Introduction to Magnetic Materials

Every material when placed in an external magnetic field ***H*** responds in different magnitudes and different ways. Some materials get magnetized either temporarily or permanently, others do not get magnetized but repulse the external magnetic fields. Materials are classified according to the magnetization state of the material.

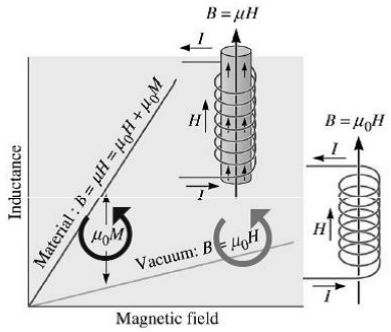
The intensity of magnetization (M) of a material is defined as the dipole moment per unit volume of the material.

$\boldsymbol{M = \frac{m*2l}{2l*a} = \frac{m}{a}}$ which is the dipole strength per unit area of cross section.

The magnetization of the material $\boldsymbol{M = \chi_m H}$

where the magnetic susceptibility $\boldsymbol{\chi_m}$ of the material is the ratio of the magnetization ***B*** to the magnetic field ***H*** ie., $\boldsymbol{\chi_m = \frac{M}{H}}$

Consider a long solenoid of length $\boldsymbol{l}$ with air as the core and having **n** turns. The magnetic field strength when a current $\boldsymbol{I}$ flows through the solenoid $\boldsymbol{H = \frac{nI}{l}}$ A/m.



The magnetic flux density $\boldsymbol{B_o = \mu_o H}$ Tesla (Wb /m^2)

Where $\boldsymbol{\mu_o = 4\pi \times 10^{-7}\ H/m}$

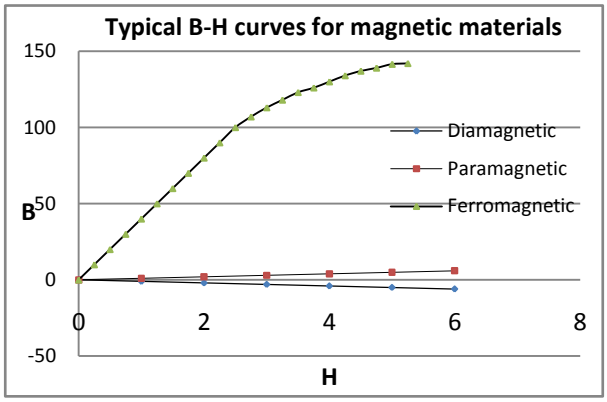
When a material of susceptibility $\boldsymbol{\chi_m}$ is introduced inside the solenoid the total magnetic flux of the system is the sum of the flux due to the coil and the flux due to the magnetization of the material.

$$\boldsymbol{B = \mu_o H + \mu_o M = \mu_o(H + M) = \mu_o(H + \chi_m H) = \mu_o(1 + \chi_m)H}$$

Defining the relative permeability of the material $\boldsymbol{\mu_r = (1 + \chi_m)}$

The magnetic flux density **B** $= \boldsymbol{\mu_o \mu_r H = \mu H}$, where $\boldsymbol{\mu = \mu_o \mu_r}$ is the permeability of the material.

Magnetic materials can be classified on their susceptibility to be magnetized by an external magnetic field and on their relative permeability.



Materials with susceptibilities less than 0 ($\boldsymbol{\chi_m}$ *negative*) are classified as diamagnetic materials. They tend to repel the lines of force of the external magnetic field. The diamagnetic susceptibilities are in the range of -10^{-3} to -10^{-6}. Diamagnetic materials possess a relative permeability less than 1.

Materials with a small positive susceptibility >0 ($\boldsymbol{\chi_m}$ *positive*) are classified as paramagnetic materials. Paramagnetic materials tend to show feeble magnetization in the presence of an external field. The susceptibility of the material is of the order of 10^{-4} to 10^{-5} and relative permeability is slightly more than 1.

Materials with a large positive susceptibility>>0 ($\boldsymbol{\chi_m}$ *positive and large*) are classified as ferromagnetic materials. Ferromagnetic materials are easily magnetized in the presence of an external magnetic field and exhibit a large relative permeability of the order of 10^5-10^6.

Origin of Magnetism in materials

Any current loop creates a magnetic field with the direction of the current deciding the direction of the field. It is imperative that the atomic level currents due to the electrons in the orbits could result in magnetic fields. The spin of the electrons can also be one of the major contributors to the magnetization in materials. In addition there is also a feeble contribution from the nuclei as well which could be neglected for all practical evaluations. The net contribution from an atom to the magnetization would depend on the magnitudes of the individual components and the statistical behavior of the collection of atoms would decide the magnetic susceptibility of the material.

The basic atomic model of orbiting electrons around the nucleus constitutes tiny current loops at atomic levels. If the electrons are assumed to move in an orbit of radius r with a constant speed v, the period of rotation T, then the current $\boldsymbol{I = \frac{e}{T} = \frac{e\omega}{2\pi} = \frac{ev}{2\pi r}}$

The magnetic moment associated with the electron's moment in the orbit

$$\boldsymbol{\mu_e = I.A = I * \pi r^2 = \frac{ev}{2\pi r}\pi r^2 = \frac{1}{2}evr = \frac{1}{2}e\omega r^2}$$

The angular momentum of the orbiting electron $L = m_e vr$ and the magnetic moment can be written as

$\boldsymbol{\mu_{orb} = \left(\frac{e}{2m_e}\right)L}$

Thus the magnetic moment of the electron is proportional to it's angular momentum. The ratio of the magnetic moment to the angular momentum $\boldsymbol{\gamma = \frac{\mu_{orb}}{L} = \left(\frac{e}{2m_e}\right)}$ is known as the gyro magnetic ratio. Due to the negative charge of the electron, the vectors $\vec{\boldsymbol{\mu}}$ *and* $\vec{\boldsymbol{L}}$ point in opposite directions and perpendicular to the plane of the orbit. The angular momentum of the electron is a multiple of $\hbar$ (quantum mechanical concepts).

The magnetic effect of the orbital motion of the electron is either zero or very small because of the cancellation of the magnetic moments of electrons orbiting in opposite directions.

Apart from the orbital magnetic moments, electrons have the property of spin and a spin angular momentum $\vec{S}$ associated with it. $\vec{S}$ is of the same order as the angular momentum $\vec{L}$.

The magnetic moment due to the spin of the electrons is almost twice that of the orbital movement and the contribution from the spin to the magnetic moment can be written as $\boldsymbol{\mu_{spin} = \sqrt{s(s+1)}\frac{e\hbar}{m}}$.

The total magnetic moment of an atom is the vector sum of orbital and spins magnetic moments.

The net magnetic moment due to electrons

$\boldsymbol{\mu_e = g_e\frac{e\hbar}{2m}}$ where $\boldsymbol{g_e}$ is the Lande g factor (spectroscopic splitting factor of the energy levels) given by $g_e = 1 + \frac{j(j+1)+s(s+1)-l(l+1)}{2j(j+1)}$

From this the smallest non zero value of the spin magnetic moment due to electrons (when s=j and l=0) is obtained as $\boldsymbol{\mu_s = \frac{e\hbar}{m}}$

This is twice the orbital magnetic moment and hence determines the susceptibility of materials. The magnetic moment being quantized; the smallest unit of magnetic moment $\boldsymbol{\mu_B = \frac{e\hbar}{2m} = 9.27 \times 10^{-24} J/T}$ is called the Bohr magneton.

The magnetic moments of protons and neutrons are much smaller than the electron magnetic moment and are usually neglected.

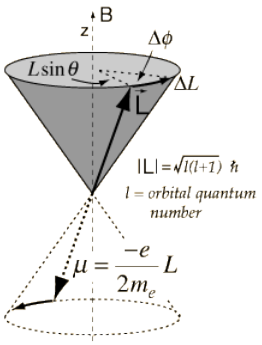
Larmor precession

A magnetic moment directed at some finite angle with respect to the applied magnetic field direction, the magnetic moment experiences a torque $\boldsymbol{\mu} \times \boldsymbol{B}$. This causes $\boldsymbol{\mu}$ to precess (rotate) about the magnetic field direction. (This is analogous to the precession of a spinning top around the gravity field.)

For static magnetic moments or classical current loops, the torque tends to line up the magnetic moments with the magnetic field B, so this represents its lowest energy configuration.

In the case of an electron in orbit around a nucleus, the magnetic moment is proportional to the angular momentum of the electron. The torque exerted the external field produces a change in angular momentum which is perpendicular to that angular momentum, causing the magnetic moment to precess around the direction of the magnetic field rather than settle down in the direction of the magnetic field. This is called Larmor precession.

When a torque is exerted perpendicular to the angular momentum L, it produces a change in angular momentum ΔL which is perpendicular to L, causing it to precess about the z axis. The effect of the torque as follows:



$$\tau = \boldsymbol{\mu} \times \boldsymbol{B} = |\boldsymbol{\mu B} \sin \boldsymbol{\theta}| = \frac{\Delta \boldsymbol{L}}{\Delta \boldsymbol{t}} = \frac{\boldsymbol{L} \sin \boldsymbol{\theta} \Delta \boldsymbol{\varphi}}{\Delta \boldsymbol{t}} = \boldsymbol{L} \sin \boldsymbol{\theta}\ \boldsymbol{\omega_L}$$

The precession angular velocity (Larmor frequency) is given by $\frac{d\boldsymbol{\phi}}{\boldsymbol{dt}} = \boldsymbol{\omega_L} = \frac{\boldsymbol{e}}{\boldsymbol{2m_e}} \boldsymbol{B}$ since $\frac{\boldsymbol{\mu}}{\boldsymbol{L}} = \left(\frac{\boldsymbol{e}}{\boldsymbol{2m_e}}\right)$.

The Larmor frequency forms the basis for magnetic resonance.

The Larmor precession frequency for electrons is 14GHz/ T which forms the basis of the electron spin resonance.

The Larmor precession frequency for protons is 7.8 MHz/ T which forms the basis of the Nuclear magnetic resonance.

Thus the magnetic moment due to a precessing charge can be evaluated as

$\boldsymbol{\mu_{ind}} = \frac{1}{2} \boldsymbol{e\omega r^2} = \frac{\boldsymbol{Be^2r^2}}{\boldsymbol{4m}}$ where r is the radius of the precessing orbit. The sign of this induced magnetic moment is negative by Lenz's law (it opposes the magnetic field that induced the precession).

If there are N_a number of atoms per unit volume and each atom contains Z electrons we can estimate the total induced magnetisation as $\boldsymbol{M} = \boldsymbol{N_a Z \mu_{ind}} = -\frac{\boldsymbol{N_a Z e^2 r^2 B}}{\boldsymbol{4m}} = -\frac{\boldsymbol{N_a Z e^2 r^2 \mu_o H}}{\boldsymbol{4m}}$

Hence the induced susceptibility $\boldsymbol{\chi_m} = \frac{\boldsymbol{M}}{\boldsymbol{H}} = -\frac{\boldsymbol{N_a Z e^2 r^2 \mu_o}}{\boldsymbol{4m}}$.

This will yeild an extremely small negative value of the order of 10^{-5} for most materials and is recognised as the diamagnetic response of all materials.

Diamagnetic materials

Diamagnetism is a property due to which certain materials are repelled by both poles of a magnet. When a short rod of diamagnetic material is placed in a magnetic field, it aligns itself at right angles to or across the direction of the magnetic lines of force. The meaning of term "diamagnetic" in Greek is "across magnetic".

The orbital motion of electrons is equivalent to tiny atomic current loops, producing magnetic fields. In most materials, the magnetic fields of the orbiting electrons balance each other and add up to zero in the absence of an external field. However, in the presence of an external magnetic field, the interaction of external field

with the electrons induces an internal field which tends to align the current loops in a direction opposite to the applied field.

This effect on atomic scale is similar to that due to Lenz's law induced magnetic fields tend to oppose the change which created them. If magnetic response is only due to these phenomena then the material is classified as diamagnetic. Diamagnetism is exhibited by a substance only in the presence of an externally applied magnetic field.

Atoms with closed electronic shells and sub shells are generally diamagnetic (-ve $\chi_m \; and \; \mu_r < 1$). The classical diamagnetic susceptibility is given by

$$\chi_d = \frac{Ne^2\mu_0}{6m}\langle r^2 \rangle$$

where N is the number of atoms per unit volume and $<r^2>$ is the average value of the square of the radius of the orbit. From the above it is observed that diamagnetic susceptibility is temperature independent.

All materials have inherent diamagnetism. Diamagnetism is detectable and observable only with sensitive instruments and in the presence of powerful magnets. Examples of diamagnetic substances include water, wood, sodium chloride, most organic compounds such as petroleum, some plastics, and many metals including copper, particularly the heavy metals with many core electrons, such as mercury, gold, bismuth and antimony. Most substances usually considered as nonmagnetic may be strictly called as diamagnetic.

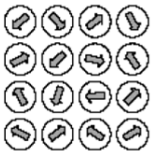
The volume magnetic susceptibility of water is $= -9.05\times10^{-6}$

Bismuth the most strongly diamagnetic material has $= -1.66\times10^{-4}$.

However, superconductors show strong diamagnetic effect (and offer no resistance to the formation of the current loops and conduction of electricity). Lines of magnetic flux are deflected away from the material due to diamagnetism and are expelled completely. These materials can are used in creating strong repulsive magnetic fields and are used in levitation experiments / applications.

Para magnetism

Paramagnetic materials are weakly attracted by magnetic fields. When a small rod of paramagnetic material is placed in a magnetic field, it aligns with or alongside the lines of force. The term paramagnetic is derived from a Greek word meaning "alongside magnetic".


Paramagnetic

Para magnetism is generally a characteristic of materials with partially filled 3d shells, where the Hund's rule restricts the anti parallel alignment resulting in the net spin magnetic moment for the atoms.

Materials with unpaired electron spins in the atomic / molecular orbitals have permanent magnetic dipoles even in the absence of an applied field. These dipoles are randomly oriented and do not interact with one another. The thermal energy of the system being greater than the magnetic energy $k_BT > \mu.B$, the thermal agitation result in random ordering and a net zero magnetic moment.

In the presence of an external magnetic field these dipoles tend to align to the applied direction leading to a net magnetic moment in the direction of the applied field. The induced magnetization is weak and linearly dependent on the applied magnetic field. When the magnetic field is removed, the dipoles relax back to their normal random orientation and the magnetization becomes zero.

Quantum theory of Paramagnetic materials (solids).

Some of the features of the quantum theory of Paramagnetism are:

The magnetic dipoles of a molecule / atom /ion in a material are allowed only certain fixed orientations for J (the total angular momentum) the allowed levels are 2J+1 (j, j-1,j-2…..0 …..-j) and the allowed energy levels

in the presence of an external magnetic field B is given by $\boldsymbol{E_j = -m_j g\mu_B . B = m_j g\mu_o \mu_B H}$ where m_j is the magnetic quantum number which describes the orientations of the angular momentum with respect to the z direction.

The magnetic moment of the dipoles are given by $\boldsymbol{\mu_j = g_e \mu_B}$ where $\boldsymbol{g_e}$ is the Lande g factor and μ_B is the Bohr magneton. The applied magnetic field aligns the μ_j as per the magnetic quantum number m_j.

For a material with N dipoles per unit volume, the net magnetization is the statistical average of the allowed μ_j orientations and is given by

$$\boldsymbol{M = N}\left[\frac{\sum_{-j}^{+j} \boldsymbol{m_j g\mu_B * exp}\left(\boldsymbol{m_j g\mu_o \mu_B H}/_{\boldsymbol{KT}}\right)}{\sum \boldsymbol{exp}\left(\boldsymbol{m_j g\mu_o \mu_B H}/_{\boldsymbol{KT}}\right)}\right] \qquad \text{eqn. 1.0}$$

Clearly the magnetization will depend on the value of the exponent $\left(\boldsymbol{m_j g\mu_o \mu_B H}/_{\boldsymbol{KT}}\right)$.

Case 1:

If $M_j\, g\mu_o \mu_B H \ll KT$ i.e. the thermal energy is significantly higher (high temperatures) than the magnetic interaction energy with field, the ratio will be much less than 1.

Expanding the exponential terms as a power series and simplifying the terms the net magnetization

$$M = Ng\mu_{B.} * \frac{g\mu_o \mu_B H}{KT} \frac{j(j+1)}{3} = \frac{Ng^2 \mu_o \mu_B^2 H}{KT} \frac{j(j+1)}{3}$$

The magnetic susceptibility $\chi = \frac{M}{H} = \frac{Ng^2 \mu_o \mu_B^2}{KT} \frac{j(j+1)}{3} = \frac{C}{T}$ which is the classical Curies law of paramagnetic materials where the Curie constant $C = \frac{Ng^2 \mu_o \mu_B^2}{K} \frac{j(j+1)}{3}$. The paramagnetic susceptibility is thus inversely proportional to the absolute temperature.

Curie's law is obeyed under generally prevailing conditions of low magnetization ($\mu_B H \lesssim k_B T$), i.e. when only a relatively small fraction of atomic dipoles are aligned, with the magnetic field. Curie's law indicates that the Magnetization M depends on the applied field H (the stronger magnetic field aligns more dipoles) and the susceptibility χ. However χ is inversely proportional to the temperature i.e. the magnetization decreases if the temperature is increased (increased thermal agitation prevents alignment of dipoles).

Case 2:

If $M_j\, g\mu_o \mu_B H \gg KT$ i.e. the magnetic interaction energy is much greater than the thermal energy the exponent will be greater than 1.

Equation 1 can be written as

$$M = Ng\mu_B \left[\frac{\sum_{*j}^{j} m_j * exp\left(m_j g\mu_o \mu_B H/_{kT}\right)}{exp\left(m_j g\mu_o \mu_B H/_{kT}\right)}\right] = Ng\mu_B \frac{\sum_{*j}^{j} m_j * exp\left(m_j\, x\right)}{\sum exp\left(m_j\, x\right)} \quad \text{where } x = \frac{g\mu_o \mu_B H}{kT}$$

This can be simplified by taking $a = \frac{x}{j}$ to

$$M = Ng\mu_B J\left[\frac{2j+1}{2j} coth\left(\frac{2j+1}{2j}\right) a - \frac{1}{2j} coth\left(\frac{a}{2j}\right)\right] = Ng\mu_B J . B_j(a)$$

where $B_j(a) = \left[\frac{2j+1}{2j} coth\left(\frac{2j+1}{2j}\right) a - \frac{1}{2j} coth\left(\frac{a}{2j}\right)\right]$ is the Brillouin function which describes the local field induced magnetization.

When the dipoles are aligned completely, the magnetisation of the material is saturated and the saturation magnetization is given by $M_s = Ng\mu_B j$.

Hence the magnetization can be written as $M = M_s B_j(a)$.

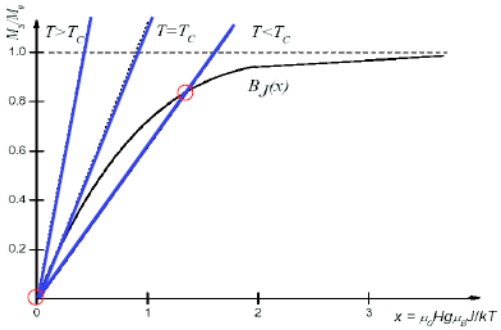
When j= $\frac{1}{2}$ the Brillouin function reduces to $M = M_s \tanh(a)$.

It the limit of large j the Brillouin function converges to the classical Langevin's function L(a)= $cot\, h(a) - \frac{1}{a}$.

[L(a) can be written as a series expansion in a as $\frac{a}{3} - \frac{a^3}{45} + \frac{2a^5}{945} - \cdots$. For small values of **a** the function then converges to $\frac{a}{3}$.]

For small values of ***a*** (large values of T) the magnetization reduces to $M = M_s \frac{a}{3}$ and the susceptibility is given by $\chi = \frac{Ng^2\mu_o\mu_B^2}{3KT}$ which is similar to the Curies theory of Paramagnetism.

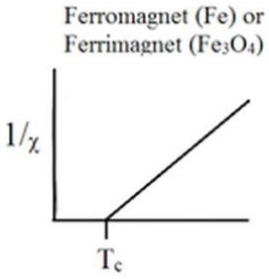
The variation of $\frac{M}{M_s}$ is represented in the figure for three different cases of the temperature (as compared to T_c the curie temperature of the material)



Examples of paramagnetic materials at room temperature include aluminium (Al), manganese (Mn), platinum (Pt), Oxygen (gas and liquid), and rare earth ions Ce, Nd.

Weiss Molecular field concept.

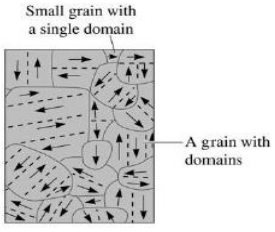
The variation of $\frac{1}{\chi}\ vs\ T$ is expected to be a straight line passing through the origin. However, some materials show a variation in this behaviour with the straight line showing a positive intercept ***T_c*** on the temperature axis.



Weiss in 1907 showed that this could be due to a molecular field which is the field at any point due to the neighbouring dipoles. If M is the magnetisation in the material then the magnetic field at any point is proportional to M and hence the field at any point in the material could have an additional contribution = λM. This field has the tendency to align the dipoles in the direction of the field and hence would be a case of spontaneous magnetisation. Therefore the Curies law is modified as $\frac{M}{H+\lambda M} = \frac{C}{T}$ which gives us $\chi = \frac{C}{T-T_c}$ where $T_c = \lambda C$ is the Curie temperature above which the materials shows the paramagnetic behaviour. Below ***T_c*** the material behaves as a ferromagnetic material. However most of the common materials have a low ***T_c*** and hence at normal temperatures does not show the spontaneous magnetisation.

<u>Ferromagnetism</u>

Ferromagnetism is the property by which certain materials like iron form permanent magnets, or are attracted to magnets. Ferromagnetic materials have very high magnetic susceptibilities, ranging from 1000 up to 100,000. Ferromagnetic materials exhibit spontaneous magnetization and exhibit sharp hysteresis characteristics in the magnetisation versus magnetising field.

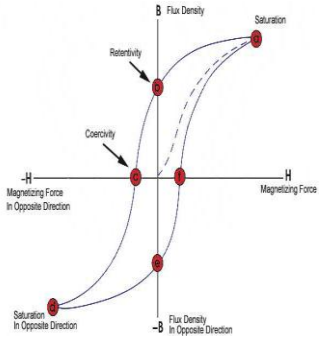


Ferromagnetism can be considered as a case of a Paramagnetic material with a high molecular field constant λ and a very high T_c .

The local molecular field can result in a high ordering of spins in certain materials like Fe, Co, Ni etc, result in the materials being easily magnetised). The presence of unpaired spins in the 3d shells of these materials

gives a large dipole moment for the atom as a whole. (Cobalt has a T_c >1000K, Fe has a T_c >750K and Ni has a T_c >350K)

In Ferromagnetic materials when an external magnetic field is applied the magnetic moments are aligned in the direction of the applied field and domains grow at the expense of their neighbours. Microscopic regions in which large numbers of dipoles are aligned are called magnetic domains. The unpaired electron spins to line up parallel with each other. This quantum mechanical interaction at the atomic level gives rise to long range order and creates magnetic domains. The alignment directions of the individual regions are random throughout the material. Hence the bulk of the material is usually unmagnetized or weakly magnetized in the absence of magnetic field.



The magnetisation of the material in the presence of an external magnetic field tends to exhibit the classic M-H hysteresis. When the external field is strong and all the spins are aligned the magnetisation shows a saturation value. When the external field is removed, sizable number of dipoles still maintains the alignment resulting in a net magnetization which is the retentivity of the material. Thus the material gets permanently magnetized. This remnant magnetisation can be removed if a coercive field Hc is applied in the reverse direction. Since the material exhibits hysteresis, it is obvious that it has a memory of the previous experience of external fields and hence can be used as memory materials. The flipping of the magnetisation in opposite directions is achieved by applying a saturation magnetisation field Hs in the appropriate direction.

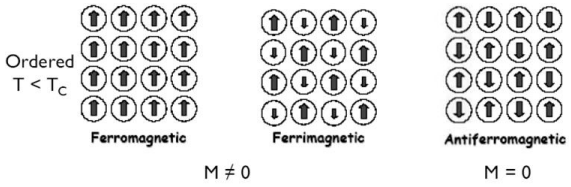
All ferromagnets have a maximum temperature at which the thermal motion of the dipoles becomes violent, the alignment of dipole moments and spontaneous magnetization cannot be maintained. Phase change from ferromagnetic to paramagnetic behaviour with the usual weak magnetization occurs. This critical temperature is called as the Curie temperature. The magnetic susceptibility above the Curie temperature is given by $\chi = \frac{C}{T-\theta}$ where θ is the transition temperature constant.

Ferromagnetic materials can be characterized by their Curie temperature in addition to their Permeability, Coercive field and Remnant Magnetization.

Apart from iron, other materials exhibiting ferromagnetic property are nickel, cobalt, some of the rare earths gadolinium, dysprosium, samarium and neodymium in alloys with cobalt. They have important applications in fabrication of magnets, electromagnets, transformers; magnetic storage media e.g. tape recording, computer hard disks etc.

Anti ferro magnetic materials

The magnetisation of a material also depends on the type of ordering that exist in some of the ordered materials. In the case of ferro magnetic materials it is seen that there is a long range ordering of the magnetic dipoles that lead to strong magnetisation.



The class of anti ferro magnetic materials such as MnO, NiO, CoO etc in which the electron spins associated with the atoms at different crystallographic sites are ordered such that the net magnetisation of the material is zero below a certain temperature called as the Neel temperature T_N. Above the Neel temperature the materials behave as paramagnetic with the magnetic susceptibility inversely proportional to temperature.

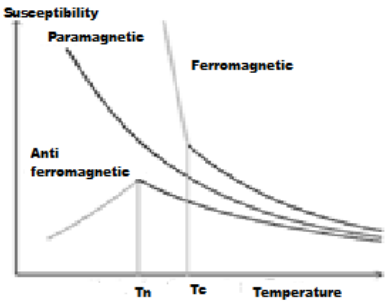
Ferri magnetic materials

Ferri magnetic materials are a class of ordered structures in which the magnetic moments at particular crystal sites are anti parallel and unequal. These materials are treated as two sub lattices of a crystal with different magnetic moments and anti parallel alignments. Generally these materials contain cations of two

or more types with different magnetic moments and hence show a net magnetisation not equal to zero. Examples of such materials are $NiFe_2O_4$, $CoFe_3O_4$, and $BaFe_{12}O_{19}$ etc.

Ferri magnetic materials like ferro magnetic materials show significant magnetisation below the transition temperatures. Above T_c the materials display paramagnetic behaviour.

Magnetic susceptibility vs temperature



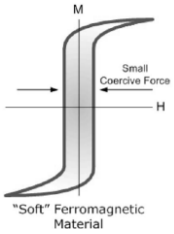
The temperature dependence of the susceptibility for the Para, Ferro and antiferro magnetic materials are summarised as shown. For paramagnetic materials the susceptibility χ_m varies monotonically as $1/T$ following the Curies law.

Ferromagnetic materials follow the Curie Weiss law and exhibit a paramagnetic behaviour above the Curie temperature.

Anti-ferromagnetic materials show an increase in susceptibility till the Neel temperature above which the material behaves as a paramagnetic material.

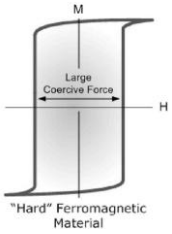
Soft and Hard Magnetic materials

Ferromagnetic materials can be classified as soft and hard materials depending on the nature of the hysteresis displayed by the material.



Soft magnetic materials are easily magnetisable and de-magnetisable. They are characterised by a small coercivity and large saturation magnetisation. The hysteresis loop is narrow and has low losses.

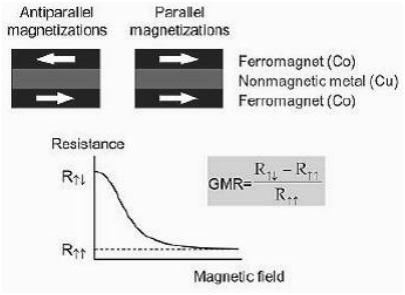
Soft magnetic materials find application in high frequency switching of the magnetisation and are used in transformers, motors and generators.



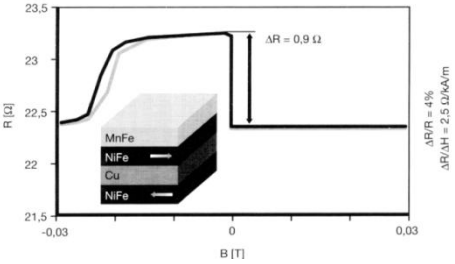
Hard magnetic materials on the other hand are difficult to magnetise and demagnetise. They exhibit a very high retentivity and require a large coercive field to demagnetise the material. The area under the hysteresis curve is large indicating the large amount of energy loss.

The high retentivity of the material makes it ideal for magnetic storage of information as in hard disk drives. The current capabilities are close to 1 Terra bits per square inch.

Gaint Magneto Resistance device.



Magneto resistance has been observed in layered magnetic materials where the resistance across the thickness of two magnetic layers (generally Cobalt) separated by a non magnetic layer (generally Copper) shows a dependence on the magnetisation states of the individual layers. The resistance to current flow depends on the direction of magnetisation of the two layers and can show large variations in the resistance. The effect has been attributed to the spin scattering of the electrons when they flow through the material. The scattering of electron is reduced when the magnetisation of the two layers is parallel. When the spin state of the two layers are anti parallel the scattering and hence the resistance increases.



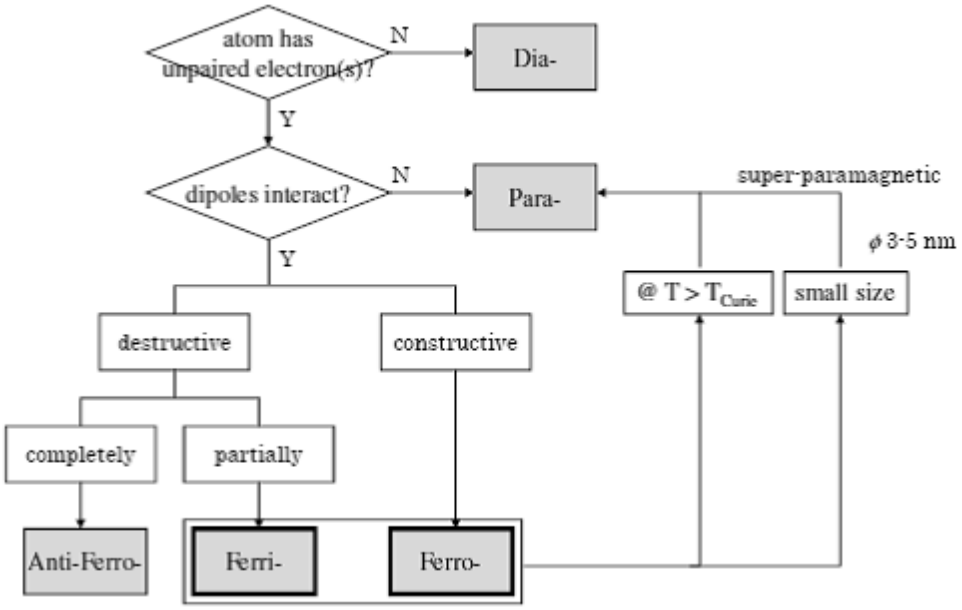
When the magnetic layers are in the range of 3 – 5nm with the separation layer about 25nm, it has been observed that the change is resistance can be as high as 50% of which is significant for any practical measurements and applications.

The Giant Magneto Resistor finds application in the read head of magnetic memories. One of the layers ferromagnetic (soft magnetic

material) layer is pinned to an anti-ferro magnetic material and the other (soft magnetic material) free layer's spin orientation is flipped by the magnetisation of the domain (hard magnetic material) on the recording media.

General classification of magnetic materials

A general scheme for classifying materials according to the atomic characteristics is represented.



Questions and Problem set

1. Derive and expression for the Bohr Magneton and calculate the value.
2. Discuss the concepts of Larmor precision and gyromagnetic ratio.
3. Elaborate on two tests which can differentiate a paramagnetic material from a diamagnetic material
4. Discuss the parameters that distinguish ferro, antiferro and ferri magnetic materials
5. Classify magnetic materials on the basis of the magnetic susceptibility.
6. Bring out the differences between soft and hard magnetic materials.
7. Write a note on applications of magnetic materials
8. Discuss the magnetic hysteresis of materials.
9. Discuss magnetic memory materials.
10. An electron in a hydrogen atom moves in a circular orbit of radius 0.065nm. The electron makes 10^{16} revolutions per second. Calculate the orbital magnetic moment.
11. The saturation magnetic induction of nickel is 0.65 Wbm^{-2}. If the density of nickel is 8906 kgm^{-3} and atomic weight is 514.7. Calculate the magnetic moment of nickel in Bohr magneton.

Magnetism titbits

- The first truly scientific study of magnetism was made by the Englishman William Gilbert (1540–1603), who published his classic book On the Magnet in 1600. He experimented with lodestones (magnetite) and iron magnets, formed a clear picture of the Earth's magnetic field, and cleared away many superstitions that had clouded the subject.
- James Clerk Maxwell (1831–1879), Scottish physicist, who developed the classical theory of electromagnetic fields described by the set of equations known as Maxwell's equations.
- Pierre Curie (1859–1906) was a French physicist who worked extensively on magnetic materials. He and his wife, Marie (Sklodowska) Curie (1867–1934), later became famous for their research on radioactivity.
- Pierre Weiss (1865–1940), French physicist deserves to be called the "Father of Modern Magnetism" because almost the whole theory of ferromagnetism is due to him, and his ideas also permeate the theory of ferrimagnetism. Most of his work was done at the University of Strasbourg.
- The existence of isolated magnetic poles, or monopoles, is not forbidden by any known law of nature, and serious efforts to find monopoles have been made [P. A. M. Dirac, Proc. R. Soc. Lond., A133 (1931) p. 60; H. Jeon and M. J. Longo, Phys. Rev. Lett., 75 (1995) pp. 1443–1446]. The search has not so far been successful.