Module 1: Introduction

Lecture 01: History and overview of magnetic recording

Objectives:

This module will serve as a necessary introduction to the course as well as the manifestation of the magnetic anisotropy property of solid state materials focused to magnetic recording devices, viz., magnetism. We will start our quest with a look at the historical development of magnetic recording techniques. This would not only provide an account of the evolution of the magnetic recording techniques, but would also point towards the future of recording process. This would be followed by understanding the directional dependence of magnetic properties of magnetic materials or magnetic anisotropy and the factors that influence this. We will close this chapter by taking a look at the soft and hard magnetic materials and their characteristics.

Therefore, the following five lectures would cover the following topics:

1. How magnetic recording has evolved over the years?
2. What are the different forms of magnetic media?
3. What is magnetic anisotropy energy and what are the factors that contribute to it?
4. What is magnetostriction?
5. What are soft and hard magnetic materials?

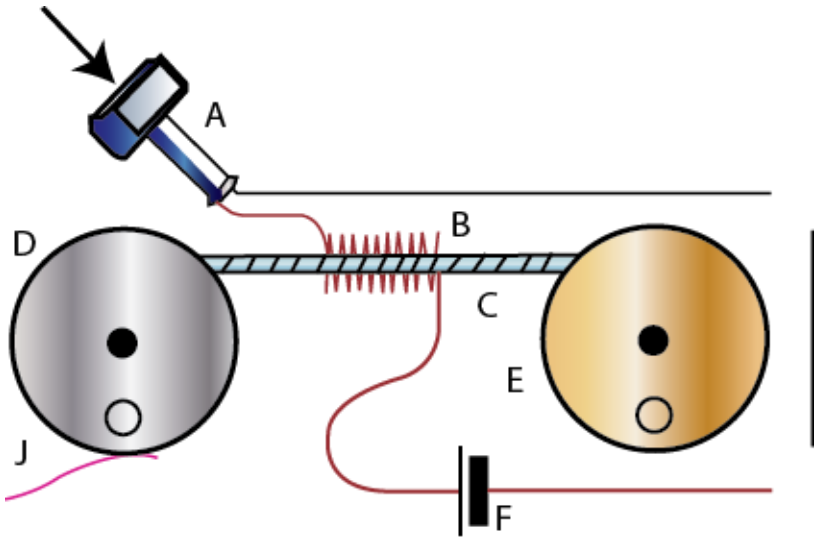


Figure 1.1: Schematic drawing of analogue magnetic recording.

Introduction:

Magnetic recording referring to the storage of data on a magnetized medium is generally classified into two groups of related technologies: media and recording heads. While the first one consists of all technologies concerned with the production and the use of magnetic disks and tapes for storing information, the later one covers all the technologies connected to the process of writing information on the media or reading information from the written media.

Digital recording for storage of computer was first developed by IBM. Magnetic disk drive, called RAMAC, was available in 1957. Earlier to this, magnetic tapes was invented using a paper tape coated either with dried ferromagnetic liquid or with iron powder. Later oxide tapes were developed by 3M Corporation, which ensured the availability of audio recorders in 1940 and video recorders in 1956.On the other hand, the analogue magnetic recording was first demonstrated by a Danish engineer Poulsen by recording acoustical signals on a ferromagnetic wire using an electromagnet connected to a microphone, as shown in Figure 1.1. However, there were two major problems in the recording process: (i) the reproduction of signal was very weak due to the absence of an amplifier, and (ii) low signal to noise ratio due to the nonlinear nature of the recording process.

Magnetic tapes:

Magnetic tapes are the most widely used recording medium for audio and video signals. They are produced as particulate tapes and metal evaporated tapes. The first type is produced in a wide variety of widths at high coating rates and at low cost. However, the major disadvantage of this method is that the magnetic particles only occupy less than 50% of the tape volume. On the other hand, the second type of tapes generally exhibits better performance characteristics but costly to produce. Particulate magnetic recording tapes consist of a coating of magnetic materials with a coating thickness of 3 – 5 μm on a flexible, nonmagnetic substrate, as shown in Figure 1.2.

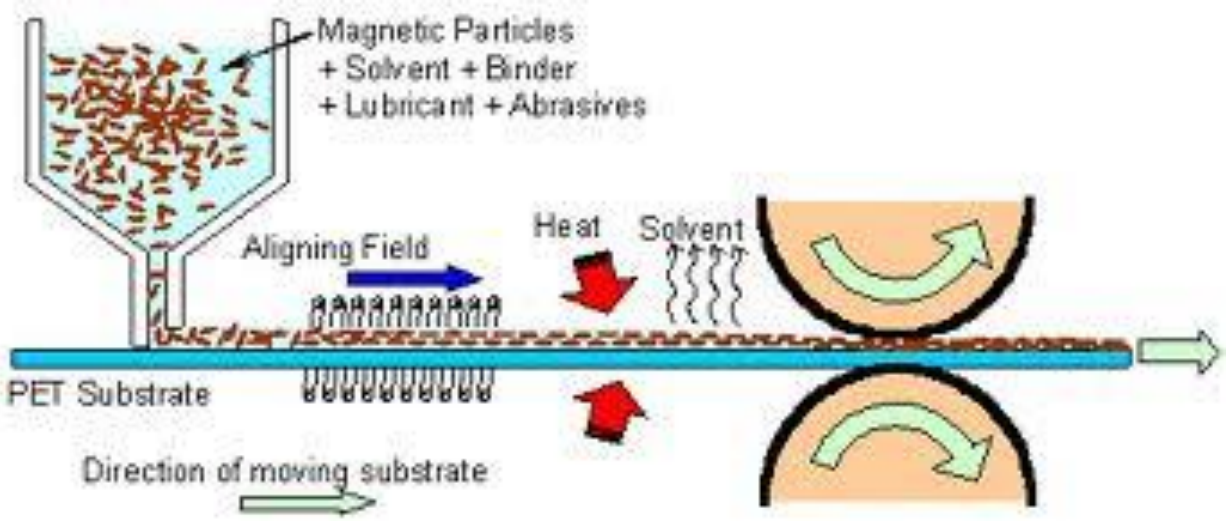


Figure 1.2: Schematic setup for preparing the magnetic tapes.

The coating consists of magnetic particles, a binder to contain and disperse the particles, and lubricants to ease the motion of the tape and abrasives to reduce the wear of the tape. The magnetic particles are acicular (elongated) with a typical dimension of 250 nm in length and 50 nm in width and are of single domain particles, which can be easily magnetized parallel to their long axis. This arrangement is mainly used in conventional longitudinal magnetic recording, as shown in Figure 1.3a.

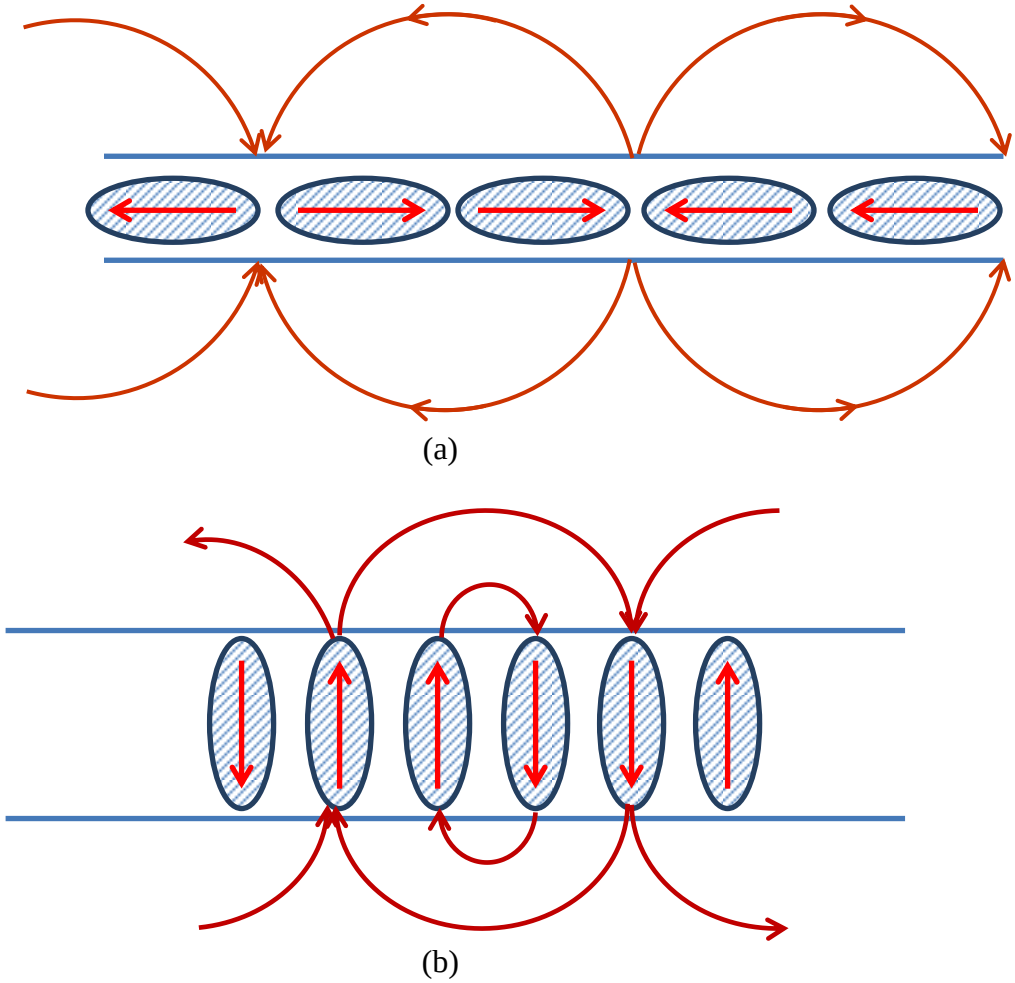
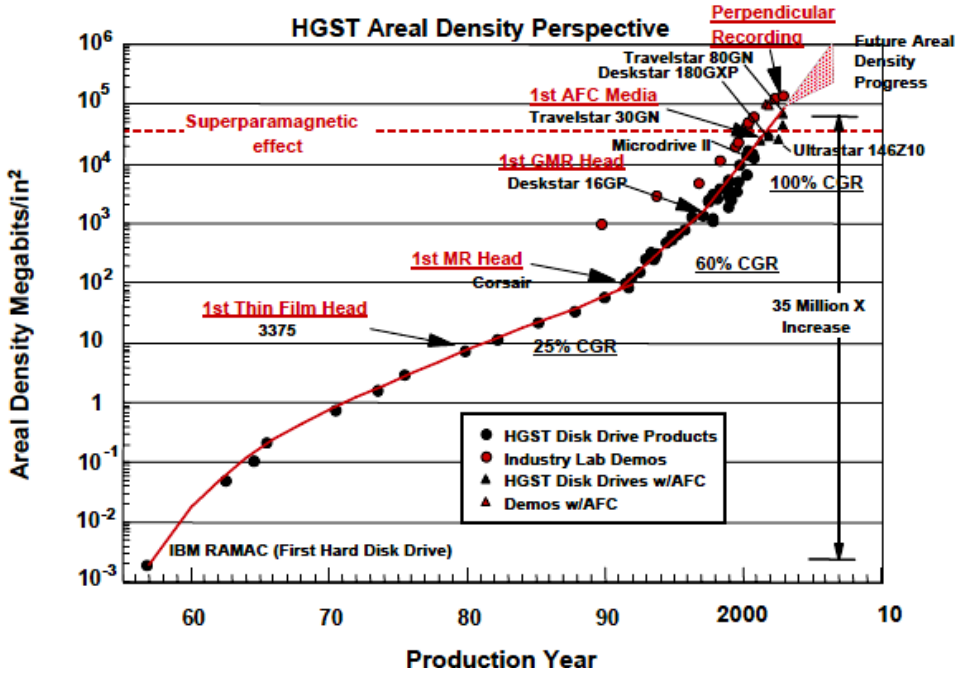


Figure 1.3: Schematic diagrams of arrangments of acicular magnetic particles for (a) longitudinal and (b) perpendicular magnetic recording tapes.

However, the areal densities are limited in the longitudinal magnetic recording. Hence, efforts have been made to fabricate tapes for perpendicular recording in which the long axes of the particles are aligned perpendicular to the surface as shown in Figure 1.3b. This arrangement provides high recording densities despite several difficulties which have been not addressed in the development of perpendicular magnetic recording.

Module 1: Introduction
Lecture 02: History and overview of magnetic recording

The original first hard disk drive (HDD), RAMAC had a storage density of 2000 bit/in^2. The increase in data storage densities since then has beenincessant and the present storage density of 620 GB/in^2 represent an increase of a factor of 10^8. The progress in storage densities is shown in Figure 2.1.The rate of increase in storage densities has accelerated from 25 % to 100 % over the period between 1970 – 1990 and 1995 – 2005 due to the shift of smaller disks, the use of thin film recording media, and the development of advanced read/write heads with the improved signal to noise ratios.



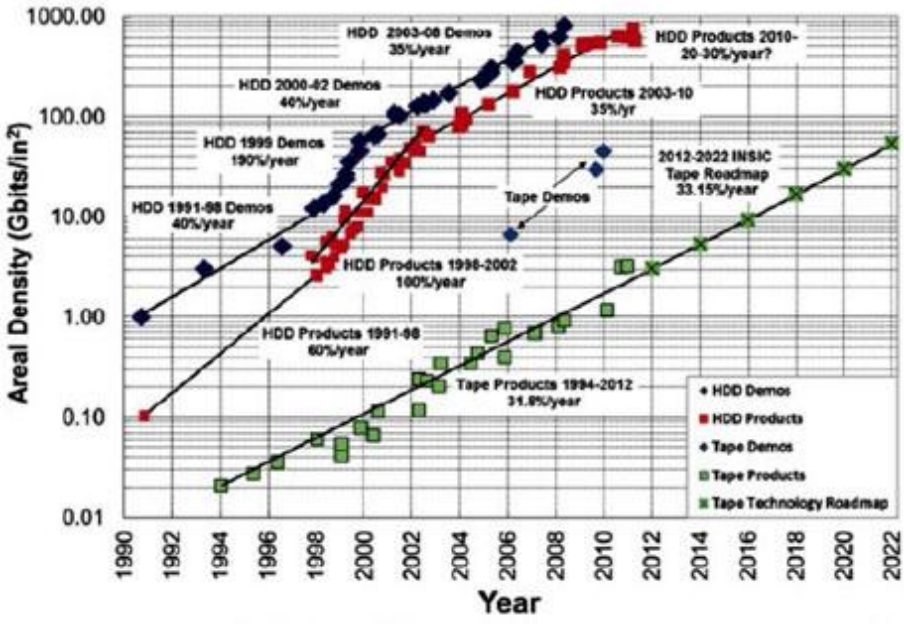
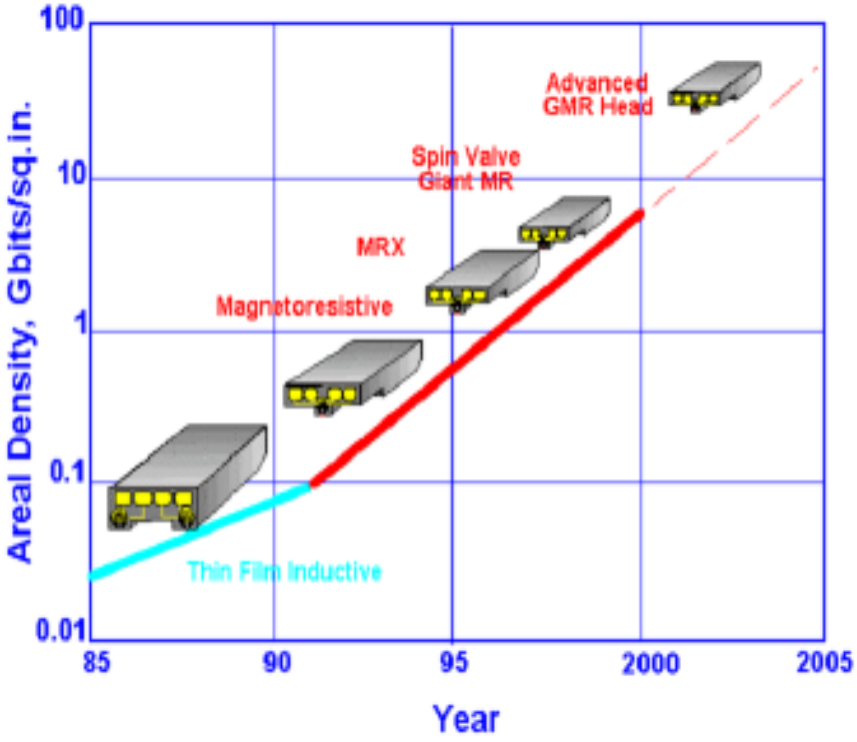
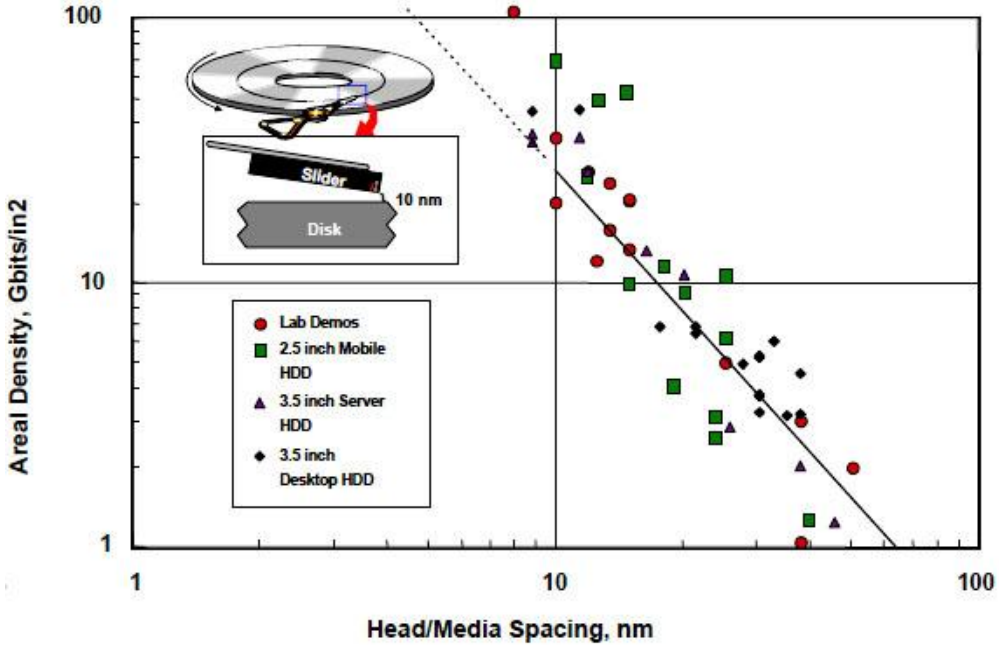


Figure 2.1: Improvement in areal density over the time [1,2].



(a)



(b)

Figure 2.2: (a) Areal density over the time with different heads and (b) physical spacing between the head and media [1].

The projections for the current and future HDD from Western Digital Corporation over the time is also shown in Figure 2.1, in which it is imagined that the development of smaller magnetoresistive (MR) read heads, improvement in actuation between the MR head and media surface, as shown in Figure 2.2, and micromechanics will provide the next stages of evolution. It is also proposed to follow bit patterned media, and scanning tunnelling microscope (STM) like storage in the future.

Materials suitable for magnetic recording:

The most widely used magnetic recording materials in the earlier days is gamma ferric oxide (γ-Fe_2O_3) which has been used in magnetic tapes since 1937. The coercivities of such tapes were in the range of 250 – 400 Oe for the particles of size aspect ratio of 10:1 on length to diameter ratio[3]. The magnetic properties of these particles were not affected by the working environment in the vicinity of the room temperatures as the Curie temperature of the particles was more than 500 ^{o}C. The magnetic properties of the Fe_2O_3 particles were further improved by modifying the surface using Co. The coercivity of the Co surface modified Fe_2O_3 increased to about 900 Oe [3] due to the increase in anisotropy of the materials with the Co addition. Later, the chromium dioxide powder was exercised for recording due to their high saturation magnetization as compared to the iron oxide. However, it is more expensive than the iron oxide which reduced its commercial attraction. Iron powder was also used as a recording medium. This has considerably high saturation magnetization (1700 emu/cc) than the oxide particulate media and had a high coercivity of 1.4 kOe. Eventually, the thin metallic alloy films were proposed as a magnetic medium for high performance, high storage density, hard disk drives. Hexagonal ferrites with high coercivity of 4.6 kOe for the disk shaped barium ferrite particles have also been proposed as one of the suitable materials for magnetic recording. CoCrPt based alloys were the recent outcome for recording as they have improved corrosion resistance compared to pure cobalt. In last few decades, serious efforts have been made to develop metallic thin film recording medium using various types of technology, including the perpendicular magnetic recording media in which the magnetic domains are oriented with the magnetizations normal to the plan of the medium have been pioneered by Iwasaki in Japan [4].More details regarding the properties of the materials used for recording is provided in later lectures.

Another area of interest in magnetic recording is that of magneto-optical devices [5]. These make use of the Faraday and Kerr effects in which the direction of polarization of light is rotated in the presence of a magnetic field. The advantage of the magneto-optical disks is to develop recording disk with significantly increased densities with faster access time. However, the concept of magneto-optical recording has currently not been continued, as the recording of information depends on thermomagnetic magnetization of the materials.

References:

[1]. http://www.hitachigst.com

[2]. http://www.wdc.com

[3]. R.E. Hummel, Electronic Properties of materials, Springer, 2012, Chapter 17.

[4]. S. Iwasaki, IEEE Trans. Magn. 16 (1980) 71.

[5]. R.J. Gambino, T. Suzuki, Magneto-optical recording materials, Wiley-IEEE Press, 1999.

Module 1: Introduction
Lecture 03: Magnetic Anisotropy

Introduction:

Anisotropy plays an important role in understanding the nature of magnetic hysteresis loop for a given material. It refers to the fact that when no magnetic field is applied to a given magneticmaterial, the direction of magnetization prefers to point in a certain direction calledeasy axis. Figure 3.1 shows a typical situation where for zero applied field, themagnetization ***M*** would point along the easy axis shown (α= 0). When a field***H*** is applied, the magnetization is pulled towards the field direction. As the fieldis increased, the magnetization points closer to the field direction. For any intermediate valuesofα, the magnetization is being attracted in opposite directions, i.e., up by the field ***H*** and down by theanisotropy.

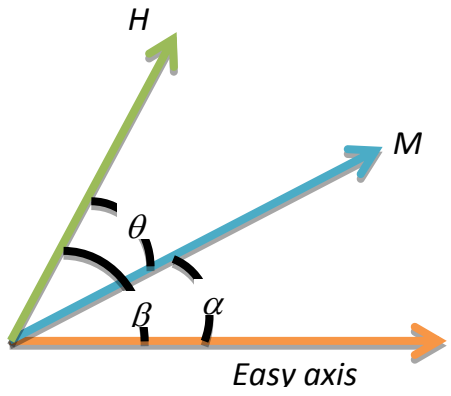


Figure 3.1: Schematic drawing of magnetization, applied field and easy axis for a material.

Let us assume that all the magnetization is pointing in the same direction in a magnetic material, and the material exhibits an easy axis of magnetization. In such scenario, we can describe the energyper unit volume of the magnetization of this material by

$$E = K\,sin^2\alpha \qquad (3.1)$$

where*K* is called the anisotropy constant with an unit of energy per unit volume (J/m^3). Hence, the energy term,*E*, is also energy per unit volume. In general, the magnitude of uniaxial anisotropy is described in terms of the anisotropy field, which is defined as the field needed to saturate the magnetization of a uniaxial crystal in the hard axis direction, as given in eqn.(3.2)

$$H_k = \frac{2K}{\mu_0 M} \qquad (3.2)$$

In general, the energy of the magnetization is given by,

$$E = K\,sin^2\alpha - \mu_0 MH\,cos(\beta - \alpha) \qquad (3.3)$$

where, the first term is anisotropy energy. The second term is due to the magnetic field and the difference in the angle (β-α) is the angle between $\boldsymbol{H}$ and $\boldsymbol{M}$. In order to get equilibrium, we required firstderivative to be zero. Therefore, taking derivative of eqn.(3.3) with respect to the angle results,

$$\frac{dE}{d\alpha} = 2K \sin\alpha \cos\alpha - \mu_0 MH\,sin(\beta - \alpha) = 0 \qquad (3.4)$$

Taking the value of β as 90^o for the equilibrium angle for the magnetization relative to the easy axis and considering the eqn.(3.2) gives➔

$$\sin\alpha = \frac{H}{H_k} \qquad (3.5)$$

The above eqn. indicates that when $\boldsymbol{H}$ = 0, the magnetization points along the easy axis and when $\boldsymbol{H} = \boldsymbol{H_k}$, the magnetization points along the direction of $\boldsymbol{H}$.For any intermediate value of the applied field, the magnetization points at a value of angle given by eqn.(3.5) rotating smoothly between the easy axis and the applied field.

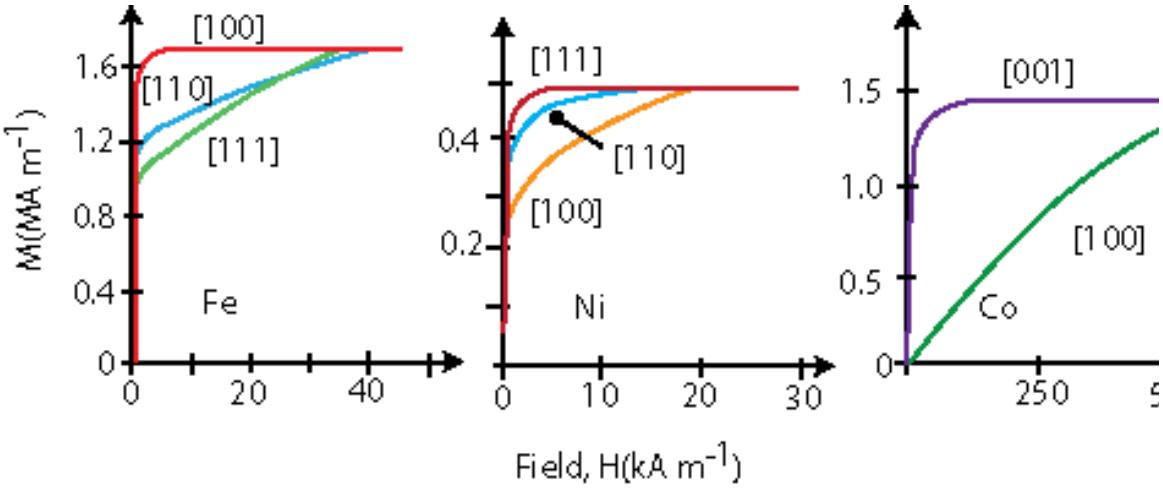


Figure 3.2: Magnetization of single crystals of Iron, Nickel and Cobalt.

Magnetocrystalline anisotropy:

Figure 3.2 depicts the initial magnetization curves of single crystals of the different 3*d* ferromagnetic elements. It is clearly seen that they show a different approach to saturation when magnetized in different directions. For example, the iron shows a ⟨100⟩ as easy directions and ⟨111⟩ as hard directions, while the nickel exhibits ⟨111⟩ as easy axis and ⟨100⟩ as hard directions. This property can be understood by analysing the development of anisotropy energy in different symmetries as given below:

For Hexagonal:

$$E_a = K_1 \sin^2\theta + K_2 \sin^4\theta + K_3 \sin^6\theta + K_3' \sin^6\theta \sin 6\phi$$

For Tetragonal:

$$E_a = K_1 \sin^2\theta + K_2 \sin^4\theta + K_2' \sin^4\theta \cos 4\phi + K_3 \sin^6\theta + K_3' \sin^6\theta \sin 6\phi \quad (3.6)$$

For Cubic:

$$E_a = K_{1c}(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_{2c}(\alpha_1^2\alpha_2^2\alpha_3^2)$$

where α_i are the direction cosines of the magnetization. The K_{1c} term is equivalent to $K_{1c} = K_{1c}(\sin^2\theta\, cos^2\phi \sin^2\phi + \cos^2\theta \sin^2\theta)$. When, θ=0, ϕ=0, this term reduces to eqn.(3.1).

Origin of magnetocrystalline anisotropy:

There are two distinct sources of magnetocrystalline anisotropy: (i) single-ion contributions and (ii) two-ion contributions. The first one is essentially due to the electrostatic interaction of the orbitals containing the magnetic electrons with the potential created at the atomic site by the rest of the crystal. This crystal field interaction stabilizes a particular orbital and by spin-orbit interaction, the magnetic moment is aligned in a particular crystallographic direction. For example, a uniaxial crystal having 2×10^{28} ions/m^3, described by a spin Hamiltonian DS^2 with D/k_B = 1 K and S = 2 will have anisotropy constant $K_1 = nDS^2 = 1.1\times10^6$ J/m^3.

Figure 3.3: Schematic drawing of broadside and head-to-tail configurations for a pair of ferromagnetically coupled magnetic moments.

On the other hand, the later contribution replicates the anisotropy of the dipole-dipole interaction. Considering the broadside and head-to-tail configurations of two dipoles, as shown in Fig.3.3, each with moment *m*, the energy of the head-to-tail configuration is lower by $3\mu_0 m^2/(4\pi r^3)$ and hence the magnets tend to align head-to-tail. In non-cubic lattices, the dipole interaction is an appreciable source of ferromagnetic anisotropy.

Module 1: Introduction
Lecture 04: Magnetic Anisotropy

Shape Anisotropy:

The magnetostatic energy of a ferromagnetic ellipsoid, as shown in Fig.4.1, with magnetization M_S is given as

$$E_m = \frac{1}{2}\mu_0 V N M_S^2 \qquad (4.1)$$

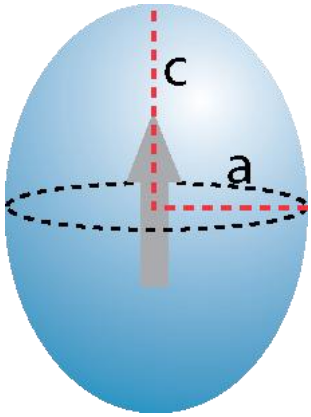


Figure 4.1: Magnetization of a prolate ellipsoid of revolution with *c*>*a*, and no magnetocrystalline anisotropy. *c*-axis is the easy direction of magnetization.

The anisotropy energy is related to the difference in energy ΔE when the ellipsoid is magnetized along its hard and easy directions. N is the demagnetization factor for the easy direction. N'=(1/2)(1-N) is the demagnetization factor for the hard directions. Hence,

$$\Delta E_m = \frac{1}{2}\mu_0 V M_S^2 \left[\frac{1}{2}(1-N) - N\right]$$

➔

$$\Delta E_m = \frac{1}{4}\mu_0 V M_S^2 [1-3N]$$

$$K_{sh} = \frac{1}{4}\mu_0 M_S^2 [1-3N] \qquad (4.2)$$

The shape anisotropy is zero for a sphere, as N = 1/3. Shape anisotropy is only fully effective in samples which are so small that they do not break up into domains.

Induced Anisotropy:

In some materials, the magneticanisotropy can be induced by many ways: (i) fabricate a film in the presence of a magnetic field, (ii) heat treat the materials in the presence of external applied magnetic field, and (iii) apply uniaxial stress.In the first two cases, after such treatment, the material may exhibit an easyaxis of magnetization that points in the direction of the magnetic field that was applied.This induced anisotropy is certainly independent of any crystalline anisotropy or anyother form of anisotropy that might be present. Figure 4.2 shows the typical example of inducing the anisotropy in the ferromagnetic materials by field annealing. One of the classical materials that exhibits the magnetic field induced anisotropy is Permalloy. If there are no stray magnetic fields present during deposition, then the easy axis of anisotropy will be found to be in the direction of theearth's magnetic field.

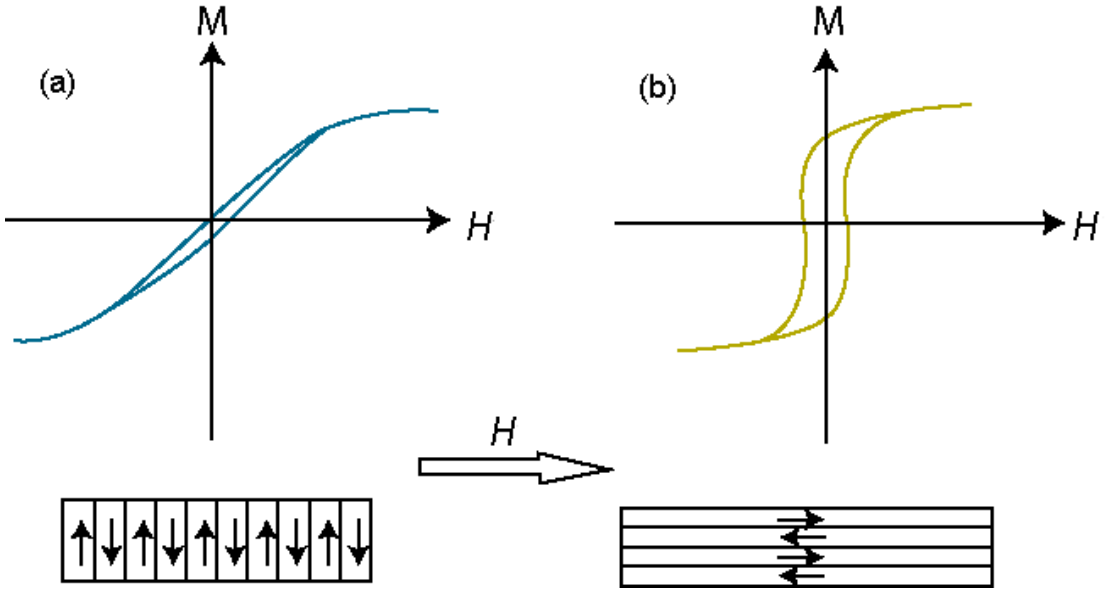


Figure 4.2: Magnetization of a thin film with induced anisotropy created by annealing in a magnetic field. The sheared (open) loop in a (b) is observed when the measuring field *H* is applied perpendicular (parallel) to the annealing field direction.

In the last case, the uniaxial anisotropy is induced by applying uniaxial stress in a ferromagnetic solid. The magnitude of the stress-induced anisotropy is

$$K_{u\sigma} = \frac{3}{2}\sigma\lambda_S \qquad (4.3)$$

where λ_S is the saturation magnetostriction. Both the single-ion and two-ion anisotropy contribute to the stress induced anisotropy. The largest values of uniaxial anisotropy are found in hexagonal and other uniaxial crystals. Smallest values are found in cubic alloys and amorphous ferromagnets.

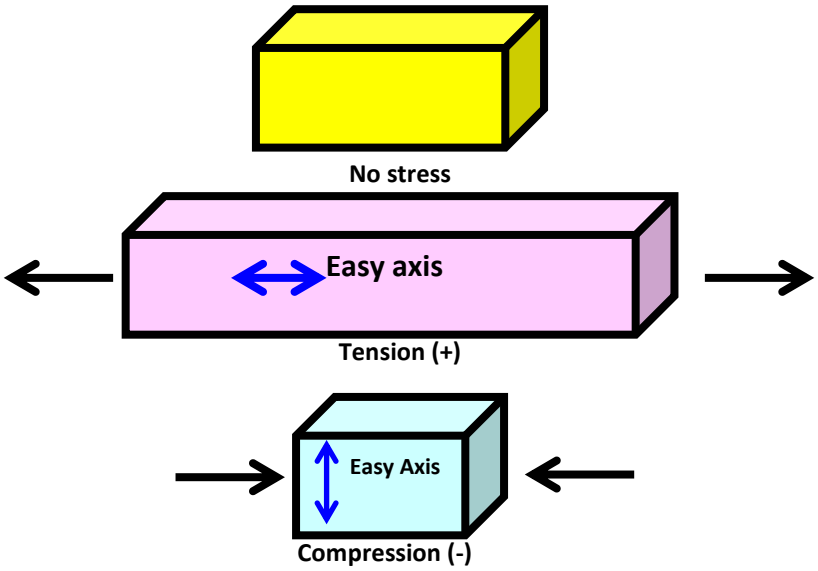


Figure 4.3: Schematic drawing of bars to demonstrate the inducing an easy-axis in a material with the positive magnetostriction.

Magnetostrictive Anisotropy:

Another important form of anisotropy in magnetic materials is due to magnetostriction, a change of volume of an isotropic crystal due to magnetic order.Magnetostriction relates the stress in a magnetic material to ananisotropy created by that stress. The magnetostriction constant λ isthe constant of proportionality. Figure 4.3 showsschematic views of bars with different applied stress conditions. If $\lambda$is positive, then application of atensile stress to the bar creates an easy axis in the direction ofthe applied stress. If a compressive stress is applied, then the direction of the easyaxis created will be perpendicularto the stress direction. On the otherhand, if the magnetostriction constant for the material is negative, then this is allreversed: a tensile stress will create an easy axis perpendicular to the stress direction,and a compressive stress will create an easy axis in the directionof the appliedstress.The value of $\lambda$is defined in the following way: Suppose onehas a given length of a non-magnetic material. If the material has a positive

value of λ, then causingthe materialtobecomemagneticwill cause the materialto lengthenor stretch in the direction of the magnetization. The fractional increase in length isdefined as the magnetostriction constant, λ. If the material has a negative value of λ, then the material will shorten in the direction of the magnetization.

Quiz:

(1) What is anisotropy?
(2) What is the role of anisotropy in the magnetic materials?
(3) Which materials possess high magnetocrystalline anisotropy? Why?
(4) Summarize the different ways to induce the anisotropy in the magnetic materials.
(5) Which type of materials exhibit large shape anisotropy? Can the shape anisotropy play a crucial role in bulk materials?
(6) Is it possible to produce a permanent magnet of arbitrary shapeusing shape anisotropy alone?

Module 1: Introduction
Lecture 05: Soft and Hard magnetic materials and Stoner-Wohlfarth theory

Soft and Hard magnetic materials:

Ferromagnetic materials are basically divided into two broad classes: Soft magnetic materials and hard magnetic materials. Figure 5.1 depicts a typical magnetic hysteresis loop of ferromagnetic materials, when they are placed under an external magnetic field. The area under the hysteresis loops mainly help to quantify them as hard or soft magnetic materials.

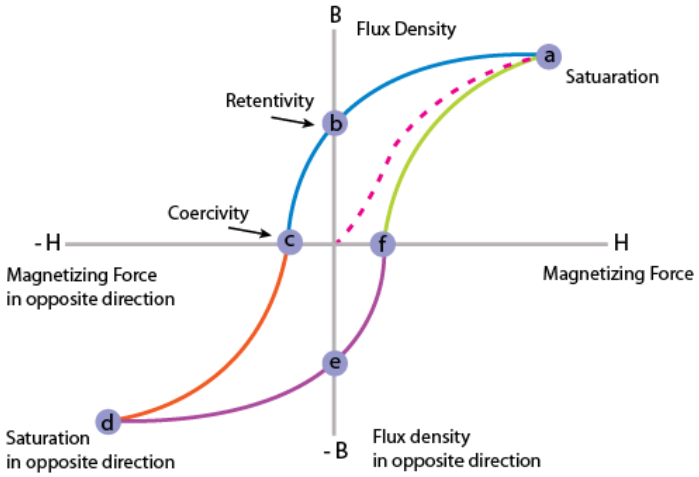


Figure 5.1: Typical magnetic hysteresis loop of a ferromagnetic material.

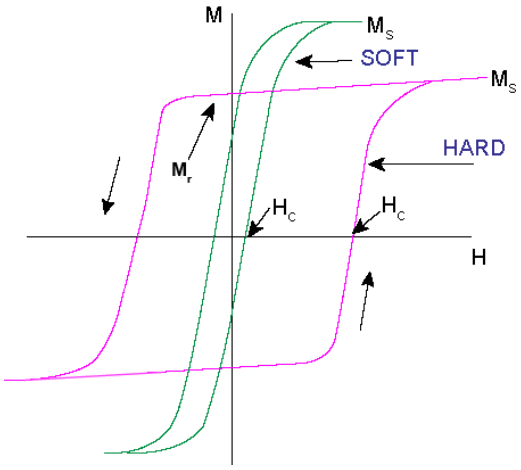


Figure 5.2: Typical magnetic hysteresis loops of soft and hard ferromagnetic materials.

Figure 5.2 displays comparative magnetic hysteresis loops for both soft and hard magnetic materials. Hard magnetic materials generally show low initial permeability (close to the origin in Fig.5.1) and high coercive force (H_C>1000 Oe). These materials are generally used for disk media or for a permanent magnet application. On the other hand, soft magnetic materials exhibit high initial permeability and also low coercivity (<100 Oe). These materials are used for a transformer or a magnetic head application. Since both the types of ferromagnetic materials have different magnetic parameters associated with the hysteresis, their magnetization reversal behaviour would also be different. Now, we shall try to understand the magnetization reversal behaviour using Stoner-Wohlfarth(SW) model.

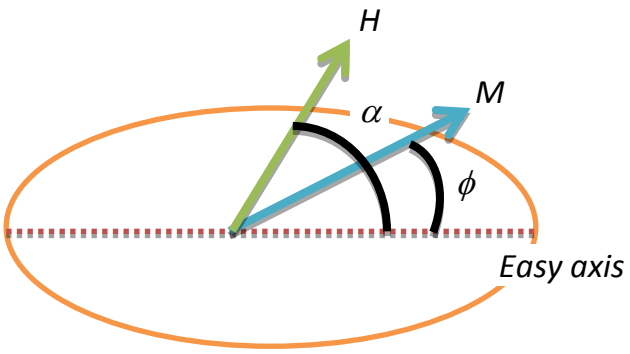


Figure 5.3: Schematic of SW particle.

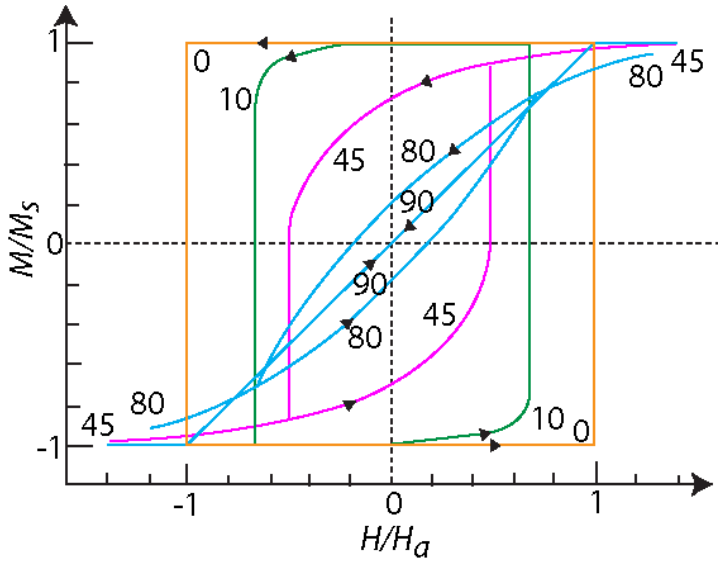


Figure 5.4: Variation of magnetic hysteresis loop of a SW particle with angle,ϕ, between the field direction and easy axis.

Stoner-Wohlfarth Model:

This is a simple analytical model describing the hysteresis. Consider a uniformly magnetized ellipsoid with uniaxial anisotropy of shape or magnetocrystalline origin (called as SW particle, as shown in Fig.5.3) in a field applied at an angle ϕ to the anisotropy axis. The energy density is

$$E_{total} = K_u \sin^2 \phi - \mu_0 MH \cos(\alpha - \phi) \qquad (5.1)$$

Minimizing the E_{total} with respect to θ gives either one or two energy minima. The hysteresis arises in the field range where two minima are present. Switching is the irreversible jump from one minimum to another, which occurs when $d^2E/d\phi^2 = 0$. The typical hysteresis loop for the SW particle is shown in Fig.5.4. The loop shape is perfectly square when α=0 and in such case the coercivity is equal to the anisotropy field, i.e.,

$$H_C = \frac{2K_u}{\mu_0 M_S}$$
$$H_C = \frac{2K_1}{\mu_0 M_S} + \frac{(1-3N)M_S}{2} \qquad (5.2)$$

whereK_u is the sum of the magnetocrystalline anisotropy, K_1 and the shape anisotropy, K_{sh}, having same axis.

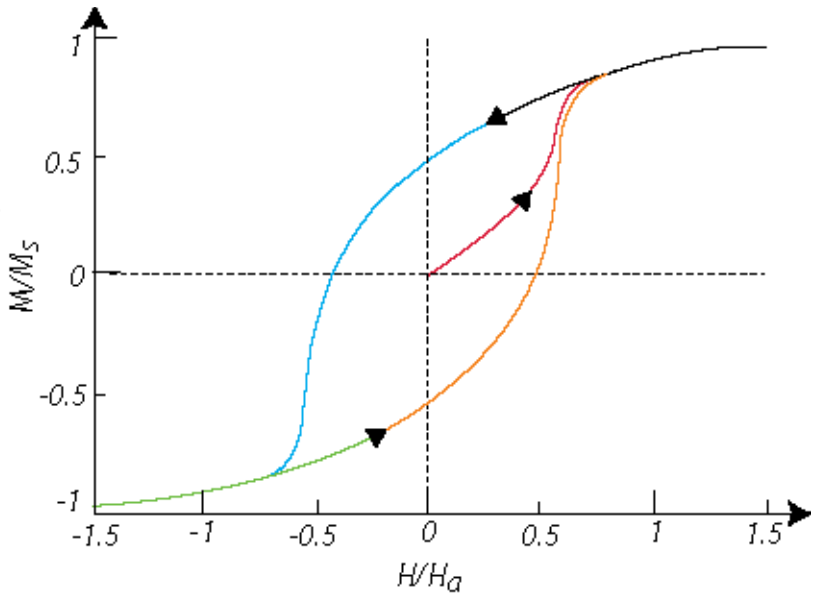


Figure 5.5: Hysteresis loop for a randomly oriented array of SW particles.

An array of non-interacting magnetic particles with a random distribution of anisotropy axes is a crude model for a real polycrystalline magnet. The hysteresis loop of such magnet is given in Fig. 5.5. The remnance for the array of particles is ½M_S and the coercivity is 0.482H_a. If the anisotropy directions are distributed at random within the place, a case similar to particulate recording media, the remnance is 0.637M_S (=2/π) and the coercivity is 0.508 H_a.

Another possible relation (Henkel plot) between two remnance curves for the system of non-interacting particles was pointed by Wohlfarth. The remnance on the initial magnetization curve, M_r, is obtained by applying a field H to the virgin state, and reducing it to zero. The remnanceM_{rd} is obtained in a reverse field after saturating the magnetization. They are related by

$$2M_{ri}(H) = M_r - M_{rd}(H) \qquad (5.3)$$

The deviations from a linear plot of M_{ri} versus M_{rd}, known as Henkel plot, are the evidence for the existence of finite interacting particles.

Quiz:

(1) What is soft and hard magnetic maetrials?

(2) What is Henkel plot? How does it useful to study the interaction between the particles?

(3) Show that the coercivity of an ensemble of SW particles aligned with a common easy axis varies as $\cos^{-1}\alpha$?

(4) Who does the Stoner-Wohlfarth particles exhibit square hysteresis loop along the easy-axis direction?