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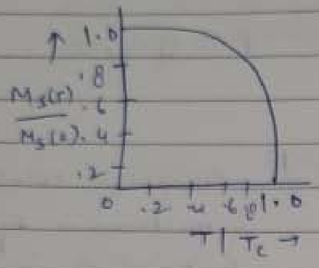
B.Sc (PS) Comp. Sci VI Sem
Solid state Physics.

beyond the temperature T_c which is known as ferromagnetic Curie Temperature. The variation of spontaneous magnetization with temperature is shown in fig.(3)



spontaneous magnetization Vs Temp. for $T<T_c$.

It becomes maximum at 0K when all the moments are lined up in a particular direction under the influence of the exchange field. This variation of M_s enables one to classify the Paramagnetic - ferromagnetic transition as a second order phase transitions i.e transition characterized by an order parameter (e.g M_s in this case) which is non-zero only below T_c.

Paramagnetic Region!-

Consider the magnetization in the region well above the Curie temperature. For $T>T_c$, the spontaneous magnetization is zero and an external field will have to be applied to produce some magnetization. This field should, however be weak enough to avoid the saturation state. In such a state, we find from eq.(5) that $x<<1$ and we can write

$$B_J(x) \equiv \frac{(J+1)}{3J}x$$

Therefore, the expression eq. (3) becomes

$$M = Ng\mu_B(J+1)\frac{x}{3}$$

$$x = \frac{gJ\mu_B(B+\lambda M)}{KT} \quad \text{—— (12)}$$

Thus,

$$M = \frac{Ng^2\mu_B^2 J(J+1)}{3KT}(B+\lambda M) \quad \text{—(13)}$$

which gives $\chi = \frac{\mu_0 M}{B} = \frac{\mu_0 M}{B_a+\lambda M}$ —(14)

multiplying eq. 13 both sides by μ_0.

$$\mu_0 M = \frac{Ng^2\mu_B^2\mu_0 J(J+1)(B+\lambda M)}{3KT.}$$

$$\text{or } \frac{\mu_0 M}{B+\lambda M} = \frac{Ng^2\mu_B^2\mu_0 J(J+1)}{3KT.}$$

$$\chi = \frac{Ng^2\mu_B^2\mu_0 J(J+1)}{3KT.}$$

also $\chi = \frac{C}{T}$.

$$\frac{\mu_0 M}{B_a+\lambda M} = \frac{C}{T.}$$

$$\mu_0 MT = CB_a + \lambda MC$$

$$\mu_0 M\left(T - \frac{C\lambda}{\mu_0}\right) = CB_a.$$

$$\frac{\mu_0 M}{B_a} = \frac{C}{T - \frac{C\lambda}{\mu_0}}$$

$$\text{or } \chi = \frac{\mu_0 M}{B_a}$$

$$\text{hence } \chi = \frac{C}{T - \frac{C\lambda}{\mu_0}} = \frac{C}{T-T_c} \quad \text{—(15)}$$

$$T_c = \frac{C\lambda}{\mu_0} \quad \text{or} \quad C = \frac{\mu_0 T_c}{\lambda} \quad \text{—(16)}$$

$$\& \; T_c = \frac{\lambda Ng^2\mu_B^2 J(J+1)}{3K.} \quad \text{(17)}$$

The expression eq (15) is known as Curie-Weiss law.

It satisfactorily describes the temperature dependence of susceptibility in the paramagnetic region provided the temperature is well above the Curie temperature. The Curie temperature determined from the theory of spontaneous magnetization differs by a few degrees from the experimentally determined value for the paramagnetic region.

Concept of ferromagnetic Domain and ferromagnetic Hysteresis:-

A ferromagnetic material has spontaneous magnetization i.e it behaves like a magnet. Iron is a typical ferromagnetic material. But it is well known that not all pieces of iron are magnets. A piece of iron has to be magnetized to make it a magnet. If all ferromagnetic materials have spontaneous magnetization what is the difference between a piece of magnetized ferromagnetic material and a piece of unmagnetized ferromagnetic material?

In an unmagnetised, although there is spontaneous magnetization due to the strong internal magnetic field, the orientation order of the spin magnetic moment does not extend throughout the material. The atoms (spin magnetic moments) within a small region get aligned in a specific direction. This small region within which there is a single direction of orientation is called a <u>ferromagnetic</u> <u>domain</u>. A ferromagnetic material consists of a large number of domains within each of which all the spin magnetic moments are oriented in one specific direction. The domains are all magnetized in different directions as shown in fig 1.

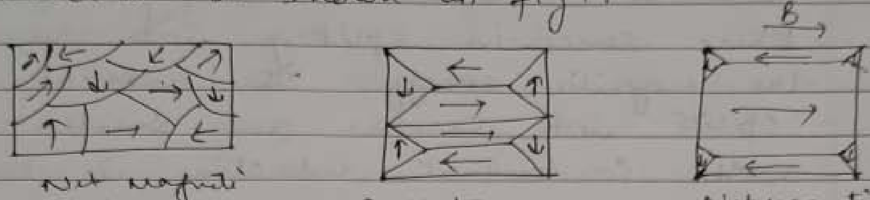


fig 1.

Because of random orientation → net magnetization is zero. Such a piece is said to unmagnetized. When the material is subjected to external magnetic field, those domains which are parallel or nearly parallel to magnetic field grows at the expense of those which are unfavourable. In other words, more and more atomic magnetic moments orient themselves in the direction of the field, so that size of the favourably oriented domains will become larger (see fig 1.)

Normally a ferromagnetic material remains in the unmagnetized status with large number of domains randomly oriented. The reason for this is that in the magnetized state, the material would be a source of large magnetic field surrounding the material as shown in fig. 2.

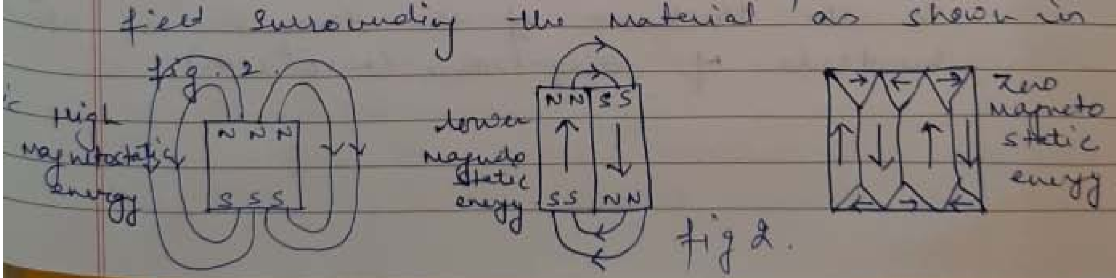


fig 2.

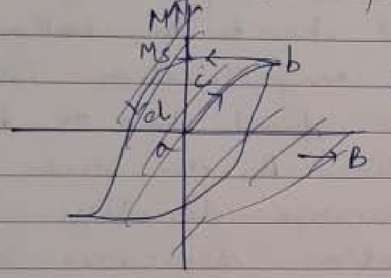
The magnetostatic energy of the field is quite high. By splitting into smaller domains, the external field would be reduced, thereby decreasing the magnetostatic energy. This is illustrated in fig (2)(b) & 2(c), where successive splitting into domains lowers the magnetic energy. The material normally splits into smaller and smaller domains with concomitant reduction in the magnetostatic energy. The opposing mechanism is the exchange energy which tends to align the spin magnetic moments parallel, so as to reduce the number of domains. Eventually an equilibrium state is attained with an optimum domain size. The size of the domains is normally of the order of

Domain wall: Two adjacent domains which are alligned in different directions are seprated by a thin region called the Domain wall. The domain wall is nothing but a large number of spin magnetic moments in which successive spins are gradually changing their orientations in small steps, upto the orientation of the adjacent domain. The change in orientation takes place over about several hundred atomic distances. So the thickness of the domain is about hundreds of angstroms ($\sim 10^{-2} \mu m$).

Ferro magnetic Hypteresis:-

The ferromagnetic material normally does not possess net magnetization due to the random orientation of the magnetic domain. If the material is subjected to an external magnetic field, the domains in the favourable directions grow in size and thus the material acquires a net magnetization.

The variation of magnetization as a function of the field is shown in fig. 1



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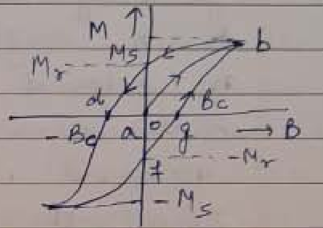

Hysteresis curve of a ferromagnetic material

Initially for small fields the variation is linear and then the curve becomes non-linear. This variation is shown by the portion 'ab' of the curve. At a certain magnetic field the magnetization reaches a maximum and does not increase further. At this stage, the magnetization has reached its maximum value called the saturation magnetization M_s. Further, increase in the field cannot increase the magnetization any more as already all the spins are in the direction of the field.

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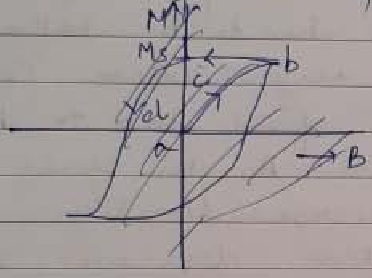

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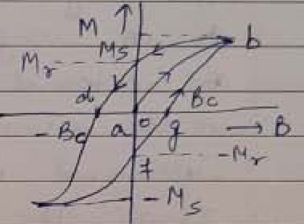

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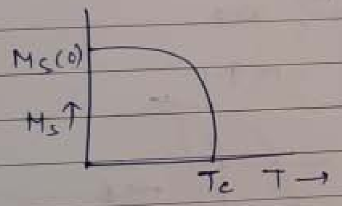
After the material reaches its saturation magnetization, if the external magnetic field is gradually reduced, the magnetization decreases, but it does not retrace the curve along ba, but takes the path bc as shown. This means that the magnetization M lags behind the applied field B. The magnetization will have a higher M value at each value of B. When B becomes zero, the magnetization will have a non-zero magnetization M_r called the remanent magnetization.

If now a permanently magnetized ferromagnetic material has to be taken back to its original zero magnetization configuration, an external magnetic field has to be applied in the reverse direction. As the field is increased in the reverse direction from zero, the magnetization decreases from M_r, as shown by the portion cd in the Hysteresis curve. The magnetization becomes zero at $B = -B_c$. This field is called the coercive field. It is defined as the field that has to be applied in the reverse direction to completely demagnetize a permanent magnet. If the field is now increased in the negative direction, the material attains saturation magnetization $-M_s$ in the reverse direction. A symmetrical curve is traced in the negative quadrant as shown. The closed curve is called the Hysterasis loop. When a ferromagnetic material is taken through a cycle of Hysteresis loop, there will be energy loss due to the dissipated energy required to push the domain walls back and forth. The hysteresis loss will be more due to the presence of imperfections in the crystal. The area of the hysteresis loop is a measure of the energy loss.

The saturation magnetization M_s of a ferromagnetic material is temperature dependent. Above the curie temperature, the ferromagnetic material becomes paramagnetic i.e saturation magnetization in the material vanishes. As the temp. is increased from 0K, the saturation magnetization decreases from a maximum value and becomes zero at the curie temperature T_c. The variation of M_s as a function of temperature is shown in the fig.



Variation of saturation magnetization as a function of temperature.

~~Easy and~~ Hard and Soft ferromagnetic Materials! -

Soft ferromagnetic materials! -

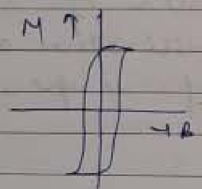
- They are those which can be easily magnetized and demagnetized. i.e they have a less coercive field.

→ Hysteresis loop for these material will be thin and long, consequently the energy loss which is equal to the area of the hysteresis loop is very low. E.g are Iron-Silicon alloys, Iron-Co-Manganese alloy etc. ~~or~~

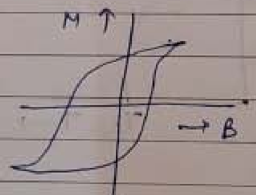
→ Applications; they can be used in transformer cores, motors, generators, sensors etc.

Hard magnetic materials:-

→ They are those which are difficult to magnetize and demagnetize. They are used in application where permanent magnets with high magnetic fields are required. A hard magnetic material has high coercive field and hence a wide hysteresis loop as shown in fig. E.g of hard magnetic materials are alnico, rare earth metal alloys with Mn, Fe, Co, Ni, etc.



Soft



Hard.

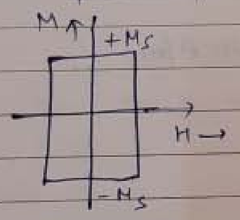
Ferrimagnetic materials or Ferrites:-

They are a special class of ferromagnetic materials. They exhibit all properties of ferromagnetic materials like high permeability, saturation magnetization, hysteresis etc.

→ They have special characteristics which make them highly suitable for high frequency applications and in special magnetic devices.

→ The special feature of ferrites is that, in the magnetized state, all the spin magnetic moments are not oriented in the same direction. Some of them are oriented in the opposite direction. But since the spin magnetic moments are of two types with different values, the net magnetic moment will be finite. Ferrites have the molecular formula $Me^{2+}O.Fe_2^{3+}O_3$, where Me stands for a divalent metal such as Fe, Mn, Co, Ni. The crystal structure of ferrite is the inverse spinel structure.

Hysteresis curve of a ferrite:-



	Parameter	Diamagnetic	Paramagnetic	Ferromagnetic
1.	Response to a magnetic field	gets feebly repelled	get feebly attracted	gets very strongly attracted
2.	Status of atomic dipoles in the absence of ext. field	No permanent dipoles	Permanent dipoles randomly oriented	Permanent dipoles aligned within a domain
3.	Relative permeability	$\chi < 1$	$\chi > 1$	Very high
4.	Magnetic susp	of the order of -10^{-8}	of the order of $+10^{-8}$	positive and very high
5.	Temp. dependence of magnetic susp.	independent of temp.	$= \frac{C}{T}$	$= \frac{C}{T - T_c}$

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Page

Q1. Magnetic susceptibility of aluminium at room temp. is 0.82×10^{-8}. Calculate its magnetization when a field of 0.25 T is applied.

Ans. $\chi = \mu_0 \frac{M}{B}$

$$M = \chi \frac{B}{\mu_0} = 0.82 \times 10^{-8} \times \frac{0.25}{4\pi \times 10^{-7}}$$

$$M = 1.63 \times 10^{-3}\ \text{A/m.}$$

Q. A Paramagnetic salt contains 10^{26} ions/m^3 with magnetic moment $0.1\mu_B$. Calculate the magnetization in a field of 1 T at 300 K.

Ans. $M = \frac{N\mu^2}{k_B T} B$

$$= \frac{10^{26} \times (0.1 \times 9.27 \times 10^{-24})^2 \times 1}{1.38 \times 10^{-23} \times 300}$$

$$= .020\ \text{A/m.}$$