Module 05: Advances in Recording Technology and Materials

Lecture 31: Magnetic recording media and its requirements

Objectives:

In the earlier lectures, we have covered the discussion on recording and readback theories, aspects of various types of magnetic recording head. Another important part of the magnetic recording is the media, as it contains all the recorded information. Although there are lot of components in the disk to function properly, it is no wonder that many refer to a magnetic disk drive simply as a magnetic disk. Note that a magnetic media is composed of either closelypacked magnetic particles, continuous magnetic thin films depositedon a substrate, or artificially designed nanostructure for recording the information. Hence, they are called as particulate, thin-film disks, and patterning media, respectively. As the magnetic recording media is one of the core parts of the magnetic disk, it is important to understand various requirements for a material to act as a medium, availability of different types of media and their functionality for recording and storing the digital information. Hence in this module, our primary motivation is to provide detailed information on

1. Magnetic recording media and its requirement,

2. Various types of media (Particulate, thin films and pattern media),

3. Properties of the medium,

4. Perpendicular recording,

5. High density recording, and

6. Future projections on ultrahigh density magnetic recording.

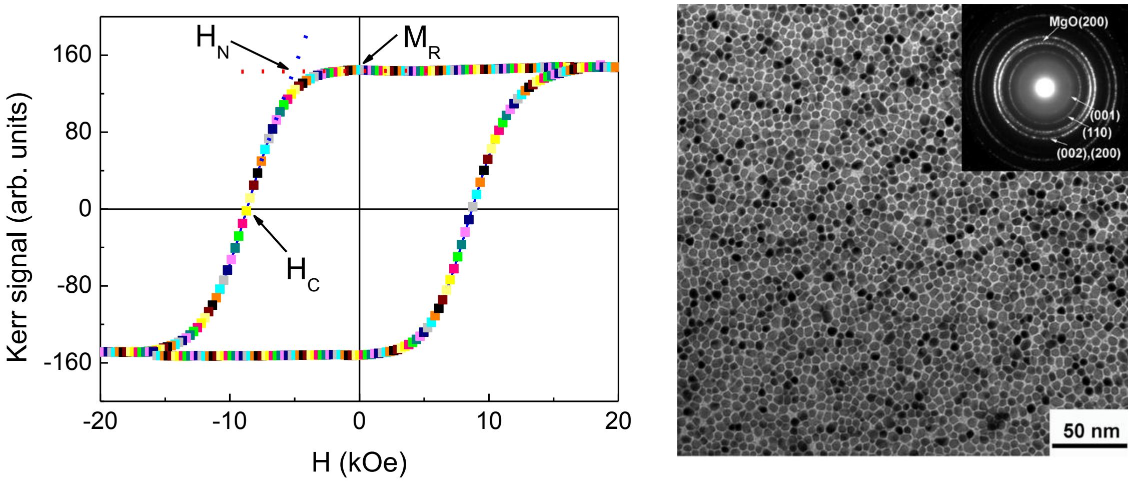
Magnetic recording media:

Magnetic disks are generally classified as flexible disks or floppy disk and hard disk based on the types of substrates used. The first types commonly use the polyester substrates suitable for removable disk storage. For example, 1.4 MB floppy disk and zip disk. Hard disks usually use Al-Mg based light weight substrates, glass, and ceramic substrates. Since they are rigid, it allows higher rotation speed, reduced magnetic spacing, and accommodates high linear data and track densities.

Rigid disk drives and disks have shrunk in size over the years. The first rigid disks, manufactured in 1957, were 24 inch in diameter. Later up to 1970, 14 inch diameter disks with a thickness of 0.075 inch dominated the industry. The sizes were rapidly decreased during the 1980s. The late 1980s saw the 95 mm diameter (3.5 inch) disks with 0.8 mm thickness, which dominates the disk volumes of this day.48 mm disks were emerged out in late 1990s. Different sizes of the disks were produced over a last decade suitable for various consumer electronics.The magnetic disks were classified according to their form factor as listed in Table 31.1 [1].

Table 31.1: Form factor of the magnetic disks.

Form Factor (in.)	24	14	8	5.25	3.5	2.5	1.8	1.3
Diameter (mm)	606	355	210	130	95	65	48	33



(b)

(a)

Figure 31.1: (a) Typical magnetic hysteresis (M-H) loop and (b) nanogranular microstructure of a material suitable for magnetic recording application [2].

Requirements of magnetic medium:

In order to use the magnetic materials in a recording medium, these materials should have the following basic requirements (see Figure 31.1) for high density recording:

1. Coercivity (H_C): A high coercivity in the materials is necessary to accommodate very sharptransitions. Coercivities of the hard magnetic materials are often determined by magnetocrystalline anisotropy, meaning that high anisotropymaterials,such as CoCrPt, FePt based alloys, are required. However, the coercivity of the materials should not exceed the writing capability of the currently available write heads, which does not allow efficient writing in the medium.

2. Magnetization at remnant state (M_R): High values of remnant magnetization (>95 % of Saturation magnetization) in small thickness (δ) films are preferred to obtain adequate readback signals with the minimumthickness spacing loss. For MR heads, the product $M_r\delta$ should match that of the MR element (or spin valve free layer).

3. Negative nucleation field: This is defined as the reversing field (preferably in the second quadrant of a hysteresis loop) at which the magnetization starts to drop from its value at saturation. The more negative the nucleation field, the more stable the remnant magnetic state should be, since a larger reversing field is required to alter the magnetization. The value of the nucleation field should also scale with the component of anisotropy in the direction of the applied magnetic field.

4. Nearly squared M-H loop is very much important (see eqn.(14.15))to achieve a sharp transitions and satisfactory overwrite ratio.

5. As shown in Figure 31.1b, fine and well isolated single domain particles with uniform size distributionsand large anisotropy are required to obtain sufficient coercivity and to reduce the switching field distribution. This is needed to reduce the noises in the media.

6. Very smooth surface on top of the disk and reliable mechanical stability are needed to attaining small magnetic spacing with the acceptable tribological performance.

References:

[1]. K.G. Ashar, Magnetic Disk Drive Technology, Heads, Media, Channel, Interfaces and Integration, IEEE Press, New York, 1997.

[2]. A. Perumal et al., FePtAg-C nanogranular films fabricated on a heat resistant glass substrate for perpendicular magnetic recording, Journal of Applied Physics 108 (2010) 083907.

Module 05: Advances in Recording Technology and Materials

Lecture 32: Particulate and Thin Film Media

Particulate media:

The first rigid disk drives employed the particulate magnetic recording layers made of acicular magnetic particles in organic polymer matrix with avolume fraction of 20-45%. These magnetic particles are first preparedthrough complex chemical reaction process and then they are dispersed inpolymer binder, solvents, dispersants, lubricants, etc. Subsequently, the mixture iscoated on rotating disk substrates at very high speed [1]. The film, while still in fluid, is passed under a magnetic field to circumferentially align the acicular particles, and thereby improving the magnetic properties. The wet film is then backed in an oven that locks the particles into a thin film on the substrate. A post bake process thins hard coating to the required thickness, also leaving a smooth finish. Finally, the lubrication layer is made with a perfluoropolyether lubricant and the disk is ready for testing.

Table 32.1: Materials used for the particulate media and their properties:

Sl.	Particulate Media	Magnetic particles	Coercivity (Oe)	Saturation magnetization (emu/cc)
1.	Iron oxide	γ-Fe_2O_3	250 – 400	~350
2.	Co-modified Iron oxide	γ-Fe_2O_3 + Co	400 – 900	~ 350
3.	Chromium oxide	CrO_2	300 – 900	~ 400
4.	Barrium Ferrite	$BaFe_{12-2x}Co_xTi_xO_{19}$	600 – 1900	290 – 340
5	Metal particles	Fe-Ni Fe-Co	690 – 1130 940 – 2010	~ 670 680 – 920

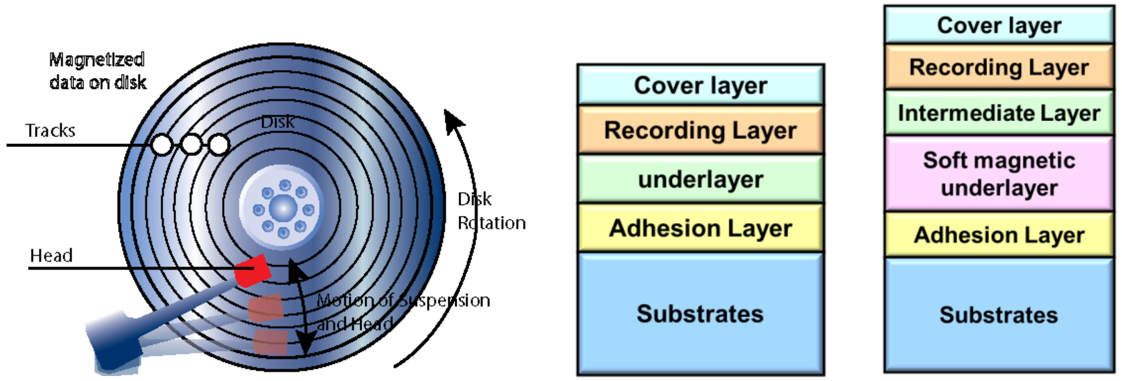
Table 32.1 lists the most commonly used particulate magnetic media.The coercivity of particulate media is mainly due to magnetocrystallineanisotropy and shape anisotropy of the magnetic particles. The magnetic particles were made of γ-iron oxide developed for tape recording at the end of the World War II. To increase the coercivity of the γ-iron oxide particles, a surface layer of Co was added. This increases the magnetocrystallaine contribution to the total coercivity.As the required recording densitiesrise, the coercivities of the particles are also increased. Therefore, the metalparticles and barium ferrite were proposed as alternative choices for high-densityapplications. However, the fabrication of particulate media with higher coercivity was not so easy. In later 1980s, the development of thin-film media helped to attain high coercivity and low noise, in comparison with the particular disks. Therefore, the particulate media in rigid disks were quickly replaced by the more superior thin film media.

Thin film media:

The particulate media technology is limited in its areal density and is no longer used in rigid-disk drives, as the rigid disks made using thin film technology showed enhanced properties. The magnetic thin film fabricated using the thin film deposition techniques exhibits higher magnetization than the particulate thin films, which allows the use of very thinner films on the rigid substrate. Also, the thin films are endowed with much higher coercivity values than the particulate films.

Thin film disk structure and properties:

Figure 32.1 shows the schematic view of (a) top section and (b) cross sectional structures of the thin film media suitable for longitudinal and (c) perpendicular magnetic recording. The selection of substrate for the application mainly comes from its light weight, high strength and low cost. A fine and very smooth surface is required for a rigid disk to provide uniform readback signal from low-flying heads. On top of a disk, Ni-P surface is abrasively polished to a 1 nm root-mean-square finish followed by a texturing process resulting in circumferential grooves (see Figure 32.1a), which serves two purposes: the added roughness minimizes the head stiction on the disk surface and it induce a circumferential magnetic anisotropy on the disk, resulting in uniform magnetic readback signals during the course of disk rotation.



(a) (b) (c)

Figure 32.1: Schematic view of (a) top section and cross sectional view of a thin film media suitable for (b) longitudinal and (c) perpendicular recording.

As shown in Figure 32.1b, the thin films disks require an adhesion layer to make enough stick on the substrate for a long life of at least 10 years duration. In case of perpendicular magnetic recording, the double-layered media, where the recording layer is deposited on top of a soft magnetic underlayer with an appropriate intermediate layer, is suitable for recording purpose.Hence, the soft magnetic underlayer made of CoTaZr, CoNbZr, FeTaN, FeTaC, FeAlSi, and FeCoNi single layer films, synthetic anitiferromagnetic, hard magnet biased soft underlayer and laminated type soft underlayers were used for utilizing the single pole head with enhanced magnetic field for writing the recording layer. However, this soft magnetic underlayer is not mandatory for the case of longitudinal recording, as ring heads were used for writing the media.

Also, the thin films media requires an underlayer (intermediate layer for the perpendicular recording) to help nucleate and grow microstructure inducing appropriate magnetic properties in the recording layer. Underlayers present a microstructure that is replicated by the superimposed recording magnetic thin films. Grain structures are critical in determining thin film disk noise, and the structure can be controlled in the magnetic film by modifying the properties of the underlayer.Ferromagnetic materials with the hard magnetic properties such as high coercivity above 3000 Oe, highremanence (100 %), considerably sharp switching without tail nature of the hysteresis are needed as a magnetic film in the recording layer. The materials currently used in the recording layer are CoCrTa, CoCrPt, CoPtNi and FePt based alloys. The coercivity of a magnetic layer is generally an extrinsic property.However, it is largely determined by the magnetocrystalline anisotropy due to the formation of alloys.On the other hand, the coercivity can be greatly affected by film stress,crystal defects, grain size, grain orientation, grain boundaries, etc. The coercivity is also a strong function of switchingtime and temperature due to the superparamagnetic effect.

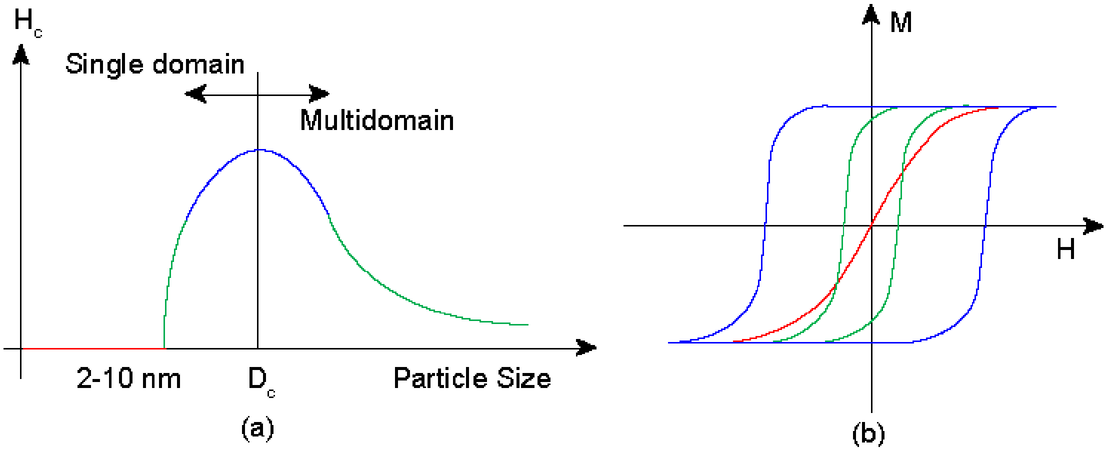


Figure 32.2: (a) Variation of coercivity with the particle size and (b) the corresponding variation of magnetic hysteresis loop shape.

The correlationbetween microstructures and coercivity tends to be complicated and qualitative.For example, let us examine how coercivity varies with grain sizeor medium thickness. As shown in Figure 32.2, it is common that the coercivityof magnetic thin films increases with decreasing the average particle size until it reaches a peak at a critical size in the range of 10 – 30nm. The decrease in coercivity with increasing film thickness above the critical thickness is attributed to a combination of magnetostatic interaction and an increasedout-of-plane *c*-axis orientation of the grains. For independent magneticparticles, the coercivity peaks at a critical grain size that separatessingle domain and multidomain regimes. In the single domain particle regime, the shape of the magnetic hysteresis loop tuns out to be almost square shaped suitable for recoding purpose. For magnetic thin films, thecritical thickness is also dependent on the material and process. Below the critical thickness, the coercivity drops rapidlywith decreasing thickness because of the superparamagnetic effect whichcauses thermally assisted switching of magnetic grains. Also, the shape of the hysteresis changes from square shape to flat loop shape (see Figure 32.2b).

As linear recording density is scaled up, the remnance-thicknessproduct $M_r\delta$of the thin-film disk needs to be scaled down. For example,at an areal recording density of above 100Gbits/in^2, the product of $M_r\delta$is expected to be ~0.2memu/cm^2, and medium thickness to be 10 nm. This isat the regime where film coercivity may drop quickly with thickness.Therefore, attaining high coercivity in real thin films is an increasinglychallenging task.Thin film disks need a protection of the magnetic layer from therecording head, which makes surface contact during turn-on and shutdown of thedisk drive. Amorphouscarbon of about 10 – 15 nm is used as protection layer in thin film disk industry, as the materials' properties can be tailored by incorporation of dopants such as hydrogen or nitrogen. The overcoat not only servesto protect the magnetic layer, but also acts as a support structure for the lubricant. The final layer in the thin film disk structure is the lubricant. The lubricant is typically a perfluoropolyether organic polymer with a thickness between 1 and 3 nm. Lubricants serve to reduce friction and wearbetween the carbon overcoat and the recording head. Important lubricant propertiesembodied in the perfluoropolyethers are chemical inertness, low vapor pressure toprevent evaporative loss, a low contact angle allowing uniform wetting of the carbonovercoat surface, and a chemical affinity for the overcoat, preventing spin-off anddesorption.

References:

[1].E. Koster, Particulate Media in Magnetic recording technology, edited by C.D. Mee and E.D. Daniel, McGraw Hill, New York, 1996.

Module 05: Advances in Recording Technology and Materials

Lecture 33: Media Substrates

Introduction:

Since the thin film based recording materials have to be deposited on a typical rigid substrates for sustaining the films over a period of time and to avoid any damages during the read and writing process, several methods have been employed to support the recording films.As we knew well that the tapes and flexible disks use plastic films in the early days, today's tapes and diskettes use a polyethylene terephthalate (PET, also called as Mylar) films. Rigid disks use an aluminium, glass, and ceramic based substrates. The selection and the usage of different types of substrates are mainly determined by the type of recording conditions. Hence, in this lecture, we will briefly cover the different types of substrates such as flexible media substrates and rigid media substrates.

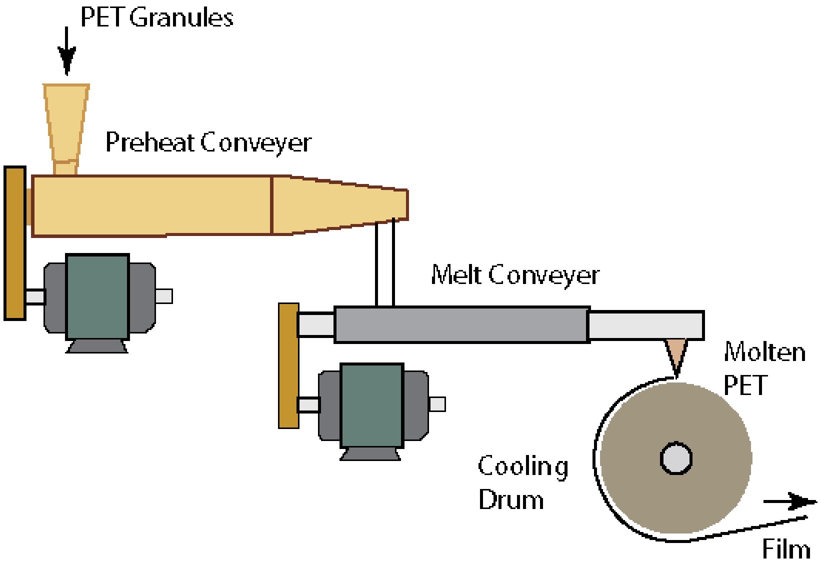


Figure 33.1: Schematic arrangements of the set up for preparing the PET films.

Flexible Media Substrates:

PET is one of the many long molecule materials where the cross linking between the molecules causes uneven surfaces due to lumping effects. However, the efforts are made to develop new base films by combining the PET with other polymers. Figure 33.1 shows the typical schematic arrangement of the system for preparing the PET films (see also Fig. 1.2). PET, a group of complicated polymer esters made from terephthalicacide and ethylene glycol, has molecular weight between 15,000 and 30,000. The creation of continuous films is started by thoroughly drying the granules so that the water content is as low as possible. These granules are fed into one end of the conveyor, where they are melted at a temperature around 300 ^{o}C and form a liquid syrup-like substance. This is forced through an extrusion head under uniform pressure to form the liquid sheet that immediately cooled by contact with a cooling drum to avoid the formation of any spherulites. The non-uniform pressure can result in the pulsations where the thickness of the film is not very uniform.Subsequent to the preparation, the strength of the films is increased by stretching the films both in lengthwise and sideways and finally fixed and cooled. The finalized PET film varies in width from 0.6 to 4 meters and is trimmed from the edges.Table 33.1 summarizes the properties of various base films and Figure 33.2 shows the typical stress – strain curves of the PET films, where the residual stress deforms and buckles the films, when it is heated.

Table 33.1: Characteristics of the various base films:

Property	**Unit**	**PET**	**PEN**	**Kapton**	**PBO**
Density	Kg/m^3	1395	1355	1420	1540
Melting temperature	^{o}C	263	272	-	-
Young’s Modulus	kg/mm^2	500-850	650-1400	300	5000
Tensile strength	kg/mm^2	25	30	18	60
Tensile elongation	%	150	95	70	1-2
Coff. thermal expansion	10^{-6}/°C	15	13	20	-
Moisture absorption	%	0.4	0.4	2.9	1.5

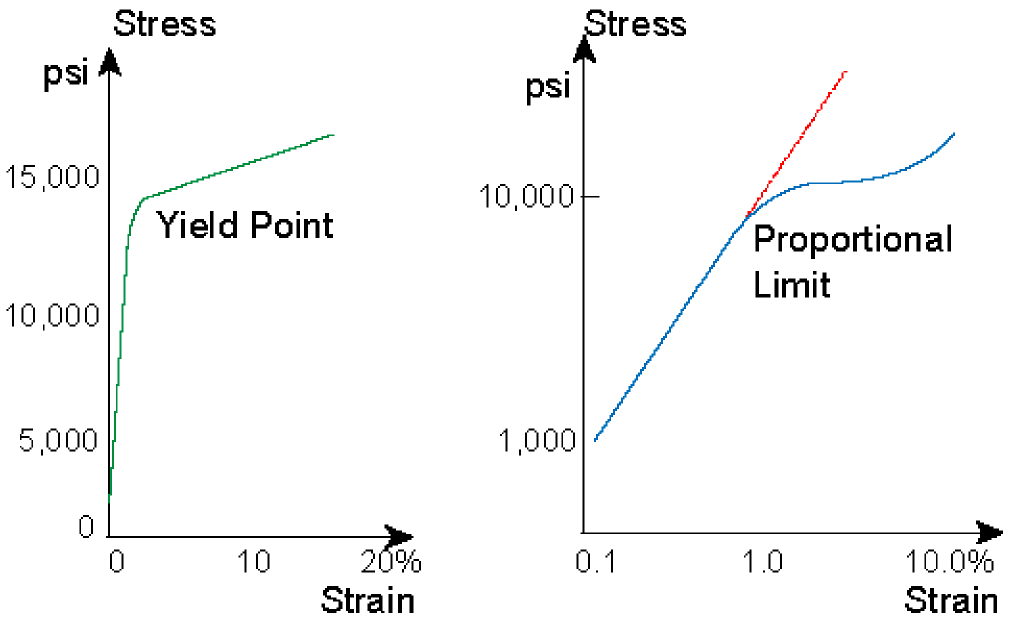


Figure 33.2: Stress – Strain curves of the PET films.

High temperature application requires special films, such as polyimide film named Kapton, which maintain their properties up to 400 ^{o}C. These films are often used in the flight data recorders on board commercial airlines. Also, the polyimide based substrates are good candidates for the flexible disks for perpendicular recording of CoCr based films.Kapton is very expensive and hence limited in only on selected applications. Alternative base films such as PEN, which has 20 % higher mechanical strength and thermal stability, and polybenzoxazole (PBO), a rigid-rod polymer were developed. However, all these base films were not considered for the recent devices due to the limited data storage density per unit area.Tapes are often back coated with the carbon black to provide rougher surface for better tracking. The back coating also lowers the tape's resistivity and thereby prevents electrostatic build-up.

Rigid Disk Substrates:

Rigid disk based substrates are mandatory for preparing the thin based media for increasing the areal density. The final disk surface should be ideally be free of any voids and has a clear mirror finish, with the surface roughness in nm scale. This is essentially needed to fly the head at a closest possible distance with respect to the disk surface. Aluminium based alloys ranging the thickness of mm to sub mm scale is used at the initial stages. However, they were very soft and to increase the strength and reduce the weight, magnesium was added. Furthermore, the addition of Mn and Cr helps to improve the corrosion resistance [1].Later, a Ni alloy of micrometer thickness is electroplated onto the aluminium disk, which acts a cover layer that covers the faults in the aluminium surfaces.

Table 33.2:A comparison of physical properties of Disk substrate materials

Property	NiP	Soda Lime Glass	Alumino-silicate	Glass-Ceramic	Carbon	SiC
Density (kg/m^3)	2700	2500	2500	2700	1800	3200
Young’s modulus (GPa)	72	75	85	83	35	460
Surface Hardness (kg/mm^2)	500	540	590	650	650	2500
Yield Strength (MPa)	117	37	-	>200	90	400

Plating technology was also tried in the manufacture of the disk with a thin metal film. The aluminium disk was first nickel plated and the magnetic films wereprepared on top of it. However, the plated disk had the problem of corrosion. Recent disk fabrication process uses the Al-Mg based alloys, which provide a fine and very smooth surface required for a rigid disk to provide uniform readback signal from low-flying heads. On top of the Al-Mg disk, Ni-P surface is abrasively polished to a 1 nm root-mean-square finish followed by a texturing processresulting in circumferential grooves. The added roughness on the disk surface minimizes the head sticking on the disk surface and induces a circumferential magnetic anisotropy on the disk, resulting in uniform magnetic readback signals during the course of disk rotation. Other types of disks such as glass, ceramics, silicon carbides and carbon were also established and some of the properties of such substrates are listed in Table 33.2 [2].

The following key points were considered while choosing the substrate for rigid disk application:

1. Young's modulus should be high to produce a thin disk, and to reduce the flutter at high rotational speed. The typical value of the Young's modulus is around 80 GPa for Al alloy with the Ni-P overcoat.
2. The substrate should have sufficient hardness to prevent damage and head slap against the disk.
3. Other specifications such as materials properties, coefficient of thermal expansion, physical requirements, and surface properties under static and dynamic conditions, regarding the substrates for the disk applications are discussed IDEMA standards [3].

References:

[1]. E.J. Westerman, SMART symposium WS 1-A-1 (1986).

[2]. K.E. Johnson, Thin Film Media in K. Ashar, Magnetic Disk Drive Technology, IEEE, New York, 1997.

[3]. International Disk Drive Equipment and Materials Associate (IDEMA), Doc. No. D2-91.

Module 05: Advances in Recording Technology and Materials

Lecture 34: Patterned Media

In the last few lectures, we have discussed the particulate and thin films based media for the recording applications. Although the thin films based media had advantages over the particulate media for high density recording, one of the major problems with the thin film media is the non-linear transition shift and track edge noise at very high areal density recording. Hence, the search for an alternate media for the future recording resulted to be patterned media. Figure 34.1 shows the typical road map of the hard disk recording density since 1991. After the utilization of the perpendicular magnetic recording in thin film based media, the next focus is project on Heat assisted magnetic recording and patterned media.

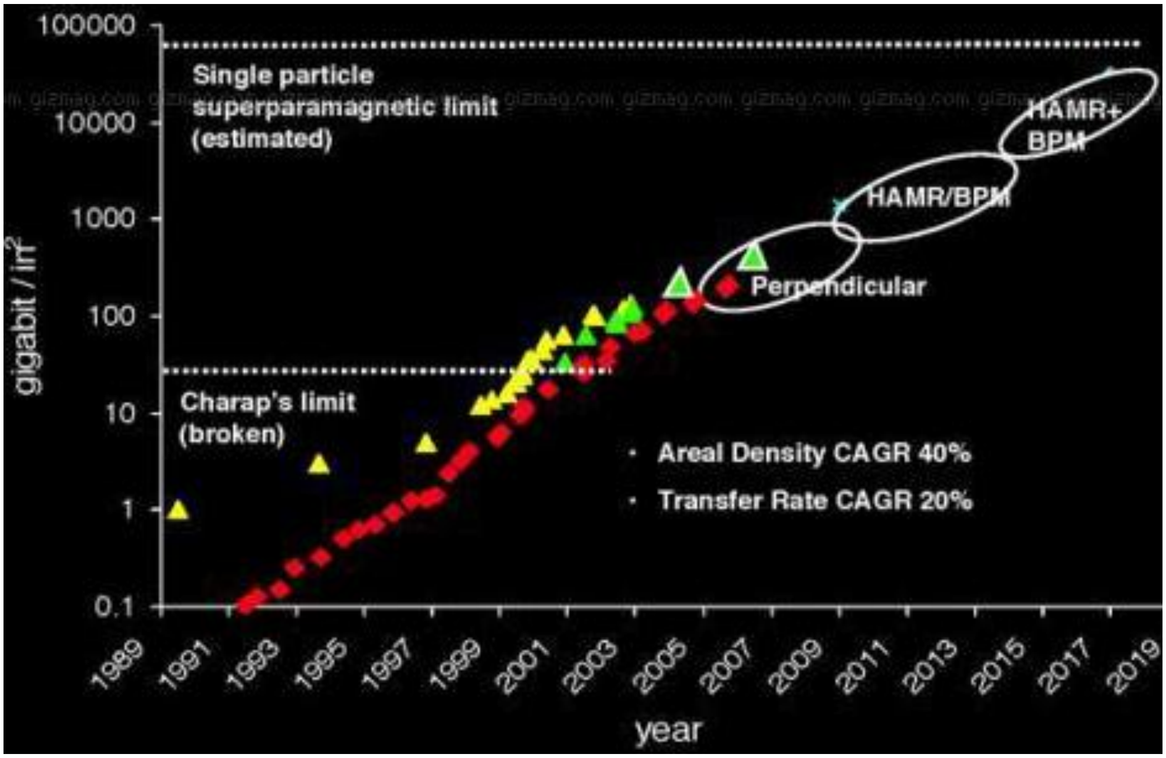


Figure 34.1: Roadmap of Hard disk recording density [1].

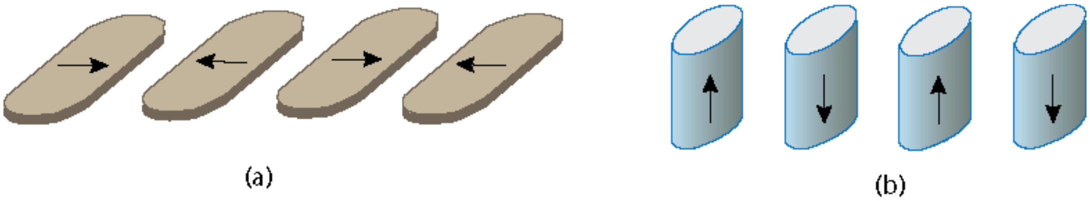


Figure 34.2: Schematic representation of a patterned media for longitudinal and perpendicular magnetic recording.

The idea of the patterned media started in 1963 itself, when the physically etched discrete tracks were proposed to improve the capability of head positioning [2]. However, the next step towards the patterned media was only developed in late 80s by IBM group after the induction of efficient lithography techniques. Subsequently, there were many discussions on patterned media recording technology [3-5] both on longitudinal and perpendicular recording as shown in Figure 1. The potential advantages of the patterned media cover elimination of nonlinear transition shift and track edge noise, reduction of medium noise, and the extension of superparamagnetic effect. Out of these, the last attribute is the most attractive one for patterned media.

Superparamagnetic limit in a single domain particle:

We have already discussed the occurrence of the superparamagnetic effect in the thin film media. According to the limit, when the average size of the particles decreases in its single domain state, then the ability of the particle to store the magnetization in one direction is not guaranteed due to the thermal energy, as shown in Figure 34.3.The loss of magnetic properties in such small particles may arise due to the reduction in the average magnetocrystalline anisotropy energy with decreasing particle size.

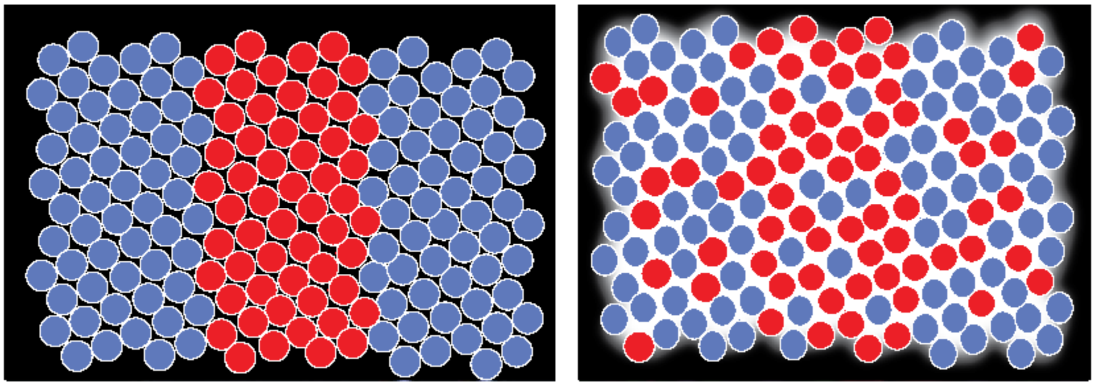


Figure 34.3: Schematic representation of bits under stable and unstable conditions.

Therefore, the thermal stability was defined as the ratio between the anisotropy energy and the thermal energy, as given in eqn.(34.1).

$$Thermal\ stability = \frac{K_u V}{k_B T} \geq 40 \tag{34.1}$$

According to the eqn.(34.1), the thermal stability of the particles decreases largely with decreasing the size the particles and hence one needs a material with high anisotropy such that the product of the anisotropy energy and the volume of the particles does not reduces a lot. The concept of patterned media offers to push out the superparamagneticlimit several orders of magnitude. In conventional recording a bitmust contain ~100 exchange-decoupled magnetic grains as required bysignal-to-noise ratio (SNR), each of these magnetic grains must be thermallystable (see Figure 34.3). In contrast, a patterned bit can contain one or any numberof exchange-coupled magnetic grains because there is no longer transitionnoise due to exchange coupling. If only the superparamagnetic limit isconcerned, patterned magnetic densities can be ~100 times that of conventionalrecording if the same medium material is used. In practice, thelimit of patterned media will be constrained by patterning defects, signal to noise ratio, head design, and servo requirements.

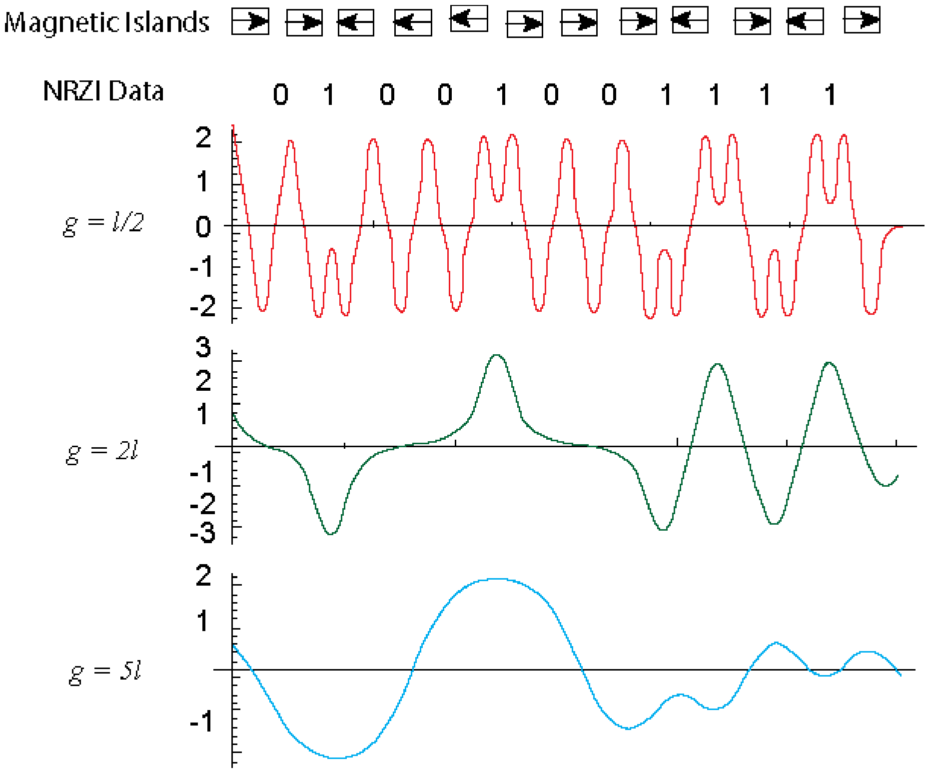


Figure 34.4: Readback waveforms of longitudinal patterned media.

Read/write processes and noises in patterned media:

The read/write experiments on patterned nickel (Ni) islands have been performedby magnetic force microscope (MFM) tips and by quasi-static MRheads. For longitudinal patterned islands, the edge of the island is ideallya sharp step transition (from 0 to $\pm M_r$), which generates a voltagepulse similar to that from a step transition (from $-M_r$ to $+M_r$) but withhalf of the amplitude. If the read head is Karlqvist-head-like, as demonstrated earlier, and theislands are very thin, then the isolated pulse is given as

$$V_{SP}(x) \propto \left(\tan^{-1}\left(\frac{x+g/2}{y}\right)-\tan^{-1}\left(\frac{x-g/2}{y}\right)\right) \tag{34.2}$$

Where g is the gap length and y is the magnetic spacing. This equation is similar to the one we obtained earlier in the read back signal in lecture 29. The efficiency of the read-back signal from the recorded pattern (longitudinal recording) in the patterned media can be simulated for different gap length as shown in Figure 34.4. Assume that the island length is l, and magnetic spacing, $y=g/4$ and the recorded pattern is given as shown in Figure 34.4.It is clear from the figure 34.4 that the linear bit shifts still exist in patternedmedia. However, if we take $g$as $2l$, which is equal to bit length, then the recorded bits can berecovered like conventional longitudinal recording with peak detection. With even more advanced detection schemes, even higher recording densities at $g \sim 5l = 2.5 \times$*bit length* may be realized.

Challenges in patterned media:

Although conventional nonlinear transition shift no longer exists inpatterned media because the location of transition is now defined bylithography, several issues related to the bit writing have to be resolved. Furthermore, the patterning defects such as island irregularities, missing islands, merging islands, etc become the major source of noise in the patterned media. Though the lithographic techniques are used to produce the patterned media, the major challenge is to find a suitable low cost patterning technology. Although the critical dimension required is smaller than that in the VLSI technology, but the patterns in magnetic media are periodic and much simpler than semiconductor memory cells. Therefore, the other lithography processes using nano-imprinting, laser interference lithography, self-assembly patterning, etc would be suitable for making patterning media. However, this subject is really challenging and expected to advance in the years to come.

References:

[1]. Mark Kryder, Fifty Years of Disk Drives and the exciting road ahead, Seagate Technology, Sep 2006.

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[3]. S.E. Lambert et al, IEEE Trans. Magn. 25 (1989) 3381; J. Appl. Phys. 69 (1991) 4724.

[4]. S.Y. Chou et al, J. Appl. Phys. 76 (1994) 6673.

[5]. R.L. White et al, IEEE Trans. Magn. 33 (1997) 990.

Quiz:

(1) What are the requirements of the magnetic medium to use as a magnetic recording?

(2) What are the different materials used in particulate media?

(3) What are the limitations in the particular media technology towards high density recording?

(4) What are the advantages of the thin film media for high density recording?

(5) What is superparamagnetic effect?

(6) What are the key points considered while choosing the substrate for rigid disk applications?

(7) What are the advantages and challenges in pattern media as compared to thin film media?

Module 05: Advances in Recording Technology and Materials

Lecture 35: Properties of magnetic thin films: Part 1

Introduction:

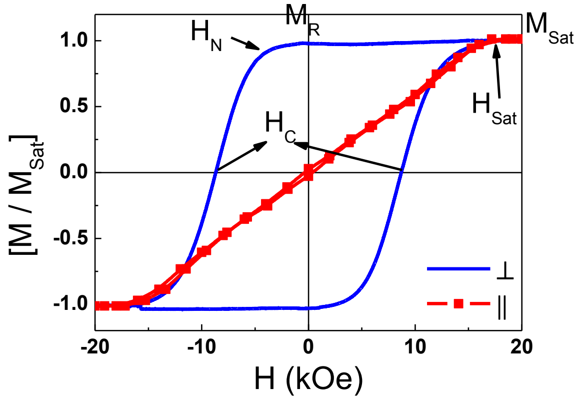
The choice of materials for the magnetic recording comes mainly from the control of the magnetic properties suitable for the recording purpose. The magnetic properties of the materials are learned from the magnetic hysteresis (M-H), i.e., the response of the sample magnetization with respect to the change in the applied field. The control of the shape and size of the hysteresis is the heart of designing the materials for magnetic related applications. Numerous magnetic parameters can be extracted from the M-H loop, which are mainly optimized with respect to the fabrication conditions for a particular application. As the study of M-H loops and associate phenomena is very much important, in the next four lectures, we shall cover

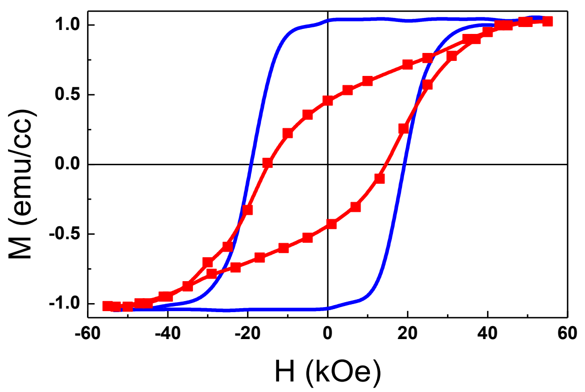
1. Magnetic hysteresis loops for recording,

2. Coercivity and remnant flux, slope at coercivity,

3. Effects of switching field distribution on the magnetic properties, and

4. Effects of time and temperature on the stability of the magnetic properties.





(a) (b)

Figure 35.1: Typical M-H loops of a hard magnetic material with (a) perfect orientation of easy axis perpendicular to the film plane, and (b) considerable random distribution of easy axis.

Magnetic hysteresis loops for recording:

Figure 35.1shows the M-H loops measured along the two directions of the thin film samples: perpendicular to the film plane (blue curve) and parallel to the film plane (red). It is clear from the figure 35.1a that the magnetic loop measured under perpendicular direction exhibited a clear almost square shaped loop, while the loop measured in the film direction showed almost a linear variation with the field up to 15 kOe field and then saturates at higher fields. These results reveal that the film has magnetization easy-axis perpendicular to the film plane and hard axis exists along the film plane. If the easy-axis orientation is not perfect along the perpendicular direction, then the magnetization measured along the hard axis direction depictsa definite hysteresis as shown in Figure 35.1b. Such behaviours arecorrelated to the crystal structure and microstructural properties of the films. Therefore, the optimization of the magnetic properties of the films with respect to the fabrication conditions is very much essential.

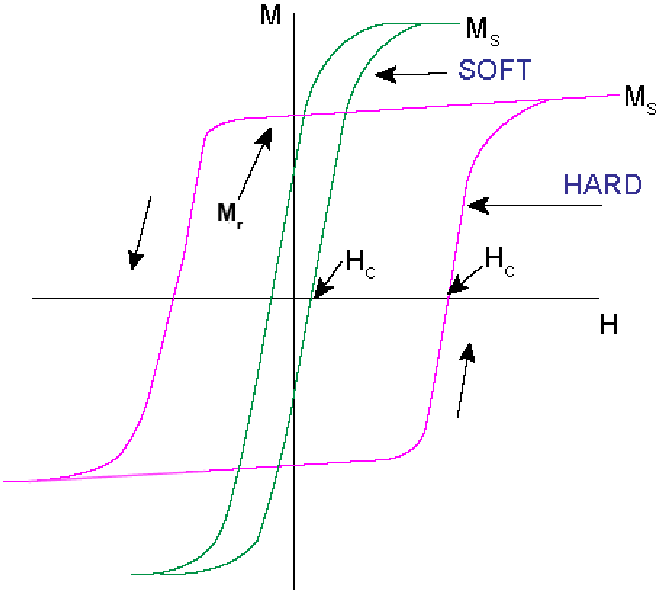


Figure 35.2: Typical M-H loops of a hard and soft magnetic material.

Coercivity:

In materials science, the coercivity (also called as coercive field or coercive force) of a ferromagnetic materials is the intensity of the externally applied field required to reduce the materials' magnetization to be zero (see Figure 35.2) after the magnetization of the samples has been driven to saturation in either of the directions. Hence, the coercivity generally measures the resistance of a ferromagnetic material to becoming demagnetized.

Magnetic materials with the coercivity less than 10 Oe are usually called as soft magnetic materials, while those with larger than 100 Oe are called hard magnetic materials (see Figure 35.2). Note that the coercivity is not affected by the demagnetization because the magnetization is zero at the coercivity point. Hence, the materials with high coercivity are used naturally as magnetic recording media since their high value of coercivity prevents the material from demagnetization if the demagnetization field is smaller than the coercivity. The shape of the M-H loop is often specified by the remanencesquareness (S), defined as the ratio of the magnetization at the zero applied field after the magnetization of the sample has been driven to saturation to the saturation magnetization of the sample, and the coercive squareness(S*). The value of S* is correlated to the coercivity through the following relation as given in eqn.(35.1).

$$\left.\frac{dM(H)}{dH}\right|_{H=H_C} = \frac{M_R}{H_C(1-S^*)} \tag{35.1}$$

whereM_R is the remanence as given in Figure 35.1. When S* approaches to 1, the shape of the hysteresis loop turns out to be perfect square.

Slope at Coercivity:

The slope of the M-H loops as well as the coercivity of the materials has good correlation with the exchange coupling between the adjacent grains in the recording media. It is known that the materials required for the application of recording media should have fine particles which are well isolated from each other. In such scenario, the exchange coupling between the grains strongly depends on the grain boundary thickness. The exchange coupling between the grains is indirectly calculated from a parameter called slope at coercivity, which is defined as.

$$\alpha = 4\pi \left.\frac{dM(H)}{dH}\right|_{H=H_C} = 4\pi \frac{M_R}{H_C(1-S^*)} \tag{35.2}$$

The values of α required for recording are reported to be between 1.5 and 3. Honda et al [1] showed a good correlation between the slope at coercivity, exchange constant and the coercivity of the medium. It was reported that with increasing the exchange constant, the values of loop slope increases significantly and at the same time, the coercivity of the media decreased largely due a strong exchange coupling between the grains. With increasing the loop slope, the noise in the recording media increases due to the exchange coupling. Hence, the study of control of the loop slope at coercivity in relation with the exchange coupling between the grains provides a good understanding between the microstructure and magnetic properties of the nanogranular thin films.

References:

[1]. N. Honda, IEEE trans. Magn. 38 (2002) 1615.

Module 05: Advances in Recording Technology and Materials

Lecture 36: Properties of magnetic thin films: Part 2

Product of $M_R\delta$:

As the demand for high areal density increases, the thickness of the films (δ) utilized for the magnetic recording medium decreases. However, there is a superparamagnetic limit, where the average grain size of the magnetic layer becomes less thermally stable with a reduction in the grain size. Therefore, a small thermal agitation will deteriorate the stored magnetic information. Moreover, even before the superparamagnetic limit is reached, as the film thickness is reduced, additional factors negatively impact magnetic coupling, such as the smaller grain size and the non-uniformity of the films. Scaling the media parameters involve both a reduction in grain diameter and the media's effective magnetic thickness, $M_R\delta$, where M_R is the remanent magnetization of the media. Scaling of $M_R\delta$ is needed in order to scale the transition parameter, which is the effective width of the boundary between the bits and limits how close the bits can be recorded.The typical value of $M_R\delta$ for the recording purpose varies between 0.4 memu/cm^{2}to 4 memu/cm^2.

The transition parameter for magnetic films with $S^* = 1$ and for which the contribution to the transition parameter from the details of the recording head are negligible is approximately (following eqn.(14.15)) given as,

$$a \approx \left[\frac{4M_R\delta\left(d+\frac{\delta}{2}\right)}{H_C}\right]^{\frac{1}{2}} \tag{36.1}$$

Since the output signal depends on the magnetic flux $M_R\delta$, the best way to reduce the transition parameter is to increase the coercivity to the highest level that can be written with the recording head field.

Switching field distribution:

In the magnetic recording media, the switching field distribution (SFD) is an important micromagnetic characteristic curve, which measures the ability to record short transitions, i.e., a small SFD results in higher resolution. Also, it is defined as the dispersion of the fields required to reverse the magnetization direction of the individual grains. The SFD can be a serious limitation factor on the areal recording density. When a group of particles is placed in a magnetic field, they will not rotate in unison, because they exhibit various degrees of resistance to domain rotation and they also influenced by the magnetic field from the neighbours due to the interaction fields. If we assume that these particles do not interact and respond to the field independently, then all the particles rotate together and the whole medium becomes fully magnetized without any intermediate dynamic range. In reality, the fabrication of magnetic granular films with uniform grain distribution is one of the challenges from the application point of view.

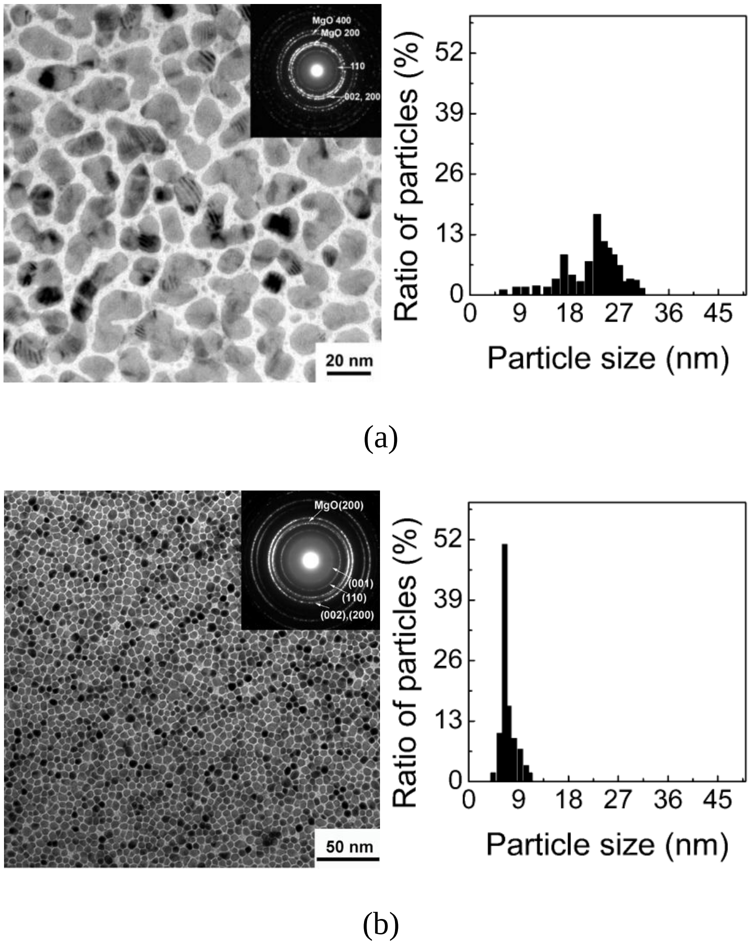


Figure 36.1: TEM micrographs and distribution histogram of particle sizes in FePtC alloys films with different carbon content (a) 20 vol.% C and (b) 40 vol.% C [1].

Figure 36.1depicts the typical TEM image of FePtCgranular thin films and their size distributions. It could be clearly observed that in FePtC (C=20 vol.%) the particle size distribution is not uniform and exhibits two peaks in the particle size distribution. With increasing the C to 40 vol.%, the particle morphology changed largely and showed almost narrow size distribution. Even in the narrow size distribution, we could see that the particle size ranges between 5 to 10 nm. This suggests that the different sized particles would have different coercivities and when we measure the magnetic properties as a whole, the loop slope around the coercivity is not expected to be sharp (see Figure 36.2). The loop slope at coercivity is mainly determined by the size distribution in particles. Recalling our discussion in lecture 32, the coercivity of the particles in the single domain state changes largely with decreasing particle sizeand the coercivity distribution around the maximum value of coercivity can be correlated to the distribution of the particle size in the granular medium. The distribution in coercivity can be taken as the values up to 50 % of its maximum value (see Figure 36.2).

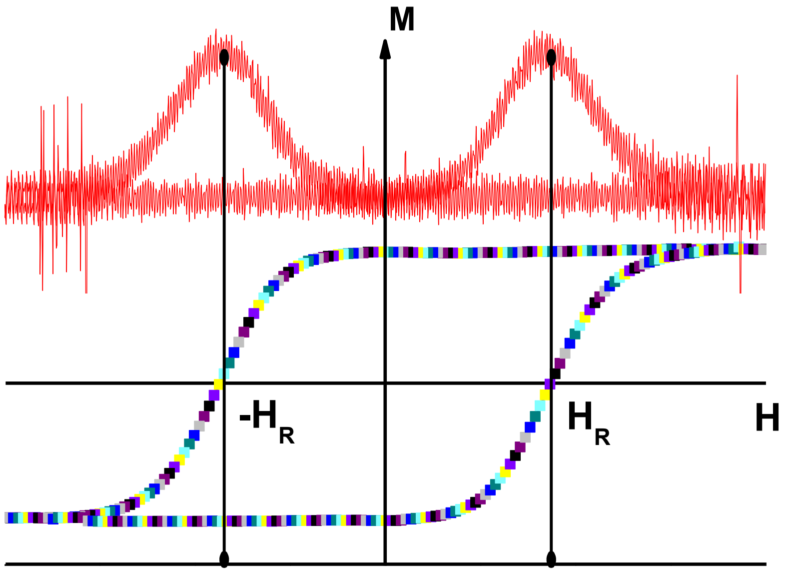


Figure 36.2: M-H loop and derivative of the M-H loop for a hard magnetic material.

Several methods are used for the determination of SFD: (1) The first one is the magnetizing field range wherein 50 % of the particles switches its magnetization, which can be derived from the remanence magnetization curves as shown in Figure 36.3a.

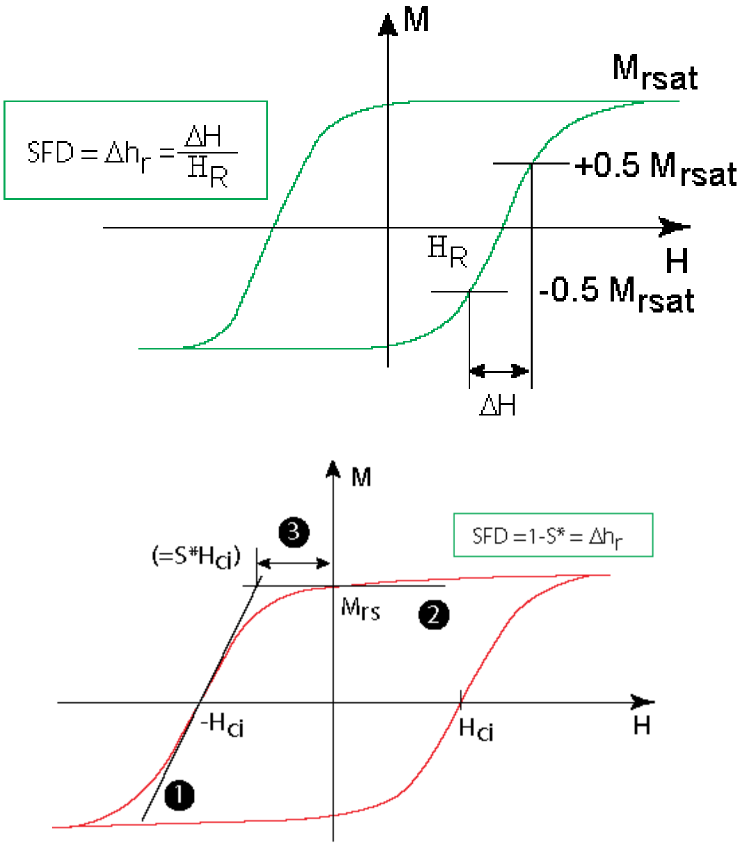


Figure 36.3: The definition of switching field distribution.

The SFD is defined as,

$$SFD = \Delta h_R = \frac{\Delta H}{H_R} \tag{36.2}$$

Where ΔH is the field range in which the magnetization varies between -0.5 M_{sat} to +0.5M_{sat} and H_R is the remanence coercivity.The second way of determining the SFD is made by drawing the tangent to the M-H loop at M=0 (see Figure 36.3b). Draw another line through the point (0, M_R) parallel to H-axis. The distance from the intersection between the first drawn tangent and the M-axis is equals $S^{*}\times H_C$. The SFD is defined here as

$$SFD = 1 - S^{*} \tag{36.3}$$

The values of 1-S^* have been found to closely match with the values of ΔH_R.

References:

[1].A. Perumal et al, Appl. Phys. Exp. 1 (2008) 101301.

Module 05: Advances in Recording Technology and Materials

Lecture 37: Properties of magnetic thin films: Part 3

Effects of time and temperature on the magnetic properties:

Since the magnetic properties of the materials are affected by the environment such as temperature, external field, and stability time, the discussion of effects of various parameters on the stability of the magnetic properties is essential to extend the materials for particular applications.

When the mean time of spontaneous reversal of a collection of independent particles due to thermal fluctuations is comparable to observation time, the measured magnetization is a function of measurement time. This is generally called magnetic viscosity or magnetic after effect. Here, the magnetization is expect to vary exponentially,

$$M(t) = M_0 e^{-t/\tau} + M_t\left(1 - e^{-t/\tau}\right) \tag{37.1}$$

where, M_0 and M_t are the initial magnetization at time t=0 and final magnetization after a considerable time t, respectively. In the presence of constant opposing field, M_t = - M_0, then the above equation can be rewritten as

$$M(t) = M_0 e^{-t/\tau} - M_0\left(1 - e^{-t/\tau}\right)$$

$$M(t) = M_0\left(2e^{-t/\tau} - 1\right) = M_0\left(2e^{\left[-f_0 t\, exp\left(-\frac{K_u V}{K_B T}\right)\right]} - 1\right) \tag{37.2}$$

where, $\tau = \tau_0 e^{\frac{K_u V}{K_B T}}$, is known as relaxation time or time constant required for a magnetic particle to switch its magnetization. Interestingly, the above equation reveals that the magnetization decay is extremely sensitive to the thermal effect. A simple calculation using the room temperature data (T = 300 K, k_B = 1.381×10^{-23} m^2kgS^{-2} and K_u = 2×10^6 ergs/cc) for a particle of below 10 nm shows a sharp falling in magnetization within the 10 days from the initial recording. It is important to note that for the ultrahigh density recording, the scaling on the bit size and average particle size is needed and hence one to get suitable materials with high anisotropy for compensating the loss due to the decrease in particle size.

We have seen that the magnetization decays is very sensitive to the value of the energy, which depends on the particle size.In addition, the value of energy barrier can be lowered by the presence of the applied field. Let us consider the switching process of a single domain particle by applying the external magnetic field along the easy axis. The energy density of the particle is defined as,

$$\frac{E}{V} = K\,sin^2\theta - \mu_0 H M_S \cos(\phi - \theta) \qquad (37.3)$$

Where ϕ and θ are the angles between the applied field and magnetization directions with respect to the easy axis, respectively. Substituting the angle ϕ=180^o, the eqn.(37.3) turns out to be,

$$\frac{E}{V} = K\,sin^2\theta + \mu_0 H M_S \cos\theta \qquad (37.4)$$

By calculating the values of $\sin^2\theta$ and $\cos\theta$, we can derive the equation for the maximum energy. There are two local minimums of energy at θ=0 ($E_{min}=\mu_0 M_S HV$) and at θ=180^o ($E_{min}=-\mu_0 M_S HV$), respectively.To switch the magnetization from 0 to 180^o, the magnetization must jump the peak energy barrier, as shown in Figure 37.1, which can be obtained by taking the derivative of the eqn.(37.4) to be zero.

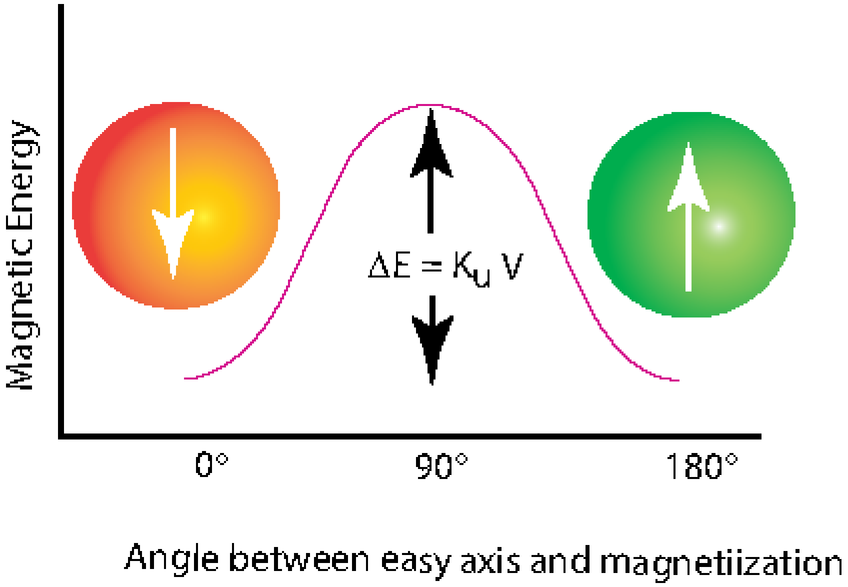


Figure 37.1: Schematic representation of magnetization switching between the angles 0 to 180^o.

$$\frac{1}{V}\frac{dE}{d\theta} = 2K\cos\theta\sin\theta - \mu_0 H M_S \sin\theta = 0$$

$$(2K\cos\theta - \mu_0 H M_S)\sin\theta = 0$$

This gives,

$$\cos\theta = \frac{\mu_0 H M_S}{2K};\ \sin\theta = \sqrt{1 - \left(\frac{\mu_0 H M_S}{2K}\right)^2} \tag{37.5}$$

Substituting the values of $\cos\theta$ and $\sin\theta$ in eqn.(37.4), gives

$$\frac{E_{max}}{V} = K\left[1 - \left(\frac{\mu_0 H M_S}{2K}\right)^2\right] + \mu_0 H M_S \frac{\mu_0 H M_S}{2K}$$

$$\frac{E_{max}}{V} = K - K\left(\frac{\mu_0 H M_S}{2K}\right)^2 + 2K\left(\frac{\mu_0 H M_S}{2K}\right)^2$$

$$\frac{E_{max}}{V} = K\left[1 + \left(\frac{\mu_0 H M_S}{2K}\right)^2\right] \tag{37.6}$$

Module 05: Advances in Recording Technology and Materials

Lecture 38: Properties of magnetic thin films: Part 4

Therefore, the difference in the energy barrier can be calculated by subtracting the eqn.(37.6) to minimum energy condition,

$$\Delta E = E_{max} - E_{min} = KV\left[1 + \left(\frac{\mu_0 H M_S}{2K}\right)^2\right] - \mu_0 H M_S V$$

$$= KV\left[1 + \left(\frac{\mu_0 H M_S}{2K}\right)^2 - \frac{\mu_0 H M_S}{K}\right]$$

$$\Delta E = KV\left[\left(1 - \frac{\mu_0 H M_S}{2K}\right)^2\right] = KV\left[\left(1 - \frac{H}{H_0}\right)^2\right] \qquad (38.1)$$

where, the ratio H_0=2$K/\mu_0 M_S$ is referred as intrinsic coercivity and when we apply the field H is equal to H_0, then the energy barrier turns out to be zero, indicating that the magnetization reversal takes place when the externally applied field exceeds H_0. This is true even without considering the effect of thermal energy. Although the eqn.(38.1) is true for the perfect alignment between easy axis and applied field direction, in real media, the alignment of easy axis is not perfect and hence the eqn.(38.1) can be written in general form

$$\Delta E = KV\left[\left(1 - \frac{H}{H_0}\right)^n\right] \qquad (38.2)$$

where the value of n varies between 1.5 and 2.Now, substituting the eqn.(38.1) in eqn.(37.2) in place of energy (K_uV), we get the general equation for magnetization as

$$M(t) = M_0\left(2e^{\left[-f_0 t \, exp\left(-\frac{KV\left(1-\frac{H}{H_0}\right)^n}{K_B T}\right)\right]} - 1\right) \qquad (38.3)$$

In order to study the effects of temperature and time on the stability of the magnetic bits recorded in the magnetic medium, MFM signal amplitude was extracted from MFM images by averaging the output signal across 1.5 μm track width. Figure 38.1shows the 10 kfci written bits observed at different temperature [1]. The bits were observed right away after raising the temperature. At room temperature and 150 ^{o}C, well-defined bits are observed. There is no reversed domain inside bits as a result of high thermal stability factor, large negative nucleation field, unity squarenessvalue and strong exchange coupling. At 200 ^{o}C, more reversed domains are observed both in the center and transition area of the bits. The amount of reversed domains increases with waiting time particularly at higher temperature. The normalized MFM signal amplitude of 10 kfci written bits is given in Figure 38.2as a function of waiting time at different temperatures. With this time scale, no detectable signal decay was observed at a temperature below 100 ^{o}C. At 150 ^{o}C, about 3 % signal decay was observed after 6-hour waiting. At 200 ^{o}C, significant signal decay up to 12 % was observed after 6-hour waiting. For Stoner-Wohlfarth (SW) grain assembly, the magnetization thermal decay can be simply described by eqn.(38.3), if no thermal barrier distribution and no external magnetic field are taken into consideration. The value of f_o is taken as 10^9 Hz in the present analysis. The observed thermal decay at 150 and 200 ^{o}C can be accounted for eqn.(38.3) if the thermal stability factor is taken to be 35.5 and 33.6, respectively. With a factor of 40, no observable signal decay within this time scale can be expected from eqn.(38.3). To evaluate the temperature dependence of FePt grain K_u in double-layered disks, out-of-plane hysteresis loops were taken at different temperatures by Polar Kerr effect.

Figure 38.1: MFM images of written bits of 10 kfci observed at RT, 150 ^{o}C, and 200 ^{o}C for [MgO 4-nm/FePt 3-nm]$_3$ /MgO 4-nm /SiO$_2$ 4-nm /Fe-Ta-C 200-nm /Glass disc. The size of the image is 20 μm in length and 1.5 μm in width [1].

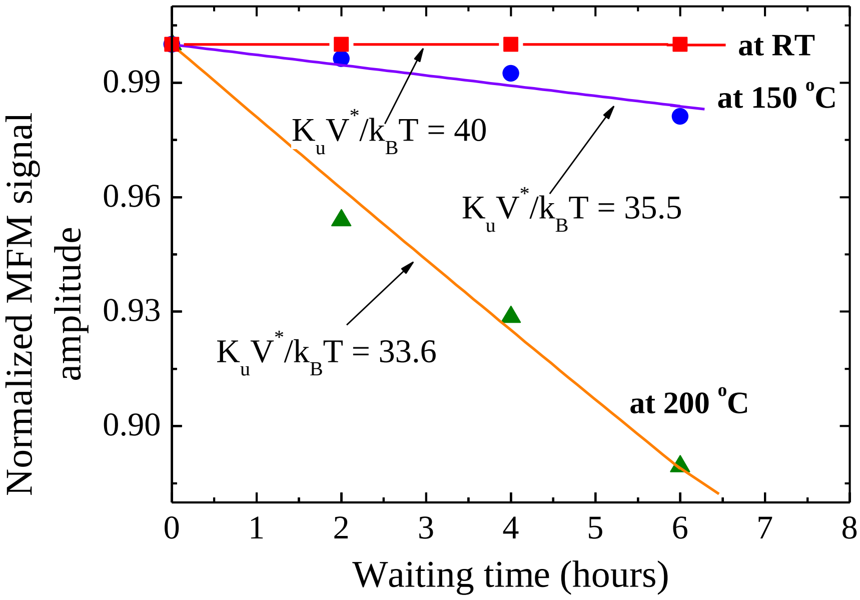


Figure 38.2: MFM signal decay at different temperatures for Disk 743. The solid lines are fitting curves for 150 °C and 200 °C and simulation curve for RT from eqn. (38.3) [1].

Similarly, rearranging the eqn.(38.3) gives as

$$H_C(t,T) = H_0\left\{1 - \left[\frac{K_BT}{KV} ln\left(\frac{f_0 t}{0.693}\right)\right]^{1/n}\right\} \tag{38.4}$$

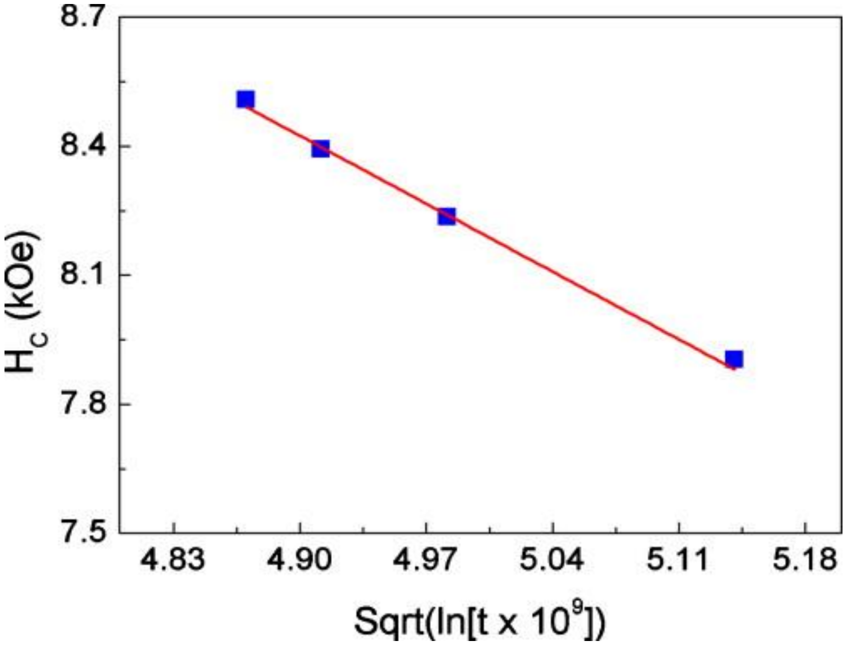


Figure 38.3: Variation in coercivity as a function of square root of logarithmic time for the post annealed double-layered film [3].

The eqn.(38.4) is called as Sharrock's law [2].The Sharrock's equation takes care both the time dependent (when the temperature is fixed constant) and temperature dependent coercivity when the time for measurement is kept constant. Figure 38.3 shows the utilization of the model to study the time dependent coercivity in the FePt based alloys for magnetic recording applications [3].

References:

[1].Z. Zhang et al, J. Magn. Magn.Mater.287 (2005) 224.

[2]. M.P. Sharrock, J.T. Mckinney, IEEE Trans. Magn. 17 (1981) 3020.

[3]. A. Perumal, L. Zhang, Y.K. Takahashi, and K. Hono, J. Appl. Phys. 108 (2010) 083907.

Quiz:

(1) What magnetic parameters are important while choosing materials for magnetic recording?

(2) What is the role of switching field distribution on the magnetic recording?

(3) What is thermal stability?

(4) What are the parameters affect the thermal stability of the media?

Module 05: Advances in Recording Technology and Materials

Lecture 39: Future projection on magnetic recording

We have already discussed the various aspects associated with the magnetic recording. Also, we have briefly seen through the write process, read process using various types of magnetic heads and the improvement in the areal densities of existing recording technology (longitudinal magnetic recording). One of the series problems faced in the current longitudinal magnetic technology is that with increasing the areal density, the scaling on the bit size and average particles have come down, which is limited by the superparamagnetic effects. Hence, it is believed that the present technology will not survive for long time and new technology have to be adopted for further improvement in the recording process. Hence, in this lecture, we shall cover

1. Improvement in the perpendicular recording for high areal density,

2. Heat assisted magnetic recording,

3. Patterned media

4. Bit patterned media.

Improvement in the perpendicular magnetic recording

We have already discussed the requirement of alternative recording technology (perpendicular recording), as compared to the exiting recording technology (longitudinal recording) and the possible head for writing the perpendicular recording media. However, we have not discussed the types of media required for the perpendicular recording. As we understand that for perpendicular recording, there must be a magnetic anisotropy perpendicular to the surface of the film of sufficient magnitude that the demagnetization does not force the magnetization to lie in the film plane. Figure 39.1 shows the typical geometry used in perpendicular recording, where the magnetic anisotropy (K) and the external magnetic field ($H_{app.}$) directions are shown perpendicular direction to the film plane, while the magnetization makes an angle θ with respect to the normal to the film plane.

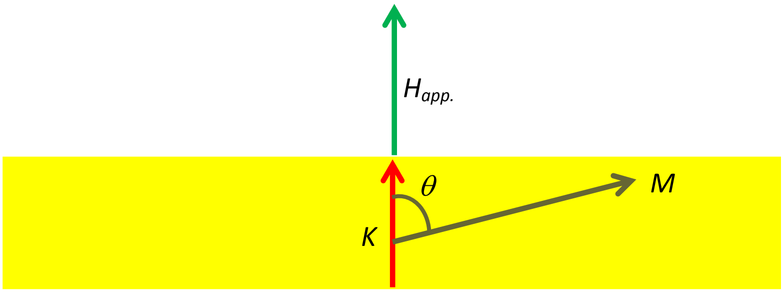


Figure 39.1: Geometry for perpendicular recording.

In this scenario, the total energy density is given by

$$E = K\, sin^2\theta - \frac{1}{2} H_d M_S \cos\theta - M_S H_{app.} \cos\theta \qquad (39.1)$$

and the demagnetization field, $H_d = -4\pi M_S \cos\theta$. Hence, the eqn.(39.1) turns out to be

$$E = K\, sin^2\theta + 2\pi M_S^2 cos^2\theta - M_S H_{app.} \cos\theta \qquad (39.2)$$

The equilibrium angle for the magnetization is obtained by taking the derivative of the energy density with respect to the angle, θ.Hence, eqn.(39.2) differentiated with respect to the angle,

$$\frac{dE}{d\theta} = 2K \sin\theta \cos\theta - 4\pi M_S^2 \sin\theta \cos\theta + M_S H_{app.} \sin\theta = 0 \qquad (39.3)$$

$$\frac{dE}{d\theta} = sin\,\theta\,[(2K - 4\pi M_S^2)\,cos\,\theta] + M_S H_{app.}\,sin\,\theta = 0 \tag{39.4}$$

The solution for the energy minimum is sinθ=0, but the stability of the solution requires$\frac{d^2E}{d\theta^2} > 0$,

$$\frac{d^2E}{d\theta^2} = \left[(2K - 4\pi M_S^2)[cos^2\theta - sin^2\theta]\right] + M_S H_{app.}\,cos\,\theta > 0 \tag{39.5}$$

The above eqn.(39.5) requires $(2K - 4\pi M_S^2) > 0$for stability in any value of external magnetic field, including $H_{app.} = 0$. The satisfaction of the above condition for various materials is summarized in Table 39.1 for comparison.

Table 39.1: Anisotropy energy and saturation magnetization for the magnetic materials proposed for perpendicular magnetic recording.

Sl.	**Materials**	$\boldsymbol{K_u}$ **(erg/cc)**	$\boldsymbol{M_S}$ **(emu/cc)**	$\boldsymbol{2\pi M_S^2}$	$\boldsymbol{(K - 2\pi M_S^2)}$	**Remarks**
1	Cobalt	4.5×10^6	1422	1.27×10^7	< 0	Not stable
2	CoCr based alloys	2×10^6	450	1.27×10^6	> 0	Stable
3	FePt	4×10^7	1100	7.61×10^6	> 0	Stable

It could be clearly seen from the table that the condition for the stability is not satisfied for pure Cobalt, but the CoCr based alloys and FePt based alloys satisfy the stability condition.A careful observation of the values reveals that the CoCr based alloys exhibit the difference $K - 2\pi M_S^2 \approx 0$, indicating that the CoCr based alloys with smaller particles size would not be suitable for the perpendicular recording, as the magnetocrystalline anisotropy energy in the smaller particles decreases with decreasing the particle size.

Module 05: Advances in Recording Technology and Materials

Lecture 40: Trilemma in magnetic recording

Recently, FePtAgC based alloy films with nanogranular microstructure were considered as one of the promising materials for high density magnetic recording using perpendicular magnetic recording scheme [1,2].The advantages of the perpendicular recording system over the longitudinal recording are manifold: (i) a very high thermal stability can be achieved even in small grain (with diameter along in-plane direction) with cylindrical grain structure (along normal to the film plane direction), as shown in Figure 40.1, (ii) The single pole head in a recording media with a soft underlayer can generate twice the field of longitudinal recording head (see Lecture 30). This allows one to write a medium with higher coercivity, further decreasing grain size and maintaining media thermal stability. (iii) The read-back signal from perpendicular medium with soft underlayer is larger as compared with equivalent longitudinal medium, improving signal-to-noise ratio, (iv) Commonly, the perpendicular media grains are strongly oriented, which results in smaller medium noise and a sharper recorded transition. (v) Also, the demagnetization field in the perpendicular medium is small at the transition region. This allows writing narrower magnetic transitions and improves thermal stability of high density data.

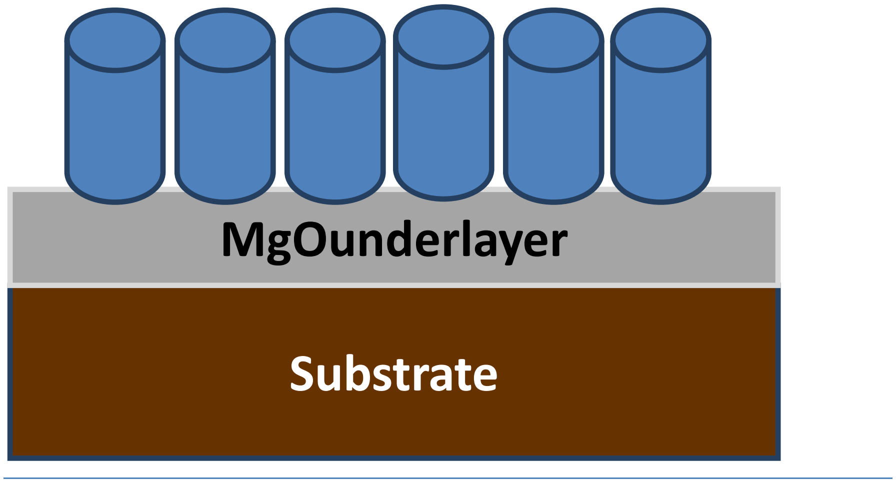


Figure 40.1: Schematic drawing of arrangements of FePt based alloys grains perpendicular magnetic recording media.

It is important to highlight that the introduction of perpendicular recording technology postpones the superparamagnetic problem. However, this solution can only delay the problem for short duration. On the other hand, clearly, a reduction in the grain size can be compensated for by an increase in the magnetocrystalline anisotropy constant. This results in an increase in the anisotropy field of the medium, as given by, $H_K = 2K/M_S$ and increasesthe medium coercivity. Therefore, one needs a larger write fields. Unfortunately, the maximum field of the writing heads is limited in the current technology and this poses a huge difficulty to the use of magnetic materials with high anisotropy fields. This establishes a well-known magnetic recording trilemma (see Figure 40.2).

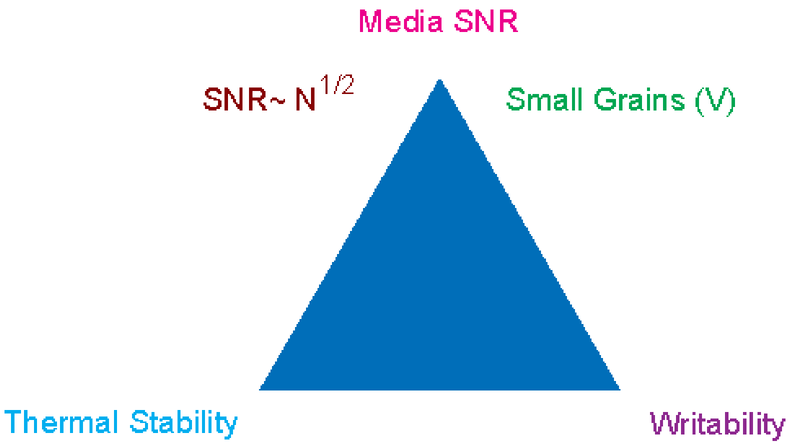


Figure 40.2: Schematic drawing of the magnetic recording trilemma.

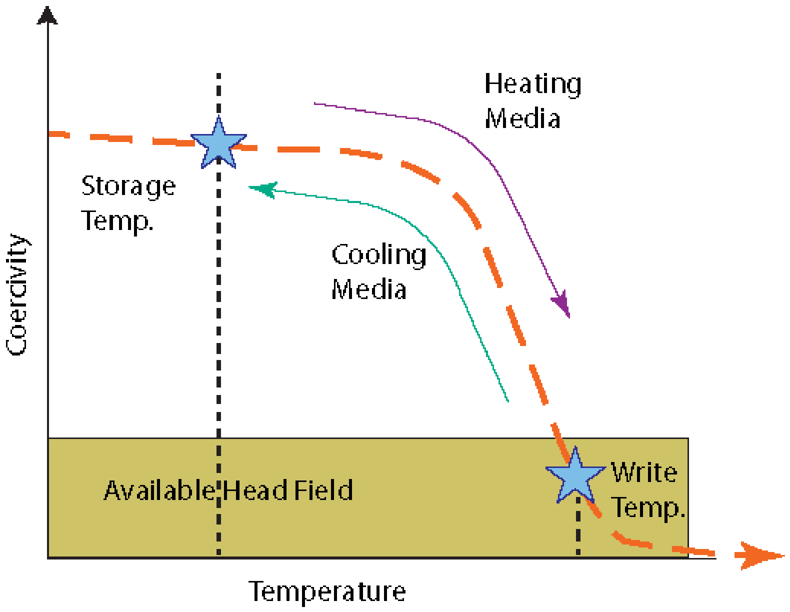


Figure 40.3: Temperature dependent perpendicular coercivity for a ferromagnetic material.

Currently, various research teams in industry and academia are actively involved in searching new solutions for the future. Two types of approaches have been proposed to push the areal densities above Terabits/inch^2. In the first type, an additional source of energy is needed to assist the applied magnetic field in reversing the bit magnetization, thus allowing higher anisotropy media to be used. These additional energies can either be provided by both heat-based processes, where locally heating the bit [3] and lower the anisotropy during writing or by adding a radio-frequency magnetic field [4]. The second type of approaches involves the use of lithographically patterned media, which has the advantage that the head designs similar to those in production todaycan still be used, but with radically different media. In the following, we shall discuss both of these suggested methods.

Ultrahigh density recording: Heat assisted or temperature assisted Magnetic Recording

Heat assisted magnetic recording (HAMR, Seagate acronym) or temperature assisted recording (TAR, Hitachi acronym) involves localized thermal heating of the media before the writing process. It is well known that the magnetic properties such as coercivity, saturation magnetization, magnetic anisotropy, and anisotropy field decreases with increasing temperature above room temperature for a ferromagnetic material. Particularly, the magnetic anisotropy constant decreases with increasing temperature at a faster rate than the magnetization. This leads to a reduction in the anisotropy field and coercivity with increasing temperature, as shown in Figure 40.3.Figure 40.4 depicts the writing scheme of the HAMR/TAR. Since the temperature raise in the materials decreases the magnetic parameters, the general idea is to heat the localized zone of the medium using a laser spot during the writing process such that the coercivity of the medium comes down to level of head fields. After the writing process and when the materials come back to room temperature, the material presents high anisotropy values and correspondingly, large thermal stability. This would allow increasing the recording capability by the factor of 100, i.e., the areal density of above 50 Terabits/inch^2.Although the HAMR technology has ability to write high anisotropy materials, this technology requires number of novel components, such as controlling Curie temperature in medium, light delivery system, the thermomagnetic writer, a robust head disk interface, and high anisotropy media with proper thermal design. Also, designing these components into a high performance data storage system requires system level optimization. Hence, this technology poses a number of technical challenges that must first be addressed before the industrialization.

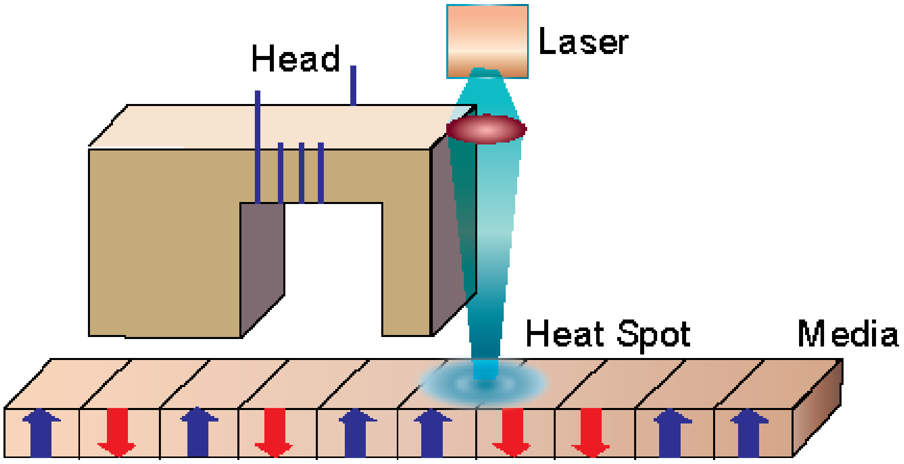


Figure 40.4: Schematic picture of the HAMR/TAR writing.

Patterned media:

One of the important advantages of conventional magnetic recording over other recordings, such as dynamic random access memory (DRAM) and flash, is the use of a continuous featureless recording medium using the magnetic heads fabricated through the lithography techniques.

However, to push the recording densities beyond the limit of conventional continuous granular media, two forms of lithographically patterned media have been proposed: discrete (or patterned) track media and bit patterned media, as shown in Figure 40.5.For example, the areal density of 520 Gigabits/inch^2 requires the bit dimensions of 15 nm (spacing between the transitions) × 81 nm (track pitch). The ratio between the later one to earlier one is called as bit aspect ratio, which is 5.4 for the above case. While the track pitch is limited by lithography process, the spacing between the transitions are not limited by rather the thin film deposition processes used to produce the read and write head elements. Nevertheless, we need to understand that what kind of advantages a nanofabrication of media would bring compare to the continuous unstructured media which is quite in-expensive.

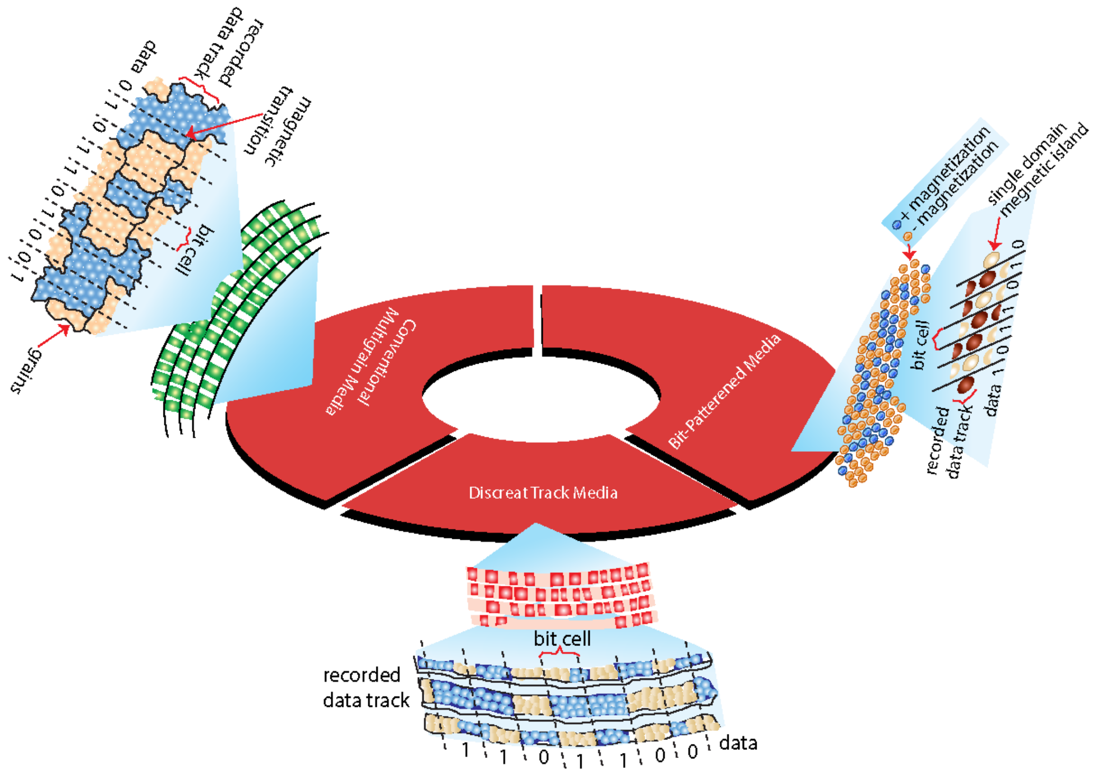


Figure 40.5: Schematic drawing of the continuous drawing bits, discrete track bits, and patterned media bits.

References:

[1]. A. Perumal, L. Zhang, Y.K. Takahashi, and K. Hono, J. Appl. Phys. 108 (2010) 083907.

[2]. L. Zhang, A. Perumal, Y.K. Takahashi, and K. Hono, J. Magn. Magn.Mater.322 (2010) 2658.

[3]. S. Batra et al, IEEE Trans Magn 42 (2006) 2417.

[4]. J. G. Zhu, X. C. Zhu, and Y. H. Tang, IEEE Trans. Magn. **44** (2008) 125.

Module 05: Advances in Recording Technology and Materials

Lecture 41: Patterning Media

In this lecture, we shall discuss on the discrete and patterned tracks, patterned bits, and magnetic property requirements for patterned media.

Problems encountered in the conventional media:

The bit length and the width in the conventional magnetic recording are defined by the field gradient from the write head with the assumption that the grains in the bits are small and are well separated to avoid any exchange coupling. On the other hand, the track locations in the media are defined by the servo marks and hence there is a mis-registration of the head to the track locations from the revolution to revolution due to the mechanical vibrations and non-perfect following of the track by the write head. This problem increases with decreasing the bit width for the increase in the areal densities. Also, there should not be any signal from the space between the different tracks to avoid any noise, which is possible only if the medium is either non-magnetic or recessed from the head. Such arrangements reduces the problem of noise signal coming out of poorly written bits and partially erased information at the edges of the track. This additional noise can be avoided, if one incorporates the discrete tracks. In the discrete track media, the tracks (track width) are well defined by lithography process, while the spacing between the transitions is still limited by the write head field gradient. This suggests that the materials requirement for the discrete track media is similar to the conventional recording media.

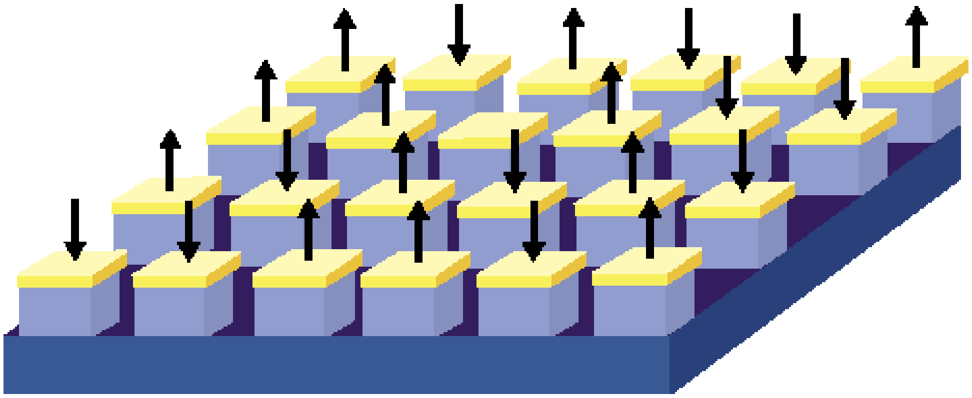


Figure 41.1: Schematic drawing of Bit patterned media.

Advantages of patterned media:

On the other hand, bit patterned media is a technology that allows to record data in a uniform array of magnetic grains, storing one bit per grain, as opposed to regular hard-drive technology, where each bit is stored in a few hundred of magnetic grains to get adequate signal to noise ratio. As shown in Figure 41.1, this media consists of a periodic array of discrete magnetic elements either prepared artificially by different lithography techniques or self-organized spontaneously. Each element is a bit that is well isolated from other elements but the magnetization inside the bit is strongly exchange coupled, compared to the conventional recording media. Therefore, the energy barrier of the bit is larger than that of the corresponding bit in conventional media and hence the thermal stability is improved. Another advantage of the patterned media is the elimination of the transition noise between bits as they are completely separated. However, the relative orientation of the magnetic easy axis of the islands and head field must be the same for every bit on the disk. This requirement automatically favours the use of materials with strong perpendicular anisotropy. The transition from the conventional magnetic recording to perpendicular recoding has occurred around 2006 with the advantage of larger write fields and higher areal densities in the perpendicular magnetic recording. However, the fabrication of the low cost and large area patterned structures without any damages and faults is still a challenge and various lithography processes are attempted to enhance the methods for achieving ultrahigh density pattern. Figure 41.2 shows the schematic process for the fabrication of patterned bits using the e-beam or other lithography process. In this process, a master pattern, generated at considerable expense, is replicated by a two-generation nano-imprint lithography process. Subsequently, a number of imprinting templates that are copiesof the master pattern are created and then replicated the patterns from the imprinting templatesonto millions of disks.

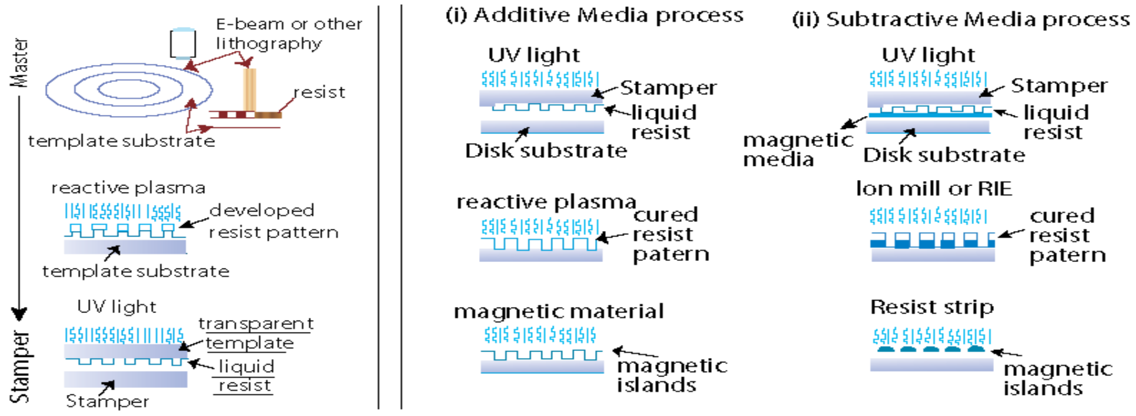


Figure 41.2: Schematic diagram of the patterning process to produce the bits on the disk substrates.

Magnetic properties of the patterned media:

The magnetic property requirement for the bit patterned media is different from the conventional media. In the case of bit patterned media the entire bit to the information write must switch as a single unit which requires a highly exchange coupled behaviour within a single bit. Similarly, the bit switching between the grains should be identical to avoid the requirement of different field to switch different bits. This is typically defined as switching field distribution, which should be narrower. However, in the real scenario, there are several factors contributing to switching field distributions: (i) the magnetic property variation within the bit considered for writing, and (ii) magnetic exchange interaction between the bits. Hence, the applied field necessary to switch a particular bit depends on the sum of the magnetostatic fields produced by the other bits in the bit patterned media. This can be controlled by manipulating the magnetization of the media and hence the switching field distribution. However, one should also keep a note that this is limited by the fact that the same magnetostatic stray fields are responsible for the signal detected by the read element.

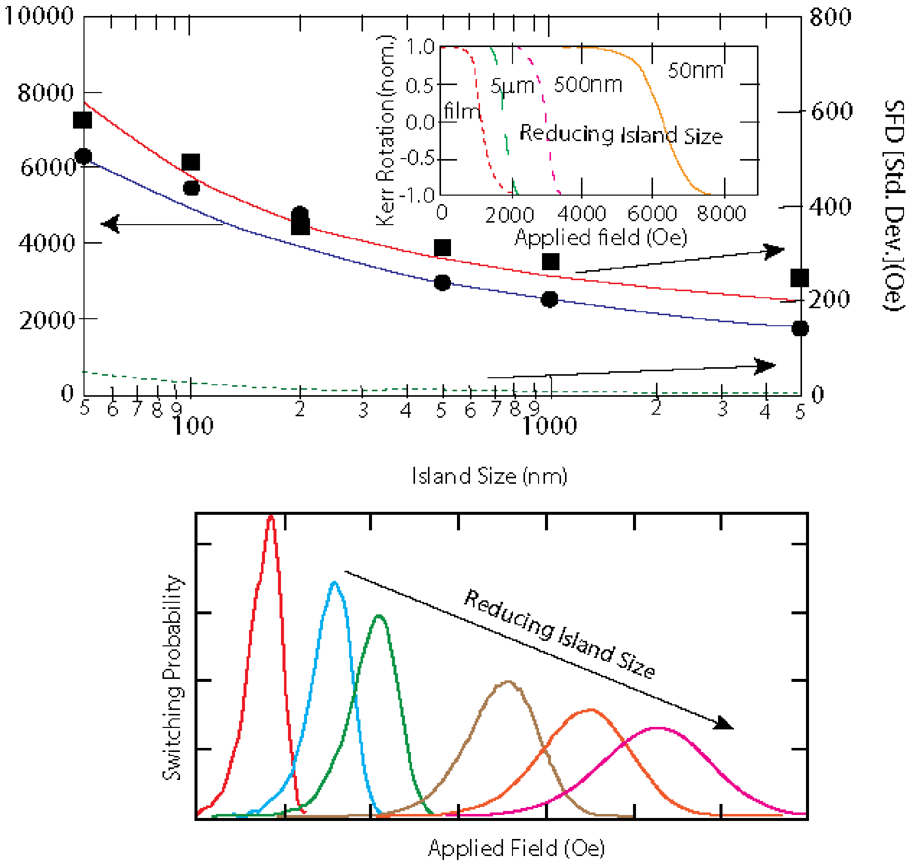


Figure 41.3: (a) Variations of remnant coercivity and SFD for thin films and different islands, and (b) simulated switching field distributions as a function of various island sizes [1].

In the case of a continuous film, the magnetization reversal occurs by nucleation of a small domains reversed at random sites followed by the domain wall motion. Hence, the reversal field of the thin films depends on both the nucleation reverse field, and the depinning field needed to displace the domain wall. Thomson et al [1] reported that the remanent coercivity, defined as the reverse field required to reduce the remanent magnetization to zero, is about few hundred Oe for a continuous film, and increases with decreasing the island size, as depicted in Figure 41.3. For an island of 50 – 100 nm diameters, the remanent coercivity increased to 5000 Oe, as compared to 1000 Oe for the continuous film. In addition, the tail nature of the remanent curves increases with decreasing the average island size, and the functional form of the switching field distribution changes from the Gaussian distribution for small islands (50 nm) to more log-normal form for large sized island (>μm). This suggests that the single domain islands reverse in a different manner, as compared to the parent film. Also, if the local anisotropy of the film varies as a function of position, then the field required to switch individual islands will also vary. Furthermore, the lithography and patterning process would induce variations in the island anisotropy due to the damage at the island edges [2]. These effects play an important role when the size of the island approaches to a nanometer scale. Therefore, the determination of underlying physics and the control of the intrinsic anisotropy distribution will be an important requirement in all the nanomagnetic devices.In summary, the prospects for commercialization of patterned media into hard disk drive products depend on the simultaneous progress on scientific discovery, engineering innovation, and the ability to create a cost effective manufacturing processes, which should eventually lay a path to higher densities in the range of 5 to 50 Terabits/in^2 to attract the industries with large investment based on this new manufacturing technology.

References:

[1]. T. Thomson et al, Phys. Rev. Lett. 96 (2006) 257204.

[2]. J.M. Shaw et al, Phys. Rev. B 78 (2008) 024414.

Quiz:

(1) What are the improvements possible in the perpendicular magnetic recording to enhance the areal density?

(2) What are the materials satisfy the stability condition for perpendicular magnetic rercording?

(3) Describe the magnetic recording trilemma?

(4) How the heat assisted magnetic recording or patterned media helps to improve the area density of recording in the future?