CH2C01U Electric and Magnetic Phenomena, Thermodynamics and Elementary Solid State Physics

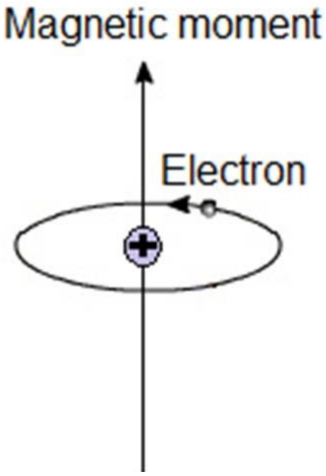
Lecture 1: Magnetization in materials

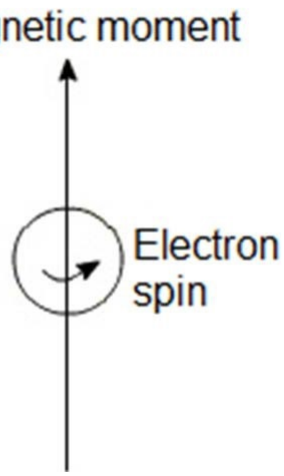
Lecturer: Dr. Shinoj V K

1.1 Introduction

A magnetic field is the magnetic effect of electric currents and magnetic materials. A magnetic field is produced by an electrical charge in motion e.g. current flowing in a conductor, orbital movement and spin of electrons. **Magnetic flux density, B**: It is the magnitude of the field strength within a substance subjected to a field H.
B = μH (Tesla or $Weber/m^2$).
μ, is called the permeability, is the measure of the degree to which a material can be magnetized. Analogous to electric dipole, a magnetic dipole can be defined as two monopoles of opposite and equal strength separated by a certain distance. A magnetic monopole, however, is not observed in nature.

1.1.1 Magnetic moments





All materials are made up of large number of atoms. In each atom the electron revolve round the nucleus in fixed orbits. The revolving electron forms a very small current loop and each current loop has magnetic dipole moment. In addition to orbital motion of electron, each electron has a spin motion also. This spin motion also contribute to magnetic dipole moment of atom. Magnetism in a material arises due to alignment of magnetic moments.

1.2 Magnetization

With the application of a magnetic field magnetic moments in a material tend to align and thus increase the magnitude of the field strength. This increase is given by the parameter called magnetization, M. It is the total magnetic moment per unit volume. Its unit is A/m.

$$B = \mu_0 H + \mu_0 M \tag{1.1}$$

The intensity of magnetization can be defined as the magnetic moment developed per unit volume of the substance when subjected to uniform magnetic field. The intensity of magnetization is proportional to magnetising field. $M \propto H$.

$$M = \chi_M H \tag{1.2}$$

Where χ_M is the magnetic susceptibility. Hence the magnetic susceptibility is the ratio of intensity of magnetization to magnetizing field. It is the measure of capacity of material to get magnetized.

1.2.1 Relation between Magnetic induction and susceptibility

When a specimen is kept in magnetizing field, it gets magnetized. The resultant field is,

$$B = \mu_0(H + M) = \mu_0(H + \chi_M H) = \mu_0 H(1 + \chi_M) \tag{1.3}$$

$$\frac{B}{H} = \mu_0(1 + \chi_M) \tag{1.4}$$

But,

$$\frac{B}{H} = \mu \tag{1.5}$$

μ, the absolute permeability.

$$\mu = \mu_0(1 + \chi_M) \tag{1.6}$$

i.e.

$$\mu_0 \mu_r = \mu_0(1 + \chi_M) \tag{1.7}$$

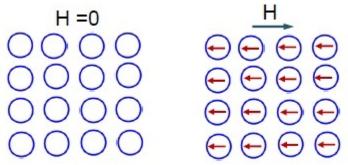
$$\chi_M = \mu_r - 1 \tag{1.8}$$

1.3 Types of Magnetism

Depending on the existence and alignment of magnetic moments with or without application of magnetic field, three types of magnetism can be defined:

1.3.1 Diamagnetism

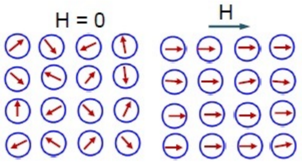
It is a weak form of magnetism which arises only when an external field is applied. It arises due to change in the orbital motion of electrons on application of a magnetic field. There is no magnetic dipoles in the absence of a magnetic field and when a magnetic field is applied the dipole moments are aligned opposite to field direction. The magnetic susceptibility, χ_M $(\mu_r - 1)$ is negative.The permeability is less than unity.



eg. Al2O3, Cu, Au, Si, Zn

1.3.2 Paramagnetism

In a paramagnetic material the cancellation of magnetic moments between electron pairs is incomplete and hence magnetic moments exist without any external magnetic field. However, the magnetic moments are randomly aligned and hence no net magnetization without any external field. When a magnetic field is applied all the dipole moments are aligned in the direction of the field. The magnetic susceptibility is small but positive. i.e. B in a paramagnetic material is slightly greater than that of vacuum.

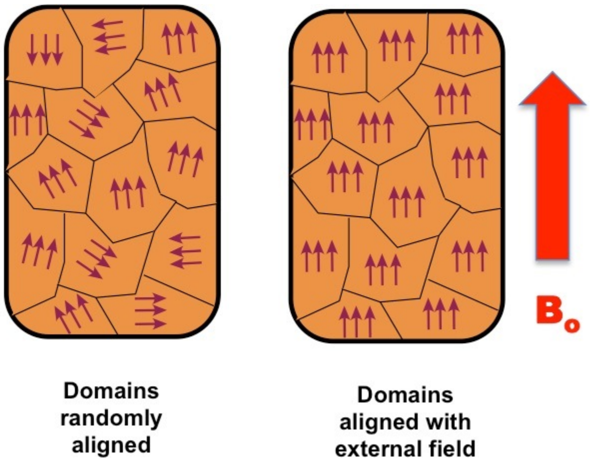


eg. Al, Cr, Mo, Ti, Zr

1.3.3 ferromagnetism

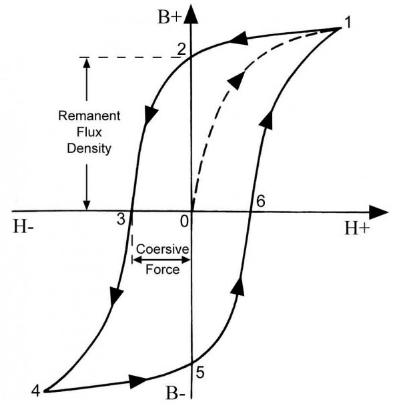
Certain materials posses permanent magnetic moments in the absence of an external magnetic field. This is known as ferromagnetism. Permanent magnetic moments in ferromagnetic materials arise due to uncancelled electron spins by virtue of their electron structure. The coupling interactions of electron spins of adjacent atoms cause alignment of moments with one another. The origin of this coupling is attributed to the electron structure. Ferromagnetic materials have incompletely filled d orbitals and hence unpaired electron spins. χ_M is large and variable. The magnetization exist in ferromagnetic materials in the absence of applied magnetic field is called the spontaneous magnetization. The spontaneous magnetization of ferromagnetic substances are stable only below certain temperature known as Curie temperature. Above curie temperature the thermal effects offset the spin alignment and the they become paramagnet.
e.g. Iron, Cobalt, nickel etc.

1.3.4 Ferromagnetic domain



The spontaneous magnetization of ferromagnetic material is explained by introducing the concept of ferromagnetic domain. According to this concept, a single crystal of ferromagnetic solid is divided into a number of small regions called domains each one of which is spontaneously magnetized by exchange field. The magnetization vector of different domains are however randomly oriented so that no net magnetization in the material as a whole. In the presence of external field, the domains pointing in the direction of field grow at the expense of those pointing in the other direction thereby resulting in some non-zero magnetization in the material. On decreasing the field, the magnetization doesn't follow the same path. There exist some nonzero magnetization even after removing the field altogether. This is called the remanent magnetization or remanence.

1.3.5 Hysterisis



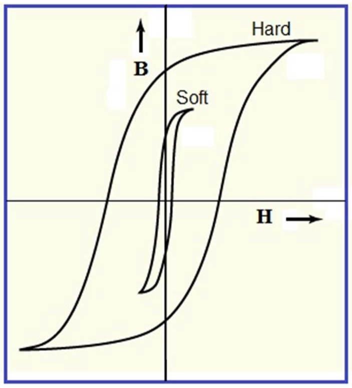
When a ferromagnetic material is magnetized in one direction, it will not relax back to zero magnetization when the imposed magnetizing field is removed. The magnetising curve shown in figure is not reversible; that is if H is increased until the material is saturated, when H is reduced again the value of B does not reduce to zero along the same line. The lack of retraceability of the magnetization curve is the property called hysteresis and it is related to the existence of magnetic domains in the material. Once the magnetic domains are reoriented, it takes some energy to turn them back again.

In figure 5.6 the point 0, where the axes cross, represents a ferromagnetic material that is not magnetised. As the current in the coil is increases, H also increases and between points 0 and 1 B increases following the magnetisation curve. At point 1 the material has reached saturation and B will no longer increase. Now we start to reduce the current in the coil so that we can demagnetise the material, as stated before the graph will not following the same path it did when the current increased but instead goes from point 1, through point 2 then down to point 3. At point 2 H=0, therefore the current has reached zero but there is still some remnant flux density so that the material is still partially magnetised. The current is now reversed so that H is in the opposite direction than before and H has a negative value, therefore when the current is increased, the value of H reduces. At point 3 the material is finally demagnetised and the value of H at this point is called the coercive force. If the reversed current increases furtherer we reach point 4, where the material saturates so that the magnetic poles of the domains face in the opposite direction to those at point 1. The reversed current is now reduced and reaches zero at the point 5 however, once again, some flux remains. If the current is now increased in the original direction all the flux has gone at point 6 and saturation is reached once more at point 1.

This property of ferrromagnetic materials is useful as a magnetic "memory". The magnetic memory aspects of iron and chromium oxides make them useful in audio tape recording and for the magnetic storage of data on computer disks.

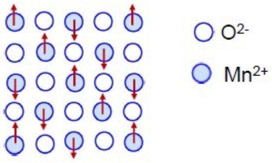
1.3.5.1 Hard and Soft magnets

Based on their hysteresis characteristics ferro and ferrimagnetic materials can be classified as hard and soft magnets. Soft magnets have a narrow hysteresis curve and high initial permeability and hence easy to magnetize and demagnetize. **Hard magnetic materials** retain their magnetism even after the removal of the applied magnetic field. Hence these materials are used for making permanent magnets. In permanent magnets the movement of the domain wall is prevented. They are prepared by heating the magnetic materials to the required temperature and then quenching them. Impurities increase the strength of hard magnetic materials. They have large hysteresis loss due to large hysteresis loop area.Susceptibility and permeability are low. Coercivity and retentivity values are large.



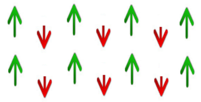
Soft magnetic materials are easy to magnetize and demagnetize. These materials are used for making temporary magnets. The domain wall movement is easy. Hence they are easy to magnetize. By annealing the cold worked material, the dislocation density is reduced and the domain wall movement is made easier. Soft magnetic materials should not possess any void and its structure should be homogeneous so that the materials are not affected by impurities. They have low hysteresis loss due to small hysteresis area. Susceptibility and permeability are high. Coercivity and retentivity values are less.

1.3.6 Antiferromagnetism



Antiferromagnetism, type of magnetism in solids such as manganese oxide (MnO) in which adjacent ions that behave as tiny magnets (in this case manganese ions, Mn2+) spontaneously align themselves at relatively low temperatures into opposite, or antiparallel, arrangements throughout the material so that it exhibits almost no gross external magnetism. Like ferromagnetic materials antiferromagnetic materials also possess dipole moment due to spin of electron. The opposite alignment of adjacent dipoles due to exchange interaction. The susceptibility is very small and is positive. In antiferromagnetic materials, which include certain metals and alloys in addition to some ionic solids, the magnetism from magnetic atoms or ions oriented in one direction is canceled out by the set of magnetic atoms or ions that are aligned in the reverse direction.

1.3.7 Ferrimagnetism



In ferrimagnetic materials, the magnetic moments are lined up on different sublattices in opposite directions, somewhat like, but different from, antiferromagnetic materials (compare the two diagrams). The main difference here is that opposing moments have unequal strengths so a net magnetism results, as shown in the diagram below using two different sized arrows. Each arrow represents a magnetic moment.For ferrimagnetism to happen, the sublattices must consist of two different materials or two different oxidation states of one element, such as Fe^{2+} and Fe^{3+} ions, which differ in the strength of their magnetic moments.

Ferrimagnetic materials possess magnetic dipole moment due to the spin of the electron. A ferromagnetic material is composed of more state of different transition elements. The susceptibility is very large and positive.
E.g. Nickel, Ferrite and Ferrous ferrite