

## Syllabus

UNIT	CONTENTS
UNIT -I	<p>Crystal Structure and bonding: Crystalline and amorphous solids. Translational symmetry. Lattice and basis. Unit cell. Reciprocal lattice. Fundamental types of lattices (Bravais Lattice).</p> <p>Miller indices Lattice planes. Simple cubic. Face centered cubic. Body centered cubic lattices.</p> <p>Laue and Bragg's equations. Determination of crystal structure with X-rays, X-ray spectrometer. Ionic, covalent, metallic, van der Waals and hydrogen bonding. Band theory of solids. Periodic potential and Bloch theorem. Kronig-Penny model (Qualitative).</p>
UNIT-II	<p>Lattice structure and properties: Dulong Petit, Einstein and Debye theories of specific heats of solids. Elastic and atomic force constants. Dynamics of a chain of similar atoms and chain of two types of atoms. Optical and acoustic modes. Electrical resistivity. Specific heat of electron. Wiedemann-Franz law. Hall effect. Response of substances in magnetic field, dia-, para- and ferromagnetic materials. Classical Langevin theory of dia and paramagnetic domains.</p> <p>Curie's law. Weiss' theory of ferromagnetism and ferromagnetic domains.</p> <p>Discussion of BH hysteresis.</p>
UNIT-III	<p>Electronic devices: Types of Semiconductors (p and n). Formation of Energy Bands, Energy level diagram. Conductivity and mobility. Junction formation, Barrier formation in p-n junction diode. Current flow mechanism in forward and reverse biased diode (recombination), drift and saturation of drift velocity.</p> <p>Derivation of mathematical equations for barrier potential, barrier width. Single p-n junction device (physical explanation, current voltage characteristics and one or two applications). Two terminal devices. Rectification.</p> <p>Zener diode. Photo diode. Light emitting diode. Solar cell. Three terminal devices. Junction field effect transistor (JFET). Two junction devices. Transistors as p-n-p and n-p-n. Physical mechanism of current flow. Characteristics of transistor.</p>

UNIT-IV	<p>Amplifiers (only bipolar junction transistor). CB, CE and CC configurations. Single stage CE amplifier (biasing and stabilization circuits), Q-point, equivalent circuit, input impedance, output impedance, voltage and current gain. Class A, B, C amplifiers (definitions).</p> <p>RC coupled amplifiers (frequency response). Class B push-pull amplifier. Feedback amplifiers. Voltage feedback and current feedback. Effect of negative voltage series feedback on input impedance. Output impedance and gain. Stability, distortion and noise.</p> <p>Principle of an Oscillator, Barkhausen criterion, Colpitts, RC phase shift oscillators. Basic concepts of amplitude, frequency and phase modulations and demodulation</p>
UNIT-V	<p>Nanostructures: Introduction to nanotechnology, structure and size dependent properties.</p> <p>3D, 2D, 1D, 0D nanostructure materials and their density of states, Surface and Interface effects. Modelling of quantum size effect. Synthesis of nanoparticles - Bottom Up and Top Down approach, Wet Chemical Method. Nanolithography. Metal and Semiconducting nanomaterials. Essential differences in structural and properties of bulk and nano materials (qualitative description). Naturally occurring nano crystals. Applications of nanomaterials.</p>

## Unit - I

### Lattice

A lattice is in general defined as a discrete but infinite regular arrangement of points (lattice sites) in a vector space Bravais Lattice

In solid state physics one usually encounters lattices which exhibit a discrete translational symmetry. If one considers for instance the vector space  $\mathbb{R}^3$  this means that a translation of the whole lattice by any translation vector given by

$\vec{T} = m\vec{a}_1 + n\vec{a}_2 + o\vec{a}_3$ ,  $m, n, o \in \mathbb{Z}$  leaves the lattice unchanged.

A lattice that can be characterised in this way is referred to as a Bravais lattice. All lattice points are equivalent, i.e. all properties remain invariant under translations by any vector  $\vec{T} = m\vec{a}_1 + n\vec{a}_2 + o\vec{a}_3$ . Also, an observer sitting on one specific lattice point would see the same environment as when sitting on any other. However, if there are lattice points with different environments they cannot form a Bravais lattice! (This is an equivalent definition of a Bravais lattice.)

### Primitive Translation Vectors

The linear independent generating vectors  $\vec{a}_i$  of the translations are called primitive translation vectors or primitive lattice vectors. However, for a given lattice the choice of the primitive translation vectors is not unique

Let's illustrate this for the two-dimensional Euclidean space: Any two linear independent vectors  $\vec{a}_1$  and  $\vec{a}_2$  form a basis and can be used as generators for a two-dimensional lattice:

A two-dimensional Bravais lattice can be created as the set of integer linear combinations of two (linear independent) vectors (called primitive translation vectors).

In physics, the reciprocal lattice represents the Fourier transform of another lattice (usually a Bravais lattice). In normal usage, this first lattice (whose transform is represented by the reciprocal lattice) is usually a periodic spatial function in real-space and is also known as the direct lattice. While the direct lattice exists in real-space and is what one would commonly understand as a physical lattice, the reciprocal lattice exists in reciprocal space (also known as momentum space or less commonly K-space, due to the relationship between the Pontryagin

duals momentum and position.) The reciprocal lattice of a reciprocal lattice, then, is the original direct lattice again, since the two lattices are Fourier Transforms of each other.

The reciprocal lattice plays a fundamental role in most analytic studies of periodic structures, particularly in the theory of diffraction. In neutron and X-ray diffraction due to the Laue conditions the momentum difference between incoming and diffracted X-rays of a crystal is a reciprocal lattice vector. The diffraction pattern of a crystal can be used to determine the reciprocal vectors of the lattice. Using this process, one can infer the atomic arrangement of a crystal.

### Bravais lattice

In geometry and crystallography, a Bravais lattice, studied by Auguste Bravais (1850), is an infinite array of discrete points in three dimensional space 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.

When the discrete points are atoms, ions, or polymer strings of solid matter, the Bravais lattice concept is used to formally define a crystalline arrangement and its (finite) frontiers. 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 equivalent lattice point, namely those separated by the translation of one unit cell (the motif).

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

Miller indices form a notation system in crystallography for planes in crystal (Bravais) lattices.

In particular, a family of lattice planes is determined by three integers  $h$ ,  $k$ , and  $\ell$ , the Miller indices. They are written  $(hkl)$ , and denote the family of planes orthogonal to  $h\mathbf{b}_1 + k\mathbf{b}_2 + \ell\mathbf{b}_3$  where  $\mathbf{b}_i$  are the basis of the reciprocal lattice vectors. (Note that the plane is not always orthogonal to the linear combination of direct lattice vectors  $h\mathbf{b}_1 + k\mathbf{b}_2 + \ell\mathbf{b}_3$  because the reciprocal

lattice vectors need not be mutually orthogonal.) By convention, negative integers are written with a bar, as in  $\bar{3}$  for  $-3$ . The integers are usually written in lowest terms, i.e. their greatest common divisor should be 1.

There are also several related notations:

the notation  $\{hkl\}$  denotes the set of all planes that are equivalent to  $(hkl)$  by the symmetry of the lattice.

In the context of crystal directions (not planes), the corresponding notations are:

$[hkl]$ , with square instead of round brackets, denotes a direction in the basis of the direct lattice vectors instead of the reciprocal lattice; and

similarly, the notation  $\langle hkl \rangle$  denotes the set of all directions that are equivalent to  $[hkl]$  by symmetry.

Miller indices were introduced in 1839 by the British mineralogist William Hallows Miller. The method was also historically known as the Millerian system, and the indices as Milleria, although this is now rare.

The Miller indices are defined with respect to any choice of unit cell and not only with respect to primitive basis vectors, as is sometimes stated.

### Difference between Amorphous solids and crystalline solids

Amprhous Solids	Crystalline Solids
1. Solids that don't have definite geometrical shape.	They have characteristic geometrical shape
2. Amorphous solids don't have particular melting point. They melt over a wide range of temperature.	They have sharp melting point
3. Physical properties of amorphous solids are same in different direction, i.e. amorphous solids are isotropic	Physical properties of crystalline solids are different in different directions. This phenomenon is known as Anisotropy.
4. Amorphous solids are unsymmetrical	When crystalline solids are rotated about an axis, their appearance does not change. This shows that they are symmetrical
5. Amorphous solids don't break at fixed cleavage planes.	Crystalline solids cleavage along particular direction at fixed cleavage planes.

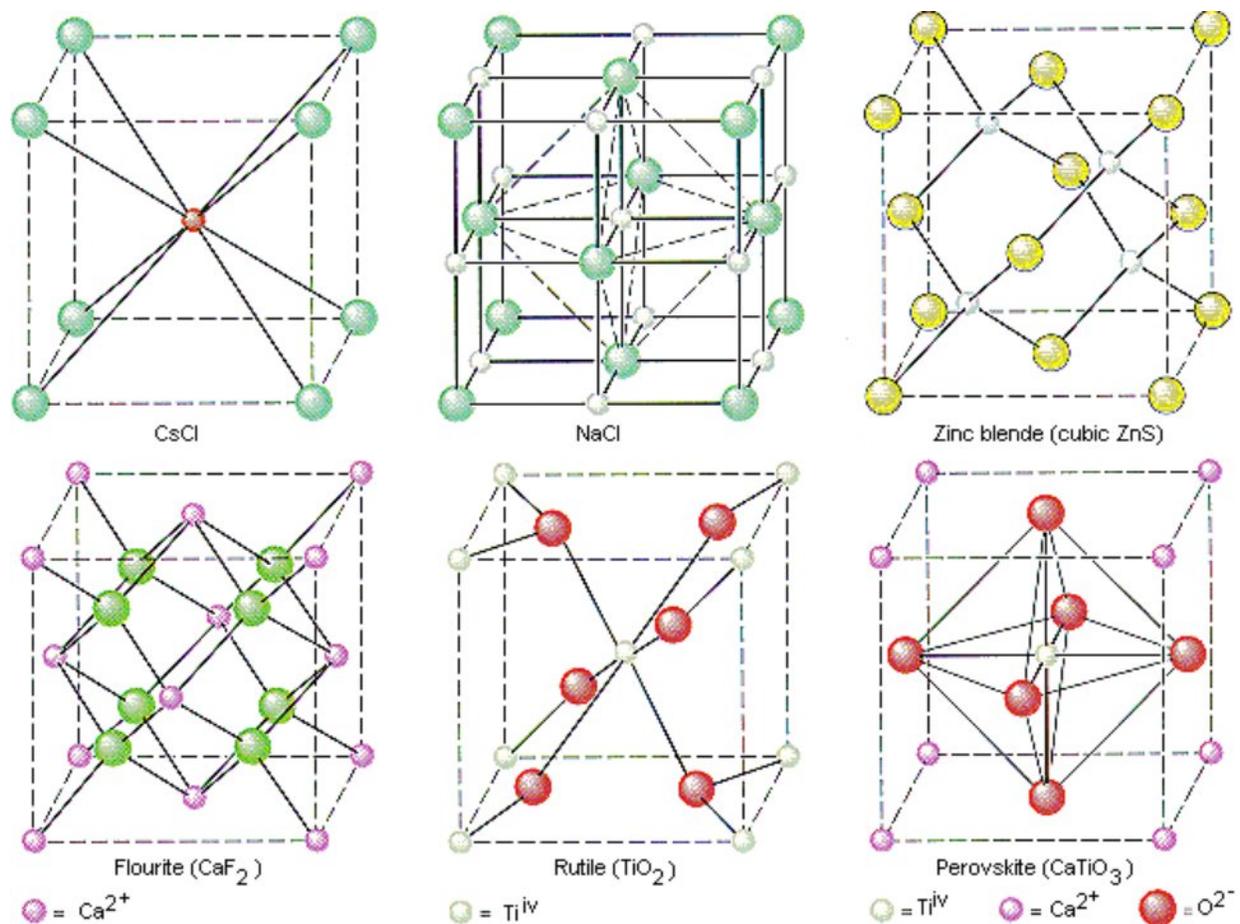
### Unit Cells: The Simplest Repeating Unit in a Crystal

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.



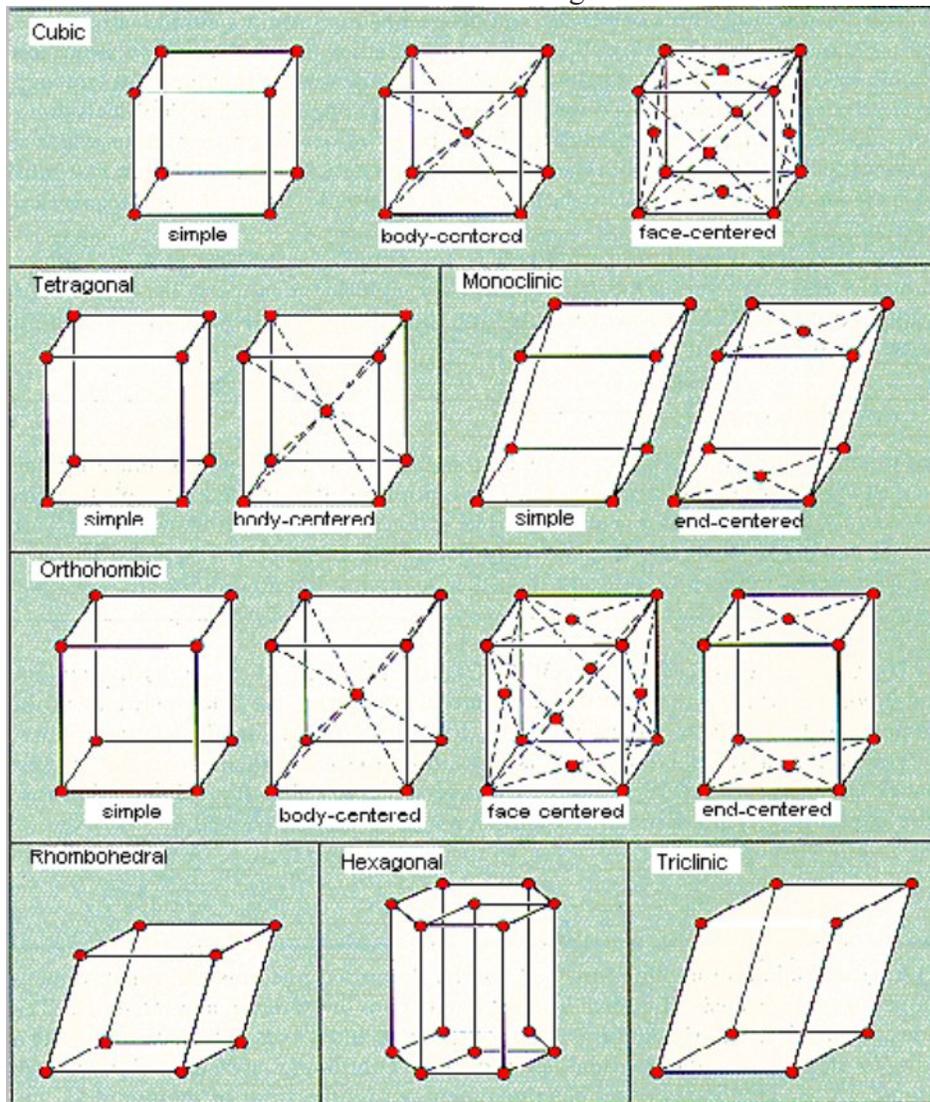
In 1850, Auguste Bravais showed that crystals could be divided into 14 unit cells, which meet the following criteria.

The unit cell is the simplest repeating unit in the crystal.

Opposite faces of a unit cell are parallel.

The edge of the unit cell connects equivalent points.

The 14 Bravais unit cells are shown in the figure below.



These unit cells fall into seven categories, which differ in the three unit-cell edge lengths ( $a$ ,  $b$ , and  $c$ ) and three internal angles ( $\alpha$ ,  $\beta$  and  $\gamma$ ), as shown in the table below.

The Seven Categories of Bravais Unit Cells

Category	Edge Lengths
Cubic	$(a = b = c)$
Tetragonal	$(a = b \neq c)$
Monoclinic	$(a \neq b \neq c)$
Orthorhombic	$(a \neq b \neq c)$
Rhombohedral	$(a = b = c)$
Hexagonal	$(a = b \neq c)$
Triclinic	$(a \neq b \neq c)$

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 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.

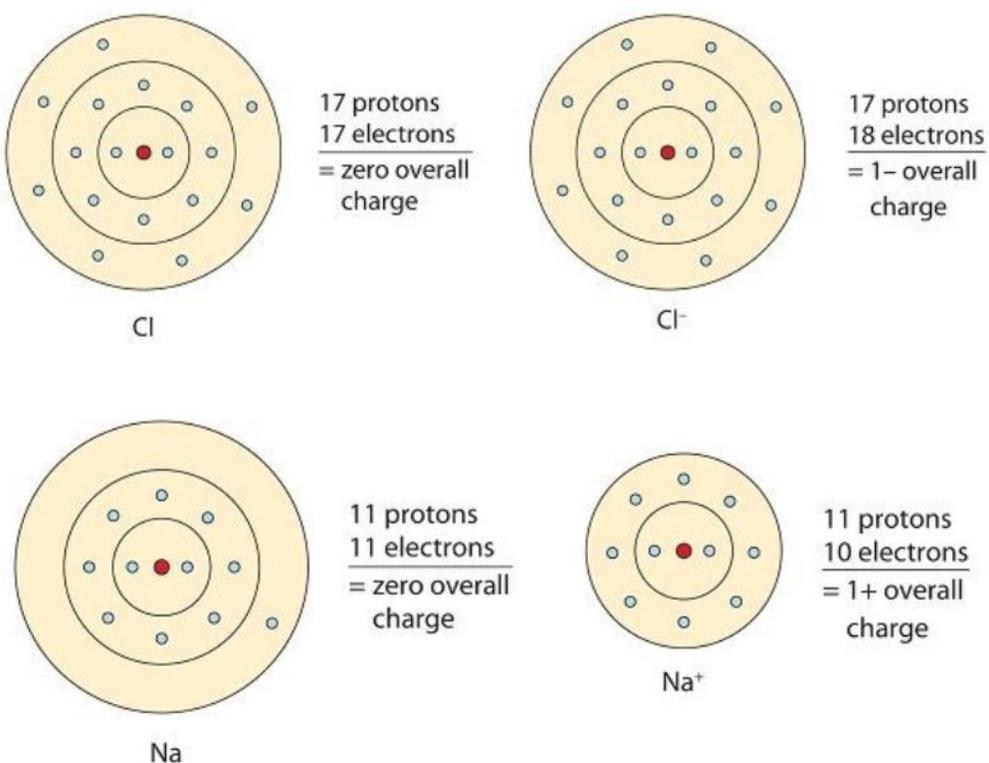
The face-centered cubic unit cell is the simplest repeating unit in a cubic closest-packed structure. In fact, the presence of face-centered cubic unit cells in this structure explains why the structure is known as cubic closest-packed.

## Ionic bonding

Ionic bonding is the complete transfer of valence electron(s) between atoms. It is a type of chemical bond that generates two oppositely charged ions. In ionic bonds, the metal loses electrons to become a positively charged cation, whereas the nonmetal accepts those electrons to become a negatively charged anion. Ionic bonds require an electron donor, often a metal, and an electron acceptor, a nonmetal.

Ionic bonding is observed because metals have few electrons in their outer-most orbitals. By losing those electrons, these metals can achieve noble gas configuration and satisfy the octet rule. Similarly, nonmetals that have close to 8 electrons in their valence shells tend to readily accept electrons to achieve noble gas configuration. In ionic bonding, more than 1 electron can be donated or received to satisfy the octet rule. The charges on the anion and cation correspond to the number of electrons donated or received. In ionic bonds, the net charge of the compound must be zero.

This sodium molecule donates the lone electron in its valence orbital in order to achieve octet configuration. This creates a positively charged cation due to the loss of electron.



This chlorine atom receives one electron to achieve its octet configuration, which creates a negatively charged anion.

The predicted overall energy of the ionic bonding process, which includes the ionization energy of the metal and electron affinity of the nonmetal, is usually positive, indicating that the reaction is endothermic and unfavorable. However, this reaction is highly favorable because of the electrostatic attraction between the particles. At the ideal interatomic distance, attraction between these particles releases enough energy to facilitate the reaction. Most ionic compounds tend to

dissociate in polar solvents because they are often polar. This phenomenon is due to the opposite charges on each ion.

## Covalent Bonding

Covalent bonding is the sharing of electrons between atoms. This type of bonding occurs between two atoms of the same element or of elements close to each other in the periodic table. This bonding occurs primarily between nonmetals; however, it can also be observed between nonmetals and metals.

If atoms have similar electro negativities (the same affinity for electrons), covalent bonds are most likely to occur. Because both atoms have the same affinity for electrons and neither has a tendency to donate them, they share electrons in order to achieve octet configuration and become more stable. In addition, the ionization energy of the atom is too large and the electron affinity of the atom is too small for ionic bonding to occur. For example: carbon does not form ionic bonds because it has 4 valence electrons, half of an octet. To form ionic bonds, Carbon molecules must either gain or lose 4 electrons. This is highly unfavorable; therefore, carbon molecules share their 4 valence electrons through single, double, and triple bonds so that each atom can achieve noble gas configurations. Covalent bonds include interactions of the sigma and pi orbitals; therefore, covalent bonds lead to formation of single, double, triple, and quadruple bonds.

## Metallic bond

Metallic bonding is the force of attraction between valence electrons and the metal ions. It is the sharing of many detached electrons between many positive ions, where the electrons act as a "glue" giving the substance a definite structure. It is unlike covalent or ionic bonding.

The electrons and the positive ions in the metal have a strong attractive force between them. Therefore, metals often have high melting or boiling points. The principle is similar to that of ionic bonds.

The metallic bond causes many of the traits of metals, such as strength, malleability, ductility, luster, conduction of heat and electricity.

Because the electrons move freely, the metal has some electrical conductivity. It allows the energy to pass quickly through the electrons, generating a current. Metals conduct heat for the same reason: the free electrons can transfer the energy at a faster rate than other substances with

electrons that are fixed into position. There also are few non-metals which conduct electricity: graphite (because, like metals, it has free electrons), and ionic compounds that are molten or dissolved in water, which have free moving ions.

### **Van der Waal bonds**

The van der waal bonds occur to some extent in all materials but are particularly important in plastics and polymers. These materials are made up of a long string molecules consisting of carbon atoms covalently bonded with other atoms, such as hydrogen, nitrogen, oxygen, fluorine. The covalent bonds within the molecules are very strong and rupture only under extreme conditions. The bonds between the molecules that allow sliding and rupture to occur are called van der Waal forces.

When ionic and covalent bonds are present, there is some imbalance in the electrical charge of the molecule. Take water as an example. Research has determined the hydrogen atoms are bonded to the oxygen atoms at an angle of  $104.5^\circ$ . This angle produces a positive polarity at the hydrogen-rich end of the molecule and a negative polarity at the other end. A result of this charge imbalance is that water molecules are attracted to each other. This is the force that holds the molecules together in a drop of water.

### **Hydrogen bond**

The hydrogen bond is really a special case of dipole forces. A hydrogen bond is the attractive force between the hydrogen attached to an electronegative atom of one molecule and an electronegative atom of a different molecule. Usually the electronegative atom is oxygen, nitrogen, or fluorine, which has a partial negative charge. The hydrogen then has the partial positive charge.

To recognize the possibility of hydrogen bonding, examine the Lewis structure of the molecule. The electronegative atom must have one or more unshared electron pairs as in the case of oxygen and nitrogen, and has a negative partial charge. The hydrogen, which has a partial positive charge tries to find another atom of oxygen or nitrogen with excess electrons to share and is attracted to the partial negative charge. This forms the basis for the hydrogen bond.

In other words - The hydrogen on one molecule attached to O or N that is attracted to an O or N of a different molecule.

### **Band Theory of Solids**

A useful way to visualize the difference between conductors, insulators and semiconductors is to plot the available energies for electrons in the materials. Instead of having discrete energies as in the case of free atoms, the available energy states form bands. Crucial to the conduction process is whether or not there are electrons in the conduction band. In insulators the electrons in the valence band are separated by a large gap from the conduction band, in conductors like metals the valence band overlaps the conduction band, and in semiconductors there is a small enough gap between the valence and conduction bands that thermal or other excitations can bridge the gap. With such a small gap, the presence of a small percentage of a doping material can increase conductivity dramatically.



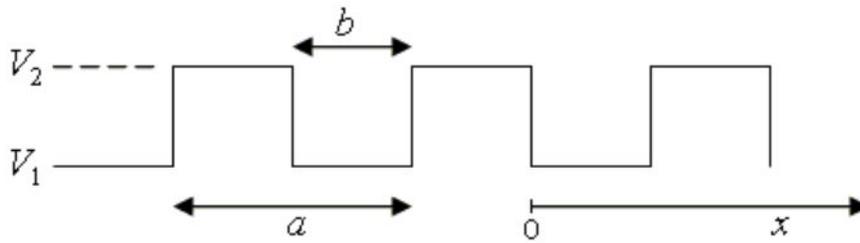
An important parameter in the band theory is the Fermi level, the top of the available electron energy levels at low temperatures. The position of the Fermi level with the relation to the conduction band is a crucial factor in determining electrical properties.

### Kronig-Penney Model

The Kronig-Penney model is a simplified model for an electron in a one-dimensional 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 Kronig-Penney model, the potential  $V(x)$  is a periodic square wave.



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.

## UNIT-II

### Dulong-Petit Law

In 1819, shortly after Dalton had introduced the concept of atomic weight in 1808, Dulong and Petit observed that if they measured the specific heat per unit mass of a variety of solids, and divided by the atomic weights of those solids, the resulting per-atom specific heat was essentially constant. This is the Dulong-Petit law, although we have since given a name to that constant, which is  $3R$  or  $3k_B$ , depending on whether the relative atomic mass (atomic weight) or the absolute atomic mass is used.

This law isn't precisely true, and isn't always true, and is never true at low temperatures. But it captures some physics that we will later call the equipartition theorem. We will write Dulong-Petit's law as:

$$C_p = 3Nk_B$$

where N is the total number of atoms.

Electrical resistivity (also known as resistivity, specific electrical resistance, or volume resistivity) is an intrinsic property that quantifies how strongly a given material opposes the flow of electric current. A low resistivity indicates a material that readily allows the flow of electric current. Resistivity is commonly represented by the Greek letter  $\rho$  (rho). The SI unit of electrical resistivity is the ohm-metre ( $\Omega \cdot \text{m}$ ). As an example, if a  $1 \text{ m} \times 1 \text{ m} \times 1 \text{ m}$  solid cube of material has sheet contacts on two opposite faces, and the resistance between these contacts is  $1 \Omega$ , then the resistivity of the material is  $1 \Omega \cdot \text{m}$ .

Electrical conductivity or specific conductance is the reciprocal of electrical resistivity, and measures a material's ability to conduct an electric current. It is commonly represented by the Greek letter  $\sigma$  (sigma), but  $\kappa$  (kappa) (especially in electrical engineering) or  $\gamma$  (gamma) are also occasionally used. Its SI unit is siemens per metre (S/m) and CGSE unit is reciprocal second ( $\text{s}^{-1}$ ).

### Electron Specific Heat

Using Fermi-Dirac statistics (as opposed to Einstein-Bose for phonons), a small fraction of the electrons are available to participate in specific heat. This fraction contributes a specific heat:

$$C_{\text{electrons}} = \frac{\pi^2 N_A k^2 T}{2E_F} \text{mole}^{-1}$$

It is important only for low temperatures in metals where it becomes larger than the T-cubed dependent phonon contribution. At those low temperatures it becomes part of the Einstein-Debye specific heat expression.

### Wiedemann-Franz law

The ratio of the thermal conductivity to the electrical conductivity of a metal is proportional to the temperature. Qualitatively, this relationship is based upon the fact that the heat and electrical

transport both involve the free electrons in the metal. The thermal conductivity increases with the average particle velocity since that increases the forward transport of energy. However, the electrical conductivity decreases with particle velocity increases because the collisions divert the electrons from forward transport of charge. This means that the ratio of thermal to electrical conductivity depends upon the average velocity squared, which is proportional to the kinetic temperature. The molar heat capacity of a classical monoatomic gas is given by

$$c_V = \frac{3}{2}R = \frac{3}{2}N_A k$$

Qualitatively, the Wiedemann-Franz Law can be understood by treating the electrons like a classical gas and comparing the resultant thermal conductivity to the electrical conductivity. The expressions for thermal and electrical conductivity become:

$$\begin{array}{ll} \text{Conductivities} & \kappa = \frac{n\langle v \rangle \lambda k}{2} \\ & \text{Thermal} \end{array} \qquad \begin{array}{l} \sigma = ne^2 \lambda / m \langle v \rangle \\ \text{Electrical} \end{array}$$

Using the expression for mean particle speed from kinetic theory

$$\langle v \rangle = \sqrt{\frac{8kT}{\pi m}}$$

the ratio of these quantities can be expressed in terms of the temperature. The ratio of thermal to electrical conductivity illustrates the Wiedemann-Franz Law

$$\frac{\kappa}{\sigma} = \frac{4k^2 T}{\pi e^2} \quad \text{is in the form of the Wiedemann-Franz Law} \quad \frac{\kappa}{\sigma} = LT \quad \text{but the constant is wrong!}$$

While qualitatively agreeing with experiment, the value of the constant is in error in this classical treatment. When the quantum mechanical treatment is done, the value of the constant is found to be:

$$L = \frac{\kappa}{\sigma T} = \frac{\pi^2 k^2}{3e^2} = 2.45 \times 10^{-8} \text{ W}\Omega / \text{K}^2$$

## Hall Effect

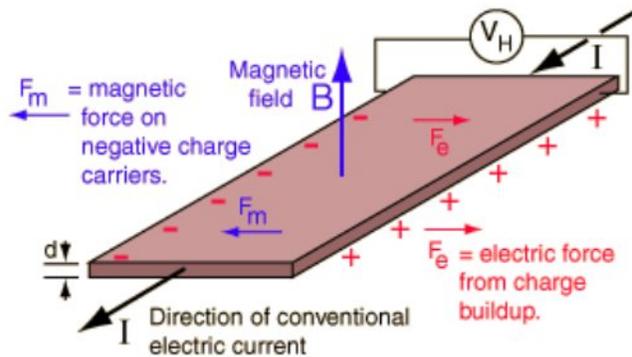
If an electric current flows through a conductor in a magnetic field, the magnetic field exerts a transverse force on the moving charge carriers which tends to push them to one side of the conductor. This is most evident in a thin flat conductor as illustrated. A buildup of charge at the sides of the conductors will balance this magnetic influence, producing a measurable voltage between the two sides of the conductor. The presence of this measurable transverse voltage is called the Hall effect after E. H. Hall who discovered it in 1879.

Note that the direction of the current  $I$  in the diagram is that of conventional current, so that the motion of electrons is in the opposite direction. That further confuses all the "right-hand rule" manipulations you have to go through to get the direction of the forces.

The Hall voltage is given by

$$V_H = \frac{IB}{ned}$$

$n$  = density of **mobile charges**  
 $e$  = electron charge



The Hall effect can be used to measure magnetic fields with a Hall probe.

## Diamagnetism

The orbital motion of electrons creates tiny atomic current loops, which produce magnetic fields. When an external magnetic field is applied to a material, these current loops will tend to align in such a way as to oppose the applied field. This may be viewed as an atomic version of Lenz's law: induced magnetic fields tend to oppose the change which created them. Materials in which this effect is the only magnetic response are called diamagnetic. All materials are inherently diamagnetic, but if the atoms have some net magnetic moment as in paramagnetic materials, or if there is long-range ordering of atomic magnetic moments as in ferromagnetic materials, these stronger effects are always dominant. Diamagnetism is the residual magnetic behavior when materials are neither paramagnetic nor ferromagnetic.

Any conductor will show a strong diamagnetic effect in the presence of changing magnetic fields because circulating currents will be generated in the conductor to oppose the magnetic field changes. A superconductor will be a perfect diamagnet since there is no resistance to the forming of the current loops.

## Paramagnetism

Some materials exhibit a magnetization which is proportional to the applied magnetic field in which the material is placed. These materials are said to be paramagnetic and follow Curie's law:

$$M = C \left( \frac{B}{T} \right)$$

$M$  = magnetization       $B$  = magnetic field  
 $C$  = Curie's constant       $T$  = Temperature in Kelvins

All atoms have inherent sources of magnetism because electron spin contributes a magnetic moment and electron orbits act as current loops which produce a magnetic field. In most materials the magnetic moments of the electrons cancel, but in materials which are classified as paramagnetic, the cancellation is incomplete.

## Ferromagnetic

Ferromagnetic materials have a large, positive susceptibility to an external magnetic field. They exhibit a strong attraction to magnetic fields and are able to retain their magnetic properties after the external field has been removed. Ferromagnetic materials have some unpaired electrons so their atoms have a net magnetic moment. They get their strong magnetic properties due to the presence of magnetic domains. In these domains, large numbers of atom's moments (10<sup>12</sup> to 10<sup>15</sup>) are aligned parallel so that the magnetic force within the domain is strong. When a ferromagnetic material is in the unmagnetized state, the domains are nearly randomly organized and the net magnetic field for the part as a whole is zero. When a magnetizing force is applied, the domains become aligned to produce a strong magnetic field within the part. Iron, nickel, and cobalt are examples of ferromagnetic materials. Components with these materials are commonly inspected using the magnetic particle method.

### Curie law

According to the Curie's law of magnetism, the intensity of magnetisation (M) of a magnetic material is

- directly proportional to the magnetic induction (B),
- inversely proportional to the temperature (T) of the material.

that is

$$M \propto B/T \quad \text{---(1)}$$

as  $B \propto H$  (magnetic intensity)

Thus equation 1 becomes

$$M \propto H/T$$

$$\text{or } M/H \propto 1/T$$

$$\text{or } \chi \propto 1/T \quad (\text{because magnetic susceptibility } \chi = M/H)$$

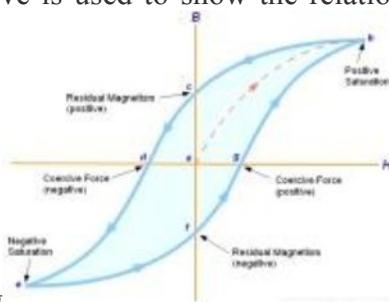
$$\chi = C/T$$

where C is a constant of proportionality and is called Curie constant

Thus, according to the Curie's law, magnetic susceptibility is inversely proportional to the temperature of the material.

### B-H curve

A B-H curve is used to show the relationship between magnetic flux density (B) and magnetic

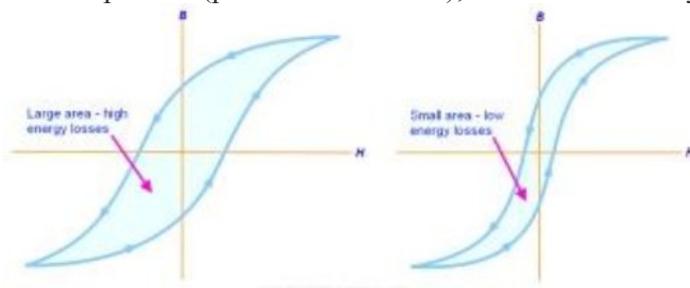


field strength

th (H) for a particular material.

When tested experimentally, a ferromagnetic (i.e. strongly magnetic) material such as iron will produce a curve similar to that shown above. Firstly, notice that here is an upper/lower limit to the magnetic flux density which may be achieved, which occurs at positive or negative saturation, respectively. This is related to the crystalline structure of the iron, where each crystal has its own – initially random – magnetic orientation. Increasing the magnetic field strength in either direction causes more and more magnetic 'domains' to align with the external magnetic field, but once almost all of the domains have aligned themselves, then little further increase in magnetic flux density is possible. The ferromagnetic material is said to be saturated.

A second key observation is that the curve demonstrates magnetic hysteresis or 'lag' as the sample is alternatively magnetised in the positive and negative directions. When initially magnetised, the curve follows points *a–b* on the graph, but on reducing *H* to zero, some residual magnetism remains (point *c* - also known as the remanent flux density). In order to fully demagnetise the specimen, it is necessary to apply a negative magnetic field strength (point *d* - called the coercive force). Making *H* increasingly negative leads to negative saturation (point *e*). If *H* is reduced back to zero, point *f* is reached (negative residual magnetism). As *H* becomes positive, the flux density reduces to zero (point *g*) and then becomes positive, finally returning back to point *b* (positive saturation), after which the cycle *b–g* repeats.



The area enclosed by the B-H curve (shaded light blue above) is proportional to the energy loss as the ferromagnetic material is magnetised with varying polarity by connection to an alternating (AC) power supply. This energy loss is undesirable and causes unwanted heating of the material. In general, harder ferromagnetic materials have higher hysteresis losses, since more energy is required to realign the magnetic domains. Steel, to which a small proportion of silicon has been added, is commonly used for applications such as transformer cores and motor rotors, due to its lower hysteresis loss. For smaller applications, such as inductor cores, passive filters, miniature

transformers and antennas, then ferrite (a ceramic-like combination of metallic oxides including ferric oxide) is a popular choice.