

Fabrication and Application of Patterned Magnetic Media

by

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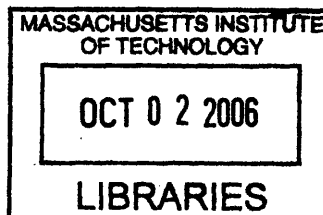
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Abstract

In order to overcome the superparamagnetism in thin film magnetic recording media, a novel magnetic medium, called patterned medium, is studied here as a potential candidate for the future hard disk storage application. Within the patterned medium, one bit is stored in one magnetic unit, which has to be prepared “to-precision” along the track at uniform periodicity. A variety of magnetic recording media will be introduced and compared first. Detailed discussion will be focused on the potential techniques for patterned media fabrication. IP environment, market competition and business models will be given at the end.

Thesis supervisor: Professor Caroline Ross

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Chapter 1 Introduction

Magnetic memories and sensors, invented over 100 years ago, have played a key role in the development of information storage devices, such as audio cassettes, video tapes and hard drives. In 1956, IBM introduced the RAMAC hard disk with platters two feet in diameter that held the equivalent of 100,000 bytes, which is less than the capacity of a single 3½ inch floppy disk today. After the RAMAC hard disk, desktop computer hard disks were introduced with 5MB using 5.25" platters. In recent years, the density of hard drive disks has doubled every year, resulting in more than a cumulative 20 million fold increase since the introduction of RAMAC. Today's entry level drives have at least 8,000 times more capacity. At the same time, platter size was reduced to 3.5" for desktops, 2.5" for laptops and 1" for handhelds.

Most magnetic devices manufactured today are thin-film based, such as video tapes and hard drive disks. Within these devices, a layer of magnetic thin film is used as a recording media. In current hard drive disks (HDD), which usually have a multilayer structure, magnetic materials are sputtered onto a glass substrate. The bit is the basic unit to evaluate the storage capacity. In current hard drive technology, each bit is composed of a number of magnetic grains, which are oriented at the same direction either in the magnetic film plane or perpendicular to it. The data storage density is measured as areal density, which is the product of track density and bit density. The data storage density depends on the bit size and the transitional region between two bits.

New nanofabrication technology, offering unprecedented capabilities in the manipulation of material structures and properties, opens up new opportunities for engineering innovative magnetic materials and devices. The concept of patterned magnetic storage media (also called discrete media) was proposed for a long time ago. In a patterned media recording system, each island of magnetic material is isolated from the others, allowing each tiny cell to act as a bit.

In this paper, a brief review of the historical development of hard drive disks will be introduced first, from particulate media, which was used in RAMAC, to the current thin

film media and to patterned media which is a promising solution for future data storage application. Then, concentration will be focused on the recent advances in fabrication of patterned magnetic media. In the end, a variety of magnetic properties of patterned media are studied in detail.

Chapter 2 Evolution of Hard Drive Media

2.1 Particulate media

The first hard drive disk was made of particulate media, which were extensively used as recording media back in the 1970s.



Figure 2.1 Images of particulate media left:Fe₂O₃ right: CrO₂

All the particles are a needle shape, and usually the aspect ratio a/b is in the range of $1/6 \sim 1/10$. (shown in Figure 2.1) The shape anisotropy determines the coercivity here. In order to increase the storage density, small grain size is normally preferred in the magnetic recording. However, in particulate media, it is difficult to reduce of the particulate size beyond a certain point while maintaining the coercivity due to thermal assisted switching. And the coercivity of particulate media is low. In the case of Iron oxide (γ -Fe₂O₃), used in some tape recorders, its coercivity is about 20~32 kA/m (250~400Oe). The coercivity of the nanoscale ferromagnetic particles is about 160 kA/m (2000Oe). In addition, the particulate media generally have a low remanence. This is because the magnetic moments of the particle are randomly oriented. The coating process causes a rougher media surface compared to that of thin film media which are generally manufactured by sputtering. Because of these reasons, the particulate media is obsolete in hard drive recording.

2.2 Thin Film Media

Thin film media have dominated the hard drive market since the 1980s. The magnetic metallic thin films are deposited using vacuum deposition technology on solid substrates, which results in a much smoother surface than that of the particulate media. Magnetic materials are sputtered from the source to the target in a sputtering machine, such as DC magnetron sputtering machine. The high magnetization of metallic films allows the use of thinner films on the hard disk substrates, such as Al or glass substrate. The current thickness of thin film media is about 15 nm, enabling the possibility of storing high density data, which will be discussed later. Compared with particulate media, the corresponding coercivity of thin film media is much higher. The high magneto-crystalline anisotropy of new materials contributes to a higher total coercivity.

There are two types of thin film media, longitudinal media and perpendicular media, depending on the magnetization orientation. In longitudinal media, the magnetization is oriented parallel to the thin film plane. Flux leaks from the magnets arranged with similar poles facing each other. (Figure 2.2 left) On the contrary, the magnetization of perpendicular media is pointed out of the film plane, either up or down. (Figure 2.2 right) In both cases the magnetic field is detected by the hard drive head.

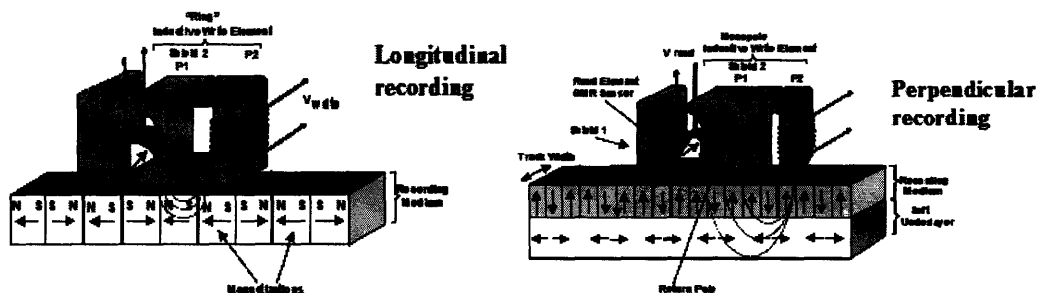


Figure 2.2 Comparison of longitudinal media (left) and perpendicular media (right)
(Pictures borrowed from Hitachi Global Storage Technologies)

Areal density is used to describe the data storage density of the thin film disks. The disks are divided into circular tracks, and ultimately bits, which are located on the tracks. Track density is used to measure the distance between two parallel tracks, and linear density

measures the packing density of bits within a single track. Hence, the areal density can be expressed as

$$\text{Areal density} = \text{Track density} \times \text{Linear density}$$

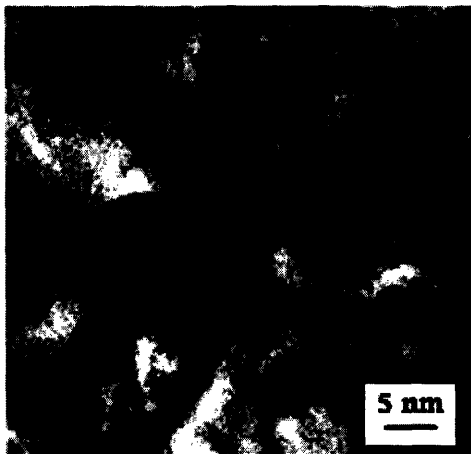
Efforts have been made to increase both the track density and linear density. In longitudinal media, the length of each bit decreases as the linear density increases (Figure 2.2 left). The shrinking of bit length results in a stronger demagnetization field, which makes further shrinking of bit length more difficult.

This intrinsic drawback of longitudinal media prevents the further decreasing of bit size, triggering the introduction of perpendicular media. The bits are oriented perpendicularly to the thin film plane. There is a soft underlayer under the magnetic film (illustrated in Figure 2.2 right). It completes a magnetic circuit composed of writing head, magnetic domain and the underlayer itself. In the case of perpendicular recording, a strong writing magnetic field generated by HDD head goes directly through the magnetic domain beneath the head. The writing field in perpendicular media is stronger than the fringing magnetic field in longitudinal recording. (Figure 2.2 right). A stronger writing field means materials with higher coercivity can be used and the corresponding domain size can be further reduced. Compared with longitudinal media, the thermal stability of perpendicular media is better. Another advantages of perpendicular media arises from the fact that its output signal is larger due to the high magnetization of the perpendicular recording layer. The reason will be discussed further in the following chapters.

Several companies have already released or will soon release hard drives featuring perpendicular recording technology. In January 2006 Seagate began shipping a 2.5 inches perpendicular recording hard drive for notebooks. Hitachi has not released perpendicular recording hard drives, but it demonstrated drives with an areal density of $35 \times 10^9 \text{b/cm}^2$ ($230 \times 10^9 \text{b/in}^2$) in April 2005. They are anticipating having both 20G Microdrives (the kind used in the iPod mini) and 1 Gb 3.5 inches personal computer drives available by

2007, but they are actually planning to have a 2.5 inches laptop drive that uses perpendicular recording out before the end of 2005.^[2.1]

Since the invention of RAMAC in 1950s, manufacturers have tried their best to shrink the magnetic grains, making it possible that more data can be store on the hard drive disks. However, there are several factors that eventually prevent hard drive manufacturers from continuing to shrink the magnetic grains that make up data bits. The superparamagnetic effect is the major factor that will ultimately limit hard drive density. Superparamagnetism (or superparamagnetic effect) is observed in very fine particles (depicted in Figure 2.3), where the energy required to change the direction of the magnetic moment of a particle is comparable to the ambient thermal energy.



At this point, the rate at which the particles will randomly reverse direction becomes significant. When the first commercial hard drives appeared in 1956, the idea of the superparamagnetic effect was known, but it was not a concern. Hard drives did not need to store much data, and the physical size of the drives was not limited.

Figure 2.3 Magnetic grains of hard drive^[2.2]

Now the superparamagnetic effect has moved to the forefront of hard drive manufacturers' concerns. Back two years ago, Hitachi experts estimated that the superparamagnetic effect would begin to really show itself in 2006, though this estimate is constantly changing.^[2.3] Whilst, the truth is most big hard drive manufacturers have begun massive fabricating perpendicular magnetic recording hard drive in 2006 to avoid the superparamagnetic effect in the longitudinal media.

2.3 Patterned Media

However, perpendicular recording is not a panacea for all storage requirements. Rather, it is a stepping stone that will give the disk drive industry breathing room to explore and invent new methods of extending magnetic recording. One method called patterned media, for example, may one day reduce the size of a bit to a single grain as compared to the 100 or so grains that comprise a bit today. The approach uses lithography to etch a pattern onto the platter. Ideally, the novel technology should be easily and economically replicated, adding no significant cost to the drive and potentially improving areal densities by another factor of 10. ^[2.4]

Over more than 40 years, the evolution of thin film media can be categorized as: a) the use of higher coercivity materials, b) reduction of thin film thickness and moment, c) reduced exchange coupling, d) enhanced head sensitivity. The materials used in current hard drive disks have coercivity about 240 kA/m (3000 Oe). The thin film thickness is about 15 nm. And the current commercialized hard drive disks have a recording density about $47 \times 10^6 \text{b/cm}^2$ ($310 \times 10^6 \text{b/in}^2$). Because of the superparamagnetism barrier, researchers are looking for alternative solutions by patterning the storage medium, such as patterned media. Actually, patterned media can be divided into three categories: 1) patterned servo marks, 2) patterned or discrete tracks, 3) patterned bits.

2.3.1 Patterned Servo Marks

Servo marks are magnetic positioning information recorded on the disks to position the HDD's magnetic heads onto the data tracks. Previously, it was typical to write the servo tracks by using the HDD's own head and positioning it using an external actuator. There are three important requirements in servo mark writing technologies: 1) high quality, 2) high productivity, 3) low equipment costs.

The quality of servo marks greatly affects the positioning accuracy of the HDD. Because the current servo writing is a serial process, it is very time-consuming. And, since the

writing process usually takes place inside a clean room, the facility investment is very high. Figure 2.4 shows a batch of writing machines inside a clean room.

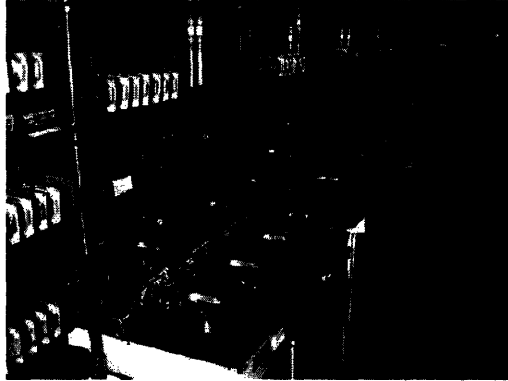


Figure 2.4 Servo information writers in a clean room^[2.5]

Different approaches have been developed to achieve better servo quality, higher productivity and lower equipment cost. Uematsu et al^[2.5] reduced the moving mass of the servo writer by employing an interferometer to increase the servo bandwidth of the system. The advantage of this technique is its relatively easy application, since most improvements are made based on current servo duplication systems. And corresponding reliability of the new duplication systems can also be higher than the original systems. However, the major problem of this technique is that the servo masks are still written serially.

A parallel writing process could result in a large increase in efficiency and corresponding decrease in cost, especially as the areal density increases. One early approach is trying to write the servo marks in a magnetic printing process.^[2.5] The major advantage of this technique is that it is a parallel process which is much faster than the serial writing process. Magnetic printing uses a master disk fabricated lithographically by electron beam. After development, the master disk forms a ridge/groove structure according to the servo pattern. A sub-micro thick soft magnetic layer is sputtered onto the master disk afterwards.

The magnetic duplication process is shown in Figure 2.5. First the slave disk is initially magnetized in one direction. Then, make intimately contact between the master and slave disk. The servo features are transcribed to the disk media using an external magnetic field in the reverse direction. The magnetic parts in the disk are reversed in the contact positions according to the land/groove structures in the mask disks.

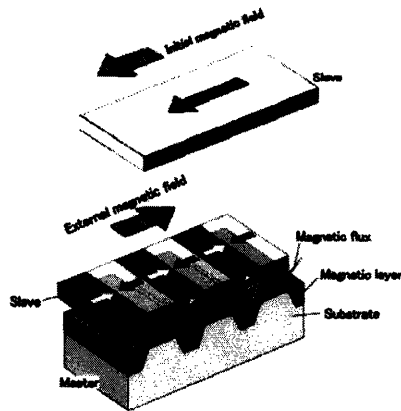


Figure 2.5 Magnetic duplication of the slave disk^[2.6]

Magnetic patterns can also be transferred when the master disk is fabricated by depositing a magnetic film onto a nonmagnetic flat substrate and subsequently patterning it lithographically, resulting in the magnetic parts remaining only at the mesas the master medium. (depicted in Figure 2.6) In the previous scheme, the magnetic film also exists at the valley. (depicted in Figure 2.5) The duplication processes for both masks are the same.

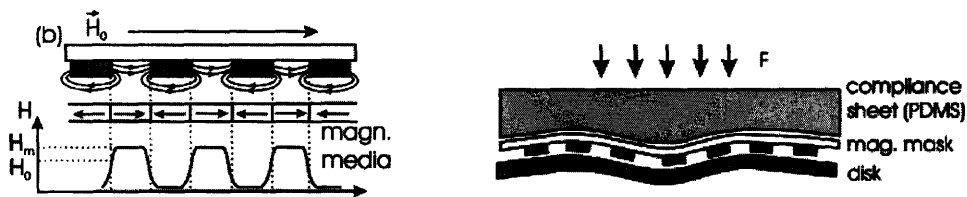


Figure 2.6 Another contact printing scheme^[2.7]

In addition, a thick polydimetoxysilane (PDMS) elastic compliance layer is deposited on the back side of the master layers to improve the contact uniformity. The compliance of the PDMS layer insures approximately uniform pressure over the full area of contact. (illustrated in Figure 2.6) The printing processes for the latter mask is the same as mentioned before: a) dc erasing b) contact printing. A pressured gas system^[2.8] can also

be used to apply uniform pressure. Figure 2.7 shows an air channel structure for close and full surface contact system.

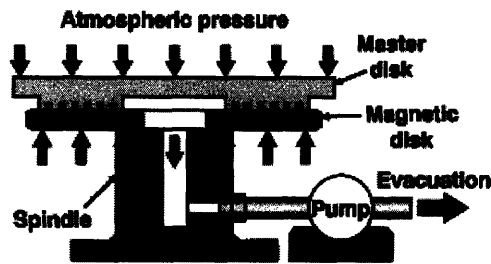


Figure 2.7 A scheme for an air channel system^[2.8]

In addition to the patterned servo marks, patterned magnetic bits used to store data information can also be duplicated in this way. Magnetic features on 100nm scale have been duplicated successfully, while smaller scales with 10nm resolution remain to be demonstrated in the future.^[2.8]

Master disk lifetime is an extreme critical issue when considering the commercial viability of the magnetic lithography technology. Ishida et al^[2.8] has demonstrated that the master disk is durable over one million pieces of the printed media production. Contamination is also one of the critical issues needed to be considered. The contamination test, conducted by Ishida et al^[2.8], shows the contact printing process does not increase contamination on the printed disks. Besides, the magnetic printing technique can also be applied to perpendicular recording media.

One of the drawbacks of the parallel writing system is that the rigid mask should be fabricated by electron beam lithography, which is a serial, time consuming process. To massively produce patterned disks, a number of masks are needed. Uniformity between each mask will also be an issue. For the current technique level, the patterned features of magnetic printing scheme are not small enough to compete with that of commercial products. Also due to manufacturability reason, magnetic printing is still only a potential scheme for the mass production, and has not been commercialized yet.

2.3.2 Patterned/Discrete Track (PT/DT)

To achieve a better SNR (signal-noise-ratio) in HDD continuous media, patterned track media have been proposed and investigated for more than 15 years. In patterned track media, the tracks are separated physically and magnetically by grooves. The grooves between the tracks should be either filled with non-magnetic materials or trenches which give little or no magnetic response to the head. The track width is usually defined lithographically, while the down-track bit size is still defined by the magnetic field and its gradient from the writing head as in the conventional magnetic recording. The materials used in the patterned track media are the same as the ones used in continuous media. The discrete tracks may reduce the problems of poorly written bit and partial erase on the edge of the tracks which yields a significant noise during side reading. Furthermore, because the width of the data track is now defined by the disk surface patterning process instead of the write head, the write-track-width-tolerance requirements can also be loosened, allowing for potential improvements in head yields.

Back in 1987, Lambert and his group fabricated the patterned tracks as narrow as $0.5 \mu\text{m}$ lithographically.^[2.9] The processes are illustrated in the following Figure 2.8.

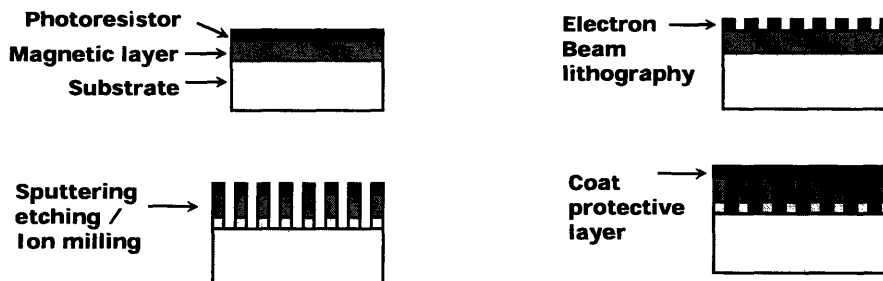


Figure 2.8 Processes to fabricate patterned tracks

First, a layer of Co-alloys of various compositions was sputtered onto the substrates which were cleaned by sputter etching before hand. Discrete circular tracks were defined on the disk surface by sputter etching. A photoresist (PR) mask is made by electron beam lithography. To ensure the discontinuity of the tracks, the trenches between the tracks are

etched deeper than the magnetic film. In Lambert's experiment, the radial distance between two tracks is made relatively wide ($200\ \mu\text{m}$), making it possible that heads with wide track width could read the signals from the narrowest tracks below, reducing the influence from the neighboring tracks. To reduce the non-uniformity of the response from the edges of the heads, heads with track width wider than media tracks were used. Experiment results demonstrate the normalized media noise voltage scales with the (track width)^{1/2}. Magnetic servo patterns have also been fabricated using the same way later by Lambert.^[2.10] A combination of patterned servo marks and patterned tracks was proposed to increase the amplitude of the readback signal of patterned tracks.

However, due to the cost issue, patterned track media has not been considered as a standard manufacturing process since the industry was not facing superparamagnetic effects at that time.

More recently, in order to relieve the thermal stability challenge posed by the superparamagnetic effect, patterned track media have received renewed interest as a promising approach. Instead of fabricating patterned tracks in a longitudinal media, Soeno et al^[2.11] have produced patterned tracks in perpendicular media, including the soft under layer (SUL), using electron beam patterning followed by etching the magnetic layers as mentioned above. Tracks as wide as $0.33\ \mu\text{m}$ were fabricated in a perpendicular magnetic recording layer of CoCrPt with a SUL layer. (shown in Figure 2.9) By using electron beam lithography, the experiments have a potential for making tracks with width less than $0.1\ \mu\text{m}$.

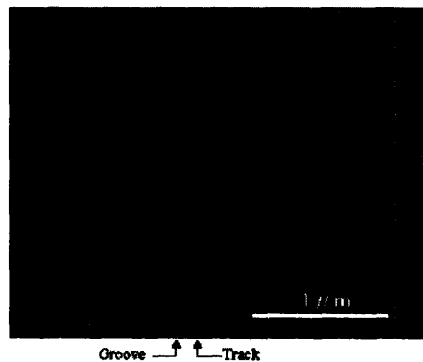


Figure 2.9 SEM image of patterned track media^[2.11]

The experiment results showed improved writability, due to a better flux distribution from the head, and reduced cross track reading, as expected. However, its manufacturability is still limited by the slow lithography processes of track patterning. The electron beam lithography process mentioned above will be too slow and expensive to be introduced into a product.

In addition to the method mentioned above, there are several other techniques developed to fabricate patterned track media. Tatsuaki Ishida et al.^[2.12] proposed a method using embossed disks with discrete magnetic tracks and servo marks. The tracks and the servo marks are made by etching the glass substrate or injection molding using photopolymerization of a polymer substrate. C. Chappert et al.^[2.13] have fabricated planar patterned magnetic media using ion irradiation. By ion irradiation through a lithographically-made resist mask, the magnetic properties of CoPt multilayers were patterned without affecting their roughness and optical properties. Ion irradiation is used to “disorder” the magnetic properties in the trench regions leaving the patterned tracks intact.

There are advantages and disadvantages to all of the aforementioned methods, but none have met the objective of being cost effective in a large-scale manufacturing process and also providing adequate smooth top surface allowing further reduction of head-to-media spacing requirement. A practical patterning process for manufacturing a cost-effective patterned track media is needed.

To meet the low cost, high reliability process requirement, D. Wachenschwanz et al.^[2.14] have developed a nanoimprint lithography (NIL) technique used to create a land/groove structure on NiP-plated AlMg substrates. Such unpatterned substrates are extensively used in conventional continuous media HDD today. In this case, the patterned tracks are fabricated in longitudinal media, while it has been proposed that a similar process can be employed for patterning the soft under layer (SUL) of the perpendicular media also.^[2.15] In the case of longitudinal media, the tracks are textured circumferentially in order to

provide a preferred easy-axis magnetic orientation.^[2.16] The processes are depicted in Figure 2.10.

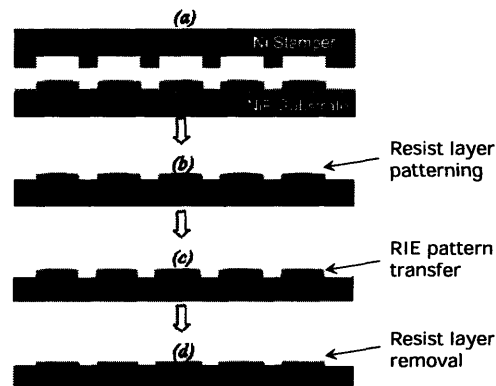


Figure 2.10 Nanoimprint lithography (NIL) processes for patterning the tracks^[2.14]

For longitudinal media, substrate surface texturing is required before magnetic layer deposition to produce a preferred easy magnetic axis along the circumferential direction of the disk once the magnetic layer is deposited. In case of perpendicular media, the substrate texturing will not be required. Patterning can be done either on the substrate or in the soft underlayer (SUL). A rigid silicon master is first fabricated by either a laser beam or electron beam. Then the patterns are transformed to Ni stampers that will be used to emboss the resist. Current, the technique is extensively used in fabrication of optical storage disks such as CDs and DVDs. With laser beam patterning, tracks as wide as 285 nm with approximate $9 \times 10^9/\text{cm}^2$ ($60 \times 10^9/\text{in}^2$) areal density have been demonstrated. By using electron beam lithography, the track width can reach 127 nm with about $31 \times 10^9/\text{cm}^2$ ($200 \times 10^9/\text{in}^2$) areal density. (shown in Figure 2.11)

In fact, the nanoimprint lithography technique has also been extensively investigated as a potential approach for the mass production of patterned bit media, which will be discussed in the next chapter.

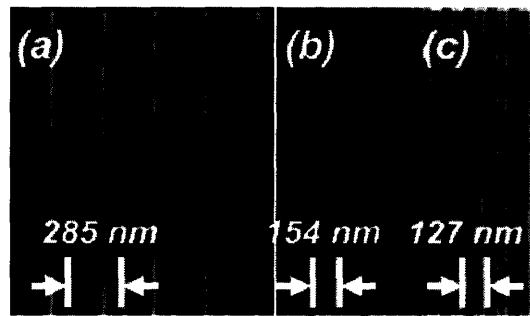


Figure 2.11 SEM images of patterned tracks 285nm (laser beam) 154nm (electron beam) and 127nm (electron beam)^[2.14]

The groove/ land structure of the patterned media lead to head slider flying instability. The media surface can be planarized by SiO₂ deposition followed by etching of the extra SiO₂. K. Hattori et al.^[2.17] have fabricated the patterned tracks in perpendicular media using both techniques discussed above: a) EB lithography, b) NIL. Tracks as narrow as 90 nm have been fabricated using NIL. Results from flying performance test are shown in Figure 2.12.

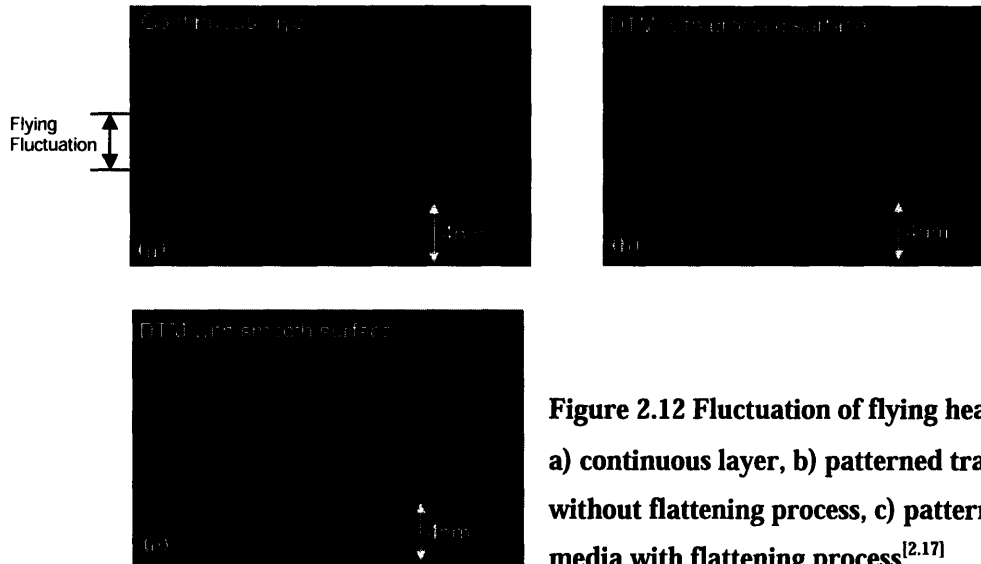


Figure 2.12 Fluctuation of flying head slider a) continuous layer, b) patterned track media without flattening process, c) patterned track media with flattening process^[2.17]

The flying height of current HDD head is about 10nm, and it will be reduced to about 5nm in the near future.^[2.18] Figure 2.12 describes the measurement result of the head fluctuation for three different media: a) continuous media, b) patterned track media

without planarization process, c) patterned track media with planarization flattening process. Compared to the continuous media, the flying height of the head slider is not stable on the patterned track media without flattening process. The fluctuation is about 10nm, while it is about 2nm in the continuous media. With the additional flattening process, the fluctuation for the patterned track media is comparable to that of the continuous media. A surface roughness Ra smaller than 1nm can be achieved.^[2.17]

2.3.3 Patterned bits

In most cases, the patterned bit media have been simply called patterned media. And we will use this terminology. A patterned recording medium, shown in Figure 2.13, is a promising solution for future data storage. There are a variety of techniques developed to fabricate patterned media. In this section, we will introduce the basic concept of patterned media and discuss the potential advantages of the patterned media. The fabrication techniques will be discussed in detail in chapter 3.

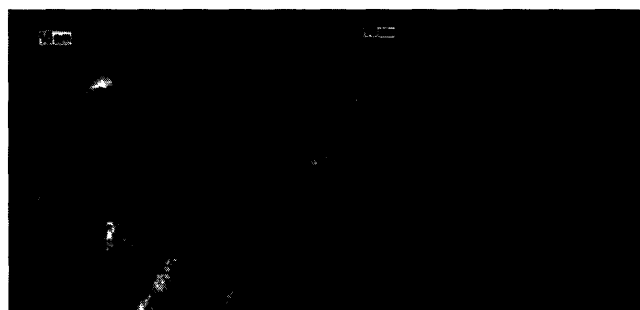
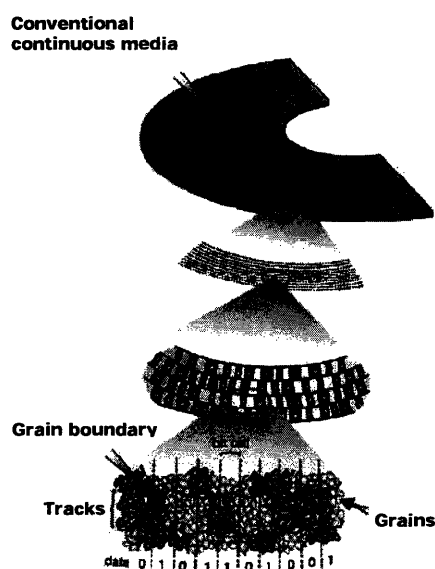


Figure 2.13 a) Illustration of conventional continuous media^[2.19] (left), b) TEM images of longitudinal media^[2.20] (right)

Before starting to discuss patterned media, we will take a close look at the conventional thin film magnetic disks again. Figure 2.13 a) illustrates the insight of a current continuous media. The pictures in Figure 2.13 b) are transmission electron micrographs (TEM) of two different disk media which illustrates how the grain structure has evolved

over time. The TEM on the left is a magnetic media that supports a data density of about $1.6 \times 10^9/\text{cm}^2$ ($10 \times 10^9/\text{inch}^2$) with an average grain diameter of about 13 nm. The magnetic media on the right supports a data density of $4 \times 10^9/\text{cm}^2$ ($25 \times 10^9/\text{inch}^2$) with an average grain diameter of about 8.5 nm.

Within the continuous media, a stream of bits is recorded as regions of opposite magnetization on a single track. At high magnification from TEM images, it becomes apparent that within each bit cell there are many tiny magnetic grains. These grains are randomly created during the deposition of the magnetic film. Each grain behaves like an independent magnet whose magnetization can be flipped by the write head during the data writing process.

All the magnetic grains in a bit cell can be flipped uniformly. There are zigzag structures forming between the two oppositely magnetized bits. When the magnetic grains are small enough, relatively straight transition region can be formed so that it is easy to detect which bit cells contain a boundary and which do not. However, if the grain size does not reduce as we increase the areal density, signals from the transition area will become proportionally noisier, eventually preventing the readback system from accurately recovering the data. This is called transitional noise which will be discussed in chapter 4. To keep the transitional noise low enough for a reliable readback signal, roughly 50~100 grains are needed per bit cell.

So the mission is simple: trying to make grains as small as possible to reduce the transitional noise, as areal density increases. The mission has been successfully carried out for several decades so far. A number of techniques have been continuously developed to reduce the effective size of the magnetic grains. Today, current magnetic information storage media are based on continuous thin films with exchange decoupled grains ~ 7nm.^[2.20] At this size, however, further shrinkage of grains size would cause the magnetization of the individual grains to be unstable. The thermal energy of the magnetic grains $k_B T$ (k_B -Boltzmann constant, T - temperature) can overcome their magnetization energy $K_u V$ (K_u -magnetic anisotropy, V - volume), which causes the grains to reverse spontaneously resulting in the loss of data or the unreliable data. Since we need to keep

reducing size (and therefore V) to record at higher densities, another way to maintain thermal stability would be to increase K_u . However, raising K_u too high results in a media coercivity which is too high; in other words, the data would be thermally stable, but no write head would be able to generate a strong enough field to write the data in the first place. In this way, thermal stability will ultimately limit the maximum areal density achievable with conventional thin film recording.

The concept of patterned media was firstly proposed by R. New et al.^[2.22] and S. Chou et al.^[2.23] in 1994. The patterned media usually consist of a regular array of magnetic elements, each of which has uniaxial magnetic anisotropy. The easy axis can be oriented parallel or perpendicular to the substrate plane. Unlike thin film media, in patterned media, one bit is stored in one magnetic unit, which has to be located precisely along the track with uniform periodicity. Because the bits are physically separated, there is no magnetic exchange coupling between neighboring bits. Different from thin film media, high coercivity materials are unnecessary in patterned media, except for the magnitude to overcome the magnetostatic interactions, which will be discussed in chapter 4.

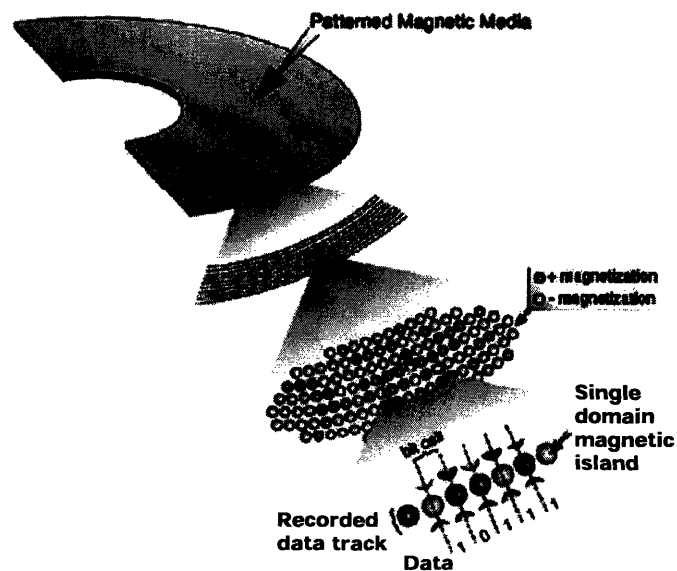


Figure 2.14 Insight of patterned media^[2.24]

Since we no longer need on the order of 100 grains per bit cell, but just one grain for each bit cell, the storage density can be increased roughly two orders of magnitude^[2.25] compared with normal thin film media. In 2005, Hitachi demonstrated an areal density of $35 \times 10^9 \text{b/cm}^2$ ($230 \times 10^9 \text{b/in}^2$) on perpendicular recording technology.^[2.26] Since each island is a single magnetic domain, patterned media is thermally stable, even at densities far higher than can be achieved with conventional media. According to the above statement, in patterned media, the thermal stability issues will occur only at extremely high densities which are around 3Tb/cm^2 (20Tb/in^2). In addition to its ultra-high data storage density, another major advantage of patterned media is elimination of transition noise. This is because the bits are now defined by the physical location of the elements and not by the zigzag transitional boundary between two oppositely magnetized domains.

In thin film media, since there are many grains in each bit, the head detects the average magnetization from all grains within the bits. Different from the continuous media, a bit consists of either a single grain or a number of magnetic grains which are strongly exchange coupled and behave like a single magnetic domain in patterned media. The anisotropy of all the bits in patterned media is supposed to be aligned at a specific angle relative to the reading head. The same as in the thin film media, patterned media can be divided into two types, depending on the magnetization orientation of the bits: a) longitudinal – in plain oriented, b) perpendicular – normal to the film surface.

In the case of longitudinal patterned media, substrate texturing is needed to arrange all the magnetic bits in a circumferential form. Different approaches have been tried to orient the easy axis for longitudinal media. For example, the longitudinal patterned media have been fabricated by epitaxially growing a 20-nm-thick Co ($10\bar{1}0$) film on a chromium layer on a MgO (110) substrate.^[2.26] It can also be prepared by patterning a (110) single-crystal iron thin film on a sapphire substrate.^[2.28] Some results show that it is easier to correctly write islands patterned in longitudinal media as compared to perpendicular media.^[2.27] However, it is quite difficult and expensive to achieve this goal using current thin film processes.

On the other hand, the patterned bits can be relatively oriented easily normal to the film surface to form a perpendicular recording medium. Several potential candidates for fabricating the patterned perpendicular media have been investigated, such as interface anisotropy materials Co/Pt, Co/Pd and CoPtCr alloy grown with the c-axis normal to the substrates, which are commonly used in continuous media. It is more likely that the patterned perpendicular media will be the choice of patterned media due to higher writing field, as the situation in the conventional thin film media.

In both cases, thin media is preferred, because the writing field is more likely to unintentionally write neighboring bits with the tails of the head field gradient in thick media. The taller the pillar, the greater the head field a neighboring bit will experience, and hence more likely it will be inadvertently written. Because of this reason, patterned media with a thickness of the bit spacing will be desired. In the case of perpendicular media, this mean the shape anisotropy of high aspect ratio magnetic island will not be used to achieve a high perpendicular anisotropy.

Chapter 3 Fabrication of Patterned Media

There are various approaches for fabricating nanoscale patterned media, including lithographic methods and self assembly methods. In this chapter, we will focus on these methods which have been used, or can be potentially used, to fabricate the patterned magnetic media. The corresponding advantages and disadvantages of these methods will be discussed in terms of their potential for future commercial applications. Since patterned media development is still in a primitive stage, there is no consensus on the optimum fabrication methods. Among all types of fabrication processes, lithographic methods have been most extensively studied and employed by far.

3.1 Lithographic Techniques

The lithographic methods used to fabricate patterned media can be subcategorized into: a) optical lithography, b) X-ray lithography, c) electron beam lithography, d) imprint lithography or nanoimprint lithography (NIL). Basically, all lithography methods share a similar scheme. The desired pattern is generated in a resist layer first during lithography process, then transferred into the magnetic materials by standard industrial semiconductor processing steps, such as etching (subtractive) or deposition (additive). In an etching process, a layer of magnetic materials is coated on the substrate first. The specific pattern is achieved by etching through lithographically generated masks. In a deposition process, the mask is first patterned on the substrate, and then magnetic materials are deposited on top or within it. Figure 3.1 illustrates three standard process steps.

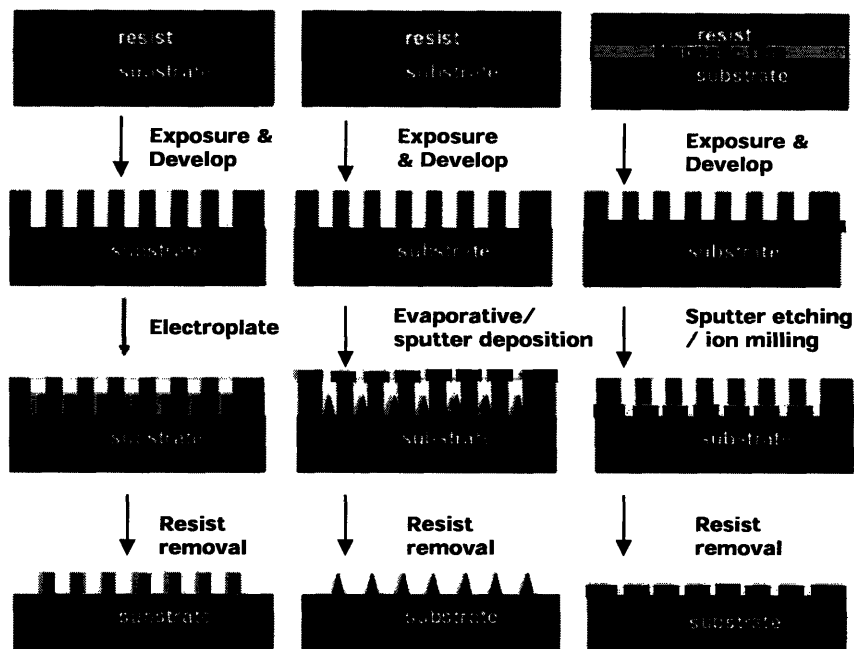


Figure 3.1 Fabrication processes of patterned media(from left to right):
 a) electrodeposition, b) evaporative/sputter deposition, c) etching^[3.1]

The difference between two additive deposition processes (electrodeposition and evaporative deposition) arises from the step coverage difference. Good step coverage in electrodeposition results in a columnar structure, while poor step coverage in evaporative deposition yields a conical structure after resist lift off. Deposition processes, such as electrodeposition, are followed by removing the mask or by chemical mechanical polishing (CMP), which planarizes the top surface making it possible that head could fly sub-10nm above the media surface.^{[3.2][3.3]}

3.1.1 Optical lithography methods

Conventional optical lithography is limited in resolution. The minimum feature size achievable by the optical lithography can be expressed as

$$W = \frac{k_1 \lambda}{NA}$$

where k_1 is a constant for a specific lithographic process (usually it is around 0.5) and λ and NA are the exposure wavelength and numerical aperture of the optical lithography tool. Higher resolution requires smaller W value.

Another major limitation besides resolution in optical lithography is the depth of focus (DOF), which is governed by the equation

$$DOF = \frac{k_2 \lambda}{NA^2}$$

where k_2 is a constant for a specific lithographic process. Usually, a higher DOF value is desired in lithography process. In the case of patterned media fabrication, the DOF requirement is relatively not so critical compared to resolution demands. So the strategy to meet the continued demands for higher resolution is simple: either using light with shorter wavelength or trying to increase NA value. However, it is relatively difficult to increase NA value, such as by using water/oil immersion techniques. Hence, most efforts have been focused on application of shorter wavelength light. In the semiconductor industry, the current 65nm lines are produced using 193nm illumination. Liquid immersion optical lithography might be used beyond the 45nm node.^[3,4]

To achieve an areal density $150 \times 10^9 \text{b/cm}^2$ ($1 \times 10^{12} \text{b/in}^2$), the patterned bits should have a sub 12nm dimension. (~ 24 nm periodicity) With respect to this requirement for patterned media fabrication, the resolution in conventional optical lithography is not high enough. New optical lithography techniques, such as extreme ultraviolet (EUV) lithography or X-ray lithography, are expected to be used in manufacturing to achieve smaller features. EUV lithography is a projection optical technology that uses 13.5 nm wavelengths. At this wavelength, all materials are highly absorbing, so the imaging system is composed of mirrors coated with multilayer structures designed to have high reflectivity at 13.5 nm wavelength. These short wavelength lithography techniques are still not commercially available and would likely be very expensive for patterned media fabrication.

Interference lithography (IL) is one way to achieve a higher resolution using current optical lithography equipment. Interference lithography is carried out by combining two beams of coherent radiation at a specified angle at the exposure plane. Interference of the two beams produces a sinusoidal intensity pattern with a period given by

$$P = \frac{\lambda}{2 \sin \theta}$$

where λ is the wavelength and θ is the recombination half-angle. The setup is illustrated in Figure 3.2.

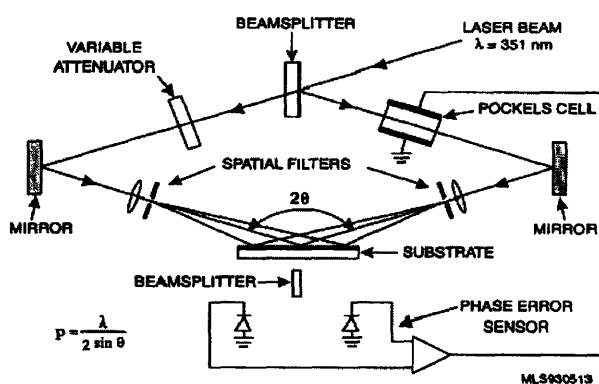


Figure 3.2 Interference lithography setup^[3.5]

Standard subtractive processes for fabricating patterned magnetic by interference lithography are depicted in Figure 3.3. In this case, patterned is first formed in a resist layer by direct illumination, and then transferred into the magnetic layer below, which has been deposited onto the substrate prior to the patterning.

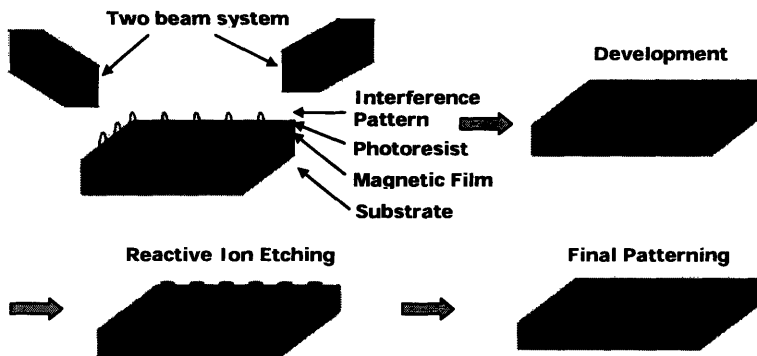


Figure 3.3 Fabrication of patterned dots using IL

Patterned islands of a variety of materials have been fabricated and investigated. A. Fernandez, et al.^[3.6], Y. Hao, et al.^[3.7] and other groups^{[3.8][3.9]} have demonstrated the ability to fabricate arrays of Co and Ni dots with periodicities ranging from 70nm to 100nm by interference lithography. Magnetic multilayer dots and corresponding multilayer films, such as Co/Pt and CoNi/Pt, have also been fabricated and investigated.^[3.10-3.15]

Interference lithography can be incorporated into a variety of process schemes: a) direct exposure and developing of photoresist,^[3.8-3.11] b) master stamper fabrication for nanoimprinting,^[3.16] c) direct annealing of pre-deposited films.^[3.17-3.20]

The advantages of the interference lithography are: a) parallel process gives rise to high throughput, b) large area regular arrays. (up to 25.4cm wafer^[3.4]) The disadvantage of the interference lithography is mainly because of its limited wavelength. The minimum period is limited to $\lambda/2$ as θ is 90 degrees. Hence, it is difficult to achieve the sub-50 nm resolution required for patterned media, even by using a short wavelength source. (KrF $\lambda=248$ nm, ArF $\lambda=193$ nm, F₂ $\lambda=157$ nm) In practice, the minimum feature size for interference lithography is also limited by wavelength distribution of the illumination source. In 193nm excimer laser, the wavelength distribution is too broad to produce sufficiently sharp interference patterns with conventional IL. Also, the geometries are limited to periodic patterns.

Due to the aforementioned reasons, achromatic interference lithography (AIL) system has been developed to achieve a higher resolution. A 193nm wavelength laser beam is diffracted by a series of diffraction gratings to produce the interference fringes.^[3.8] The period of the patterned is given by half of the period of the phase gratings, independent of the laser wavelength. Magnetic dots with a periodicity of 100nm have demonstrated. Savas et al. also predicted that, by incorporation a 100nm soft x-ray radiation system, sub 25nm features would be capable of fabrication. Based on AIL, Solak and David^[3.21] developed a new system that enables to produce circular periodic patterns, which should

be useful in the commercial application for patterned media that requires a circular periodicity.

3.1.2 Electron beam lithography methods

Electron beam lithography (e-beam lithography) is probably by far the most widely used method to fabricate the nanoscale patterns. A typical e-beam system consists of an electron scanning microscope (SEM) and an attached beam drawing system, as illustrated in Figure 3.4.

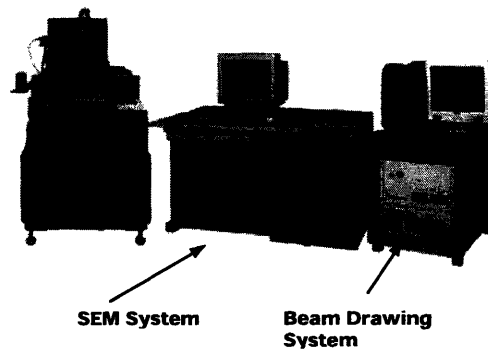


Figure 3.4 Standard e-beam lithography system^[3.22]

Breaking the diffraction limit of light, e-beam lithography is one of the ways to make features in the deep sub-micrometer regime which is a high resolution compared to other lithographic methods. Linewidths on the order of 10nm or smaller have been fabricated by electron-beam lithography. In most cases, e-beam lithography is used to pattern the polymethyl methacrylate (PMMA) layer, which will be developed afterwards to form desired features. The patterned PMMA layer can be used as a mask either for transferring the patterns into underlying magnetic layer directly or for fabricating a master stamper for imprinting application. A variety of e-beam lithography fabrication processes have been comprehensively reviewed.^[3.23-3.25] For most resists, it is difficult to go below 25 nm, and a limit of 20 nm has been cited.^[3.26]

Although e-beam lithography has a high resolution, its major drawback is that patterns are scanned in a serial sequence. The whole scanning process is slow, especially in the

case of duplicating small features over a large area, which also makes the process very expensive. This makes e-beam lithography not suitable for industrial application, while it has been widely used in laboratory based studies.^[3.27] Instead of directly patterning the disk, e-beam lithography can also be incorporated in nanoimprint lithography (NIL) which is a promising candidate for future commercial application. We will discuss nanoimprint lithography later in this chapter.

3.1.3 X-ray lithography methods

Soft X-ray lithography is capable of patterning a large substrate with submicrometer features. Figure 3.5 is a schematic of the x-ray lithography process, often referred to as proximity x-ray lithography.

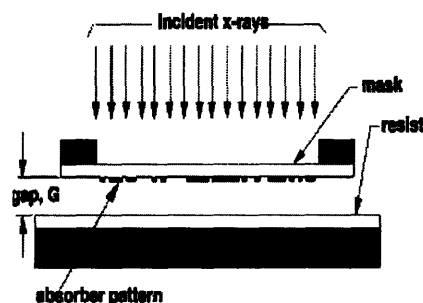


Figure 3.5 Schematic of the x-ray lithography process^[3.28]

In order to get sharp, vertical profiles in the resist film, shadow image contrast close to 10:1 is desired.^[3.28] The process involves using a thin membrane mask, typically SiN covered with a gold or tungsten absorber, held in close contact to the resist to pattern the radiation from an x-ray source. In x-ray lithography, a series of parameters need be adjusted to get higher resolution, such as absorber thickness, mask resolution, gap distance and etc. The major difficulties of achieving a sub-100nm resolution are mask fabrication and reliable gap setting below 5 μ m. Since the mask is typically patterned using e-beam lithography and the replication process 1:1 printing process, the x-ray lithography resolution is therefore limited by e-beam lithography.

C. Miramond^[3.29] et al. have fabricated permalloy cylindrical dots as small as 88nm. Dots dimensions down to 200nm have been reported by F. Rousseaux's group^{[3.30][3.31]} in 1995.

J.L. Duvail^[3.32] et al. have fabricated permalloy dots (diameter ~ 260nm, period ~ 400nm) over 4×4 mm² by electrodeposition. H.I. Smith^[3.28] predicts the practical limit for the x-ray lithography is around 20nm, which results from the stochastic nature of the resist exposure process. In order to achieve a higher throughput, a high intensity x-ray source, such as synchrotron, is needed to reduce the exposure time.

3.2 Self-assembled Nanoparticles

In addition to lithographic methods, scientists take advantage of self-ordered structures found in nature to achieve high density particle arrays. There are three major types of self-assembly methods used for patterned media: a) template growth, b) block copolymer assembly, c) self-assembled nanoparticles. A common problem for these self-assembly methods is the poor long range order. Typical ordering is over micrometer scale regions at most, and most particle arrays do not have a circular structure required for a hard disk geometry. Currently, most research work has been focused on achieving longer range order.

3.2.1 Template growth

The template growth method is based on the use of the self-organized porosity of certain microporous membranes to fabricate magnetic nanodots. C. R. Martin's group pioneered the work in the use of this methodology. Different types of membranes made of Al₂O₃, glass or silicon have been used as templates for the synthesis of nanoscale materials. Anodized Al₂O₃ membranes were the first porous structure used to grow magnetic nanostructures.^[3.33] Compared to other membranes, anodic Al₂O₃ (AAO) membranes not only show a better parallel alignment of perpendicular pores but a higher porosity and smaller interpore spacing as well, which appeals to the synthesis of high density nanoparticles.

Usually, a piece of pure Al sheet is used as the substrate material for the membrane. After a series of cleaning processes, the Al sheet is anodized in an acid solution to form porous

structures within the sheet. Anodic Al_2O_3 membranes usually have hexagonally close packed pores and can be purchased commercially. However, membranes with only a certain range of pore diameters are available. Consequently, many researchers prepare their own templates by adjusting the anodization conditions such as voltage, current density and solution pH value. Pores with different size and spacing can be synthesized in this way.

Electrochemical deposition^[3.34] is perhaps the most widely employed method to synthesize the desired nanostructures. One face of the template is coated with a metal film to act as cathode for electroplating. The volume of the pore is filled from bottom up allowing the control of the total length of wires. Usually, long nanowires (high aspect ratio structures) are fabricated in this way. It is more difficult to form low aspect ratio magnetic dots which are desired for patterned media recording. Pores as small as 9nm have been reported^[3.34] with a corresponding packing density of $70 \times 10^9/\text{cm}^2$. ($450 \times 10^9/\text{in}^2$) Figure 3.6 shows the SEM image of an AAO template^[3.35] and Ni nanodot array^[3.36] with dot diameter less than 100nm. A higher magnification SEM image (Figure 3.6b) shows that a Ni nanodot array grown from the AAO template has a hexagonal structure.

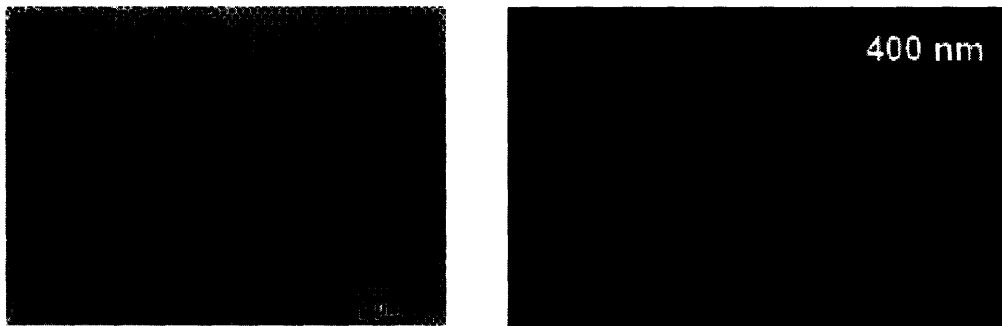


Figure 3.6 SEM image of (a)AAO template[3.35] and (b)Ni nanodot array[3.36]

The major problem of the template growth technique is its poor long range order. Similar to the magnetic thin films, the templated films are composed of a number of “grains”. Within each “grain”, all the nanowires or nanodots are well ordered. However, “grain” boundaries between the “grain” interrupt the order. Current, the “grain” size can reach up

to hundred micrometer scale. In order to achieve long range order, a variety of methods have been developed to pretexture the surface: a) moulding process,^[3.35] b) interference lithography^[3.37], c) focused ion beam (FIB) exposure.^[3.38] The AAO templates have also been used in nanoimprint techniques that will be discussed later.

Nanodots with either in-plane or perpendicular anisotropy have been fabricated using template growth so far. By using template growth techniques, pores as small as 9nm have been reported by Zhang et al.^[3.39] However, in order to satisfy the requirement for future data store application, methods to achieve the long range order pores need to be improved and the nanodot array should be arranged with a circular symmetry needed for patterned media. In my point of view, the self-assembly method mentioned above is a bit too “nature” and it will not be a viable candidate for the commercial application of patterned media.

3.2.2 Block co-polymers assembly

A block co-polymer consists of two types of immiscible monomers A and B, with length of n and m respectively, covalently linked together to form a polymer A_n-B_m . The polymer will phase separate producing periodicities in the range of 10-200nm. The corresponding thin film micro-structure depends on the n/m ratio and the surface energy of the substrate.

In the case of $n \ll m$, the A_n chains form patterned spherical structures inside B_m matrix; if $n \approx m$, an alternating lamellar structure (ABABA) will form. The matrix B_m in the first situation can be etched preferentially, leaving the periodic A_n spheres to be used as mask for the following etching processes. A variety of techniques based on block co-polymer fabrication have been reported with the islands as small as 25nm^[3.40] demonstrated.

Cheng and Ross^[3.41] developed a patterning method based on PS-PFS block copolymer for patterned bit media. A typical example is illustrated in Figure 3.7.

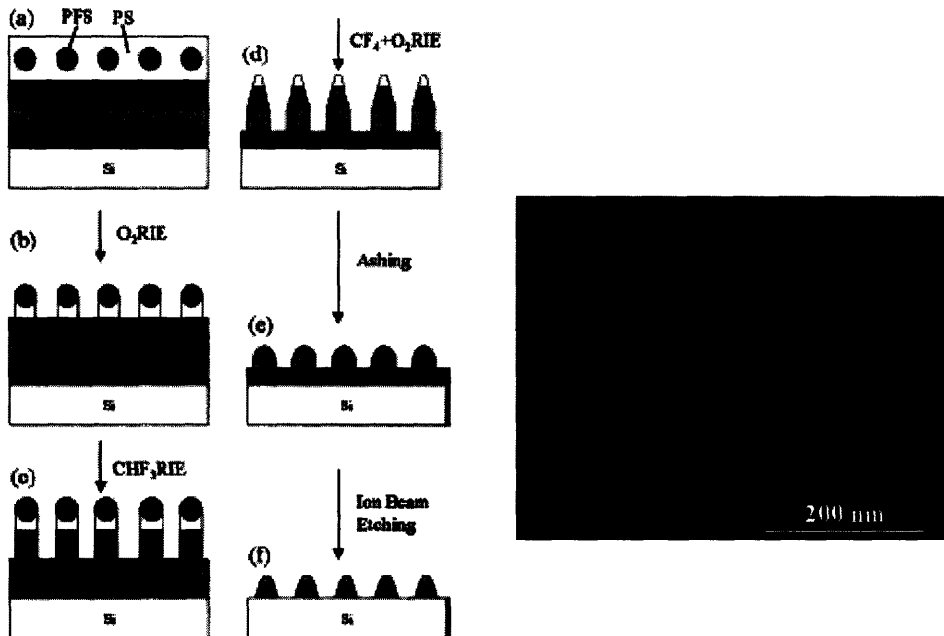


Figure 3.7 Fabrication process of the cobalt array via block co-polymer method and SEM image of O_2 -RIE etched PS-PFS copolymer^[3.41]

The process involves the formation of block co-polymer dot array which serves as the etching mask for the underlying magnetic layers. After spin coating and annealing the block co-polymer solution, the polyferrocenyldimethylsilane (PFS) dots 25nm in diameter with a 50nm periodicity were formed inside a polystyrene (PS) matrix on top of the pre-deposited magnetic layer. Due to the high chemical selectivity of O_2 -RIE over PS/PFS thin film, the PFS nanodot array was left on top of the substrate, while the PS matrix was removed (shown in Figure 3.7 right). The PFS array pattern was then transferred into the underlying magnetic layer by a series of etching processes.

Again, a long range ordered circular symmetric pattern is desired to be of interest for high density patterned media recording. Ordering of the nanodot array over a micrometer scale has been reported.^[3.42] In order to further increase the long range order, one promising solution is to artificially guide the self-assembly process. A number of techniques have been developed to do so. Most of these guidance methods can be divided into two categories: a) physical guidance: a topographical pattern is created in a substrate, such as trenches or grooves; b) chemical patterning: surface chemistry is intentionally modified so that the nanodot array only forms in the specific area.

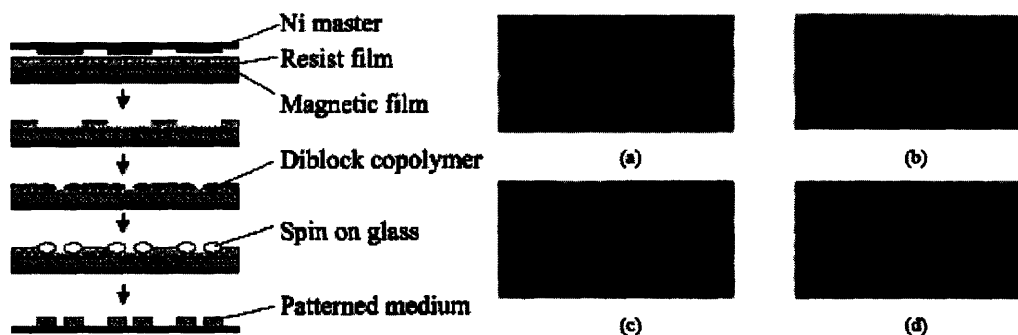


Figure 3.8 Scheme of the preparation method of patterned medium (left) and Phase-separation dot patterns of the block co-polymers in grooves with different widths (right): a) 60nm, b) 150nm, c) 200nm, and d) 250nm. The scale bar is 300nm^[3.43]

Figure 3.8 left schematically shows the steps to artificially assist the block co-polymer growth. The magnetic layer and resist film were deposited onto the substrate before patterning. A Ni imprint master was then used to create the mesa/trench structures in the resist film. The bit pattern was formed in the resist trenches using a PS-PMMA block co-polymer after substrate annealing. The PMMA spheres were removed afterwards using an oxygen plasma process. The resulting holes were filled by spin on glass (SOG). A final ion milling process removed the PS matrix and underlying magnetic layer, leaving the tracks of magnetic islands protected by SOG.

A similar approach has been reported by Cheng et al.^[3.44] A mesa/trench pattern was formed prior to the deposition of magnetic layers. Interference lithography and RIE were used to form the trenches in the substrate before hand. The block co-polymer solution (PS/PFS) was then spun-coated onto the prepatterned substrate. Oxygen plasma etching created spherical PFS nanodots both on the mesas and trenches. The following annealing process allowed the co-polymer to migrate to the trenches, leaving the mesa area free of polymer materials. A second oxygen plasma etching removed the PS matrix, leaving an array of PFS spheres in the trenches. A subsequent RIE process using the PFS spheres as an etch mask transferred the bit pattern into the underlying substrate. (Figure 3.9)

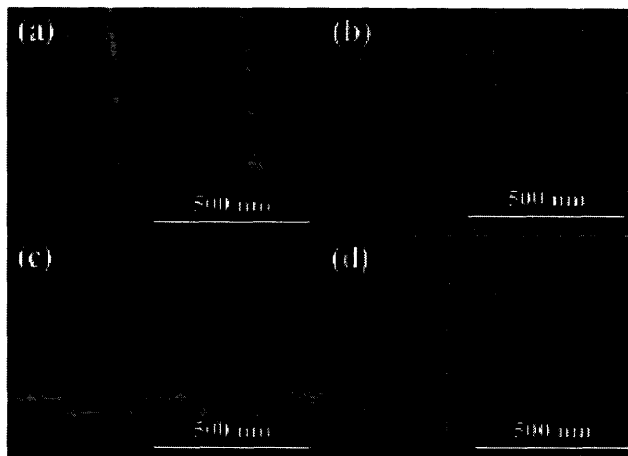


Figure 3.9 SEM images of synthesis of guided self-assembly co-polymer pattern^[3.44]

Although a variety of techniques have been developed to guide self-assembly block copolymer synthesis, these guidance schemes discussed above are in their infancy. Critical issues such as bit size distribution, individual bit alignment and side wall profile effects remain to be investigated. In addition, the magnetic properties of the particles are very non-uniform resulting from the distribution of particle size, shape, and microstructure.^[3.45] The guidance tracks further decrease the nanodot density, which reduces the advantages of assisted self-assembly techniques.

3.2.3 Nanoparticle self-assembly

Due to the potential application in patterned media and as a substitute for the thin film media, the high anisotropy self-assembly nanoparticles have drawn significant attention in recent years. Sun et al.^[3.46] firstly demonstrated the synthesis of monodisperse iron-platinum (FePt) self-assembled nanoparticles with tunable diameter as small as 3nm. The size distribution of the nanoparticles is estimated to be less than ~5%. In addition to the high packing density and small size distribution, the high magnetocrystalline anisotropy of L₁₀ phase FePt nanoparticles^[3.47] also makes them attractive due to lower superparamagnetic effect. Synthesis and assembly of magnetic nanoparticles has been achieved without using lithography. This is very appealing because of its potential for fast manufacturing of size and distribution controlled magnetic nanodots over a large area.

However, in order to be used practically as recording media, significant challenges remain to be overcome.

A variety of methods have been developed to grow self-assembled nanoparticles, such as vapor phase growth by sputtering, laser ablation or evaporation.^{[3.46][3.48-3.50]} Synthesis of Co nanoparticles with a diameter range of 2nm~11nm (standard deviation 7%) have been reported by S. Sun et al.^[3.51]

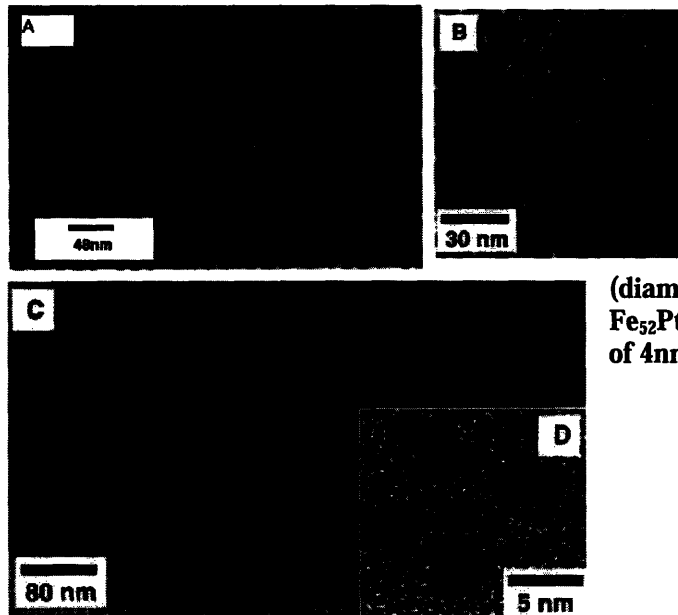


Figure 3.10 A) SEM and TEM images of cobalt nanodots with size 6nm^[3.51], B) TEM image of a three-dimensional assembly Fe₅₀Pt₅₀ nanodot array^[3.46] (diameter~6nm), C) HRSEM image of Fe₅₂Pt₄₈ nanocrystals^[3.46], D) TEM image of 4nm Fe₅₂Pt₄₈ nanocrystals^[3.46].

As can be observed from the above images, the short range order of the cobalt nanodots distribution is good, while the long range order is relatively poor. After deposition, a layer of organic ligands coats the cobalt nanodots, limiting oxidation and also preventing irreversible aggregation. The nanoparticles deposited using this method are in a disordered fcc phase and are oriented randomly. To be used as a recording medium, the fcc nanoparticles need to be annealed converting them into the high anisotropy L1₀ phase, without destroying the particle shape and arrangement.

However, temperatures above 600°C are usually needed to conduct the phase transformation, and this leads to particle agglomeration and sintering.^[3.52-3.55] Different methods have been demonstrated to suppress the surface agglomeration, and most of them fall into two categories: A) suppressing coalescence in a higher annealing

temperature, B) reducing the annealing temperature for phase transformation. A.C.C. Yu et al.^[3.56] stabilized the FePt nanoparticles with the aid of 3-aminopropyltriethoxysilane (APTS) adhesion layers. The annealing temperature can be increased up to 800°C without significant coalescence. S. Momose et al.^[3.57] used a mixture of oleic acid and oleyl amine as a particle stabilizer. The estimated particle agglomeration temperature was about 800°C also. In the second scheme, the annealing process is carried out in the ambient of a variety of gases, e.g. N₂, Ar, He and vacuum etc.^{[3.54][3.58]} Recently, C.C. Chiang et al.^[3.59] demonstrated a new method reducing the annealing temperature to as low as 325°C with assistance of PtMn underlayers. Although much progress has been made in the current years, the problem of surface agglomeration during the annealing still has not been solved completely.

One critical issue is uniformity of the chemical ordering. If only part of the nanodots have been transformed from the fcc phase to the L1₀ phase during the annealing, there would be a wide distribution of anisotropy.^{[3.55][3.60][3.61]} Y.K. Takahashi et al.^[3.62] reported there was a grain size dependence on the ordering process of FePt nanoparticles. The small FePt particles ~4nm were ordered while larger particles, ~7nm, were ordered upon annealing at 600°C for 1 hour. One way to achieve chemical ordering is to add some other element such as Au,^[3.63] Cu,^[3.64] or Ag.^[3.65] Direct synthesis of chemically ordered L1₀ phase FePt particles at 300°C has been demonstrated by B. Jeyadevan et al.^[3.66] One potential solution to form fct phase FePt nanoparticles is by using template assisted assembly. Mayes et al.^{[3.67][3.68]} pioneered this method for data storage. A self-assembled protein, ferritin, was used to form cavities (~7.5-8nm) within which CoPt or FePt particles with specific diameters can grow. However, the particle packing density in this method is lower than direct chemical synthesis.

A uniformly magnetic oriented nanoparticle array is necessary for the data storage recording. Although different attempts have been tried such as annealing under external magnetic field, there have been no effective techniques developed so far. Clearly, chemical growth of self-assembled magnetic particles has been in its early stage since its first demonstration by Sun et al.^[3.46] The advantages of the chemical synthesis method are:

a) high packing density, b) sufficient magnetic anisotropy. But the drawbacks are: a) particle agglomeration during annealing, b) poor uniformity of easy axis orientation, c) relative poor chemical uniformity. There will be a series of obstacles ahead before the self-assembled nanoparticles can be practically used as data storage media.

3.3 Nanoimprint Lithography (NIL)

We have discussed various lithographic methods and self-assembly methods in terms of patterned media recording. The major problems for lithographic synthesis are either high cost low throughput issues or insufficient resolution problems. In contrast, it takes manufactures about 10 seconds to process a new perpendicular thin film disk. On the other hand, self-assembly techniques provide us a potential high yield method to fabricate hard drives with high recording density. However, the challenges for self-assembly methods to face are equally formidable. Billions of bits are required to be packed onto the substrate with precise periodicity. And the bit size, magnetic and chemical properties should have a small distribution.

One promising approach to improve the yield, reliability and cost issues simultaneously is called imprint lithography or nanoimprint lithography, depending on the fabrication scale. Its concept is as simple as the ancient Chinese block lithography. An expensive rigid master stamper or mold with the desired patterns is first fabricated using either e-beam lithography or X-ray lithography to achieve a high resolution. Batches of daughter stampers^[3.69] are duplicated from the master stamper afterwards. In the end, millions of cheap disk duplications are made from those daughter stampers. If the reliability of the master stamper is good enough, it can be used to duplicate the disks directly and daughter stampers will not be required. This concept is being used to produce optical recording devices such as compact disks (CD) and DVD disks, where the masks are patterned by laser write and a large of number of CDs or DVDs are mass manufactured by injection molding from the master.

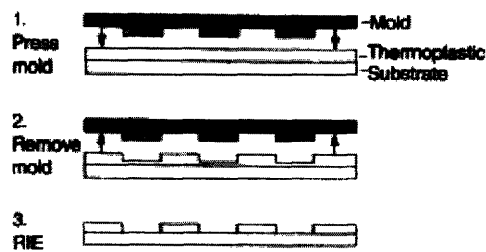


Figure 3.11 Processes of imprint lithography^[3.70]

The concept of nanoimprint lithography was firstly proposed and demonstrated by Chou^{[3.70][3.71]} and his co-workers in 1995. An early example of nanoimprint lithography is illustrated in Figure 3.11. His method uses compression molding to create a thickness contrast in a thin resist film carried on a substrate, followed by anisotropic etching to transfer the pattern through the entire resist thickness. The patterns are fabricated with the use of resist templates created by imprint lithography in combination with a lift-off process. After pattern transfer into the substrate, Ni was deposited onto the surface usually by electroplating to fill the trenches. Additional chemical mechanical polishing (CMP) could be used to smooth the top surface. Features as small as 25nm with a period of 70nm have been reported.^[3.71]

Either a thermosetting polymer such as PMMA^[3.72] or a photocuring polymer^[3.73] can be used as the resist layer. In case photocuring polymer is used as resist, it is patterned by the stamper, and subsequently cured by exposure to ultraviolet (UV) radiation. The UV cured photopolymer then serves as an etch mask. Figure 3.14 shows photocuring imprint lithography by G.M. McClelland.^[3.69] In his case, a compliant daughter stamper was fabricated first.

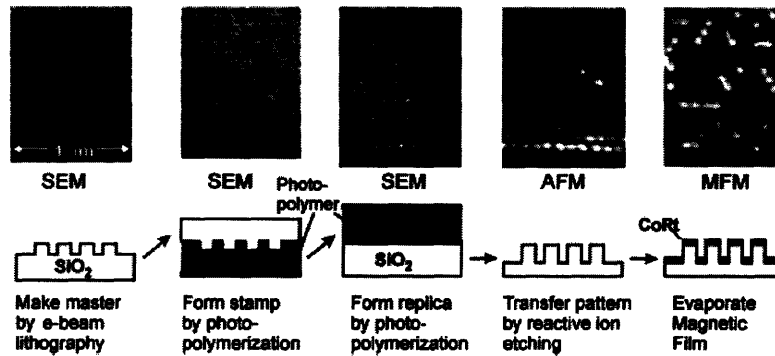


Figure 3.12 Photocuring imprinting process and corresponding SEM images^[3.69]

Regarding the rigid template, it is typically made of Si or SiO₂ and is patterned by a lithographic method such as e-beam lithography, interference lithography, x-ray lithography or some self-assembly method. In the most cases, anisotropic etching is used to transfer the patterns from the resist to the underlying substrate or magnetic films. Hence, the thickness of the resist layer is normally the same as the required etch depth due to the low selectivity of the anisotropic etch processes.

In fact, the disk substrates are not flat, usually having waviness of the order of micrometers over a millimeter length scale. A residual layer can be deposited between the organic resist layer and substrate, smoothing the contact surface between the stamper and the resist layer. However, the thickness of the residual layer need to be thinner than the etch depth to conduct successful feature transformation. Another way to adapt to nonflat substrate is the use of compliant stampers, which the stampers can deform according the waviness of the substrate. No thick residual layer is required here. Bilayer^[3.74] or even trilayer^[3.75] resister structures have been developed to minimize the nonflat contact issue.

The adhesion force between the stamper and resist layer is also a critical issue. In the case of high aspect ratio features, the adhesion force can be big enough to damage the features in the resist layer as the stamper is removed from the resist layer. Chou et al. avoided this issue by either etching a SiO₂ layer which had been deposited onto a plating base or depositing a magnetic film onto the imprinted layer and using lift-off to form islands.

In general, compared with other aforementioned techniques, nanoimprint lithography is more mature and promising for fabrication of low cost, size and position controlled magnetic nanoparticle arrays. In laboratory demonstrations, some problems such as contamination issues may still exist. A number of tool manufacturers such as Molecular Imprints^[3.76] and Nanonex^[3.77] have already begun developing nanoimprint machines.

3.4 Other Methods

Direct film patterning and dip-pen nanolithography will also be briefly mentioned here. In direct film patterning, focused Ga⁺ ion beams (FIB) have been used to directly pattern prototype magnetic structures, either by removing materials or by Ga⁺ poisoning. Islands smaller than 70nm in diameter have been demonstrated by Lin^[3.78] and Zhu^[3.79]. While FIB is a very convenient laboratory tool for fabricating test structures over small areas, it lacks the throughput and speed to be a commercialized method for patterned media.

In dip-pen nanolithography method^[3.90], the patterned array is formed by coating a conventional atomic force microscope (AFM) tip with, for example, a barium ferrite precursor solution. The pattern is generated by bringing the tip into contact with a suitably prepared substrate. Feature size less than 100nm have been produced, and smaller dimension should be possible. This is also too slow for commercial use.

Chapter 4 Magnetic Properties of Patterned Media

In recent years, substantial progress has been made in understanding and modeling of magnetic properties of small particles. However, there is still no consensus on the optimum properties of an ideal patterned media. In this chapter, we will discuss different magnetic properties in terms of patterned media.

4.1 Size Effect

The energy competition between the exchange coupling energy and the magnetostatic energy results in the formation of domain walls, which is highly size and shape dependent. For small particles, the exchange energy dominates, so the particles have uniform or near uniform single domain magnetic states. Magnetostatic energy dominates in the case of bigger particles; therefore domain walls are formed to reduce the total energy.

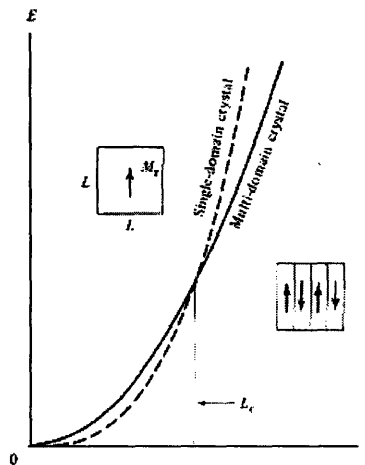


Figure 4.1 Relation between the energy E of a crystal and its linear dimensions L for two kinds of magnetic state^[4.1]

The total magnetostatic energy of a single-domain cubic crystal is proportional to the particle volume and can be expressed as $E_{ms} \propto L^3 M_s^2$ and domain wall energy is proportional to the wall area and can be given as $E_{wall} \propto L^2$. There is a critical size L_c

below which the single domain crystal will have lower energy. In addition, the critical length is strong shape and uniaxial anisotropy dependent because. Particles with dimensions smaller than the critical length, which has values of 10~20nm for high anisotropy magnetic materials,^[4.2] are expected to be uniformly magnetized. As the dimension getting bigger, the magnetization distribution becomes less uniform. A non-uniform magnetization state so called flower state develops when the particles size approaches the critical length ($\sim L_c$). The flower state, in which the magnetization is uniformly aligned to the axis, has a high remanence along the axis. As the particle size further increases, a transition to a vortex state occurs ($>L_c$). A vortex state has lower remanence as the magnetization twists goes around the axis. When the particles size is much bigger than the critical length ($\gg L_c$), domain walls begin to form to reduce the magnetostatic energy, and multi-domain particles form. Numerical studies of equilibrium states for small particle have been carried out in terms of particles size and anisotropy strength using a cubic micromagnetic model.^{[4.3][4.4]}

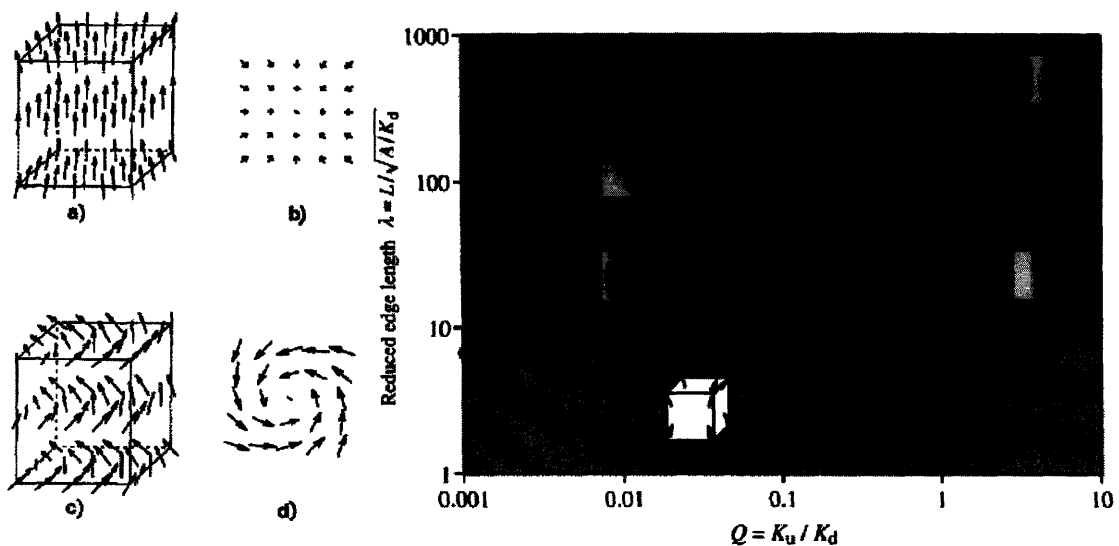


Figure 4.2 Left: equilibrium states in zero applied field (a) The flower state, (b) Top view of flower state, (c) The vortex state, (d) Top view of vortex state.^[4.3]

Figure 4.2 Right: Phase diagram of zero-field states of cubic-shaped particles with uniaxial anisotropy K_u , where $K_d = \mu_0 M_s^2 / 2$, and M_s is the saturation moment^[4.4]

The schematic illustrations of flower state and vortex state are depicted in Figure 4.2 left. Size dependent phase transitions are predicted from Figure 4.2 right. When the uniaxial anisotropy strength of the cubic is comparable to its magnetostatic energy ($Q = K_u / K_d \approx 1$), the flower state occurs between 1 to $11L_c$; while vortex state occurs around $11 \sim 50L_c$; larger cubic particles ($>50L_c$) show multi-domain structures. Also we can observe that particles more tend to remain in flower state as uniaxial anisotropy energy increases.

In magnetic recording system, a high remanence is needed; therefore the flower state is preferred. As mentioned, in order to achieve $150 \times 10^9 \text{b/cm}^2$ ($1 \times 10^{12} \text{b/in}^2$) areal density, the periodicity of the nanodots array should be less than 25 nm . The diameter of the nanodots will be around 12.5 nm if the interdot spacing is the same size. Because the nanodots fabricated by self-assembly or nanoimprinting techniques are smaller than their corresponding critical size, the nanodots in this size range are expected to be uniformly magnetized, such that the reduction in energy from creating a two domain state is less than the energy required to create a domain wall. Therefore scaling the particles to smaller dimensions is possible until superparamagnetism eventually sets in.

4.2 Various Anisotropy Contributions

Magnetic anisotropy is the term used to describe the tendency of the magnetization to lie in a particular orientation. There is a variety of magnetic anisotropy energies that simultaneously contribute to the orientation preference. They play a critical role in the performance of patterned media, and determine the remanent state the data recording state. Magnetic anisotropy can have its origin in sample shape, crystal symmetry, stress, or directed atomic pair ordering. The corresponding energy terms are: a) magnetostatic energy, b) magnetocrystalline energy, c) magnetoelastic energy, d) interface anisotropy. In the case of magnetic recording, shape anisotropy and magnetocrystalline anisotropy are the major factors. Magnetoelastic anisotropy is present in materials subjected to mechanical strain. Stressing or straining a magnetic material can produce a change in its

preferred magnetization direction. These phenomena are called the inverse Joule effect or stress-induced anisotropy, but are rarely of concern in recording media due to the smaller energy magnitude compared to the magnetostatic anisotropy or magnetocrystalline anisotropy. Interface anisotropy arises from the asymmetrical environment at the interface. A typical example of interface anisotropy is Co/Pd, Co/Pt and Co/Ag multilayer structures.^[4.5] Although the magnetization of both multilayers is predicted to be oriented perpendicular to the plane of the multilayers, the easy axis of a Co monolayer is predicted to lie in plane. Because of this reason, Co based multilayer materials (Co/Pd or Co/Pt) are promising candidates for perpendicular patterned media. The discussions of anisotropy energy will be focused on magnetostatic energy and magnetocrystalline energy in the following part.

4.2.1 Shape Anisotropy

Shape anisotropy is associated with the magnetostatic energy which originates from the “free poles” existing at the end surface. In a single prolate ellipsoidal particle, the magnetostatic energy density can be given in the following way:^[4.6]

$$\mu_{ms} = + \frac{\mu_0 M_s^2}{2} \Delta N \cos^2 \theta + Const. \quad (4.1)$$

where θ is the angle between the magnetic field vector and magnetization vector. ΔN is called the effective demagnetization factor which is the different between two demagnetization factors. One is along the easy axis of the particle and the other is perpendicular to the easy axis.

The patterned media have different structures depending on their fabrication methods. For evaporation method, patterned dots usually have a conical structure. And for electrodeposition and etching processes, the patterned dots will have a cylindrical and flat plate structure respectively.(shown in Figure 4.3) Because flat circular low aspect ratio dots are preferred in patterned media, etching synthesis is more likely to become the commercialized process for patterned media fabrication.



Figure 4.3 Patterned magnetic nanodots fabricated by electrodeposition, evaporation and etching (from left to right)^[3,32]

High aspect ratio dot array (first image from the left in Figure 4.3) is not desired due to unintentional tail writing.

4.2.2 Magnetocrystalline Anisotropy

In a uniaxial material shown, the magnetocrystalline anisotropy energy can be expressed as^[4.6]:

$$K_c = K_0 + K_1 \sin^2 \theta + K_2 \sin^4 \theta + \dots \quad (4.2)$$

K_0 , K_1 , K_2 ($K_1 > K_2$) are energy coefficients. K_0 term is usually neglected because it is independent of magnetization direction. θ is the angle between the magnetization direction and the easy axis of the crystal.

The net anisotropy of a uniaxial particle is determined by the sum of all the anisotropy contributions, including the corresponding orientation of the anisotropy axis. In some cases, magnetocrystalline energy dominates over other types of anisotropy energies. For example, in CoPtCr alloys grown with the c -axis normal to the substrate, the magnetocrystalline anisotropy is able to overcome the shape anisotropy of the film.^[4.7] (third image from the left in Figure 4.3) In order to prevent un-intentional tail writing of neighboring islands, it is critical to achieve a low aspect ratio island array with an out of plane anisotropy using magnetocrystalline anisotropy or interface anisotropy^[4.5].

Let us calculate the particle size for different materials at which superparamagnetic effect must be taken into consideration. Three circular plate like nanomagnets are composed of

pure Co, Co/Pt multilayer, and CoCrPt with c-axis perpendicular to the plate. The effective uniaxial anisotropy energy is arbitrarily taken as $0.45 \times 10^6 \text{ J/m}^3$, $2.5 \times 10^6 \text{ J/m}^3$ and $0.25 \times 10^6 \text{ J/m}^3$, respectively.^[4.8] If we choose energy ratio $K_u V / k_B T = 40$ and ($T=300k$), then the uniaxial anisotropy energy can be given as

$K_u V = 40 k_B T = 1.656 \times 10^{-19} \text{ J}$. The particle volumes for each material are $V_1(\text{pure Co})=3.68 \times 10^{-25} \text{ m}^3$, $V_2(\text{Co/Pt})=6.24 \times 10^{-26} \text{ m}^3$, and $V_3(\text{CoCrPt})=6.24 \times 10^{-25} \text{ m}^3$. Among the three materials, Co/Pt multilayer structure has the smallest volume, and its corresponding size is 3~4 nm.

4.3 Particles Magnetization and Writing

Ideally, each bit in a patterned media has uniaxial anisotropy. The magnetization orientation can either be in-plane or normal to the disk. Unlike conventional thin film media where the location of each bit is defined by the writing head, the writing process only flips the magnetization direction of the bit. The writing process in patterned media is analogous to moving a ball between two valleys separated by a mountain. The two valleys represent two equilibrium energy states that minimize the total energy including magnetostatic energy, exchange energy, crystalline anisotropy energy, and Zeeman energy. Once the ball is pushed from one valley over the top of the mountain, it will roll down to the other valley on its own. However, if the ball is released before being pushed over the peak, it will go back to its original valley.

In patterned media, all the bits are small enough that the exchange interaction will keep the magnetization uniform which leads to coherent rotation or at least can be treated as coherent rotation. The Stoner-Wohlfarth model allows an easy representation of coherent rotation. The equilibrium direction of the magnetic moment is determined by the magnetocrystalline anisotropy axis and the direction of the external field.

When the external field is along the easy axis ($\alpha = 0$), the domain switch field is $H_{sw} = 2K_u / \mu_0 M_s$ and the M-H loop is square. For field perpendicular to the easy axis, a

field of $2K / \mu_0 M_s$ is required to saturate the magnetization along the hard axis.

Practically, it is hardly ever observed due to a variety of factors, such as surface defects, surface oxidation etc. The assumptions of the model are so strong that nearly all magnetic systems reverse their magnetization very differently from its predictions. In principle coherent reversal can occur only in systems of size below typically 10nm. Typically, magnetic particles become superparamagnetic below a radius of order 20 nm.^[4.6] Hence, the rotation process has to be conducted at very low temperature 0.1~6K. The first evidence of true Stoner-Wohlfarth model was demonstrated by W. Wernsdorfer et al. in 1997.^[4.9]

As the particle size increases, incoherent reversal modes such as curling can cause the magnetization to reverse at a lower external field at the expense of exchange coupling energy. In case of curling in a prolate ellipsoid, the magnetization can easily rotate from its original direction (along the easy axis) to a plane perpendicular to the easy axis.^{[4.10][4.11][4.12]} The process occurs more easily as the particle size increases. For small particles, thermally assisted switching reduces the measured switching field below the coherent rotation value. As the particle size decreases, particles behave more like the coherent rotation model; and their corresponding switching field increases for particle size $\sim L_c$. For instance, the switching field of a 150 nm diameter nickel pillar is about $H_{sw} = 35.8$ kA/m ($H_{sw} = 450$ Oe), while the switching field increases $H_{sw} = 71.6$ kA/m ($H_{sw} = 900$ Oe) as the diameter is reduced to 40nm.^{[4.13][4.14]} The switching mechanism and switching speed can be simulated by a micromagnet model.

Switching field distribution (SFD) is one of the critical issues in writing. SFD arises from two origins: a) intrinsic variability between particles, b) magnetostatic interaction from neighboring particles. The intrinsic variability includes shape, size, magnetization orientation and microstructure. As discussed in the section 3.23, the drawbacks of self-assembly nanoparticles are: a) poor size distribution after annealing, b) poor uniformity of easy axis orientation, c) relatively poor chemical uniformity. All these factors result in a broadened switching field distribution, and the switching field typically shows a Gaussian distribution. A variety of methods, such as better lithography or assembly

processes, have been tried to enhance the particle array's geometrical, magnetic or chemical uniformity. As to the magnetostatic interaction, the net demagnetization field from the neighboring bits changes the effective switching field of a specific particle. The total magnetic field acting on any particle is equal to $9H_i$ in a square array,^[3,23] where H_i is the nearest neighbor interaction field. In the case of perpendicular recording, the effective switching field can either be $H_{sw}+9H_i$ or $H_{sw}-9H_i$ when the magnetization orientation of the neighboring particles is arranged anti-parallel or parallel, respectively. The interaction field becomes stronger as the particle spacing is reduced or the magnetic moment of the particles increases.^{[4.14][4.15][4.16]} As discussed previously (section 4.2.1), while shape anisotropy can be used to produce out of plane anisotropy, it is not desirable from a recording density perspective, and a higher out of plane shape anisotropy results in a higher magnetostatic interaction field. The corresponding M-H curve is sheared by the interaction field. On the contrary, in-plane recording shows squarer hysteresis loops because of the interaction field.^{[4.17][4.18]} The magnetostatic interaction actually stabilizes the magnetization state.

Experiment results show that switching speeds for low aspect ratio particles, which tend to reverse coherently, are faster than those of high aspect ratio particles.^{[4.19][4.20]} If the duration of the external field is less than the switching time, the magnetization direction will not reverse. Besides avoiding the inadvertent tail writing of neighboring bits, a low aspect ratio particle array is also preferred in patterned media due to the faster switching speed.^[4.21]

4.4 Recording System

To achieve reversal in nanomagnet arrays, the magnetic tip of an MFM has been used to controllably reverse the state of longitudinal magnetic bars^[4.22], sub-micrometer Co dots^{[4.23][4.24]}, and perpendicular pillars.^[4.25] This is useful for studying reversal properties and domain configurations of patterned elements. However, scanning probe microscopes are inherently slow, and thus for magnetic recording MFM writing and reading will also

be very slow and would require an array of parallel tips to achieve the high data transfer rate. Such massively parallel data storage systems have been proposed.^{[4.26][4.27]} Using conventional inductive write and GMR read elements in a flying head disk drive in patterned media disks is desirable. One of the major challenges is the need for precise synchronization of the head position to the pre-fixed island locations.

Chapter 5 IP and Business Model

In this chapter, intellectual property environment of patterned media will be outlined first. Later, competition from other existing data storage technology will be discussed. Different business models will be discussed in the end.

5.1 IP Environment

In the United States, a number of patents on patterned media have been filed since late 1990s. Most of the patents can be categorized into two major types: a) structure concepts, b) synthesis methods. The first type of patents defines the basic physical and magnetic structures of the patterned media. Sometimes, these patents also claim some fabrication methods. On the other hand, only specific synthesis methods are claimed in the second type of patents. Details such as process recipe, pattern size and size distribution are defined. Chou et al. pioneered the work in the field of patterned media. The following is an important patent filed by Chou et al in late 1990s. It provides a prototype of the patterned magnetic media for data storage purpose and one corresponding fabrication method.

Patent Number: 5,820,769

October 13, 1998

Method for making magnetic storage having discrete elements with quantized magnetic moments

A magnetic storage includes a non-magnetic substrate. A plurality of discrete single magnetic domain elements formed of a magnetic material separated by nonmagnetic materials are carried on the non-magnetic substrate. Each single magnetic domain element has the same size, shape and has, without an external magnetic field, two quantized magnetization values. The two magnetization values are of substantially equal magnitude but of differing vector directions. The plurality of single domain elements are adapted for magnetic storage of information based upon direction of the magnetization vector. Each single magnetic domain element is used to store a bit of binary information. Writing each bit becomes to flip the quantified magnetic moment directions.

Each bit can be tracked individually. The switching field of each bit can be controlled by controlling the size and shape anisotropy of each bit. Methods of fabricating the magnetic storage medium include obtaining the non-magnetic substrate and forming the plurality of single magnetic domain elements on the substrate.

With the transition from longitudinal media to perpendicular media in HDD industry, patterned media with perpendicular anisotropy are more desired compared to in-plane anisotropy. The following patent claims the physical and magnetic characters of perpendicular patterned media by Lundstrom.

Patent Number 6,999,279

February 14, 2006

Perpendicular patterned magnetic media

The invention is directed to patterned magnetic media for use in magnetic recording and data storage, and various conditioning techniques that can be used to magnetically condition the patterns. For example, a medium can be formed to exhibit a pattern of surface variations defined by patterned areas and non-patterned areas. Techniques are described for magnetically conditioning the patterned areas. The techniques may be useful for perpendicular patterned media, i.e., media having patterns formed on the media surface and having a magnetic anisotropy that is perpendicular to the plane of the medium. In particular, perpendicular magnetic anisotropy has been found to be an important factor that allows effective conditioning of patterned features having relatively small widths.

Because the basic concepts and prototypes of patterned media have been mainly claimed by previous patents, more and more patents are filed on specific fabrication methods. The following patent also filed by Chou describes a contact imprint lithography technique.

Patent Number 6,482,742

November 19, 2002

Fluid pressure imprint lithography

An improved method of imprint lithography involves using direct fluid pressure to press the mold into a substrate-supported film. Advantageously the mold and/or substrate are sufficiently flexible to provide wide area contact under the fluid pressure. Fluid pressing can be accomplished by sealing the mold against the film and disposing the resulting assembly in a pressurized chamber. It can also be accomplished by subjecting the mold to jets of pressurized fluid. The result of this fluid pressing is enhanced resolution and high uniformity over an enlarged area.

Based on our survey, more than 60 patents filed in the United State are directed related to patterned media. The actual number of the patents filed on patterned media might multiple the number mentioned above, since some groups do not use the terminology “patterned media”. For example, in the first patent mentioned previously, Chou uses discrete single magnetic domains to describe the patterned media. A trend can be observed that more and more patents have been filed on nanoimprint lithography technique over recent years. The percentage of the patents on nanoimprint lithography also increases constantly. (shown in Figure 6.1) In addition, a group from Austin, TX has contributes a number of patents on nanoimprint technique.

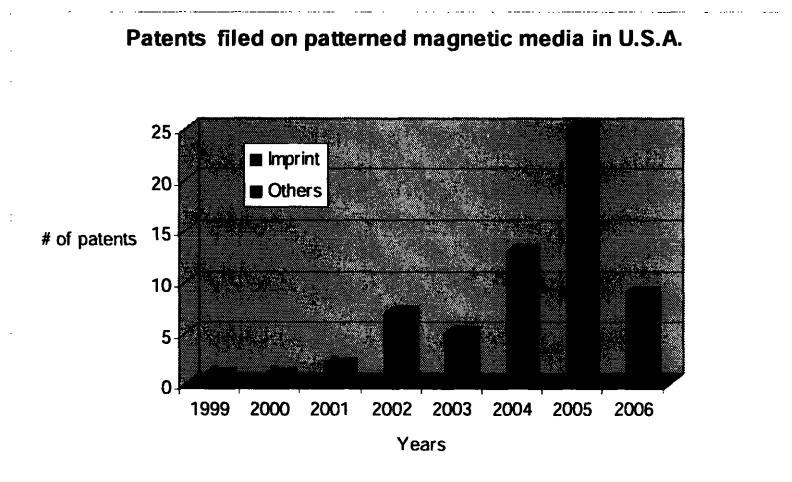


Figure 5.1 Patents filed on patterned media in US since 1999, top crimson bar represent the number of the patents filed on nanoimprint lithography technique

5.2 Market and Competition

Today data storage market is full of different storage media such as solid state drives (SSD), magnetic tapes or disks, and optical disk drives(ODD). To compare the prices of different storage media, a simple calculation will be presented in this section. Currently, we can buy 1Gb USB Drive at about \$20. 300 Gb SATA 3.5-inch hard disks cost about \$80, and one pack of 50 DVD±R disks costs about \$15 after rebate (AR). Thus, for each dollar, we can buy 50 Mb USB drive, 3.75 Gb hard drive and 14.3 Gb optical DVD disks. Because the low cost of ODD, its market value is bigger than those of other media. Figure 6.2 shows a comparison between global market value of magnetic media and that of optical media.

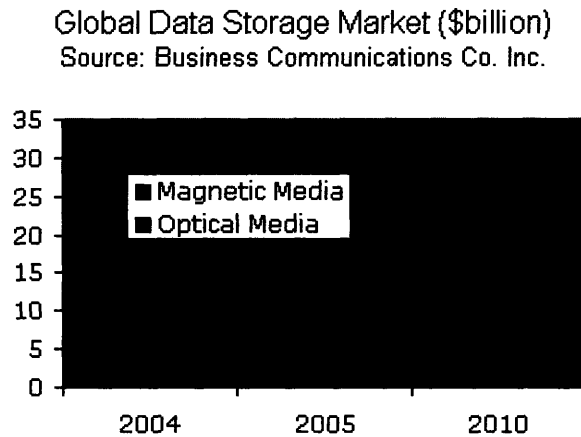


Figure 5.2 Comparison between market value of HDD and that of ODD

The total market for these two media was 16.8 billion US dollars in 2004 and 19.8 billion US dollars in 2005. The average annual growth rate of the total data storage market will be around 15.1 percent by 2010.

Compared to the optical media such as ODDs, HDDs have some inherent advantages: a) Much higher data transfer rate, b) More reliable storage. On the other hand, HDDs are much cheaper than solid state media such as USB drive.

In some cases, different media are irreplaceable for different market demand. However, as flash memory cost-per-bit decreases thanks to Moore's Law, and as hard drive cost-per-bit decreases thanks to perpendicular media recording, optical media begin to be replaced by 1.8-inch hard drive or USB drive for portable storage purpose especially in recent years.

Consumer electronics are a relative new market for HDDs. The old 3.5 and 2.5-inch hard drives are too big and heavy to be assembled in portable consumer electronics, such as cell phones and iPods. With the introduction of 1.8-inch HDDs, the consumer electronics market began to adopt HDDs as storage media. Estimated by international data corporation, the consumer electronics HDD market grew 37.4 percent in 2005, while the average growth rate for HDD was 15.5 percent. With the mass production of 0.85-inch HDD, more storage market share will be occupied by HDDs for sure.

5.3 Business Model

Options for commercializing patterned magnetic media will be presented here. These business models are based on the assumption that the patterned media recording technology that has developed to the point that a prototype hard drive disk has been made or will be made very soon. Although, most laboratory based research is focused on media fabrication rather than on machining a complete HDD system.

5.3.1 Intellectual Property (IP) model

In this model, patents licensing and engineering support are the main sources of revenue. Continuous development is required in order to keep the critical and valuable intellectual patents and one of the main expenses. The other major cost is the fees to file the patents and maintain them valid. Licenses must be carefully considered and limited. Typically, it is best to try to license the technology to a major manufacturer which dominates the market, e.g. Seagate or Western Digital, so that the royalties are then larger. For example,

it would be better to license the patented technology to a company making the entire hard drives than just the disk because direct communications with the hard drive manufacturers would make the assembly processes more compatible and reliable.

To estimate the cost of such a business one can assume a small team of five research engineers at \$100,000 per year for allowance plus benefit. There should be support personnel as well. One can assume a research facility will need three at \$50,000 for each. These support personnel could be technicians, machinists, administrative assistants. That brings personnel costs to \$650,000. Patent filing cost is about \$8,000~15,000 for each patent that include patentability search, application fees, prosecution cost, issue fees, and patent maintenance fee. This is a general estimate of a highly variable process. Actual costs may differ greatly. The materials and facilities will be dominated by the cost of prototypes because they represent a small scale run in a laboratory and are therefore very expensive. For the purposes of this paper, it will be assumed that prototypes will run about \$500,000 a year. This brings the total to roughly \$1,200,000 to \$1,500,000 a year to operate a small development crew depending on the number of patents filed.

Because of the high cost of patent filing, special cares have to be taken in patent writing. Mostly, fundamental concept of patterned structures and various synthesis methods have been filed. Typically, details such as patterned dot size range, spacing, materials composition, process steps have been specified in the patents. However, it is quite possible for this model to operate for years without actually licensing anything. It is also quite possible for the costs to increase by multiples if the prototypes end up requiring a particularly rare and hard-to-perform technique to manufacture. In such a case, strong technical collaboration between hard drive manufacturers is required.

Let us estimate the gross revenue of this IP model, if everything goes well. Assuming one patent is sold to a big hard drive manufacturer, such as Seagate, we can draw 0.1 percent from the retail price of each hard drive. Seagate took about 30 percent of the hard drive market in 2005 and the total shipment of HDD was about 300 million units. Thus the

units shipped by Seagate were about 90 million in 2005. If the average retail price is \$50 for each unit, the gross revenue can be given as

$$R = 300\text{million} \times 30\% \times \$50 \times 0.001 = 4.5\text{million}$$

According to the calculation, the IP company will be able to sustain 2~4 years if one patent is successfully sold to a manufacture.

The markets associated with data storage devices are several billions of US dollars. Over 75 percent hard drive market is controlled by four major players, i.e. Seagate, Western Digital, Hitachi, and Maxtor. An independent business using this model will probably struggle to make money. On the other hand, working as a research group in those big companies makes this model more sustainable due to strong inter-department technique collaboration and sufficient financial support.

5.2 Disk manufacturer

In this model a plant is built and staffed to make the hard drive disks and sell them to the assembly manufacturers. This process is time consuming and it is quite reasonable to assume that it would take 5 years to build the plant and train the facility to produce the device at the price that existing manufacturers charge for the work. Assuming that development of a hard drive disks that can be commercialized will take 5 more years, then there will only be another 10 years left on the life of the patent.

On the other hand, the mass production of perpendicular recording media started in 2005. Seagate specialists predict that the perpendicular media can be used for at least another 10 years with the help of heat assisted magnetic recording (HAMR) technology. Thus, it is reasonable to assume that the patents filed several years ago will have expired even before the current perpendicular media recording meet its upper limit. Of course, this also assumes that the commercialized embodiment does not include new IP that resets the IP

protection timer. In practice, anything made 10~20 years after a patent was written is bound to contain new patentable designs.

It also assumes that no competition appears and taking control of the market in the next decade. According the IDC, the hard drive disks will remain the most cost-effective data storage devices until 2019. As to the expense for this model, typically, one billion US dollars is required to build a fab alone, excluding some other costs such as equipment maintenance or products proliferation. At this point in the development of the technology, an estimate of the cost associated with a manufacturing facility would not be meaningful.

Chapter 6 Outlook and Conclusion

As we looking backward or reviewing the past, a series of techniques have been developed over years permitting magnetic hard disk drive technology to extend far beyond the previously predicted “limits” imposed by the superparamagnetic effect.

In 2000, the areal density limitations estimated by H.N. Bertram and M. Williams^[6.1] for longitudinal and perpendicular recording were 16 Gb/cm^2 (100 Gb/in^2)^[6.2] and 75 Gb/cm^2 (500 Gb/in^2) respectively. The discovery of antiferromagnetically-coupled (AFC) multi-layers broke the barrier of the longitudinal media and pushed the areal density limitation to a new high standard 20 Gb/cm^2 (135 Gb/in^2)^[6.3]. After 2 years, M. Mallery et al proposed that the areal density of perpendicular recording could reach 1 Tb/in^2 in 2002. With the mass production of AFC media HDD in 2001, A. Taratorin^[6.4] estimated that areal density with $200\sim 300 \times \text{Gb/in}^2$ is achievable for longitudinal media. Data from both Hitachi and Seagate show that the current highest demonstrated areal density is $37 \times 10^9 \text{ b/cm}^2$ ($245 \times 10^9 \text{ b/in}^2$) in 2006. The highest commercialized areal density for longitudinal media is somewhere around $17\text{-}20 \times 10^9 \text{ b/cm}^2$ ($110\text{-}135 \times 10^9 \text{ b/in}^2$).

The transition from longitudinal media to perpendicular media is taking place at about $20 \times 10^9 \text{ b/cm}^2$ ($135 \times 10^9 \text{ b/in}^2$). I believe the AFC-media might be the last technique extending the lifetime of the longitudinal media since they have been commercialized since late 80s. It will not be cost-effective to further increase the storage density of longitudinal media. The mass production of perpendicular recording media started in 2005. Seagate specialists predict that perpendicular media can be used at least for another 10 years with the assistant of heat assisted recording or tilted recording, and perpendicular media will be the technology breaking the 1 Tb/in^2 milestone. The application of patterned media will be no sooner than 2015, and the areal density should be able to reach 3 Tb/in^2 or more. The actually timeframe is hard to estimate because the first prototype device has not been built yet.

The existing markets for hard drive disks are very big and market demands will still grow robustly in the future. However, to compete with thin film media, the requirement for patterned recording media is still challenging. The most viable course of action seems to be laboratory-based development, such as in a research center in universities or within a large manufacturer.

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