT = (3/2)NkT = (3/2)RT.$

The rotational motion of each diatomic molecule possesses two degrees of freedom since the two atoms rotate about a pair of axes at right angles to each other and to the line joining the atoms. Therefore, the kinetic energy of rotational motion of one gram molecule is given by

 $W_r = N \times 2 \times \frac{1}{2} kT = NkT = RT.$

If we assume the molecules to be rigid, so that the atoms cannot vibrate with respect to each other, the contribution of energy of vibration to the total energy will be zero, i.e, $W_v = 0$. Thus the total energy of a gram molecule is given by $W_m = W_t + W_r + W_v = (3/2)RT + RT + 0 = (5/2)RT$.

The specific heat per gram molecule of the diatomic gas is given by $C_v = dW_m/dT = (5/2) R = 5/2 x 1.985 = 4/95$ calories per gram molecule per degree.

As the temperature if further increases the atoms of the diatomic gases vibrate with respect to each other. Assuming that the motion is SHM, Where, K is the force constant. This is approximately equal to 2 x for an SHM. The energy per degree of freedom is $\frac{1}{2}$ kT.

Therefore the total vibrational energy of each diatomic molecule = kT. Therefore the vibrational energy for one gram molecule of the gas is N x kT = RT

Therefore the total energy associated with one gram molecule of the gas is $W_m = W_t + W_r + W_v = (3/2)RT + RT + RT = (7/2)RT.$

Therefore $C_v = dW_m/dT = (7/2) R = 6.95 \text{ cal/gram molecule/K}$.

This theory does not explain the specific heats per gram molecule of grases at all temperature. Moreover it could not predict the experimentally observed variation of specific heat of gases like Cl₂, Br₂, I₂ etc., So attempts were made to improve it and quantum theory was applied to the problem.

Law of Dulong and Petit

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According to Dulong and Petit's law, the product of atomic weights and specific heat at constant volume is constant. This constant is known is atomic heat. Its values as calculated theoretically on the basis of kinetic theory of matter comes out to be 5.96. Since atomic weight of an element is constant, its specific heat must be constant. i.e., the value of the specific heat of various elements should be same at all temperatures. This is however, contrary to the experimentally observed facts. It has been found by experiments that the specific heat of all substances varies with temperature.

It was experimentally found by Nernst and Lindemann that the specific heat of a substance decreases with decreases in temperature and tends to be zero at absolute zero. On the other hand, the specific heat increases with increase in temperature and tends to a maximum value. Carbon, Boron and Silicon, whose atomic heat at ordinary temperature (20°C) are 1.76, 2.75 and 4.98 respectively, show an increase in these values towards 6 as their temperature is raised and finally the atomic heat of these substances becomes 6 at high temperature, but it is less than 6 at low temperature. The variation of specific heat in metals like lead, tin and platinum is very small.

The experimental observation of specific heat at low temperature indicate that specific heat decreases slowly with decrease of temperature and below a certain temperature, characteristic of each element the specific heat decreases rapidly tending finally to zero value at the absolute zero of temperature. This shows that Dulong and Petit's law is in god agreement with experimental observation at higher temperatures and deviates from experiments as the temperature decreases.

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The specific heat of copper is 0.093 cal/gm K (0.389 J/gm K) and that of lead is only 0.031 cal/gm K(0.13 J/gm K). Why are they so different? The difference is mainly because it is expressed as energy per unit mass; if you express it as energy per mole, they are very similar. It is in fact that similarity of the molar specific heats of metals which is the subject of the Law of Dulong and Petit. The similarity can be accounted for by applying equipartition of energy to the atoms of the solids.

From just the translational degrees of freedom you get 3kT/2 of energy per atom. Energy added to solids takes the form of atomic vibrations and that contributes three additional degrees of freedom and a total energy per atom of 3kT. The specific heat at constant volume should be just the rate of change with temperature (temperature derivative) of that energy.

Energy per mole = $3kTN_A$ K = Boltzmann's constant T = Temperature in Kelvins $N_A = Avogadro's number$ The Law of Dulong & Petit $C_v = \frac{\partial}{\partial T}(3kTN_A) = 3kN_A / mole = 24.94J / mole K$

Einstein's Contribution to Specific Heat Theory

Einstein's theory of specific heat: The first attempt to explain the variation of specific heat with temperature was made by Einstein in 1907 on the basis of quantum theory. According to quantum theory, heat is radiated in the form of discrete particles known as photons. Each photon has energy equal to hv where h is the Planck's constant and v is the frequency of the heat radiations.

To explain the variation of specific heat with temperature, Einstein assumed:

(i) A solid is constituted of atoms. These atoms are at rest under the action of their mutual attractions and repulsions at absolute zero of temperature. The energy of the solid in this state is zero. When the solid is heated, the atoms are set into simple harmonic vibrations about their positions of equilibrium. The frequency of these vibrations is one and the same, characteristic of the particular solid concerned.
- (ii) Each atom of a solid has 3 degrees of freedom like a molecule of monoatomic gas.
- (iii) The mean energy per degree of freedom is not kT as given by equipartition law, but as calculated by Planck by the application of quantum theory.

The value of v giving god fit for a particular solid is represented by v_E and is called **Einstein's Frequency for that solid.** θ corresponding to v_E is represented as θ_E and is called **Einstein's temperature.**

This is Einstein's equation for the atomic heat of solid at constant volume. The equation represents that the atomic heat is a function of temperature. The characteristic of experimentally observed variation of specific heat of solids are as follows:

- (i) At high temperature, the atomic heat approaches the constant value 3R as given by Dulong and Petit's law.
- (ii) The atomic heat decreases with decrease of temperature and tends to zero at absolute zero of temperature.
- (iii) The experimental curves drawn temperature versus atomic heat show that the curves have the same form for al substances.

These facts can be explained on the basis of Einstein's equation.

(i) At high temperatures, hv/kT approaches very small values and so we have Thus, according to Einstein's equation, the atomic heat approaches 3R which is in agreement with experiments and Dulong and Petit's law.

(ii) When the value of temperature tends to zero, hv/kT tends to infinity and hence1 may be neglected in the expression

Then the equation becomes

Thus according to Einstein's equation, the atomic heat tends to zero as temperature tends to absolute zero. Also, according the Einstein's equation, atomic heat decreases with decrease of temperature.

 (iii) According to Einstein's equation, the atomic heats of different elements differ only because of differences in the characteristic frequency v. At corresponding

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temperatures, such that the value of the ratio v/T are the same, then according to Einstein's equation, the atomic heat will be the same for al elements. Thus the experimental curves have the same form for al substances.

Thus Einstein's theory predicts the correct values of atomic heats for various elements as observed experimentally, i.e., the Einstein's theory is in good agreement with experimental results.

The Law of Dulong and Petit assumed that Maxwell-Boltzmann statistics and equipartition of energy could be applied even at low temperatures. Einstein recognized that for a quantum harmonic oscillator at energies less than kT, the Einstein-Bose statistics must be applied. This was the same conclusion that was drawn about blackbody radiation. The statistical distribution of energy in the vibrational states gives average energy:

$$\langle E \rangle = \frac{hv}{e^{hv/kI} - 1}$$

where this frequency is the frequency of a quantum vibrator. There are three degrees of freedom per vibrator, so the total energy is

$$E_{oscillators} = \frac{3h\nu N_A}{e^{h\nu/kT} - 1} mole^{-1}$$

In the Einstein treatment, the appropriate frequency in the expression had to be determined empirically by comparison with experiment for each element. The quantity $h\nu/k$ is sometimes called the Einstein temperature. Although the general match with experiment was reasonable, it was not exact.

$$C_{V} = \frac{\partial E}{\partial T} = \frac{3N_{A}k\left(\frac{hv}{kT}\right)^{2}e^{hv/kT}}{\left(e^{hv/kT}-1\right)^{2}}mole^{-1}$$

Debye advanced the treatment by treating the quantum oscillators as collective

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modes in the solid which are now called "phonons". The High Temperature Limit of the Einstein Specific Heat Einstein's introduction of quantum behavior showed why the specific heat became temperature dependent at low temperatures, and it had a high temperature limit which agreed with the Law of Dulong and Petit. To show this, note that for high temperatures, a series expansion of the exponential gives

$$e^{hv/kT} \approx 1 + \frac{hv}{kT}$$

The Einstein specific heat expression then becomes

$$C_{v} = \frac{\partial E}{\partial T} = \frac{3N_{A}k\left(\frac{hv}{kT}\right)^{2}\left(1 + \frac{hv}{kT}\right)}{\left(\frac{hv}{kT}\right)^{2}} mole^{-1}$$

This reduces to the Law of Dulong and Petit.

$$C_{v} = 3N_{A}k\left(1 + \frac{hv}{kT}\right) \approx 3N_{A}k \ mole^{-1}$$

Debye's theory of Specific heats

Though the Einstein's theory predicts almost correctly the variation of specific heat with temperature, it was observed that in the case of some elements like copper, aluminium, iron etc., the atomic heat at low temperature decreases more rapidly than that predicted by Einstein's theory. This disagreement is due to the assumption that the vibrations of all the atoms are simple harmonic and have one and the same frequency. In fact, the vibrations of an atom must be complex, because it is under the field of force of a large number of other vibrating atoms. Moreover, in Einstein's theory, v and hv/k have been obtained empirically and cannot be verified from any other independent physical data. Debye, therefore, modified Einstein's theory which gives excellent agreement with experiment over the whole observable temperature range.

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Debye assumed that any solid is capable of vibrating elastically in many different modes, the frequency varying from on mode to another, and the number of modes of vibration of solids is limited in number.

When a continuous solid is subjected to elastic vibrations, two kinds of vibrations are produced.

(i) Transverse vibrations, and (ii) Longitudinal vibrations.

The number of modes of longitudinal vibrations per unit volume with frequencies between v and v + dv.

POSSIBLE QUESTIONS

2 Mark

- 1. Give an explanation for T^3 law.
- 2. What is the difference between optical and acoustical phonons?
- 3. State Dulong and Petit's Law
- 4. What is lattice vibration?
- 5. Define Phonon.

6 Mark

- 6. Derive the expression for T^3 law.
- 7. Explain the lattice vibrations of linear monoatomic molecules.
- 8. Give an account of the Phonon Spectrum in Solids.
- 9. Explain the Lattice Vibrations of Diatomic Chains.
- 10. Expalin in detail about monoatomic chains.
- 11. Discribe phonon spectrum in solids.
- 12. Explain Einstein and Debye theory of specific heat capacity of solid.
- 13. Derive the expression for Dulong and Petit's law.

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Magnetic Properties of Matter: Dia-, Para-, Ferri- and Ferromagnetic Materials. Classical Langevin Theory of dia– and Paramagnetic Domains. Quantum Mechanical Treatment of Paramagnetism. Curie's law, Weiss's Theory of Ferromagnetism and Ferromagnetic Domains. Discussion of B-H Curve. Hysteresis and Energy Loss.

Magnetic Properties

All matter exhibits magnetic properties when placed in an external magnetic field. Even substances like copper and aluminum that are not normally thought of as having magnetic properties are affected by the presence of a magnetic field such as that produced by either pole of a bar magnet. Depending on whether there is an attraction or repulsion by the pole of a magnet, matter is classified as being either paramagnetic or diamagnetic, respectively. A few materials, not ablyiron, show a very large attraction toward the pole of a permanent bar magnet; materials of this kind are called ferromagnetic.

In 1845 Faraday became the first to classify substances as either diamagnetic or paramagnetic. He based this classification on his observation of the force exerted on substances in an inhomogeneous magnetic field. At moderate field strengths, the magnetization M of a substance is linearly proportional to the strength of the applied field H. The magnetization is specified by the magnetic susceptibility (previously labeled m), defined by the relation M = H. A sample of volume V placed in a field H directed in the x-direction and increasing in that direction at a rate dH/dx will experience a force in the x-direction of $F = \mu_0 VH (dH/dx)$. If the magnetic susceptibility

is positive, the force is in the direction of increasing field strength, whereas if is negative, it is in the direction of decreasing field strength. Measurement of the force F in a known field H with a known gradient dH/dx is the basis of a number of accurate methods of determining .

Substances for which the magnetic susceptibility is negative (e.g., copper and silver) are classified as diamagnetic. The susceptibility is small, on the order of -10^{-5} for solids and liquids and -10^{-8} for gases. A characteristic feature of diamagnetism is that the magnetic moment per unit mass in a given field is virtually constant for a given substance over a very wide range of temperatures. It changes little between solid, liquid, and gas; the variation in the susceptibility between solid or liquid and gas is almost entirely due to the change in the number of molecules per unit volume. This indicates that

the magnetic moment induced in each molecule by a given field is primarily a property characteristic of the molecule.

SIMILAR TOPICS

- phase
- isomerism
- proton
- light
- refraction
- inertia
- plasma
- lepton
- polarization
- liquid

Substances for which the magnetic susceptibility is positive are classed as paramagnetic. In a few cases (including most metals), the susceptibility is independent of temperature, but in most compounds it is strongly temperature dependent, increasing as the temperature is lowered. Measurements by the French physicistPierre Curie in 1895 showed that for many substances the susceptibility is inversely proportional to the absolute temperature T; that is, = C/T. This approximate relationship is known asCurie's law and the constant C as theCurie constant. A more accurate equation is obtained in many cases by modifying the above equation to = C/(T-), where is a constant. This equation is called the Curie-Weiss law (after Curie and Pierre-Ernest Weiss, another French physicist). From the form of this last equation, it is clear that at the temperature T = 1, the value of the susceptibility becomes infinite. Below this temperature, the material exhibits spontaneous magnetization i.e., it becomes ferromagnetic. Its magnetic properties are then very different from those in the paramagnetic or high-temperature phase. In particular, although its magnetic moment can be changed by the application of a magnetic field, the value of the moment attained in a given field is not always the same; it depends on the previous magnetic, thermal, and mechanical treatment of the sample.

Diamagnetism

Diamagnetism, kind of magnetism characteristic of materials that line up at right angles to a non-uniform magnetic field and that partly expel from their interior the magnetic field in which they are placed. First observed by S.J. Brugmans (1778) in bismuth and antimony, diamagnetism was named and studied by Michael Faraday(beginning in 1845). He and subsequent experimenters found that some elements and most compounds exhibit this "negative" magnetism. Indeed, all substances are diamagnetic: the strong external magnetic field speeds up or slows down the electrons orbiting in atoms in such a way as to oppose the action of the external field in accordance with Lenz's law.

The diamagnetism of some materials, however, is masked either by a weak magnetic attraction (paramagnetism) or a very strong attraction (ferromagnetism). Diamagnetism is observable in substances with symmetric electronic structure (as ionic crystals and rare gases) and no permanent magnetic moment. Diamagnetism is not affected by changes in temperature. For diamagnetic materials the value of the susceptibility (a measure of the relative amount of induced magnetism) is always negative and typically near negative one-millionth.

Paramagnetism, kind of magnetism characteristic of materials weakly attracted by a strong magnet, named and extensively investigated by the British scientist Michael Faraday beginning in 1845. Most elements and some compounds are paramagnetic. Strong paramagnetism (not to be confused with the ferromagnetism of the elements iron, cobalt, nickel, and other alloys) is exhibited by compounds containing iron, palladium, platinum, and the rare-earth elements. In such compounds atoms of these elements have some inner electron shells that are incomplete, causing their unpaired electrons to spin like tops and orbit like satellites, thus making the atoms a permanent magnet tending to align with and hence strengthen an applied magnetic field.

Strong paramagnetism decreases with rising temperature because of the dealignment produced by the greater random motion of the atomic magnets. Weak paramagnetism, independent of temperature, is found in many metallic elements in the solid state, such as sodium and the other alkali metals, because an applied magnetic field

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affects the spin of some of the loosely bound conduction electrons. The value of susceptibility (a measure of the relative amount of induced magnetism) for paramagnetic materials is always positive and at room temperature is typically about 1/100,000 to 1/10,000 for weakly paramagnetic substances and about 1/10,000 to 1/100 for strongly paramagnetic substances.

Magnetism: Magnetic properties of matter

phenomenon associated with magnetic fields, which arise from the motion of electric charges. This motion can take many forms. It can be an electric current in a conductor or charged particles moving through space, or it can be the motion of an electron in an atomic orbital. Magnetism is also...

Ferrimagnetism, type of permanent magnetism that occurs in solids in which the magnetic fields associated with individual atoms spontaneously align themselves, some parallel, or in the same direction (as in ferromagnetism), and others generally antiparallel, or paired off in opposite directions (as in antiferro magnetism). The magnetic behaviour of single crystals of ferrimagnetic materials may be attributed to the parallel alignment; the diluting effect of those atoms in the antiparallel arrangement keeps the magnetic strength of these materials generally less than that of purely ferromagnetic solids such as metalliciron.

Ferrimagnetism occurs chiefly in magnetic oxides known as ferrites. The natural magnetism exhibited by lodestones, recorded as early as the 6th century BC, is that of a ferrite, the mineral magnetite, a compound containing negative oxygen ions O^{2} -and positive iron ions in two states, iron(II) ions, Fe^{2+} , and iron(III) ions, Fe^{3+} . The oxygen ions are not magnetic, but both iron ions are. In magnetite crystals, chemically formulated as Fe_3O_4 , for every four oxygen ions, there are two iron(III) ions and one iron(II) ion. The iron(III) ions are paired off in opposite directions, producing no external magnetic field, but the iron(II) ions are all aligned in the same direction, accounting for the external magnetism.

The spontaneous alignment that produces ferrimagnetism is entirely disrupted above a temperature called the Curie point, characteristic of each ferrimagnetic material.

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When the temperature of the material is brought below the Curie point, ferrimagnetism revives.

Ferromagnetism, physical phenomenon in which certain electrically uncharged materials strongly attract others. Two materials found in nature, lodestone (ormagnetite, an oxide of iron, Fe₃O₄) and iron, have the ability to acquire such attractive powers, and they are often called natural ferromagnets. They were discovered more than 2,000 years ago, and all early scientific studies ofmagnetism were conducted on these materials. Today, ferromagnetic materials are used in a wide variety of devices essential to everyday life. *e.g.*, electric motors and generators, transformers, telephones, and loudspeakers.

Ferromagnetism is a kind of magnetism that is associated with iron, cobalt,nickel, and some alloys or compounds containing one or more of these elements. It also occurs in gadolinium and a few other rare-earth elements. In contrast to other substances, ferromagnetic materials are magnetized easily, and in strong magnetic fields the magnetization approaches a definite limit called saturation. When a field is applied and then removed, the magnetization does not return to its original value—this phenomenon is referred to as hysteresis. When heated to a certain temperature called the Curie point, which is different for each substance, ferromagnetic materials lose their characteristic properties and cease to be magnetic; however, they become ferromagnetic again on cooling.

The magnetism in ferromagnetic materials is caused by the alignment patterns of their constituent atoms, which act as elementary electromagnets. Ferromagnetism is explained by the concept that some species of atoms possess a magnetic moment—that is, that such an atom itself is an elementary electromagnet produced by the motion of electrons about its nucleus and by the spin of its electrons on their own axes. Below the Curie point, atoms that behave as tiny magnets in ferromagnetic materials spontaneously align themselves. They become oriented in the same direction, so that their magnetic fields reinforce each other.

One requirement of a ferromagnetic material is that its atoms or ions have permanent magnetic moments. The magnetic moment of an atom comes from its

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electrons, since the nuclear contribution is negligible. Another requirement for ferromagnetism is some kind of interatomic force that keeps the magnetic moments of many atoms parallel to each other. Without such a force the atoms would be disordered by thermal agitation, the moments of neighboring atoms would neutralize each other, and the large magnetic moment characteristic of ferromagnetic materials would not exist.

There is ample evidence that some atoms or ions have a permanent magnetic moment that may be pictured as a dipole consisting of a positive, or north, pole separated from a negative, or south, pole. In ferromagnets, the large coupling between the atomic magnetic moments leads to some degree of dipole alignment and hence to a net magnetization.

The French physicist Pierre-Ernest Weiss postulated a large-scale type of magnetic order for ferromagnets called domain structure. According to his theory, a ferromagnetic solid consists of a large number of small regions, or domains, in each of which all of the atomic or ionic magnetic moments are aligned. If the resultant moments of these domains are randomly oriented, the object as a whole will not display magnetism, but an externally applied magnetizing field will, depending on its strength, rotate one after another of the domains into alignment with the external field and cause aligned domains to grow at the expense of nonaligned ones. In the limiting state called saturation, the entire object will comprise a single domain.

Domain structure can be observed directly. In one technique, a colloidal solution of small magnetic particles, usually magnetite, is placed on the surface of a ferromagnet. When surface poles are present, the particles tend to concentrate in certain regions to form a pattern that is readily observed with an optical microscope. Domain patterns have also been observed with polarized light, polarized neutrons, electron beams, and X rays.

In many ferromagnets the dipole moments are aligned parallel by the strong coupling. This is the magnetic arrangement found for the elemental metals iron (Fe), nickel (Ni), and cobalt (Co) and for their alloys with one another and with some other elements. These materials still constitute the largest group of ferromagnets commonly used. The other elements that possess a collinear ordering are the rare-earth metals gadolinium (Gd), terbium (Tb), and dysprosium (Dy), but the last two become ferromagnets only well below room temperature. Some alloys, although not composed of any of the elements just mentioned, nevertheless have a parallel moment arrangement. An example of this is the Heusler alloy CuAlMn₃, in which the manganese(Mn) atoms have magnetic moments, though manganese metal itself is not ferromagnetic.

Since 1950, and particularly since 1960, several ionically bound compounds have been discovered to be ferromagnetic. Some of these compounds are electrical insulators; others have a conductivity of magnitude typical of semiconductors. Such compounds include chalcogenides (compounds of oxygen, sulfur, selenium, or tellurium), halides (compounds of fluorine, chlorine, bromine, or iodine), and their combinations. The ions with permanent dipole moments in these materials are manganese, chromium (Cr), andeuropium (Eu); the others are diamagnetic. At low temperatures, the rare-earth metals holmium (Ho) and erbium (Er) have a nonparallel moment arrangement that gives rise to a substantial spontaneous magnetization. Some ionic compounds with the spinel crystal structure also possess ferromagnetic ordering. A different structure leads to a spontaneous magnetization in thulium (Tm) below 32 kelvins (K).

Above the Curie point (also called the Curie temperature), the spontaneous magnetization of the ferromagnetic material vanishes and it becomesparamagnetic (*i.e.*, it remains weakly magnetic). This occurs because the thermal energy becomes sufficient to overcome the internal aligning forces of the material. The Curie temperatures for some important ferromagnets are: iron, 1,043 K; cobalt, 1,394 K; nickel, 631 K; and gadolinium, 293 K.

Quantum mechanical treatment of paramagnetism

In the classical electromagnetic theory is quite capable of explaining the essentials of the magnetic properties of materials. Some discrepancies between theory and experiment have come to light, however, which need to be explained. Therefore, we now refine and deepen our understanding by considering the contributions which quantum mechanics provides to magnetism. We will see in the following that quantum mechanics yields answers to some basic questions. We will discuss why certain metals that we expect to be paramagnetic are in reality diamagnetic; why the paramagnetic susceptibility is relatively small for most metals; and why most metals do not obey the Curie-Weiss law. We will

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also see that ferromagnetism can be better understood by applying elements of quantum mechanics.

Paramagnetism and Diamagnetism

We mentioned at the beginning of the previous topic that, for most solids, the dominant contribution to paramagnetism stems from the magnetic moment of the spinning electrons. We recall from topic 6 that each electron state may be occupied by a maximum of two electrons, one having positive spin and the other having negative spin (called spin up and spin down). To visualize the distribution of spins, we consider an electron band to be divided into two halves, each of which is thought to be occupied under normal conditions by an identical amount of electrons of opposite spin, as shown in Fig. 16.1(a). Now, if we apply an external magnetic field to a free electron solid, some of the electrons having unfavorably oriented spins tend to change their field direction. This can only be achieved, however, when the affected electrons assume an energy which is higher than the Fermi energy, EF, since all lower electron states of opposite spin direction are already occupied (Fig. 16.1(b)).





Thus, theoretically, the transfer of electrons from one half-band into the other would cause two individual Fermi energies (EF0 and Ef") to occur. Of course, this is not possible. In reality the two band halves shift relative to each other until equilibrium, i.e., a common Fermi energy, is reached (Fig. 16.1(c)).

Now, we recall from topic 6 that the electron distribution within a band is not uniform. We rather observe a parabolic distribution of energy states, as shown in Fig. 6.4. Thus, we refine our treatment by replacing Fig. 16.1(c) with Fig. 16.2, which depicts the density of states of the two half-bands. We observe a relatively large Z(E) near EF. Thus, a small change in energy (provided by the external magnetic field) may cause a large number of electrons to switch to the opposite spin direction.

We calculate now the susceptibility from this change in energy, DE. It is evident that DE is larger, the larger the external magnetic field strength |H|, and the larger the magnetic moment of the spinning electrons $|\mu_{ms}|$, i.e.,



Figure 16.2. Schematic representation of the density of states Z(E) in two half-bands. The shift of the two half-bands occurs as a result of an external magnetic field.

As mentioned already, the number of electrons. AN, transferred from the spin down into the spin up direction depends on the density of states at the Fermi energy, Z(EF), and the energy difference, AE (Fig. 16.2), i.e.,

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$$\Delta N = \Delta EZ(E_{\rm F}) = \mu_0 H \,\mu_{\rm ms} Z(E_{\rm F}). \tag{16.2}$$

The magnetization IMI of a solid, caused by an external magnetic field is, according to (14.8),

$$M = \frac{\mu_m}{V}.$$
 (16.3)

The magnetization is, of course, larger, the more electrons are transferred from spin down into spin up states. We thus obtain, for the present case,

$$M = \frac{\mu_{\rm ms}}{V} \Delta N = \frac{\mu_{\rm ms}^2 \mu_0 H Z(E_{\rm F})}{V}, \qquad (16.4)$$

which yields for the susceptibility

$$\chi = \frac{M}{H} = \frac{\mu_{\rm ms}^2 \mu_0 Z(E_{\rm F})}{V} \,. \tag{16.5}$$

The spin magnetic moment of one electron equals one Bohr magneton, mB (see below). Thus, (16.5) finally becomes

$$\chi_{\text{para}}^{\text{spin}} = \frac{\mu_{\text{B}}^2 \mu_0 Z(E_{\text{F}})}{V}.$$
(16.6)

The susceptibilities for paramagnetic metals calculated with this equation agree fairly well with those listed in Table 14.1 (see Problem 1). Thus, (16.6) substantiates, in essence, that only the electrons close to the Fermi energy are capable of realigning in the magnetic field direction. If we postulate instead that all valence electrons contribute to wpara we would wrongfully calculate a susceptibility which is two or even three orders of magnitude larger than that obtained by (16.6).

It is important to realize that the ever-present diamagnetism makes a sizable contribution to the overall susceptibility, so that w for metals might be positive or negative depending on which of the two components predominates. This will be elucidated now in a few examples.

To begin with, we discuss beryllium, which is a bivalent metal having a filled 2s-shell in its atomic state (see topic 3). However, in the crystalline state, we observe band overlapping (see topic 6), which causes some of the 2s-electrons to spill over into the 2p-band. They populate the very bottom of this band (see Fig. 16.3). Thus, the density of states at the Fermi level, and consequently, w para, is very small. In effect, the diamagnetic susceptibility predominates, which makes Be diamagnetic.

In order to understand why copper is diamagnetic, we need to remember that for this metal the Fermi energy is close to the band edge (Fig. 5.22).



Figure 16.3. Overlapping of 2s- and 2p-bands in Be and the density of states curve for the 2p-band.

Thus, the density of states near EF and the paramagnetic susceptibility (16.6) are relatively small. Furthermore, we have to recall that the diamagnetic susceptibility (15.17),

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 $\chi_{\rm dia} = -\frac{e^2 Z r^2 \mu_0}{6mV}$

(16.7)

is proportional to the square of an electron orbit radius, r, and proportional to the total number of electrons, Z, in that orbit. Copper has about ten 3d-electrons, which makes Z^{10} . Further, the radius of d-shells is fairly large. Thus, for copper, wdia is large because of two contributions. The diamagnetic contribution predominates over the paramagnetic one. As a result, copper is diamagnetic. The same is true for silver and gold and the elements which follow copper in the Periodic Table, such as zinc and gallium.

Intrinsic semiconductors, which have filled valence bands and whose density of states at the top of the valence band is zero (Fig. 6.6) have, according to (16.6), no paramagnetic susceptibility and are therefore diamagnetic. However, a small paramagnetic contribution might be expected for highly doped extrinsic semiconductors, which have, at high enough temperatures, a considerable number of electrons in the conduction band (see topic 8).

We turn now to the temperature dependence of the susceptibility of metals. The relevant terms in both (16.6) as well as (16.7) do not vary much with temperature. Thus, it is conceivable that the susceptibility of diamagnetic metals is not temperature-dependent, and that the susceptibility of paramagnetic metals often does not obey the Curie-Weiss law. In fact, the temperature dependence of the susceptibility for different paramagnetic metals has been observed to decrease, to increase, or to remain essentially constant (Fig. 16.4). However, nickel (above TC) and rare earth metals obey the Curie-Weiss law reasonably well.

At the end of this section we remind the reader that in dilute gases (and also in rare earth metals and their salts) a second component contributes to paramagnetism.



Figure 16.4. Temperature dependence of the paramagnetic susceptibility for vanadium, chromium, and aluminum in arbitrary units.

It stems from a magnetic moment which is caused by the angular momentum of the orbiting electrons (Section 15.3). We mentioned already in Section 15.1 that this contribution is said to be "quenched" (nonexistent) in most solids.

Finally, we want to find a numerical value for the magnetic moment of an orbiting electron from a quantum-mechanical point of view. We recall from (15.5):

$$\mu_{\rm m} = \frac{evr}{2}.\tag{16.8}$$

Now, quantum theory postulates that the angular momentum, mvr, of an electron is not continuously variable but that it rather changes in discrete amounts of integer multiples of \ only, i.e.,

$$mvr = n\hbar = \frac{n\hbar}{2\pi}.$$
(16.9)

If one combines (16.8) with (16.9) one obtains

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$$\mu_{\rm m} = \frac{enh}{4\pi m}.\tag{16.10}$$

Using n = 1 for the first electron orbit (ground state) yields, for the magnetic moment of an orbiting electron,

$$\mu_{\rm m} = \frac{eh}{4\pi m}.\tag{16.11}$$

It was found experimentally and theoretically that the magnetic moment of an electron due to orbital motion as well as the magnetic moment of the spinning electron are identical. This smallest unit of the magnetic moment is given by (16.11) and is called the Bohr magneton,

$$\mu_{\rm B} = \frac{eh}{4\pi m} = 9.274 \times 10^{-24} \left(\frac{J}{T}\right),\tag{16.12}$$

which we already introduced without further explanation in (15.3).

Ferromagnetism and Antiferromagnetism

The ferromagnetic metals iron, cobalt, and nickel are characterized by unfilled d-bands (see topic 3). These d-bands overlap the next higher s-band in a similar manner as shown in the band structure of Fig. 5.22. The density of states for a d-band is relatively large because of its potential to accommodate up to ten electrons. This is schematically shown in Fig. 16.5, along with the Fermi energies for iron, cobalt, nickel, and copper. Since the density of states for, say, nickel is comparatively large at the Fermi energy, one needs only a relatively small amount of energy to transfer a considerable number of electrons from spin down into spin up configurations, i.e., from one half-band into the other. We have already discussed in the previous section this transfer of electrons under the influence of an external magnetic field (Fig. 16.1). Now, there is an important difference between para-magnetics and ferromagnetics. In the former case, an external energy (i.e., the magnetic field) is needed to accomplish the flip in spin alignment,

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whereas for ferromagnetic materials the parallel alignment of spins occurs spontaneously in small domains of about 1-100 mm diameter. Any theory of ferromagnetism must be capable of satisfactorily explaining the origin of this energy which transfers electrons into a higher energy state.

Curie's Law

In a paramagnetic material the magnetization of the material is directly proportional to an applied magnetic field. However, if the material is heated, the magnetization is inversely proportional to temperature. i.e. $M = C \times (B / T)$ where, M is the magnetization B is the magnetic field, measured in teslas T is absolute temperature, measured in kelvins C is a material-specific Curie constantIt was first discovered experimentally by French physicist, Pierre Curie.It holds for high temperatures, or weak magnetic fields.

In contrast to dia- and paramagnetism, *ferromagnetism* is of *prime importance* for electrical engineering. It is, however, one of the most difficult material properties to understand.

• It is not unlike "ferro"electricity, in relying on strong interactions between neighboring atoms having a permanent magnetic moment *m* stemming from the *spins* of electrons.

• But while the interaction between electric dipoles can, at least in principle, be understood in classical and semi-classical ways, *the interaction between spins of electrons is an exclusively quantum mechanical effect with no classical analogon*. Moreover, a theoretical treatment of the three-dimensional case giving reliable results still eludes the theoretical physicists.

• In the advanced section, a very simplified view will be presented, here we just accept the fact that only Fe, Co, Ni (and some rare earth metals) show strong interactions between spins and thus ferromagnetism in elemental crystals.

• In *compounds*, however, many more substances exist with spontaneous magnetization coming from the coupling of spins.

There is, however, a relatively *simple theory of ferromagnetism*, that gives the proper relations, temperature dependences etc., - with one major drawback: It starts with an *unphysical assumption*.

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• This is the mean field theory or the Weiss theory of ferromagnetism. It is a phenomenological theory based on a central (wrong) assumption

Substitute the elusive spin - spin interaction between electrons by the interaction of the spins with a very strong magnetic field.

• In other words, *pretend*, that in addition to your external field there is a *built-in magnetic field* which we will call the Weiss field. The Weiss field will tend to line up the magnetic moments - you are now treating ferromagnetism as an *extreme* case of paramagnetism.

Of course, if the material you are looking at *is* a real ferromagnet, you don't have to *pretend* that there is a built-in magnetic field, becasse there *is* a large magnetic field, indeed. But this looks like mixing up cause and effect! What you want to result from a calculation is what you start the calculation with!

• This is called a self-consistent approach. You many view it as a closed circle, where cause and effect loose their menaings to some extent, and where a calculation produces some results thate are fed back to the beginning and reeated until some parameter doesn't change anymore.

• Why are we doing this, considering that this approach is rather questionable? Well - it works! It gives the right relations, in particular the temperature dependence of the magnetization.

The local magnetic field H_{loc} for an external field H_{ext} then will be

$H_{\text{loc}} = H_{\text{ext}} + H_{\text{Weiss}}$

• Note that this has not much to do with the local electrical field in the Lorentz treatment. We call it "local" field, too, because it is supposed to contain everything that acts locally, including the modifications we ought to make to account for pure local effects as in the case of electrical fields. Since our fictitious "Weiss field" is so much larger than everything coming from real fields, we simply forget about that.

Since we treat this *fictive* field H_{weiss} as an internal field, we write it as a superposition of the external field H and a field stemming from the internal magnetic polarization J:

$$H_{\text{loc}} = H_{\text{ext}} + w \cdot J$$

• With J = magnetic polarization and w = Weiss's factor; a constant that now *contains the physics of the problem*.

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This is the decisive step. We now identify the Weiss field with the magnetic polarization that is caused by it. And, yes, as stated above, we now do mix up cause and effect to some degree: the fictitiuos Weiss field causes the alignments of the individual magnetic moments which than produce a magnetic polarization that causes the local field that we identify with the Weiss field and so on.

• But that, after all, *is* what happens: the (magnetic moments of the) spins interact causing a field that causes the interaction, that, if your mind boggles a bit, that is as it should be. The magnetic polarization caused by spin-spin interactions and mediating spin-spin interaction just *is* - asking for cause and effect is a futile question.

• The Weiss factor w now contains *all the local effects* lumped together - in analogy to the Lorentz treatment of local fields, μ_0 , and the interaction between the spins that leads to ferromagnetism as a result of some fictive field.

• But lets be very clear: *There is no internal magnetic field* H_{Weiss} *in the material* before the spins become aligned. This completely fictive field just leads - within limits - to the same interactions you would get from a proper quantum mechanical treatment. Its big advantage is that it makes calculations possible if you determine the parameter w experimentally.

All we have to do now is to repeat the calculations done for paramagnetism, substituting H_{loc} wherever we had H. Lets see where this gets us.

• This is the famous Curie law for the paramagnetic regime at high temperatures which was a phenomenological thing so far. Now we derived it with a theory and will therefore call it **Curie - Weiss law**

In summary, the mean field approach ain't that bad! It can be used for attacking many more problems of ferromagnetism, but you have to keep in mind that it is only a description, and not based on sound principles.



Figure 16.5. Schematic representation of the density of states for 4s- and 3d-bands and the Fermi energies for iron, cobalt, nickel, and copper. The population of the bands by the ten nickel (3d + 4s)-electrons is indicated by the shaded area.

The energy in question was found to be the exchange energy. It is "set free" when equal atomic systems are closely coupled, and in this way exchange their energy. This needs some further explanation.

We digress for a moment and compare two ferromagnetic atoms with two identical pendula that are interconnected by a spring. (The spring represents the interactions of the electrical and magnetic fields.) If one of the pendula is deflected, its amplitude slowly decreases until all energy has been transferred to the second pendulum, which then in turn transfers its energy back to the first one and so on. Thus, the amplitudes decrease and increase periodically with time, as shown in Fig. 16.6. The resulting vibrational pattern is similar to that of two violin strings tuned at almost equal pitch. A mathematical expression for this pattern is obtained by adding the equations for two oscillators having similar frequencies, o1 and o2,

$$X_1 = b\sin\omega_1 t,$$

$$X_2 = b\sin\omega_2 t,$$

which yields

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$$X_1 + X_2 = X = 2b\cos\frac{\omega_1 - \omega_2}{2}t \cdot \sin\frac{\omega_1 + \omega_2}{2}t.$$

Equation (16.15) provides two frequencies, (o1 - o2)/2 and (o1 + o2)/2, which can be identified in Fig. 16.6. The difference between the resulting frequencies is larger, the stronger the coupling. If the two pendula vibrate in a parallel fashion, the "pull" on the spring, i.e., the restoring force, kx, is small. As a consequence, the frequency

$$v_0 = \frac{1}{2\pi} \sqrt{\frac{\kappa}{m}}$$

(see topic 1) is likewise small and is smaller than for independent vibrations. (On the other hand, antisymmetric vibrations cause large values of k and n0.) This classical example demonstrates that two coupled and symmetrically vibrating systems may have a lower energy than two individually vibrating systems would have.



Figure 16.6. Amplitude modulation resulting from the coupling of two pendula. The vibrational pattern shows beats, similarly as known for two oscillators that have almost identical pitch.

Quantum mechanics treats ferromagnetism in a similar way. The exact calculation involving many atoms is, however, not a trivial task. Thus, one simplifies the problem by solving the appropriate Schrodinger equation for two atoms only. The potential energy in the Schrodinger equation then contains the exchange forces between the nuclei a and b, the forces between two electrons 1 and 2, and the interactions between the nuclei and their neighboring electrons. This simplification seems to be justified, because the exchange forces decrease rapidly with distance.

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The calculation, first performed by Slater and Bethe, leads to an exchange integral,

$$I_{\text{ex}} = \int \psi_a(1) \ \psi_b(2) \ \psi_a(2) \ \psi_b(1) \left[\frac{1}{r_{ab}} - \frac{1}{r_{a2}} - \frac{1}{r_{b1}} + \frac{1}{r_{12}} \right] d\tau.$$

A positive value for Iex means that parallel spins are energetically more favorable than antiparallel spins (and vice versa). We see immediately from (16.17) that Iex becomes positive for a small distance r12 between the electrons, i.e., a small radius of the d-orbit, rd. Similarly, Iex becomes positive for a large distance between the nuclei and neighboring electrons ra2 and rb1.

Iex is plotted in Fig. 16.7 versus the ratio rab/rd. The curve correctly separates the ferromagnetics from manganese, which is not ferromagnetic. Figure 16.7 suggests that if the interatomic distance rab in manganese is increased (e.g., by inserting nitrogen atoms into the manganese lattice), the crystal thus obtained should become ferromagnetic. This is indeed observed. The ferromagnetic alloys named after Heusler, such as Cu2MnAl or Cu2MnSn, are particularly interesting in this context because they contain constituents which are not ferromagnetic, but all contain manganese.

The Bethe-Slater curve (Fig. 16.7) suggests that cobalt should have the highest, and nickel (and the rare earth elements) the lowest, Curie temperature among the ferromagnetics because of the magnitude of their /ex values. This is indeed observed (Table 15.1). Overall, quantum theory is capable of explaining some ferromagnetic properties that cannot be understood with classical electromagnetic theory.



Figure 16.7. Exchange integral, Iex, versus the ratio of interatomic distance, rab, and the radius of an unfilled d-shell. The position of the rare earth elements (which have unfilled /-shells) are also shown for completeness.

We turn now to a discussion on the number of Bohr magnetons in ferromagnetic metals as listed in Table 16.1. Let us consider nickel as an example and reinspect, in this context, Fig. 16.5. We notice that because of band overlapping the combined ten (3d + 4s)-electrons occupy the lower s-band and fill, almost completely, the 3d-band. It thus comes as no surprise that nickel behaves experimentally as if the 3d-band is filled by 9.4 electrons. To estimate mB we need to apply Hund's rule (Fig. 15.4), which states that the electrons in a solid occupy the available electron states in a manner which maximizes the imbalance of spin moments. For the present case, this rule would suggest five electrons with, say, spin up, and an average of 4.4 electrons with spin down, i.e., we obtain a spin imbalance of 0.6 spin moments or 0.6 Bohr magnetons per atom. The average number of Bohr magnetons may also be calculated from experimental values of the saturation magnetization, Ms0. Similar considerations can be made for the remaining ferromagnetics.

We now proceed one step further and discuss the magnetic behavior of certain nickel-based alloys. We use nickel-copper alloys as an example. Copper has one valence electron more than nickel. If copper is alloyed to nickel, the extra copper electrons

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progressively fill the d-band and therefore compensate some of the unsaturated spins of nickel. Thus, the magnetic moment per atom of this alloy (and also its Curie temperature) is reduced. Nickel lacks about 0.6 electrons per atom for complete spin saturation, because the 3d-band of nickel is filled by only 9.4 electrons (see above). Thus, about 60% copper atoms are needed until the magnetic moment (and mB) of nickel has reached a zero value (Fig. 16.8). Nickel- copper alloys, having a copper concentration of more than about 60% are consequently no longer ferromagnetic; one would expect them to be diamagnetic. (In reality, however, they are strongly paramagnetic, probably owing to small traces of undissolved nickel.)

Zinc contributes about two extra valence electrons to the electron gas when alloyed to nickel. Thus, we expect a zero magnetic moment at about 30 at.% Zn, etc.



Figure 16.8. Magnetic moment per nickel atom as a function of solute concentration. Palladium, on the other hand, has the same number of valence electrons as nickel and thus does not change the magnetic moment of the nickel atoms when alloyed to nickel. The total magnetization (14.8) of the alloy is, of course, diluted by the nonferromagnetic palladium. The same is also true for the other alloys.

We conclude our discussion by adding a few interesting details. The rare earth elements are weakly ferromagnetic. They are characterized by unfilled /-shells. Thus,

their electronic structure and their density of states have several features in common with iron, cobalt, and nickel. They have a positive /ex (see Fig. 16.7).

Copper has one more valence electron than nickel, which locates its Fermi energy slightly above the d-band (Fig. 16.5). Thus, the condition for ferromagnetism, i.e., an unfilled d- or /-band is not fulfilled for copper. The same is true for the following elements such as zinc or gallium.

We noted already that manganese is characterized by a negative value of the exchange integral. The distance between the manganese atoms is so small that their electron spins assume an antiparallel alignment. Thus, manganese and many manganese compounds are antiferromagnetic (see Fig. 15.10). Chromium has also a negative /ex and thus is likewise antifer-romagnetic (see Table 15.2).

Advertisement



Magnetic Hysteresis

The lag or delay of a magnetic material known commonly as **Magnetic Hysteresis**, relates to the magnetisation properties of a material by which it firstly becomes magnetised and then de-magnetised.

We know that the magnetic flux generated by an electromagnetic coil is the amount of magnetic field or lines of force produced within a given area and that it is more commonly called "Flux Density". Given the symbol B with the unit of flux density being the Tesla, T.

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We also know from the previous tutorials that the magnetic strength of an electromagnet depends upon the number of turns of the coil, the current flowing through the coil or the type of core material being used, and if we increase either the current or the number of turns we can increase the magnetic field strength, symbol H.

Previously, the relative permeability, symbol μ_r was defined as the ratio of the absolute permeability μ and the permeability of free space μ_o (a vacuum) and this was given as a constant. However, the relationship between the flux density, B and the magnetic field strength, H can be defined by the fact that the relative permeability, μ_r is not a constant but a function of the magnetic field intensity thereby giving magnetic flux density as: $B = \mu$ H.

Then the magnetic flux density in the material will be increased by a larger factor as a result of its relative permeability for the material compared to the magnetic flux density in vacuum, μ_0 H and for an air-cored coil this relationship is given as:

$$B = \frac{\Phi}{A}$$
 and $\frac{B}{H} = \mu_0$

So for ferromagnetic materials the ratio of flux density to field strength (B/H) is not constant but varies with flux density. However, for air cored coils or any nonmagnetic medium core such as woods or plastics, this ratio can be considered as a constant and this constant is known as μ_0 , the permeability of free space, ($\mu_0 = 4$. .10⁻⁷ H/m).

By plotting values of flux density, (B) against the field strength, (H) we can produce a set of curves called **Magnetisation Curves**, **Magnetic Hysteresis Curves** or more commonly **B-H Curves** for each type of core material used as shown below.

2.0B-H Curves for Various Metals 1.8Steel 1.61.4 Magnetic 1.2 Saturation Flux Density – B (T) 1.0 0.8Iron 0.6 0.4 Air 0.2 0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 Magnetic Field Strength -H (At/m)

Magnetisation or B-H Curve

The set of magnetisation curves, M above represents an example of the relationship between B and H for soft-iron and steel cores but every type of core material will have its own set of magnetic hysteresis curves. You may notice that the flux density increases in proportion to the field strength until it reaches a certain value were it can not increase any more becoming almost level and constant as the field strength continues to increase.

This is because there is a limit to the amount of flux density that can be generated by the core as all the domains in the iron are perfectly aligned. Any further increase will have no effect on the value of M, and the point on the graph where the flux density reaches its limit is called Magnetic Saturation also known as Saturation of the Core and in our simple example above the saturation point of the steel curve begins at about 3000 ampere-turns per metre.

Saturation occurs because as we remember from the previous magnetism tutorial which included Weber's theory, the random haphazard arrangement of the molecule structure within the core material changes as the tiny molecular magnets within the material become "lined-up".

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As the magnetic field strength, (H) increases these molecular magnets become more and more aligned until they reach perfect alignment producing maximum flux density and any increase in the magnetic field strength due to an increase in the electrical current flowing through the coil will have little or no effect.

Retentivity

Lets assume that we have an electromagnetic coil with a high field strength due to the current flowing through it, and that the ferromagnetic core material has reached its saturation point, maximum flux density. If we now open a switch and remove the magnetising current flowing through the coil we would expect the magnetic field around the coil to disappear as the magnetic flux reduced to zero.

However, the magnetic flux does not completely disappear as the electromagnetic core material still retains some of its magnetism even when the current has stopped flowing in the coil. This ability for a coil to retain some of its magnetism within the core after the magnetisation process has stopped is called **Retentivity** or remanence, while the amount of flux density still remaining in the core is called **Residual Magnetism**, B_R . The reason for this that some of the tiny molecular magnets do not return to a completely random pattern and still point in the direction of the original magnetising field giving them a sort of "memory". Some ferromagnetic materials have a high retentivity (magnetically hard) making them excellent for producing permanent magnets.

While other ferromagnetic materials have low retentivity (magnetically soft) making them ideal for use in electromagnets, solenoids or relays. One way to reduce this residual flux density to zero is by reversing the direction of the current flowing through the coil, thereby making the value of H, the magnetic field strength negative. This effect is called a **Coercive Force**, H_C .

If this reverse current is increased further the flux density will also increase in the reverse direction until the ferromagnetic core reaches saturation again but in the reverse direction from before. Reducing the magnetising current, i once again to zero will produce a similar amount of residual magnetism but in the reverse direction.

Then by constantly changing the direction of the magnetising current through the coil from a positive direction to a negative direction, as would be the case in an AC supply, a **Magnetic Hysteresis** loop of the ferromagnetic core can be produced.

Magnetic Hysteresis Loop



The **Magnetic Hysteresis** loop above, shows the behaviour of a ferromagnetic core graphically as the relationship between B and H is non-linear. Starting with an unmagnetised core both B and H will be at zero, point 0 on the magnetisation curve. If the magnetisation current, i is increased in a positive direction to some value the magnetic field strength H increases linearly with i and the flux density B will also increase as shown by the curve from point 0to point a as it heads towards saturation.

Now if the magnetising current in the coil is reduced to zero, the magnetic field circulating around the core also reduces to zero. However, the coils magnetic flux will not reach zero due to the residual magnetism present within the core and this is shown on the curve from point a to point b.

To reduce the flux density at point b to zero we need to reverse the current flowing through the coil. The magnetising force which must be applied to null the residual flux density is called a "Coercive Force". This coercive force reverses the magnetic field re-arranging the molecular magnets until the core becomes unmagnetised at point c.

An increase in this reverse current causes the core to be magnetised in the opposite direction and increasing this magnetisation current further will cause the core to reach its saturation point but in the opposite direction, point d on the curve.

This point is symmetrical to point b. If the magnetising current is reduced again to zero the residual magnetism present in the core will be equal to the previous value but in reverse at point e.

Again reversing the magnetising current flowing through the coil this time into a positive direction will cause the magnetic flux to reach zero, point f on the curve and as before increasing the magnetisation current further in a positive direction will cause the core to reach saturation at point a.

Then the B-H curve follows the path of a-b-c-d-e-f-a as the magnetising current flowing through the coil alternates between a positive and negative value such as the cycle of an AC voltage. This path is called a **Magnetic Hysteresis Loop**.

The effect of magnetic hysteresis shows that the magnetisation process of a ferromagnetic core and therefore the flux density depends on which part of the curve the ferromagnetic core is magnetised on as this depends upon the circuits past history giving the core a form of "memory". Then ferromagnetic materials have memory because they remain magnetised after the external magnetic field has been removed.

However, soft ferromagnetic materials such as iron or silicon steel have very narrow magnetic hysteresis loops resulting in very small amounts of residual magnetism making them ideal for use in relays, solenoids and transformers as they can be easily magnetised and demagnetised.

Since a coercive force must be applied to overcome this residual magnetism, work must be done in closing the hysteresis loop with the energy being used being dissipated as heat in the magnetic material. This heat is known as hysteresis loss, the amount of loss depends on the material's value of coercive force.

By adding additive's to the iron metal such as silicon, materials with a very small coercive force can be made that have a very narrow hysteresis loop. Materials with narrow hysteresis loops are easily magnetised and demagnetised and known as soft magnetic materials.



Magnetic Hysteresis Loops for Soft and Hard Materials

Magnetic Hysteresis results in the dissipation of wasted energy in the form of heat with the energy wasted being in proportion to the area of the magnetic hysteresis loop. Hysteresis losses will always be a problem in AC transformers where the current is constantly changing direction and thus the magnetic poles in the core will cause losses because they constantly reverse direction.

Rotating coils in DC machines will also incur hysteresis losses as they are alternately passing north the south magnetic poles. As said previously, the shape of the hysteresis loop depends upon the nature of the iron or steel used and in the case of iron which is subjected to massive reversals of magnetism, for example transformer cores, it is important that the B-H hysteresis loop is as small as possible.

In the next tutorial about Electromagnetism, we will look at Faraday's Law of Electromagnetic Induction and see that by moving a wire conductor within a stationary magnetic field it is possible to induce an electric current in the conductor producing a simple generator.

POSSIBLE QUESTIONS

2 mark

- 1. Write a note on magnetic materials.
- 2. State curie's law.
- 3. Give a short note on Ferromagnetic materials?
- 4. Give a short note on Diamagnetic materials?
- 5. Give an example for Dia-, Para- magnetic materials?
- 6. Explain briefly about B-H curve.
- 7. Explain shortly about Hysteresis.

6 mark

- 8. Explain classical Langevin Theory of paramagnetism.
- 9. Write short note on Dia-, Para-, Ferri- and Ferromagnetic Materials.
- 10. Draw B-H curve and explain the hysteresis loss.
- 11. Discuss quantum Mechanical Treatment of Paramagnetism
- 12. Explain Weiss's theory of ferromagnetism
- 13. Describe the classical Langevin theory of diamagnetic domain.
- 14. Distinguish between Ferri- and Ferromagnetic Materials

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Dielectric Properties of Materials: Polarization. Local Electric Field at an Atom. Depolarization Field. Electric Susceptibility. Polarizability. Clausius Mosotti Equation. Classical Theory of Electric Polarizability. Normal and Anomalous Dispersion. Cauchy and Sellmeir relations. Langevin-Debye equation. Complex Dielectric Constant. Optical Phenomena. Application: Plasma Oscillations, Plasma Frequency, Plasmons.

DIELECTRICS

Dielectric Constant

The dielectric constant measurement, also known as relative permittivity, is one of the most popular methods of evaluating insulators such as rubber, plastics, and powders. It is used to determine the ability of an insulator to store electrical energy. The complex dielectric constant consists of a real part (k'), which represents the storage capability and an imaginary part (D), which represents the loss.

Dielectric constant measurements can be performed easier and faster than chemical or physical analysis techniques making them an excellent material analysis tool. The dielectric constant is defined as the ratio of the capacitance of the material to the capacitance of air, or $k' = \frac{Cx}{Co}$ where C_x = capacitance with a dielectric material and C_o = capacitance without material, or vacuum. The k' value of dry air is 1.00053, which for most measurement applications is usually close enough to the value of a vacuum, which is 1.0000. Thus if a material is to be used for insulating purposes only, it would be better to have a lower dielectric constant, or as close to air as possible. To the contrary, if a material is to be used in electrical applications for storage of electrical charge, the higher the dielectric constant the better. More charge is stored when a dielectric is present than if no dielectric (air) is present. The dielectric material increases the storage capacity of the plate capacitor, hence the dielectric constant of any solid or liquid would be greater than 1.

Dielectric constants of common materials

 Vacuum
 1.0

 Air
 1.00053

 Pure Teflon
 2.047
Fused Quartz3.78Water78

Dissipation Factor

Dissipation factor (D) is defined as the ratio of an insulating materials resistance to its capacitive reactance at a specified frequency. It measures the inefficiency or loss of the material, is always greater than 0, but usually much smaller than the dielectric constant. D measurements are an excellent means of quality control which can yield indication of contamination or deterioration. For example, if we wanted to check the purity of epoxy or some raw material for consistency in a production run why not just measure the D. Excessive moisture would increase the dissipation factor value telling us something has changed as compared to previously established values.

A dielectric (or an insulator) is a material in which all the electrons are tightly bound to the nuclei of the atom. Ex: glass, mica, oil, plastic, etc.

Dielectric polarization

Basic atomic model



Electric field interaction with an atom under the classical dielectric model.

In the classical approach to the dielectric model, a material is made up of atoms. Each atom consists of a cloud of negative charge (Electrons) bound to and surrounding a

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positive point charge at its center. In the presence of an electric field the charge cloud is distorted, as shown in the top right of the figure.

This can be reduced to a simple dipole using the superposition principle. A dipole is characterized by its dipole moment, a vector quantity shown in the figure as the blue arrow labeled M. It is the relationship between the electric field and the dipole moment that gives rise to the behavior of the dielectric. (Note that the dipole moment is shown to be pointing in the same direction as the electric field. This isn't always correct, and it is a major simplification, but it is suitable for many materials.)

When the electric field is removed the atom returns to its original state. The time required to do so is the so-called relaxation time; an exponential decay.

This is the essence of the model in physics. The behavior of the dielectric now depends on the situation. The more complicated the situation the richer the model has to be in order to accurately describe the behavior.

The relationship between the electric field \mathbf{E} and the dipole moment \mathbf{M} gives rise to the behavior of the dielectric, which, for a given material, can be characterized by the function \mathbf{F} defined by the equation:

$$\mathbf{M} = \mathbf{F}(\mathbf{E})$$

When both the type of electric field and the type of material have been defined, one then chooses the simplest function F that correctly predicts the phenomena of interest. Examples of phenomena that can be so modeled include:

- Refractive index
- Group velocity dispersion
- Birefringence
- Self-focusing
- Harmonic generation

Dipolar polarization

Dipolar polarization is a polarization that is either inherent to polar molecules (**orientation polarization**), or can be induced in any molecule in which the asymmetric distortion of the nuclei is possible (**distortion polarization**). Orientation polarization results from a permanent dipole, e.g. that arising from the ca. 104 angle between the

asymmetric bonds between oxygen and hydrogen atoms in the water molecule, which retains polarization in the absence of an external electric field. The assembly of these dipoles forms a macroscopic polarization.

When an external electric field is applied, the distance between charges, which is related to chemical bonding, remains constant in orientation polarization; however, the polarization itself rotates. This rotation occurs on a timescale which depends on the torque and the surrounding local viscosity of the molecules. Because the rotation is not instantaneous, dipolar polarizations lose the response to electric fields at the lowest frequency in polarizations. A molecule rotates about 1ps per radian in a fluid, thus this loss occurs at about 10¹¹ Hz (in the microwave region). The delay of the response to the change of the electric field causes friction and heat.

When an external electric field is applied in the infrared, a molecule is bent and stretched by the field and the molecular moment changes in response. The molecular vibration frequency is approximately the inverse of the time taken for the molecule to bend, and the **distortion polarization** disappears above the infrared.

Ionic polarization

Ionic polarization is polarization which is caused by relative displacements between positive and negative ions in ionic crystals (for example, NaCl).

If crystals or molecules do not consist of only atoms of the same kind, the distribution of charges around an atom in the crystals or molecules leans to positive or negative. As a result, when lattice vibrations or molecular vibrations induce relative displacements of the atoms, the centers of positive and negative charges might be in different locations. These center positions are affected by the symmetry of the displacements. When the centers don't correspond, polarizations arise in molecules or crystals. This polarization is called **ionic polarization**.

Ionic polarization causes ferroelectric transition as well as dipolar polarization. The transition, which is caused by the order of the directional orientations of permanent dipoles along a particular direction, is called **order-disorder phase transition**. The transition which is caused by ionic polarizations in crystals is called **displacive phase transition**.

CLAUSIS- MOSOTTI RELATION

The polarization (P) of the dielectric is given by

$$P = \sum_{j} N_{j} p_{j} = \sum_{j} N_{j} E_{loc}(j)$$

Here, N_j is the concentration and j is the polarizability of atom j and E_{loc} (j) is the local

field at atom sites j. p_jis the dipole moment of the jth atom.

The total local field at a cubic site is given by Lorentz relation

$$E_{\text{local}} = E + 3 \in P$$

Here E is the macroscopic electric field.

P=(N_j j)(
$$E + 1/(3\varepsilon_1 0) P$$
)
P(($1 - \Sigma N_j \alpha_j$)/3 ε_0) = E N_j j

Thus, the dielectric susceptibility is given by,

$$=\frac{P}{\varepsilon_0 E}=\frac{\Sigma N_j \alpha_j}{\varepsilon_0} \left(\mathbf{1}-\frac{N_j \alpha_j}{3\varepsilon_0}\right)$$

Further, the dielectric constant,

$$\varepsilon_r = 1 + \chi_{e} = 1 + \frac{\Sigma N_j \alpha_j}{\varepsilon_0} \left(1 - \frac{N_j \alpha_j}{3\varepsilon_0} \right) = \frac{3\Sigma N_j \alpha_j}{3\varepsilon_0 - \Sigma N_j \alpha_j}$$

 $(\varepsilon_{1}r - 1))/(\varepsilon_{1}r + 2) = 1/(3\varepsilon_{1}0) [\Sigma N]_{1}j \alpha_{1}j$

Equ.(5) is called clausius-Mossotti relation

It relates the dielectric constant to the atomic polarizability provided the condition of cubic symmetry holds.

LOCAL ELECTRIC FIELD

The value of a local electric field E_{local} that acts aas site of an atom is not the same as the macroscopic average electric field E. Consider the local field at a site with the cubic arrangement of a neighbors in a crystal of a spherical shape. The macroscopic electric field in a sphere is

$$\mathbf{E} = \mathbf{E}_0 + \mathbf{E}_1 = \mathbf{E}_{-} \frac{\mathbf{1}}{\mathbf{3}\boldsymbol{\epsilon}_0} \mathbf{P}$$

But consider the field that act on the atom at the centre of the sphere. Let all the dipoles be parallel to the Z-axis and have the magnitude P. Then, the Z component of the field at the centre due to all other dipole is

$$E_{\text{diople}} = p/4\pi\epsilon \sum_{i} i \equiv \Box (3\Box z_{i}i^{\dagger}2 - r_{\downarrow}i^{\uparrow}2)/r_{i}^{5} = \frac{p}{4\pi\epsilon} \sum_{i} \frac{2z_{i}^{2}x_{i}^{2}y_{i}^{2}}{r_{i}^{5}}$$

Here, p is the magnitude of an atomic dipole moment and i's referred to different atoms.

The x,y,z directions are equivalent because of the symmetry of the lattice and of the sphere. Thus

$$\sum_{i} \frac{z_{i}^{2}}{r_{i}^{5}} = \sum_{i} \frac{x_{i}^{2}}{r_{i}^{5}} = \sum_{i} \frac{y_{i}^{2}}{r_{i}^{5}}$$

 $E_{dipole} = 0$

The correct local field is just equal to the applied field, $E_{local} = E_0$, for an atom site with the cubic environment in a spherical specimen. Thus the local field is not the same as the macroscopic field E.

We now develop an expression for the local field at a general lattice site, not necessary of a cubic symmetry. The local field at an atom is the sum of electric field E_0 . From external sources and of the field from the dipole within the specimen.

$$E_{local} = E_0 + E_1 + E_2 + E_3$$

Here,

 E_0 =Field produced by fixed charges external to the body

 E_1 = depolarization field, from a source charge density \hat{n} .P on the outer surface of the specimen,

 E_2 = Lorentz cavity field: field from polarization charges on inside of spherical cavity cut out of the specimen with the reference atom as center.

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 E_3 = Field of atom inside a spherical cavity.



Let us now calculate the total local field acting on an atom in a cubic site of a dielectric. E_1 : The value of this field depends on the geometrical shape of the external surface.

For sphere,
$$E_1 = -\frac{1}{3\varepsilon_0}P$$
.

Lorentz field,E2

The field E_2 due to the polarization charges on the surface of the fictitious cavity was calculated by Lorentz.

Let be a polar angle referred to the polarization direction.

The surface charge density on the surface of the cavity is $-P \cos$.



The area of ring- shaped element is 2 $a^2 \sin d$. Hence charge on this ring is P cos .2 $a^2 \sin d$

The electric field at the center of the spherical cavity of the radius a is

$$E2 = \int_{0}^{\pi} \frac{1}{4\pi\epsilon_{0}} (a^{-2}) (2 \ a^{2} \sin \ d) (P \cos \) (\cos \) = P/3 \epsilon_{0}$$

This is the negative of the depolarization field E_1 in a polarized sphere.

Dr. S. KARUPPUSAMY Department of Physics Karpagam Academy of Higher Education Page 7 of 14 Coimbatore-21 Therefore, $E_1+E_2 = 0$ for a sphere.

i) Field of Dipole cavity, E₃

The field E_3 due to the dipole within the spherical cavity is the only terms that depends on the crystal structure. Cubic surroundings in a sphere $E_3 = 0$, if all the atoms may be replaced by a point dipoles parallel to each other.

The total local field at a cubic site is, from equ. (3) and (4)

 $E_{\text{local}} = E_0 + E_1 + P/3 \epsilon_0 = E + \frac{1}{3\epsilon_0} P.$ Equ(5) is the Lorentz Equation.

Sellmeier Formula

For the specification of a wavelength-dependent refractive index of a transparent optical material, it is common to use a so-called Sellmeier formula [1] (also calledSellmeier equation or Sellmeier dispersion formula, after Wolfgang von Sellmeier). This is typically of the form with the coefficients A_j and B_j . That form results from a relatively simple physical model, which is applicable only to the wavelength region where the absorption is negligible. As an example, the refractive index of fused silica can be calculated as [2] where the wavelength in micrometers has to be inserted. The Sellmeier coefficients are usually obtained by a least-square fitting procedure, applied to refractive indices measured in a wide wavelength range.

Applications

Such equations are very useful, as they make it possible to describe fairly accurately the refractive index in a wide wavelength range with only a few so-called Sellmeier coefficients, which are usually obtained from measured data with some leastsquare fitting algorithm. Sellmeier coefficients for many optical materials are available in databases. Some caution is advisable when applying Sellmeier equations in extreme wavelength regions; unfortunately, the validity range of available data is often not indicated. Sellmeier data are also very useful for evaluating the chromatic dispersion of a material. This involves frequency derivatives, which can be performed analytically with Sellmeier data even for high orders of dispersion, whereas numerical differentiation on the basis of tabulated index data is sensitive to noise.

Another frequent application of Sellmeier data is the calculation of phasematchingconfigurations for nonlinear frequency conversion. Here, it is often critical to have Sellmeier data which are valid in a wide wavelength range.

Modified Equations

The literature contains a great variety of modified equations which are also often called Sellmeier formulas. Extensions to the simple form give above can enlarge the wavelength range of validity, or make it possible to include the temperature dependence of refractive indices. This can be important, for example, for calculating phase-matching configurations for nonlinear frequency conversion.

Alternatives to Sellmeier Equations

There are various other kinds of equations for refractive indices. For example, there is the old Cauchy formula, which is a bit simpler than the Sellmeier formula and still fits the refractive indices of many materials in the visible spectral region quite well, as long as the material has no absorption in the visible region. In the near infrared, however, substantially higher accuracy is achieved with the Sellmeier formula.

Cauchy's relation

Thickness measurements are not independent of the optical constants. The film thickness affects the path length of light traveling through the film, but the index determines the light waves' velocity and refracted angle. Thus, both contribute to the delay between surface reflection and light traveling through the film. Both n and k must be known or determined along with the thickness to get the correct results from an optical measurement.

The optical constants for a material will vary for different wavelengths and must be described at all wavelengths probed with the ellipsometer. A table of optical constants

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can be used to predict the material's response at each wavelength. However, it is not very convenient to adjust unknown optical constants on a wavelength-by-wavelength basis. It is more advantageous to use all wavelengths simultaneously. A dispersion relationship often solves this problem, by describing the optical constant shape versus wavelength. The adjustable parameters of the dispersion relationship allow the overall optical constant shape to match the experimental results. Compared to fitting individual n, k values at every wavelength, this greatly reduces the number of unknown "free" parameters. For transparent materials, the index is often described using the Cauchy or Sellmeier relationship. The Cauchy relationship is typically given as: where the three terms are adjusted to match the refractive index for the material. The Cauchy is not constrained by KK consistency and can produce unphysical dispersion. The Sellmeier relationship enforces Kramers-Kronig (KK) consistency, which ensures that the optical dispersion retains a realistic shape. The Sellmeier relationship can be written as:

Absorbing materials will often have a transparent wavelength region that can be modeled with the Cauchy or Sellmeier. However, the absorbing region must account for both real and imaginary optical constants. Many dispersion relationships use oscillator theory to describe absorption for various materials. These include the Lorentz, Harmonic, and Gaussian oscillators. They all share similar attributes, where the absorption features are described with an Amplitude, Broadening, and Center Energy (related to frequency of light). Kramers-Kronig consistency is used to calculate the shape of the real component after the imaginary behavior is described by the oscillator. An offset to the real component is added to account for extra absorption outside the measured spectral region. The Lorentz oscillator can be written as: where the parameters for Amplitude (A), Broadening (B), Center Energy (Ec), and offset (e1, off set) are also shown in Figure 13 for a typical Lorentz oscillator. The energy, E, is related to the frequency of a wave, n:

where h is Planck's constant and the wavelength, l, is given in nanometers. More advanced dispersion models, like the Tauc-Lorentz and Cody-Lorentz, will include terms to describe the bandgap energy.

Complex dielectric permittivity and Maxwell equations

Dr. S. KARUPPUSAMY K Department of Physics In case of dielectric polarization, the polarization of the material is related to the electric field by:

$$P = {}_{0 e}E$$

This leads to: D = 0(1 + e)E = 0 r E

For real materials D can be described as= D=(-j)E

Here, $=_0$ r, the real part of permittivity, and $r=_0$ " is a factor describing the dielectric (polarization) losses.

Here, is the conductivity of the material. Substituting for D from equation, so the equation becomes: $\nabla \times H = i (-i(p + /))E$

The complex dielectric constant is defined as below: *= -i(p + /)

Here, is the real part of the permittivity and is defined as: or $= r_0$

Here _r is known as the relative permittivity or dielectric constant and 0 is the permittivity of free space. Here the first and second term in the imaginary part of the complex permittivity represent the dielectric and ohmic losses respectively. The loss tangent is given as: tan $\delta = "/$ "

In this thesis r is used throughout to represent relative permittivity of the materials and tan is used to represent a measure for the dielectric loss.

Plasma oscillations

In the analysis of the Debye screening the plasma was assumed to be in the equilibrium, that is, the plasma charges were not moving (except for the fast random motion which is averaged out). Thus, the screening is an example of the static collective behavior. Here we are going to study an example of the dynamic collective behavior. Let us assume that the plasma consists of freely moving electrons and an immobile neutralizing background. Let the charge of the electron be q, mass m, and density n. Let us assume that, for some reason, all electrons, which were in the half-space x > 0, move to the distance d to the right, leaving a layer of the nonneutralized background with the charge density = -nq and width d. The electric field, produced by this layer on the electrons on both edges is E = 2 d = -2 nqd (for the electrons at the right edge) and E = 2 d = 2 nqd (for the electrons at the left edge). The force F = qE = -2 nq2d accelerates

the electrons at the right edge to the left, while the electrons at the left edge experience similar acceleration to the right. The relative acceleration of the electrons at the right and left edges would be a = 2(qE/m) = -4 nq2d/m. On the other hand, a = d, so that one has

d = -2 pd, 2 p = 4 nq2/m

The derived equation describes oscillations with the plasma frequency p. It should be emphasized that the motion is caused by the coordinated movement of many particles together and is thus a purely collective effect. In order to be able to observe these oscillations their period should be much smaller than the typical life time of the system.

Plasma Frequency

The plasma frequency, is the most fundamental time-scale in plasma physics. Clearly, there is a different plasma frequency for each species. However, the relatively fast electron frequency is, by far, the most important, and references to ``the plasma frequency" in text-books invariably mean the *electron* plasma frequency.

$$\omega_p^2 = \frac{ne^2}{\epsilon_0 m},$$

It is easily seen that $\omega_{\mathbf{p}}$ corresponds to the typical electrostatic oscillation frequency of a given species in response to a small charge separation. For instance, consider a onedimensional situation in which a slab consisting entirely of one charge species is displaced from its quasi-neutral position by an infinitesimal distance $\delta \mathbf{x}$. The resulting charge density which develops on the leading face of the slab is $\mathbf{\sigma} = \mathbf{e} \mathbf{n} \, \delta \mathbf{x}$. An equal and opposite charge density develops on the opposite face. The \mathbf{x} -directed electric field generated inside the slab is of magnitude $\mathbf{E}_{\mathbf{x}} = -\mathbf{\sigma}/\mathbf{e}_{\mathbf{0}} = -\mathbf{e} \mathbf{n} \, \delta \mathbf{x}/\mathbf{e}_{\mathbf{0}}$. Thus, Newton's law applied to an individual particle inside the slab yields

$$m\frac{d^{2}\delta x}{dt^{2}} = eE_{x} = -m\omega_{p}^{2}\delta x,$$

$$\delta x = [\delta x]_{0}\cos[\omega_{p}t]$$

Dr. S. KARUPPUSAMY Department of Physics Karpagam Academy of Higher Education Page **12** of **14** Coimbatore-21 Note that plasma oscillations will only be observed if the plasma system is studied over time periods τ longer than the plasma period $\tau_p \equiv 1/\omega_p$, and if external actions change the system at a rate no faster than ω_p . In the opposite case, one is clearly studying something other than plasma physics (*e.g.*, nuclear reactions), and the system cannot not usefully be considered to be a plasma. Likewise, observations over lengthscales L shorter than the distance $\nu_t \tau_p$ traveled by a typical plasma particle during a plasma period will also not detect plasma behavior. In this case, particles will exit the system before completing a plasma oscillation. This distance, which is the spatial equivalent to τ_p is called the *Debye length*, and takes the form

$$\lambda_{\rm D} \equiv \sqrt{T/m} \ \omega_{\rm p}^{-1}$$

Note that

$$\lambda_{\rm D} = \sqrt{\frac{\epsilon_0 \, \mathrm{T}}{\mathrm{n} \, \mathrm{e}^2}}$$

is independent of mass, and therefore generally comparable for different species. Clearly, our idealized system can only usefully be considered to be a plasma provided that

$$\frac{\lambda_D}{L} \ll 1$$
,

and

$$\frac{\tau_p}{\tau} \ll 1.$$

Here, τ and L represent the typical time-scale and length-scale of the process under investigation.

It should be noted that, despite the conventional requirement, plasma physics *is* capable of considering structures on the Debye scale. The most important example of this is the Debye sheath: *i.e.*, the boundary layer which surrounds a plasma confined by a material surface.

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POSSIBLE QUESTIONS

2 Mark

- 1. Define electrical susceptibility.
- 2. What is the polarization.
- 3. What is Plasma Oscillations and Plasmons.
- 4. Write a note on dielectric materials?
- 5. What is Anomalous Dispersion?
- 6. Define dielectric constant
- 7. Define dielectric Loss.

6 Mark

- 8. Deduce mathematical expressions for Cauchy and Sellmeir relations.
- 9. Discuss about the Dielectric materials, Dielectric constant and dielectric loss.
- 10. Explain local field?
- 11. Derive the expression for Clausius - Mosotti Equation.
- 12. Explain the classical theory of electric polarizability
- 13. Explain the concept of Complex Dielectric Constant.
- 14. Discuss in detail about Electronic polarization.
- 15. Derive the expression for Langevin-Debye equation.
- 16. Explain Depolarization Field and Classical Theory of Electric Polarizability

Unit V Elementary band theory

$\mathbf{UNIT} - \mathbf{V}$

Elementary band theory: Kronig Penny model. Band Gaps. Conductors, Semiconductors and insulators. P and N type Semiconductors. Conductivity of Semiconductors, mobility, Hall Effect, Hall coefficient. Superconductivity: Experimental Results. Critical Temperature. Critical magnetic field. Meissner effect. Type I and type II Superconductors.

Introduction to Band Structure

In our studies of atoms and molecules we have seen that molecular orbitals are formed by the interaction of atomic orbitals. In molecular orbitals of H₂ for example, the binding orbital σ_s is separated from the antibonding orbital σ_s^* by several electron-Volts (1eV = 23.06 kcal / mol). When three orbitals from three atoms (as in the case of H₃) combine to form MOs, we get three orbitals (σ_s , σ_n and σ_s^*), a bonding, a nonbonding and an antibonding orbital. When N atomic orbitals from N atoms interact, they give N molecular orbitals. When N becomes very large, as in the case of a solid, there will be a large number of orbitals in a given range of energy. This collection of orbitals or energy levels is referred to as an (energy) band. The study of band structure forms a central theme in the study of electronic structure of solids.

Kronig-Penney model

The Kronig-Penney model [1] is a simplified model for an electron in a onedimensional periodic potential. The possible states that the electron can occupy are determined by the Schrödinger equation,

$$\frac{-\hbar^2}{2m}\frac{d^2\psi}{dx^2}+V(x)\psi=E\psi.$$

In the case of the Kroning-Penney model, the potential V(x) is a periodic square wave.



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A virtue of this model is that it is possible to analytically determine the energy eigenvalues and eigenfunctions. It is also possible to find analytic expressions for the dispersion relation (E vs. k) and the electron density of states. [2] Derivations are given below.

This form can be used to plot the dispersion relation and the density of states for the Kronig Penney model.

Solution of the Schrödinger equation for the Kronig-Penney potential

Since the Kronig-Penney potential exhibits translational symmetry, the energy eigenfunctions of the Schrödinger equation will simultaneously be eigenfunctions of the translation operator. As we often do in solid state physics, we proceed by seeking the eigenfunctions of the translation operator. The translation operator T shifts the solutions by one period, T(x) = (x + a). Notice that any function of the form,

$$\psi_k(x) = e^{ikx} u_k(x),$$

is an eigenfunction of the translation operator with eigenvalue e^{ika} .

$$T\Psi(x) = e^{ik(x+a)}u_k(x+a) = e^{ika}\Psi(x).$$

In solid state physics, functions like this are said to have Bloch form. The convention for describing electron waves in a periodic medium is to express them in terms of the eigenfunctions of the translation operator. These eigenfunctions have a well defined frequency and form a complete set that can be used to describe any wave. An eigenfunction is specified by the k that appears in the expression for the eigenvalue. It turns out that the physical interpretation of k is nearly the same as the wave number of harmonic waves (usually also called k).

The eigenfunctions of the translation operator can be readily constructed from any two linearly independent solutions of the one-dimensional Schrödinger equation. A convenient choice is,

$$\psi_1(0) = 1, \qquad \frac{d\psi_1}{dx}(0) = 0, \qquad \psi_2(0) = 0, \qquad \frac{d\psi_2}{dx}(0) = 1.$$

The solutions in region 1 (0 < x < b) are,

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$$\psi_1(x) = \cos(k_1 x), \qquad \qquad \psi_2(x) = \frac{\sin(k_1 x)}{k_1},$$

while the solutions in region 2 (b < x < a) are,

$$\psi_1(x) = \cos(k_2(x-b))\cos(k_1b) - \frac{k_1\sin(k_2(x-b))\sin(k_1b)}{k_2},$$

$$\psi_2(x) = \frac{\cos(k_2(x-b))\sin(k_1b)}{k_1} + \frac{\sin(k_2(x-b))\cos(k_1b)}{k_2}.$$

Here

$$k_1 = \sqrt{2m(E - V_1)/\hbar^2}$$
 and $k_2 = \sqrt{2m(E - V_2)/\hbar^2}$

For energies where k_1 or k_2 are imaginary, the solutions are still real since $\cos(i) = \cosh()$ and $\sin(i) = i\sinh()$.

Any other solution can be written as a linear combination of $_1(x)$ and $_2(x)$. In particular, $_1(x + a)$ and $_2(x + a)$ can be written in terms of $_1(x)$ and $_2(x)$. These solutions are related to each other by the matrix representation of the translation operator. [3]

$$\begin{bmatrix} \boldsymbol{\psi}_1(x+a) \\ \boldsymbol{\psi}_2(x+a) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{\psi}_1(x) \\ \boldsymbol{\psi}_2(x) \end{bmatrix}.$$

The elements of the translation matrix can be determined by evaluating the equation above and its derivative at x = 0.

$$\begin{bmatrix} \boldsymbol{\psi}_1(x+a) \\ \boldsymbol{\psi}_2(x+a) \end{bmatrix} = \begin{bmatrix} \boldsymbol{\psi}_1(a) & \frac{d\boldsymbol{\psi}_1}{dx}(a) \\ \boldsymbol{\psi}_2(a) & \frac{d\boldsymbol{\psi}_2}{dx}(a) \end{bmatrix} \begin{bmatrix} \boldsymbol{\psi}_1(x) \\ \boldsymbol{\psi}_2(x) \end{bmatrix}.$$

The eigenfunctions and eigenvalues of this 2×2 matrix are easily determined to be,

$$\psi_{\pm}(x) = \frac{2\psi_2(a)}{\frac{d\psi_2(a)}{dx} - \psi_1(a) \pm \delta} \psi_1(x) + \psi_2(x), \qquad \lambda_{\pm} = \frac{1}{2} (\alpha \pm \delta),$$

where

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$$\delta = \sqrt{\alpha^2 - 4}$$

and

$$\alpha = \psi_1(a) + \frac{d\psi_2(a)}{dx} = 2\cos(k_2(a-b))\cos(k_1b) - \left(\frac{k_2}{k_1} + \frac{k_1}{k_2}\right)\sin(k_2(a-b))\sin(k_1b).$$

If periodic boundary conditions are used for a potential with N unit cells, then applying the translation operator N times brings the function back to its original position,

$$T^{N}\psi(x) = \psi(x + Na) = \lambda^{N}\psi(x) = \psi(x).$$

The eigenvalues of the translation operator are therefore the solutions to the equation $^{N} = 1$. These solutions are,

$$\lambda_{j} = \exp(i2\pi j/N) = \exp(i2\pi a j/L) = \exp(ik_{j}a)$$

where *j* is an integer between -N/2 and N/2, L = Na is the length of the crystal, and $k_j = 2 \ j/L$ are the allowed *k* values in the first Brillouin zone. The dispersion relation can be determined by first calculating for a specific energy, solving for the eigenvalues and then solving the equation above for the wavenumber *k*,

$$k = \pm \frac{1}{a} \tan^{-1} \left(\frac{\sqrt{4 - \alpha^2}}{\alpha} \right).$$

Whether the eigenvalues are real or imaginary depends on the magnitude of \therefore If $^2 > 4$, the eigenvalues will be real and the solutions fall in a forbidden energy gap. If $^2 < 4$, the eigenvalues will be a complex conjugate pair $_+ = e^{ika}$ and $_- = e^{-ika}$.

P and N type Semiconductors

p-n junction diodes are made up of two adjacent pieces of p-type and n-type semiconducting materials. p-type and n-type materials are simply semiconductors, such as silicon (Si) or germanium (Ge), with atomic impurities; the type of impurity present determines the type of the semiconductor. The process of purposefully adding impurities to materials is called doping; semiconductors with impurities are referred to as "doped semiconductors".

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p-type

In a pure (intrinsic) Si or Ge semiconductor, each nucleus uses its four valence electrons to form four covalent bonds with its neighbors (see figure below). Each ionic core, consisting of the nucleus and non-valent electrons, has a net charge of +4, and is surrounded by 4 valence electrons. Since there are no excess electrons or holes In this case, the number of electrons and holes present at any given time will always be equal.



An intrinsic semiconductor. Note each +4 ion is surrounded by four electrons.

Now, if one of the atoms in the semiconductor lattice is replaced by an element with three valence electrons, such as a Group 3 element like Boron (B) or Gallium (Ga), the electronhole balance will be changed. This impurity will only be able to contribute three valence electrons to the lattice, therefore leaving one excess hole (see figure below). Since holes will "accept" free electrons, a Group 3 impurity is also called an acceptor.



A semiconductor doped with an acceptor. An excess hole is now present.

Because an acceptor donates excess holes, which are considered to be positively charged, a semiconductor that has been doped with an acceptor is called a p-type semiconductor; "p" stands for positive. Notice that the material as a whole remains electrically neutral. In Dr. S. KARUPPUSAMY Department of Physics Karpagam Academy of Higher Education Coimbatore-21

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a p-type semiconductor, current is largely carried by the holes, which outnumber the free electrons. In this case, the holes are the majority carriers, while the electrons are the minority carriers.

n-type

In addition to replacing one of the lattice atoms with a Group 3 atom, we can also replace it by an atom with five valence electrons, such as the Group 5 atoms arsenic (As) or phosphorus (P). In this case, the impurity adds five valence electrons to the lattice where it can only hold four. This means that there is now one excess electron in the lattice (see figure below). Because it donates an electron, a Group 5 impurity is called a donor. Note that the material remains electrically neutral.



A semiconductor doped with a donor. A free electron is now present.

Donor impurities donate negatively charged electrons to the lattice, so a semiconductor that has been doped with a donor is called an n-type semiconductor; "n" stands for negative. Free electrons outnumber holes in an n-type material, so the electrons are the majority carriers and holes are the minority carriers.

Difference between semiconductors, conductors, and insulators depending upon their energy bands

Metals are good conductors of electricity. Insulators are bad conductors of electricity. Similarly, semiconductor devices are partial conductors of electricity means their conductivity lies between conductors and insulators.

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Fermi level is the energy level taken up by an electron at the temperature range of zero Kelvin. So, at the temperature of zero Kelvin the energy levels which are lower than i.e. below the Fermi level are filled completely by electrons. When we will provide energy to the electrons then they will absorb energy one by one and will excite to higher energy levels. This is clear that the electrons which are present at larger distances from the nucleus will not be much affected by the stronger nuclear forces. So, in other words we can say that these electrons are relatively free as compared to the other electrons. The classification of these materials as solids, metals and insulators is according to the positioning of the conduction as well as the valence bands.

Metals: In case of metals, electrons fill the conduction band partially. The overlapping of both the bands i.e. valence and conduction band also take place. This shows that no forbidden energy gap is present. The diagram is shown below:

Those electrons which are present below the fermi level are capable of gaining energy from some outer source and can shift to the higher energy levels above the Fermi level i.e. in the conduction band. Then these electrons will behave as free electrons. Due to the presence of these free electrons the metals behave as good conductor of electricity. When small amount of electric field is applied to the metals then the electron movement will start in the direction opposite to that of the electric field. This electron movement results in the generation of the current.

Insulators: In case of insulators the forbidden energy gap is extremely high as compared to the conductors. On the other hand its valence band is fully filled with the electrons, whereas its conduction band is empty. Let's take example of diamond. The approximate value of forbidden energy gap for diamond is nearly 6eV. As we have discussed above that the valence band is filled fully with electrons. Using the concept of Pauli's exclusion principle, no electrons will be free. So, electrons will not be able to reach the conduction band. Hence these materials act as insulators due to the absence of electrical conductance.

Semiconductors: In case of semiconductors the conduction band is empty and the valence band is fully filled with electrons. Like insulators, forbidden energy gap is not so large in case of semiconductors. The energy gap is very small. This energy gap is nearly of 1eV. For different products this energy gap is different. E.g. For silicon and germanium this energy gap is nearly 1.1eV and 0.72eV respectively.

If the temperature will be zero Kelvin then it is impossible for the electrons to cover this energy gap of 1eV. No electron will jump to the conduction band. Hence no conductivity will take

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place. It is clear that at the temperature range of zero Kelvin these substances act as insulators. But if these substances are placed at room temperature then the electrons will gain some amount of thermal energy and will shift to the conduction band. When these electrons reach the conduction band then these are free to move. Then they will start showing conductivity when some electric field is applied.

Hall Effect

The Hall Effect is a physical effect named after Edwin Hall, an American physicist who discovered that when the path of electrons running through a semiconductor was deflected by a magnetic field, a potential difference was induced perpendicular to the direction of the current. In 1985 (over 100 years after Hall's discovery), a German physicist, Klaus von Klitzing was awarded a Nobel Prize for his work with the quantized Hall Effect. The Hall Effect is the working mechanism in a wide range of devices and applications including the gauss meter, ammeters, tachometers, spectrum analyzers, paintball guns, and many more electronic devices.

The following diagram shows the basic theoretical description of the Hall Effect. If a current I in a slab of conducting material runs in the x direction through an applied magnetic field B, it will be deflected due to the magnetic force on the moving charges. Depending on whether the charge is positive or negative, the charges will build up on either face 3 or face 4 of the slab. This charge buildup causes an electrostatic potential difference between faces 3 and 4, and is referred to as the Hall voltage, VH. The Hall resistance is the ratio of VH / I, and is observed to increase as the applied magnetic field is increased.



Figure 1. Geometry for measuring the Hall voltage for a semiconductor in a magnetic field.

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Measuring the Hall effect is useful in determining many things, including the type of the semiconductor (p-type or n-type), the charge of the carriers, the concentration, mobility, and band structure of the material.

SUPERCONDUCTIVITY

Superconductivity was first observed in 1911 by the Dutch physicist H.K. Onnes in the course of his experiments on the electrical conductivities of metals at low temperatures. He observed that as purified mercury is cooled its resistivity vanished abruptly at 4.2 K. Above this temperature, the resistivity is small but finite, while the resistivity below this point is so small it is essentially zero. The temperature at which the transition takes place is called the critical temperature (T_c). The temperature (T_c) which marks the transition of a normal conductor to the superconducting state, is defined as the transition temperature. Above the critical temperature (T_c), the substance is in the familiar *normal state*, but below (T_c) it enters an entirely different *superconducting state*. The superconducting state is marked by a sudden fall of the electrical resistivity of the material to nearly zero, when it is cooled to a sufficiently low temperature.



The resistivity of a metal may be written as $\rho = \frac{m}{ne^2 \tau}$ where m= mass of the electron, e= charge of the electron n=No. of electrons per unit volume and = collision time. The vibration of the ions in a crystal decreases with decreasing temperature. This has the effect of decreasing the probability of an electron-ion collision or of increasing the collision time τ . Thus decreases as the temperature is lowered. According to the above equation, this implies that the resistivity of a metal should tend towards zero, as the temperature zero. If τ becomes infinite at sufficient low temperatures, then the resistivity vanishes entirely, which is what is observed in superconductivity.

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Unit V Elementary band theory

As the temperature is lowered below T_c , fraction of the electron becomes superconducting, in the sense that they have infinite collisions. These electrons undergo no scattering whats oever, eventhough the substance may contain some impurities and defects. It is these electrons which are responsible for superconductivity.

Onnes found that the superconducting transition is *reversible*:

When heated the superconducting sample, its normal resistivity at the Temperature T_c.

Superconductivity appears in metallic elements (silver, lead, etc) of the periodic system and also in alloys and semiconductors. The range of transition temperature at present extends from 23.2K for the alloy Nb₃, Ge₂ to 0.01 K for some semiconductors.

ISOTOPE EFFECT

The critical temperature of superconductors varies with isotopic mass. In mercury, T_c varies from 4.185 K to 4.16K as the average atomic mass M varies from 199.5 to 203.4 atomic mass unit. The experimental results within each series of isotopes may be fitted by a relation of the form M^aT_c = constant. Here is a number usually 0.2. From the dependence of T_c and the isotopic mass M, lattice vibration and the electron-lattice interactions are deeply involved in superconductivity which can studied.

PERSISTENT CURRENTS

If a superconductor has the form of ring, current can be induced in it by electromagnetic induction. One usually measures the resistivity of a superconductor by observing this current as a function of time. If the sample is in the normal state, the current damps out quickly because of the resistance of the ring. But if the ring has zero resistance, the current, once set up, flows indefinitely without any decrease in value. In a typical experiment, a lead ring could carry an induced current of several hundred years without any change. Such currents are called "*Persistent Current*". Physicists found that the upper limit for the superconducting lead ring was about 10^{-25} ohm-m. The fact that this is about $1/10^{17}$ as large at a room temperature does indeed justify taking =0 for the superconducting state.

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Unit V Elementary band theory

EFFECTS OF SUPERCONDUCTIVITY BY MAGNETIC FIELD

Superconductivity can be destroyed by the application of a magnetic field. If a strong enough magnetic field, called the *Critical Field*, is applied to a superconducting specimen, it becomes normal and recovers its normal resistivity even at T<T_c. The critical value of the applied magnetic field for the destruction of superconductivity is denoted by H_c (T) and is a function of the temperature. For a given substance, value of H_c decreases as the temperature increases from T=0K to T=T_c. The variation can be represented by the formula H_c (T) =H_c(0) [1-(T/T_c)²]

where H_c (0) is the critical field at 0K. Thus the field has its maximum value, H_c (0) at T=0K. At the critical temperature(T_c) the critical field is zero: $H_c(T_c)=0$. This result is expected because at T=T_c the specimen is already normal, and no field is necessary to accomplish the transition. A specimen is superconducting below the curve and normal above the curve.



MEISSNER EFFECT

Meissner and Ochsenfeld found that if a superconductors is cooled in a magnetic field to below the transition temperature, then at the transition, the lines of induction B are pushed out.

The expulsion of magnetic flux from the interior of a piece of superconducting material as the material undergoes the transition to the superconducting phase is known as Meissner effect. In a series of experiments on superconducting cylinders, they Dr. S. KARUPPUSAMY Karpagam Academy of Higher Education Page **11** of **22** Department of Physics Coimbatore-21

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demonstrated that, as the temperature is lowered to T_c , the flux is suddenly and completely expelled, as the specimen becomes superconducting. The flux expulsion continues for all $T < T_c$. They establish this by carefully measuring the magnetic field in the neighborhood of the specimen. Further, they demonstrated that the effect is *reversible*: When the temperature is raised from below T_c , the flux suddenly penetrates the specimen after it reaches T_c and the substance is in the normal state.



A bulk superconductor behaves in an external magnetic field as if inside the specimen $B=\mu_0 (H+M)=\mu_0 (1+)H=0$

Here M-Magnetization in the medium and its magnetic susceptibility.

Hence = -1 i.e., superconductor exhibits *perfect diamagnetism*.

BCS Theory

The modern theory of superconductivity was promulgated by Bardeen, Cooper and Schrieffer in 1957. It had as its major feature the paring of electrons. Starting from first principles, and employing a completely quantum treatment, the BCS theory explains the various observable effects, such as zero resistance, the Meissner effects, etc. In an ordinary metal the electrical resistance is the result of conduction electrons with the vibrating ions

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in the crystal lattice. In the superconducting state, the forces of attraction between the conduction electrons exceed the force of electrostatic repulsion.

Cooper pair: Normally 2 electrons repel each other, because of coulomb interaction. Suppose that, for some reason, the two electron attract each other, Cooper shows that the two electrons would than form a bound state. This is very important, because in a bound state electrons are pair to form a single system, and their motions are correlated. The pairing can be broken if an amount of energy equal to the binding energy is applied to the system. This pair of electron is called a Cooper Pair. At temperature $T < T_c$, the lattice-electron interaction is stronger than electron-electron force of coulomb. At this stage, the cooper pair of electrons have a peculiar property sailing over the lattice point without any energy exchange i.e., the cooper pair are not scattered by the lattice point. Hence no transfer of energy takes place from the electron pair to the lattice ions. If an electric field is established inside the substance, the electrons gain an additional kinetic energy and give rise to current. But they do not transfer this energy to the lattice, so that they do not gets slowed down. As a consequence of this the substance does not possess any electrical resistivity. So BCS theory explains the zero resistivity of the superconductor. The cooper pair of electrons can maintain the coupled motion upto a certain distance among the lattice points in a superconductor called coherence length. This is found to be order of 10^{-6} m.

In super-conductive materials, it results from the electron-lattice interaction. Suppose that the two electrons, 1 and 2 pass each other. Because electron 1 is negatively charged, it attract positive ion toward itself. Thus electron 2 does not see the bare electron 1. Electron 1 is screened by ions. The screening may greatly reduce the effective charge of this electron. In fact, the ions may over respond and produce a net positive charge. If this happens, then electron 2 will be attracted toward electron 1. This leads to a net attractive interaction, as required for the formation of Cooper pair. In technical literature one says that each electron is surrounded by a "Phonon cloud", and that the two electron establish an attractive interactions by exchanging phonons: for example, electron1 emits phonons which are very quickly absorbed by electron 2.

TYPES OF SUPERCONDUCTORS

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The superconductors can be classified into two distinct groups according to their behavior in external magnetic field.

Type I Superconductors

The superconductors, in which the magnetic field is totally excluded from the interior of superconductors below a certain magnetizing field H_c , and at H_c the material loses superconductivity and the magnetizing field penetrates fully are termed as type I or soft superconductors.

Ex: Tin, lead, Aluminum, Mercury, Zinc, Magnesium, Etc. The magnetization curve for type I super-conducting material is given below:



The important characteristics of type I superconductors are:

- i) They exhibit complete Meissner effect.
- ii) The critical values of magnetic field H_c at which magnetization drops are very low. The maximum known critical field for type I superconductor is of the order of 0.1T. The low value of H_c makes these materials unsuitable for use in high field superconducting magnets.

The magnetization curve shows that transition at H_c is reversible. This means that if the magnetic field is reduced below H_c , the material again acquires superconducting property and the field is expelled.

iii) Below H_c the material is superconductor and above H_c it becomes a conductor.

Type II superconductors

The superconductors in which the material loses magnetization gradually rather than suddenly are termed as type II or hard superconductors.



The important characteristics are:

- i) They donot show complete Meissner effect.
- ii) These superconductors have two critical fields: H_{c1} and H_{c2} . The specimen is diamagnetic below H_{c1} i.e., the magnetic field is completely excluded below H_{c1} . At H_{c1} the flux begins to penetrate the specimen, and the penetration of flux increases until the upper critical field H_{C2} is reached. At H_{C2} the magnetization vanishes and specimen returns to normal conducting state. The value of critical field for type II materials may be 100 times or more higher than the values of H_c for type I superconductors. Critical fields H_{c2} upto 30 T have been observed.

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The materials which display type II behavior are essentially inhomogeneous and include Nb-Zr, Nb-Ti alloys and Va-Ga and Nb-Sn inter-metallic compounds. These are technically more useful than type I superconductors due to tolerating high magnetic fields.

APPLICATIONS OF SUPERCONDUCTORS

There are many applications of superconductivity.

- i) One is in the construction of superconducting electromagnets that carry large resistance less currents and, therefore produce large magnetic fields (5-10 Tesla). If superconducting wire for magnet windings are used, currents of the order of 100 amperes can be carried by very fine wires. Thus small-size magnets can be constructed. In which a superconducting coil immersed in liquid helium (4K). Starting from zero, the current is increased until the magnetic field B reaches the desired value. At that point the switch is closed. The current now flows through the switch. The power supply is then turned off. The current will continue to flow through the coil indefinitely without resistive losses.
- Superconducting cables can be used to transmit electric power over long distance without resistive losses. This is possible only if the cost of keeping the cable below its critical temperature is less than the value of the power lost using ordinary cables.
- iii) Superconductors are used for amplifying very small direct currents and voltages.
- iv) Superconductors are employed in switching devices.
- v) Because superconductors are diamagnetic, they can be used to shield out unwanted magnetic flux, as in shaping the magnetic lens system of an electron microscope.

HIGH T_C SUPERCONDUCTIVITY

A large number of possible practical applications of the phenomenon of superconductivity has not been achieved on account of the limit to the T_c value. Because at low T_c , the maintenance of superconductivity through refrigeration requires really a very Dr. S. KARUPPUSAMY Karpagam Academy of Higher Education Page **16** of **22** Department of Physics Coimbatore-21

high cost. In last couple of years, special efforts have been made by researchers to discover high T_c superconductors.

The detailed mechanism for superconductivity in the high- T_c materials is not at present known precisely. A number of arguments have been advanced to explain high Tc. For example, it has been realized that the role of oxygen is essential for high Tc oxide superconductors. The occurrence of a strong electronic band in the infrared spectrum and its correlation with superconductivity provides evidence that the superconductivity provides evidence that the superconductivity provides evidence that the superconductivity of YBa₂Cu₃O_{7-y} materials is mediated by an excitonic mechanism. Pauling has endeavored to support the Anderson's resonating valence bond theory of superconductivity in compounds such as (Sr, Ba, Y, La)₂CuO_{4-y}: the conductivity is increased by the resonance along the O-Cu...O-Cu lines of atoms, and superconductivity is probably achieved through interaction with a phonon.

ENERGY GAP

Experiments have shown that in superconductors, for temperatures in the vicinity of absolute zero, a forbidden energy gap just above the Fermi level is observed. Energy hap equal to 2Eg at the Fermi level in superconducting state. Thus the Fermi level in a superconductor is midway between the ground state and the first excited state so that each lies an energy distance = Eg away from Fermi level. Electrons in excited states above the gap behave as normal electron. At absolute zero, there are no electrons above the gap. Eg is typically of the order of 10^{-4} eV.



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Eg is found to be a function of temperature T. Figure shows reduced values of observed energy gap Eg(T)/Eg (0) as a function of the reduced temperature T/Tc. The energy gap decreases continuously to Tc. The transition from the superconducting state to the normal state is observed to be a second-order phase transition. In such a transition, there is no latent heat, but is a discontinuity in the heat capacity.

JOSEPHSONS EFFECT

In a Josephson junction two pieces of superconductivity material are separated by a thin insulating oxide layer of thickness 2a. The insulating layer is approximately 2nm thick. The cooper pairs can tunnel through the insulator, giving a current from one superconductor into the other. The tunneling of a current through an insulating layer was discovered experimentally by I. Giaever. The behavior of current through an insulating layer sandwiched between two superconductors was first analyzed theoretically by B.D.Josephson. He predicted that a "super current" consisting of correlated pair of electrons can be made to flow across an insulating gap between two superconductors provided the gap is small enough. Such a junction is called weak link. In practice, such a junction is manufactured by depositing a thin layer of an oxide, only 1 to 2 nm thick, on the surface of one superconductor, and then placing the second superconductor on top of this.



The layer of insulator acts as a potential barrier for the Cooper pairs. A fraction of the current approaching this barrier from the left or the right manages to tunnel through the barrier and continue on the other side, without any net loss of energy. Thus, the junction permits the flow of a current even if the potential difference it is zero. The phenomenon in which the junction permits the flow of current without any net loss of energy even if the

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potential difference across it is zero is called DC *Josephson effect*. It results from the familiar tunneling phenomenon of quantum mechanics.

If we apply a DC voltage V across the junction, the results is an alternating currentthe constant voltage generates an oscillating current. The frequency of this oscillating current is directly proportional to the voltage:

This is called the AC *Josephson effect*. It is caused by the coupling between wave in one superconductor and the wave in the other. Crudely, it is analogous to the classical beat phenomenon seen in the superposition of two waves of different frequencies. The wavefunction of a cooper pair on the two sides of the junction differ in energy by 2eV; hence differ in frequency by 2ev/h. Since the charge density and the currents only depend on ψ^{-1} , the individual wave frequencies are not observable. However, when the waves are coupled, the net amplitude is modulated by the beat frequency, which equals the frequency difference. The modulation shows up in the current.

According to Eq(1), a voltage of 10^{-6} V generates an AC of a frequency of 483.6MHz. Thus, the measurements of the frequencies of AC Josephson currents can be used as avery precise and convenient method for the measurement of voltage. Potentiometers based on this method attain a precision of about 1 part in 10^8 . This effect has also been utilized for the precise determination of the value of h/e.

EXPERIMENTAL FACTS OF SUPER CONDUCTIVITY

- 1) When impurities are added to superconducting elements, the superconducting property is not lost but the transition- temperature is lowered.
- 2) ISOTOPE EFFECT: The critical temperature of superconductors varies with isotopic mass. In mercury, T_c varies from 4.185 K to 4.16K as the average atomic mass M varies from 199.5 to 203.4 atomic mass unit. The experimental results within each series of isotopes may be fitted by a relation of the form M^aT_c= constant. Here is a number usually 0.2. From the dependence of T_c and the Dr. S. KARUPPUSAMY Karpagam Academy of Higher Education Page 19 of 22 Coimbatore-21

isotopic mass M, lattice vibration and the electron-lattice interactions are deeply involved in superconductivity which can studied.

- 3) The thermal properties such as the specific heat capacity and thermal conductivity of a substance changes abruptly, when it passes over into the superconducting state.
- 4) PERSISTENT CURRENTS: If a superconductor has the form of ring, current can be induced in it by electromagnetic induction. One usually measures the resistivity of a superconductor by observing this current as a function of time. If the sample is in the normal state, the current damps out quickly because of the resistance of the ring. But if the ring has zero resistance, the current, once set up, flows indefinitely without any decrease in value. In a typical experiment, a lead ring could carry an induced current of several hundred years without any change. Such currents are called "*Persistent Current*". Physicists found that the upper limit for the superconducting lead ring was about 10⁻²⁵ ohm-m. The fact that this is about 1/10¹⁷ as large at a room temperature does indeed justify taking =0 for the superconducting state.

5) DESTRUCTION OF SUPERCONDUCTIVITY BY MAGNETIC FIELD

Superconductivity can be destroyed by the application of a magnetic field. If a strong enough magnetic field, called the *Critical Field*, is applied to a superconducting specimen, it becomes normal and recovers its normal resistivity even at T<T_c. The critical value of the applied magnetic field for the destruction of superconductivity is denoted by H_c (T) and is a function of the temperature. For a given substance, value of H_c decreases as the temperature increases from T=0K to T=T_c. The variation can be represented by the formula

$$H_c(T) = H_c(0) [1 - (T/T_c)^2]$$

where $H_c(0)$ is the critical field at 0K. Thus the field has its maximum value, $H_c(0)$ at T=0K. At the critical temperature (T_c) the critical field is zero: $H_c(T_c)=0$. This result is expected because at T=T_c the specimen is already normal, and no field

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is necessary to accomplish the transition. A specimen is superconducting below the curve and normal above the curve.



Temperature (K)

6) The destruction of superconductivity by relatively small magnetic fields prevents the superconductor from being used in a solenoid to produce extremely large magnetic fields. However, there are superconductors that behave different, which is called type-I superconductors and they have two states: superconducting and normal. The other type of superconductor called type-II exists in three states: superconducting, mixed and normal. The mixed state is resistance-less but unlike the superconducting state flux from an applied magnetic field penetrates through it. That is, the Meissner effect does not occur in these type-II superconductors. In consequences, the mixed state persists up to high magnetic fields. Type-II superconductors can be used to wind solenoid capable of producing magnetic fields above 10T.

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POSSIBLE QUESTIONS

2 Mark

- 1) Define Hall effect.
- 2) Give two examples for binary and ternary semiconductors.
- 3) List out the difference between P and N type Semiconductors.
- 4) List out the difference between conductors and semiconductors.
- 5) Define Critical magnetic field.
- 6) Define Critical Temperature.
- 7) Explain briefly about superconductors.

6 Mark

- 8) Explain Hall effect and its applications.
- 9) Explain in detail about Type I and type II Superconductors
- 10) Explain about superconductivity and give some applications.
- 11) What is Hall Effect? Show that for a p-type semiconductor the hall co-efficient R_H is given by(-1/ne).
- 12) Explain in detail how Hall coefficient can be determined experimentally.
- 13) List out the difference between type I and type II Superconductors.
- 14) Discuss P and N type Semiconductors.
- 15) Explain the concept of Kronig Penny model.

KARPAGAM ACADEMY OF HIGHER EDUCATION, COIMBATORE - 21

DEPARTMENT OF PHYSICS

CLASS: I B. Sc., PHYSICS BATCH: 2017-2020

MATHEMATICAL PHYSICS (17PHU103)

MULTIPLE CHOICE QUESTIONS

QUESTIONS	opt1	opt2	opt3	opt4	opt5	opt6	ANSWER
UNIT-IV	-	-	-	-	-	-	
The value of Jo(x) at the origin is		1	0	-1 X			0
From Bessel's functions, the value of $J_{n+1}(x)$ is	$nJ_n(x) + J_n'(x)$	$(n / x) J_n(x) - J_n'(x)$	$nJ_n(x) - J_n'(x)$	$(n / x) J_n(x) + J_n'(x)$		(1	$a / x) J_n(x) - J_n'(x)$
When 'n' is an integer, $J_n(x)$ and $J_{-n}(x)$ are	harmonic function	linearly dependent	linearly independent	orthonormal		line	early independent
Bessel's functions are	indeterminate	simple harmonic	oscillatory function	critically damped		osc	illatory function
The value of $P_1(x)$ is	х		1 x ⁻ /2	½ (x [−] -1)		х	
The identical roots of the Legendre's functions are	$m = \pm n$	$m = \pm 1$	m = 0 or $m = 1$	m = 0 or $m = -1$		m	= ± 1
If Jo and J_1 are Bessel's functions then $J_1'(x)$ is given by	$Jo(x) - 1/x J_1(x)$	– Jo	$Jo(x) + 1/x J_1(x)$	$Jo(x) - 1/x J_1(x)$		J	$o(x) - 1/x J_1(x)$
If $J_{n+1}(x) = (2/x) J_n(x) - Jo(x)$ where Jn is the Bessel function of first kind order 'n'. Then 'n' is		0	2	-1	1		1
The value of Po(x) is		1 x		0	-1		1
Let $Pn(x)$ be the Legendre polynomial, then $Pn(-x)$ is equal to	$(-1)^{n+1} P_n'(x)$	$(-1)^{u} P_{n}'(x)$	$(-1)^{n} P_{n}(x)$	P _n "(x)		(-	$(-1)^{n} P_{n}(x)$
If $P_n(x)$ is the Legendre polynomial of order 'n', then $3x^2 + 3x + 1$ can be expressed as	$3P_2 + 3P_1$	$4P_2 + 2P_1 + Po$	$3P_2 + 3P_1 + Po$	$2P_2 + 3P_1 + 2P_0$		2	$P_2 + 3P_1 + 2P_0$
The value of $P_n(-x)$ is	$-P_n(x)$	$P_n(x)$	$(-1)^{n} P_{n}(x)$	$(-1)^{n} P_{n}(-x)$		Р	$V_n(\mathbf{x})$
The value of $2J_n$ ' is	$\mathbf{J_{n-1}} - \mathbf{J_{n+1}}$	$J_{n-1} + J_{n+1}$	$\mathbf{J_{n+1}} - \mathbf{J_{n+1}}$	2 J _{n+1}		J _n	$_{i+1} - J_{n+1}$
The root of $x^3 - 6x + 4$ lies between	-1 and 0	1 and 2	-2 and 1	0 and 1		-	1 and 0

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KARPAGAM ACADEMY OF HIGHER EDUCATION, COIMBATORE – 21

DEPARTMENT OF PHYSICS

CLASS: I B. Sc., PHYSICS

СН: 2017-2020

opt1

opt2

opt3

opt5

opt4

opt6 ANSWER

MATHEMATICAL PHYSICS (17PHU103)

MULTIPLE CHOICE QUESTIONS

QUESTIONS

UNIT V					
The exponential form of a complex number is	$z = re^{i\theta}$	$z = e^{iq}$	$z = \cos q$	z = r /	$z = re^{i\theta}$
Any function which satisfies the Laplace equation is known as	harmonic	conjugate	single fun	analyticc function	harmonic function
A single valued function $f(z)$ which is differentiable at $z = zo$ it is said to be	irregular	f analytic	periodic f	all the above	analytic
If a given number is wholly real, it is found in/on	a real axis	s imaginary	x-y plane	space	imaginary
A set which entirely consists of interior points is known as	a null set	a bounded	a closed s	an open set	an open set
The symbol i with the property i 2 = -1 was introduced by	Euler	Gauss	Cauchy	Reimann	Euler
In the Argand diagram, the fourth roots of unity forms a	rectangle	square	cube	none	square
The Conjugate of 1/i is	—i —	i	1	-1	—i
The value of $i^{4} + i^{6} + i^{7}$ is	irregular	regular fu	¹ infinite	C	C
The sum of n th roots of unity are	() 1	2	3	0
In the Argand diagram, the fourth roots of unity forms a	square	rectangle	circle	rombus	square
The order of convergence of Newton Raphson method is	1	2	3	4	2
A number of the form a+ib is called a	complex	n real numb	imaginary	all the above	complex numbers
who represented argand diagram in a complex number	Argand	macmillain	ramanuja	H.K.Dass	Argand
The function of a complex variable is important in solving in the field	small prob	ol a large nur	simple	none of the above	a large number of problems
what is the order of the Euler's method?	h	h/2	h^2	h^3	h^2
The point at which the function is not differeniable is called a point of	poles	branch poi	singular	none of the above	singular
In which method the accuracy cannot be obtained as the number of the intervals inc	i bisection i	r newtons m	Euler's	all the above	Euler's
A function which satisfies the is known as a harmonic function	laplace eq	u wave equa	Bessels	all the above	laplace equation
conjucate harmonic function is also a function	harmonic	f analytic fu	r cosine	sine function	analytic function
cauchy's intergral theorem is applicable only for the region enclosed	simply cor	n multiple cu	multicon	meromorphic	simply connected
A simple curve is one which itself	cross	doesnot cr	deviate	none of	doesnot cross
A multi curve is one which itself	cross	doesnot cr	deviate	none of	cross
Multiply connected region is bounded by curves	more than	one	two	none of the above	more than two
curve encloses more than one separate region	simple cur	n multiple cu	semi	semi multiple	multiple curve
If the function f(z) is analytic for all finite values of z and is bounded is the	constant	zero	two	three	constant
An important fact in one dimensional case is the singularities are	constant	isolated	non	none of the above	isolated
Analytic point is almost equivalent to	irregular p	o regular poi	poles	branch point	regular point
ordinary points and analytic points are	equivalent	t non-equiva	zero	constant	equivalent
Two equivalent terms holomorphic points and analytic points often occur with	regular po	i irregular p	poles	branch point	regular point
A is a point, where y is differentiable in a open set around the point	meromorp	holonomic	holomorp	none of the above	holomorp

points which include regular points and removable singularities	ordinary p	cpoles	branch	extraor	dinary points	ordinary points
The function $z^2/(z-1)^3$ has	а	а	a pole	a simp	ole	a simple
The residue of the function $2z+1/z^2-z-2$ at $z=2$ is	1/3	4-Mar	2/3	5/3		5/3
For a unit circle around the origin, the value of $\sin \theta$ is	$\frac{z^2 + 1}{2iz}$	$\frac{z^2 - 1}{2iz}$	$\frac{z^2 + 1}{2z}$	$\frac{z^2 - 1}{2z}$		$\frac{z^2 - 1}{2iz}$
If a given number is wholly real, it is found in/on	a real axis	imaginary	ax-y plane	space		x-y plane
A set which entirely consists of interior points is known as	an open se	e a closed se	a banded	s domain		an open set
If a contour is a unit circle around the origin, then $ z $ is	1	0	$e^{i\theta}$	e		1
A connected open set is called	an open se	e a closed se	a banded	s domain		an open set
Which is the analytic function of complex variable $z = x + iy$	Z	Re Z	Z^{-1}	Log Z		Z^{-1}
Which is the analytic function of complex variable $Z=x+iy$	Z	sin Z	Log Z	Re Z		Sin Z
Which is the analytic function of complex variable $z=X+iY$	Z	Re Z	Log Z	e sinz		e ^{sinz}
Which is not the analytic function of complex variable z=X+iY	Z	Re Z	Log Z	Z		Z
Which is not the analytic function of complex variable z=X+iY	$ \mathbf{Z} $	Re Z	Sin Z	Re Z		Re Z
The function $Ze^{2}/(Z-a)^{3}$ has	a simple	a simple p	c a pole at 2	Z= a pole a	t Z=a of order 3	a pole at Z=a of order 3
The symbol i with the property i 2 =1 was introduced by	Euler	Gauss	Cauchy	Reiman	n	Euler
$\arg(Z_1 / Z_2)$ is equal to	arg Z ₁ +	arg Z ₁₋	real	imagina	iry	arg Z ₁₋
A single valued function $f(z)$ which is differentiable at $z = zo$ it is said to be	irregular	analytic fu	r periodic f	u all the a	bove	analytic function
The function $1/(Z-1)(Z+1)$ is analytic	at	at all point	t at all poin	nt: both b a	and c	both b and c
In order that the function $f(z) = Z ^2 / Z$, $Z \neq 0$, be continuous at $z = 0$. we should define the function of $z = 0$.	f 2	2 1		0	-1	0
The conjugate of 1/1+i is	1-i	1-i/√ 2	1-i/2	1+i		1-i/√ 2
The conjugate of $(1+i)$ $(3+4i)$ is	1+7i	1-7i	7-i	(-1-7i)		(-1-7i)
The conjugate of 1/i is	(-i)	i		1 (-1)		(-i)
The value of $i^2 + i^3 + i^4$ is	(-i)	i		1 (-1)		(-i)
If $Z=a+ib$, then real part of Z^{-1} is	a/a^2+b^2	$-b/a^{2}+b^{2}$	a/ $\sqrt{a^2+b^2}$	$^2 -b/\sqrt{a^2}$	$+b^2$	a/a^2+b^2
If $Z=a+ib$, then Im(Z^{-1}) is	a/a^2+b^2	$-b/a^{2}+b^{2}$	a/ $\sqrt{a^2+b^2}$	$^2 -b/\sqrt{a^2}$	$+b^2$	$-b/\sqrt{a^2+b^2}$
The modulus and argument of $\sqrt{3}$ - i are	2, ∏/6	2, -∏/6	4, ∏/3	4, -∏/3		2, -∏/6
$Z_1 = r_1(\cos \theta_1 + i\sin \theta_1)$ and $Z_2 = r_2(\cos \theta_2 + i\sin \theta_2)$, then $\arg Z_1 Z_2$ is	$\theta_1 + \theta_2$	$\theta_1 - \theta_2$	$\theta_1 \hat{\theta}_2$	$\theta_1 / \hat{\theta}_2$		$\theta_1 + \theta_2$
The argument of -1 + I is	- ∏/4	3∏/4	∏/4	3∏/2		3∏/4
$(1 + e^{-t\theta}) / (1 + e^{t\theta}) =$	$\cos \theta + i$	$s \cos \theta - is$	$i \sin \theta - icc$	$\sin \theta + i$	icos θ	$\cos \theta + i \sin \theta$
The sum of n th roots of unity are	C) 1		2	3	0

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