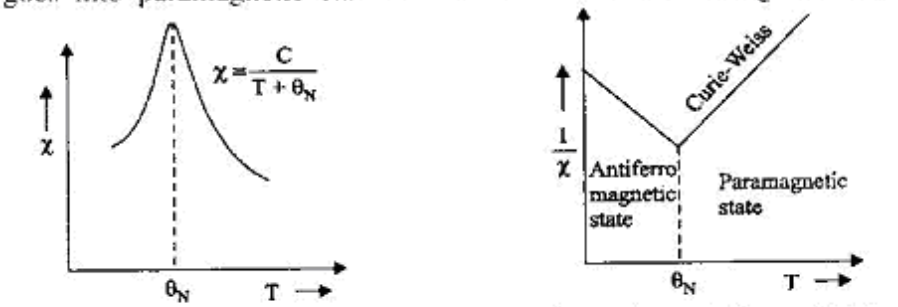
Antiferromagnetic Materials

1. Antiferromagnetic Materials

Any materials having the magnetic interaction between any two dipoles align themselves antiparallel to each other are called antiferromagnetic materials.

Antiferromagnetic materials are crystalline materials, which exhibit a small positive susceptibility in the order of 10^{-3} ***to*** 10^{-5}. Electron spin of neighbouring atoms are aligned anti-parallel. The susceptibility increases with increasing temperature and reaches a maximum at a ceratin temperature called Neel temperature, θ_N. With a further increase in temperature, the material goes into paramagnetic state. The material is antiferromagnetic below θ_N.



(a) **Susceptibility** (b) **Reciprocal Susceptibility**

Fig. . Antiferromagnetic Material - Temperature Effect

In the paramagnetic state, the variation of inverse susceptibility $\left(\frac{1}{\chi}\right)$ with temperature is linear as shown in Fig. (b). The variation of susceptibility with temperature obeys modified Curie Weiss law.

The susceptibility

$$\chi = \frac{C}{T + \theta_N} \qquad T > \theta_N$$

where, θ_N is called Curie temperature.

C is called Curie constant.

The opposite alignment of adjacent site spin magnetic moments in these materials is produced by an unfavourable exchange interaction.

Examples Manganese oxide (MnO) and Chromium oxide (Cr_2O_3).

2. Structure

The elements like Manganese and Chromium exhibit antiferromagnetism at room temperature. Antiferromagnetic materials are of little practical interest.

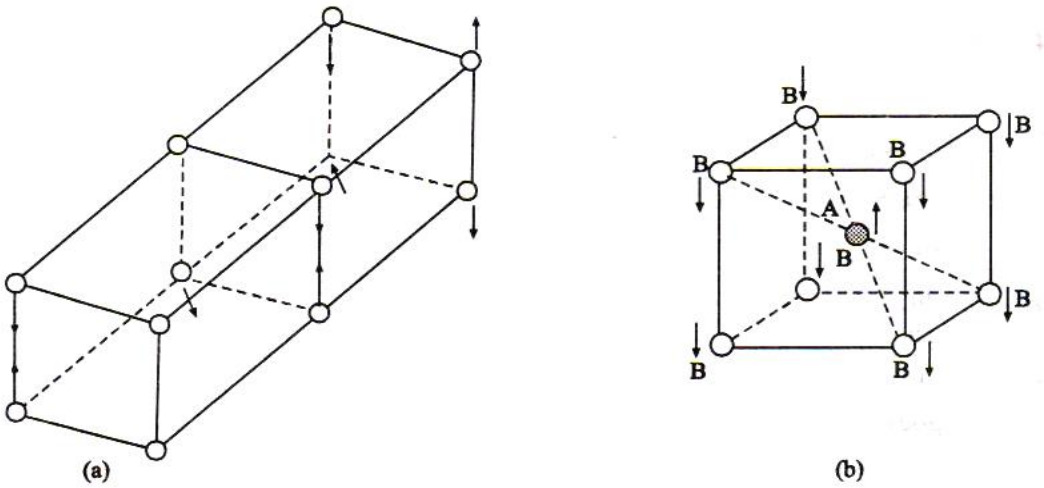


Fig. (a) Alignment of Magnetic Moment in Simple Cubic Crystal at Temperature Below Neel Temperature
(b) Alignment of Magnetic Moment in Body Centered Cubic Crystal

The antiferromagnetic character is explained with a consequence of antiparallel alignment of neighbouring magnetic moment in the crystal. As a result the magnetic moments of *A* and *B* site are cancel with each other. Therefore, net magnetic moment is nearly equal to zero.

3. Properties

1. The dipoles are aligned antiparallel with each other as shown in Fig. Therefore, the resulting net magnetization is zero.

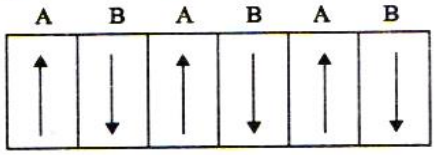


Fig. . Spin Alignment in Antiferromagnetic Material

2. The antiparallel alignment of adjacent dipoles is due to an exchange interaction between them.
3. The magnitude of susceptibility is small and positive.
4. The susceptibility (χ) increases with increase in temperature upto Neel temperature (θ_N). Beyond the Neel temperature (θ_N), the susceptibility decreases with the temperature.
5. In antiferromagnetic material, Neel temperature (θ_N) is the temperature at which susceptibility of the material is maximum.

Examples Ferrous oxide (FeO), Manganese oxide (MnO) and Chromium oxide (Cr_2O_3).

Ferrimagnetic materials (Ferrites)

Substance which possess a spontaneous magnetization in which the magnetic moments of the two sub lattice are opposite in direction but not exactly equal in magnitude are called "Ferrites".

Ferrites are compounds of iron oxides with oxides of other metals

General Formula: $X^{2+}\ Fe_2^{3+}\ O_4^{2-}$

Where $X^{2+} \rightarrow Mg^{2+}$, Zn^{2+}, Fe^{2+}, Mn^{2+}, Ni^{2+}, etc.,

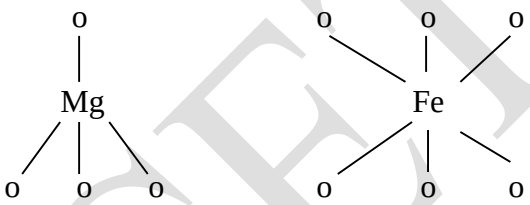
Examples: If X^{2+} is Ni^{2+} then $Ni^{2+}\ Fe_2^{3+}\ O_4^{2-}$ is a nickel ferrite.

X^{2+} is Fe^{2+} then $Fe^{2+}\ Fe_2^{3+}\ O_4^{2-}$ is a ferrous ferrite.

Ferrites formed usually have a face centered cubic structure of oxygen ions closely packed together with the divalent and trivalent metal ions in the interstitial sites. This structure is called spinal structure. There are two types of ferrites.

(i) Regular spinal ferrite structure

(ii) Inverse spinal ferrite structure



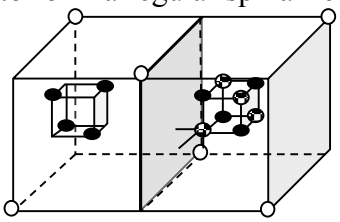
(i) Regular spinal ferrite structure:

In this type each divalent metal ion is surrounded by four O^{2-} Ions in the tetrahedral fashion. It is called "A" site. Totally in a unit cell, there will be 8 tetrahedral sites (8A)

Each trivalent metal ion is surrounded by six O^{2-} Ions in the octahedral fashion. It is called "B" site. Totally in a unit cell, there will be 16 octahedral sites (16B)

Example: $Mg^{2+}\ Fe^{3+}\ O_4^{2-}$

Thus in the regular spinal, each divalent metal ion (Mg^{2+}) exists in a tetrahedral form (A site) and each trivalent metal ion (Fe^{3+}) exists in an octahedral from (B site). Hence the sites "A" and "B" combine together to form a regular spinal ferrite structure as shown in figure.



○ Divalent metal ion

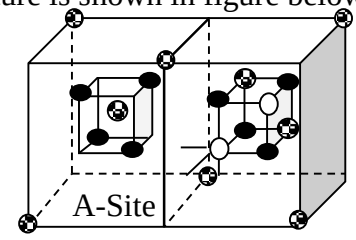
⊗ Trivalent metal ion

● Oxygen ion

(ii) Inverse spinal ferrite structure **A- Site**

Example: $Fe^{3+}\ [Fe^{2+}\ Fe^{3+}]\ O_4^{2-}$

In this, the trivalent metal ions (Fe^{3+}) occupies all the A sites (tetrahedral) and half of the B sites (octahedral) also. Thus the left out B sites will be occupied by the divalent (Fe^{2+}) metal ions. The inverse spinal ferrite structure is shown in figure below.



<u>Types of interaction present in ferrites:</u>

According to Neel, there are three types of interaction, AA, BB and AB. Out of which AA and BB are negative and considerably weak than AB interaction. Thus the effect of AB interaction dominates and gives rise to antiparallel spin arrangement.

Magnetic Moment of a ferrite molecule:

The orbital and spin magnetic moment of an electron in an atom can be expressed in terms of Bohr magnetron $\mu_B = \left(\frac{eh}{4\pi m}\right)$, saturation magnetization of a ferrite molecule can be calculated from number of unpaired spins of Fe^{2+} and Fe^{3+}

Consider Fe^{3+} $[Fe^{2+}$ $Fe^{3+}]$ O_4^{2-}

(i) Fe^{2+} ions have 6 electrons in 3d shell. Out of '6', 2 electrons are paired and 4 electrons are unpaired.

Therefore, Fe^{2+} gives 4 Bohr Magnetron.

↑↑↑↑↑

↓↓↓↓ ↑↑↑↑

(ii) Fe^{3+} ions have 5 electrons are unpaired

Therefore, $Fe3^{+}$ gives 5 Bohr Magnetron

Since we have two Fe^{3+}, totally the Fe^{3+} gives 2x5=10 Bohr magnetron.

Total magnetization = 4+10=14 Bohr Magnetron. But total magnetic moment got only 4.08 μB. Because, in ferrites half of the magnetic spins of Fe_2^{3+} ions are parallel in one direction and the remaining half of Fe_2^{3+} ions are parallel in opposite direction and hence they cancel each other and exists 4 Bohr magnetron which is nearly equal to 4.08 μB.

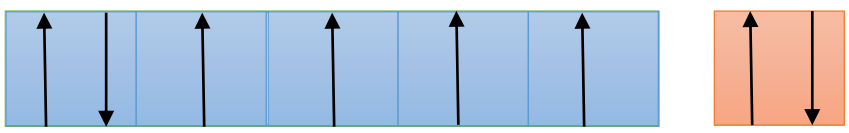
Origin of ferromagnetism and exchange interaction

The ferromagnetic property is exhibited by transition elements such as iron, cobalt and nickel at room temperature and rare earth elements like gadolinium and dysprosium.

The ferromagnetic materials possess parallel alignment of dipoles. This parallel alignment of dipoles is not due to the magnetic force existing between any two dipoles. The reason is that the magnetic potential energy is very small and it is smaller than thermal energy.

The electronic configuration of iron is $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $3d^6$, $4s^2$. For iron , the 3*d* sub shell is an unfilled one. This 3*d* subshell have five orbitals. For iron, the six electron present in the 3*d* subshell occupy the orbitals such that there are four unpaired electrons and two paired electrons as shown in figure.

3d orbital *4s* orbital

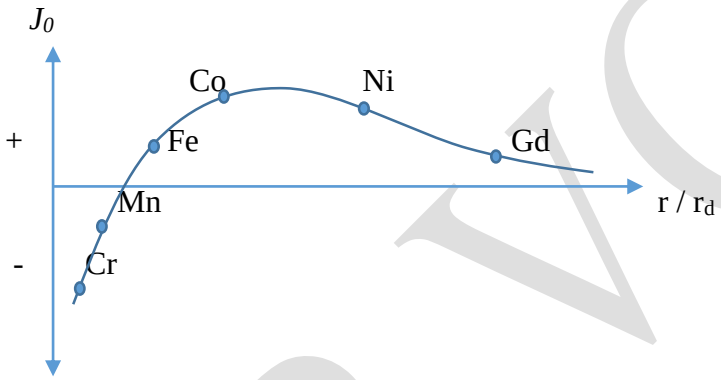


These four unpaired electrons contribute a magnetic moment of $4\mu B$. This arrangement shows the parallel alignment of four unpaired electrons. The parallel alignment of dipoles in iron is

not due to the magnetic interaction. It is due to the Pauli's exclusion principle and electrostatic interaction energy. **The Pauli's exclusion principle and electrostatic interaction energy are combined together and constitute a new kind of interaction known as exchange interaction. The exchange interaction is a quantum mechanical concept.** The exchange interaction between any two atoms depends upon the interatomic separation between the two interacting atoms and the relative spins of the two outer electrons. The exchange interaction between any atoms is given by $E_{ex} = -J_e S_1 S_2$

Where J_e is the numerical value of the exchange integral, S_1 *and* S_2 are the spin angular momenta of the first and second electrons. The exchange integral value is negative for the number of elements. Therefore, the exchange energy value is negative when the spin angular momentum S_1 *and* S_2 are opposite direction. Hence antiparallel alignment of diploe is favoured. This explains the antiparallel alignment of dipoles in antiferromagnetic materials.

In some materials like iron, cobalt and nickel the exchange integral value is positive. The exchange energy is negative when the spin angular momentum is in the same direction. This will produce a parallel alignment of dipoles. A plot between the exchange integral and the ratio of the interatomic separation of the radius of 3*d* orbital (r/r_d) is shown in figure.



For the transition metals like iron, cobalt, nickel and gadolinium the exchange integral is positive, whereas for magnese and chromium the exchange integral is negative. The positive value of the exchange integral represents the material is ferromagnetic and the negative exchange integral value represents the material us antiferromagnetic. In general, if the ratio, $r/r_d > 3$, the material is ferromagnetic, otherwise it is antiferromagnetic.

Weiss molecular Theory of ferromagnetism – Curie temperature

The metals like Fe, Co, Ni etc., exhibit magnetisation even in the absence of external field. Therefore Weiss gave a molecular field theory and postulated the existence of an internal molecular field (H_i). *This internal field is responsible for spontaneous magnetization of a ferromagnetic material, so that only the material possess magnetization even in the absence of an external field.*

The net or effective magnetic moment $H_c = H + H_i$ (1)

Where H is external field, H_i is the internal molecular field and is proportional to the intensity of magnetization

1.e., $H_i \alpha I$ (2)

$H_i = \lambda I$ (3)

Where λ is Weiss constant

Substituting equation (3) in (1), we get

$H_e = H + \lambda I$

From Langevin theory, the intensity of magnetization of the ferromagnetic material is given by

$$I = \frac{N\mu^2}{3K_BT}\left(H + \lambda I\right) \quad (4)$$

Where N is the number of atoms

$$I = \frac{HN\mu^2}{3K_BT}\left(1 + \lambda\frac{I}{H}\right)$$

(or) $$\frac{I}{H} = \frac{N\mu^2}{3K_BT}\left(1 + \lambda\frac{I}{H}\right)$$

$$\chi_m = \frac{C}{T}\left[1 + \lambda\chi_m\right] \qquad \left[\because \frac{I}{H} = \chi_m\right] \quad (5)$$

Where $C = \frac{N\mu^2}{3K_B}$

Equation (5) can be rewritten as

$$\chi_m = \frac{C}{T} + \frac{C}{T}\lambda\chi_m$$

(or) $$\chi_m = \frac{C}{T - \lambda C}$$

(or) $$\chi_m = \frac{C}{T - \theta} \quad (6)$$

This is known as Curie – Weiss law and θ is known as curie temperature.

Equation (6) has three special cases

Case 1: when $T = \theta$, $\chi_m \rightarrow \alpha$

The material is ready to attain external magnetization

Case 2: when $T > \theta$, χ_m = *1/+ve* i.e., χ_m is positive

In this case, the thermal agitation opposes the tendency of Weiss molecular field to align the molecular magnets. So it becomes paramagnetic above Curie temperature.

Case 3: when $T < \theta$, *the material behaves as ferromagnetic material* because at lower temperature Weiss molecular field energy is high and sufficient to overcome the thermal agitation.

Curie temperature

Ferromagnetic material have a critical temperature below which they behave as ferromagnetic and above which they behave as paramagnetic. This critical temperature is known as ferromagnetic curie temperature.

Spontaneous and Saturation magnetization

The molecular magnets in the ferromagnetic material is aligned in such a way that, they exhibit a magnetization even in the absence of an external magnetic field. This is called spontaneous magnetization.

We know that, $H_c = H + H_i$

Here $H = 0$, therefore $H_e = H_i$

(or) $H_e = \lambda I$

Where I is spontaneous magnetization.

Temperature dependence of spontaneous magnetization

When the external field is zero, $H_e = \lambda I$ (1)

From the Langevin theory, we can write intensity of magnetization I as

$I = I_s L(\alpha)$ (2)

Where I_s *is the* saturation magnetization

For Ferro magnets $\alpha = \frac{\mu H_e}{K_B T}$ [since $H = 0$]

(or) $H_e = \frac{\mu \alpha}{K_B T}$ (3)

Comparing equation (1) and (3), we get

$$\lambda I = \frac{\alpha K_B T}{\mu} (or) I = \frac{\alpha K_B T}{\mu \lambda} \quad (4)$$

We know $I_s = N\mu$ (5)

Dividing equation (4) by (5), we have

$$\frac{I}{I_s} = \frac{\alpha K_B T}{N \mu^2 \lambda} = \frac{\alpha}{3}\left(\frac{T}{\theta}\right) \qquad \left[\because \theta = \frac{N \mu^2 \lambda}{3 K_B}\right]$$

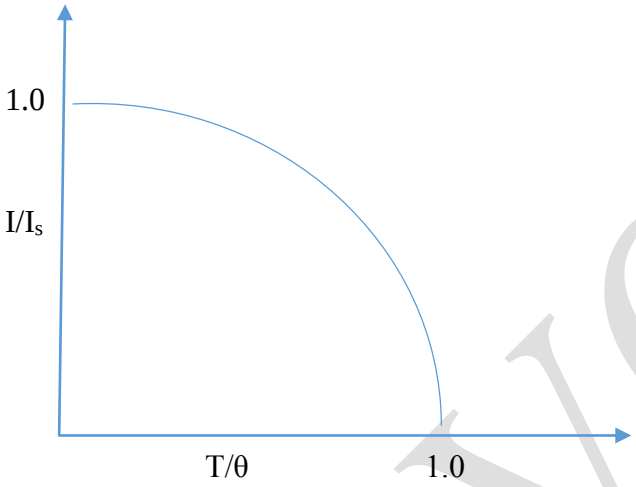
(or) $$\frac{I}{I_s} = f\left(\frac{T}{\theta}\right)$$ [where $f = \alpha/3$]

A graph is plotted between I/I_s as a function of T/θ as shown in figure. From the graph, we infer that

(i)**when the temperature is low,** Weiss field overpowers the thermal energy and it gives rise to maximum magnetization

i.e., $I/I_s = 1$

(ii) **when the temperature is increased** thermal energy increases which randomises more and more of the parallel spins and at curie temperature (T = θ), all the parallel alignment of spin vanishes give rise to zero value of spontaneous magnetization and the Material is to highly susceptible to get the external field. Thus, the substance become paramagnetic.



Explain the writing and reading of data in magnetic hard disk using Giant Magnetoresistive (GMR) sensor?

Principle

In hard disk drives, the binary data in terms of zero's (0) an one's (1) are stored by inducing magnetic moment in a thin magnetic layer and GMR effect is used as the principle to read the data in HDD. Here zero (0) represents missing transition and one (1) represents transition in the medium.

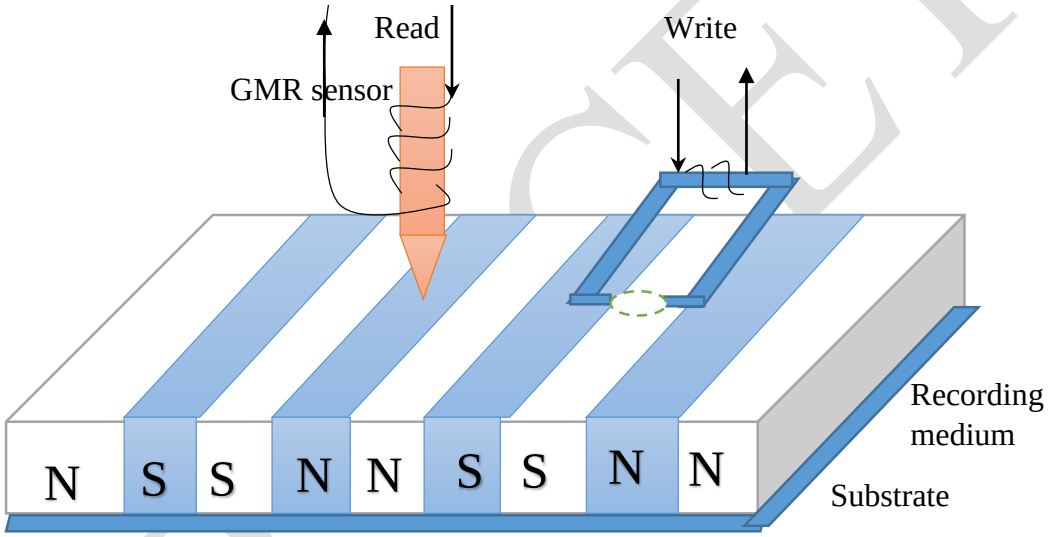
Construction

The HD consists of recording medium madeup of thin layer of magnetic garnets grown over the substrate. The GMR sensor, which is made up of ferrites and antiferromagnetic materials is used as reading element. The writing element is madeup of inductive magnetic transducer. The writing element and the GMR sensor shall be made to slide over the recording media in the longitudinal direction as shown in figure. Hence this method is also called as longitudinal recording. The flow of current through the GMR sensor and writing element shall be adjusted and inturn the magnetization is sensed (or) controlled in the recording media.

Working

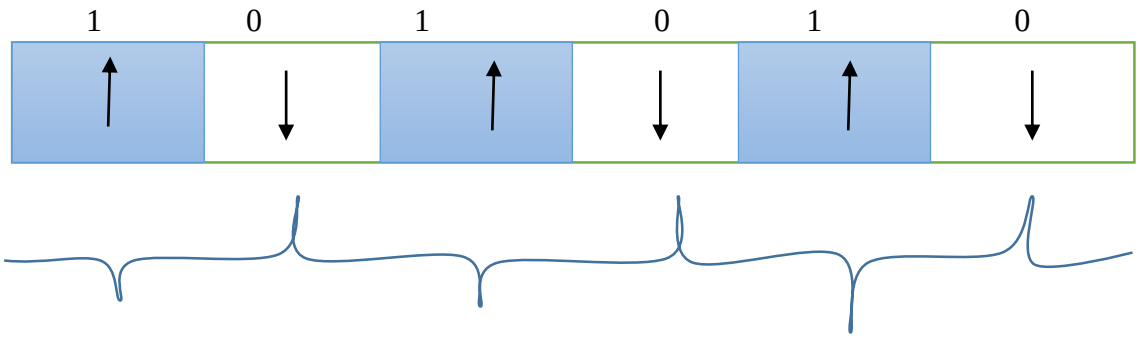
Writing / Storing

1. Initially the current is passed through the writing element and a magnetic field is induced in between the gap of the inductive magnetic transducer.
2. During writing, the amplitude of current is kept constant, and the direction of current is reversed.
3. Due to reversal of current, the magnetization orientation is reversed in the recording medium i.e., from south → North as shown in figure
4. When the induced magnetic field is greater than the coercivity of the recording media, then data is recorded in the form of 1.
5. Thus one (1) is stored as data in the recording medium as a magnetic transition.
6. When there is no magnetic transition, then it is referred as zero (0).
7. In this way the zero's (0's) and one's (1's) are stored in the recording medium.



Reading / Retrieving

8. Giant Magnetoresistive (GMR) effect is the principle used to read / retrieve the data from the recording medium.
9. When the GMR sensor is made to move near the recorded medium, then the resistance of the GMR sensor varies with respect to the orientation of the magnetic moments as follows.
10. When the layers are magnetised in parallel manner, then the resistance in the GMR sensor is minimum and therefore maximum current flows through the sensor, which represents the data as one (1)
11. When the layers are magnetised in antiparallel manner, then the resistance in the GMR sensor is maximum and therefore minimum(or) almost no current flows through the sensor, which represents the data as zero (0)
12. Therefore with the help of the reading current, the zero's (0's) and one's (1's) can be retrieved from the magnetic hard disk drive.



Advantages

- HDD can store the data in terabytes
- It has very large storage capacity
- It is compact in size and can be easily transferred from one place to another.
- The size of recording medium is reduce up to few nano meter range using nanotechnology
- GMR sensor are non-diffusive and are very sensitive in reading

Disadvantages

- HDD is slower than soli state drives
- Consume large power
- Data may be corrupted due to thermal radiation
- HDD has bulkier form factor
- GMR noise ratio is high for nano size recording media

Applications

- Used as storage devices in cloud applications
- Used in coding and signal processing units
- Used in control systems, Nano electronics, etc.,