

**Role of Bit Patterned Media in Future of Hard Disk Drives**

by

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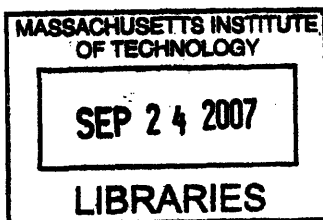
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# **Role of Bit Patterned Media in Future of Hard Disk Drives**

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Vibin Aravindakshan Submitted  
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## **Abstract**

The hard disk industry has traditionally stayed competitive by competing on the means of price alone by cutting down aggressively on cost via increase of areal density. Continuing increases in the areal density of hard disk drives will be limited by thermal instability of the thin film medium and is estimated to be limited to about 500Gb/in<sup>2</sup>. Patterned media, in which data are stored in an array of single-domain magnetic particles, have been suggested as a means to overcome this limitation and to enable recording densities greater than 1Tb/in<sup>2</sup>. However, the implementation of patterned media requires fabrication of sub-50-nm features over large areas and the design of recording systems that differ from those used in conventional hard drives. This report discusses the challenges facing patterned media, the fabrication of arrays of small magnetic particles and their magnetic properties. The practical implementation of patterned media recording schemes is assessed via technology estimates and cost analysis.

Thesis Supervisor: Caroline Anne Ross

Title: Professor of Materials Science and Engineering

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## **1. Introduction:**

The areal density of hard disk drives has always been growing at greater than 60% per annum and 421 Gb/in<sup>2</sup> laboratory demonstrations has been reported by Seagate in September 2006. The increases in data density, data rate, and other performance metrics have generally been achieved by scaling to make the read-write head smaller, the medium thinner and higher in coercivity, and the head-medium spacing smaller. The performance of the medium is limited by noise originating from the granular microstructure of the thin film, so there has been a trend to decrease the grain size. However, this trend will eventually be limited by thermal instability of the grains comprising the medium, because if they become too small, thermal energy will be sufficient to allow their magnetization to reverse spontaneously, with consequent loss of the recorded signal. This phenomenon is termed Superparamagnetic effect. The superparamagnetic effect limits the maximum density that can be achieved by scaling and thus the current technology is estimated to saturate at about 500Gb/in<sup>2</sup>.

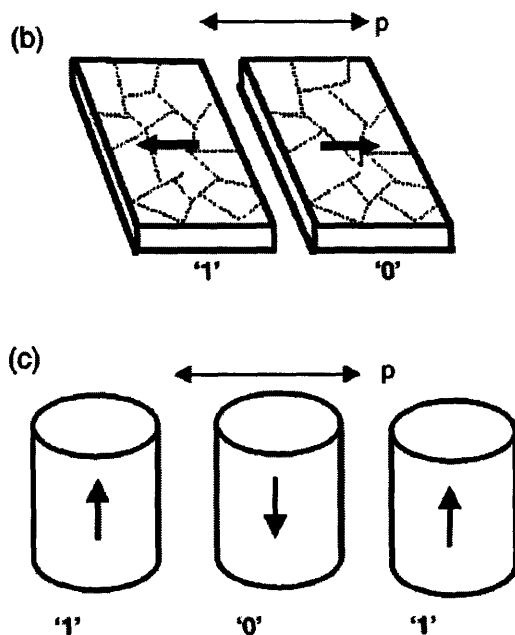
Modern hard disk media incorporate a glass or a NiP-coated aluminum alloy substrate on which a thin film stack is sputtered. The stack consists of one or more underlayers or seed films, a magnetic film, and an overcoat. The magnetic film is a polycrystalline alloy of Co, Cr, and Pt, with additional elements such as B or Ta, and is sputtered at elevated temperatures that promote segregation of non-magnetic elements to the grain boundaries, leading to partial exchange-decoupling of the magnetic grains. Each grain therefore behaves as a single-domain particle with easy axis parallel to the Co c-axis, parallel to the film plane in longitudinal media or perpendicular as in case of perpendicular recording. During the recording process, small areas of the film (bit cells) are magnetized parallel or antiparallel to the track direction (in case of longitudinal recording) or Up/Down as in case of perpendicular recording. It's the fringing fields from the magnetization transitions between these areas that are detected by the head during readback. In current high-density media, each bit cell contains of order 100 grains. Transition noise, originating from irregularities or jaggedness in the magnetization transitions, and increased by collective reversal of groups of grains, dominates the overall signal-to-noise ratio (SNR) of the system. Both the SNR and the minimum width of the transition depend on the grain size of the medium. As the down-track linear bit density increases, the grain size must

decrease to maintain an acceptable SNR. However, the grains begin to exhibit thermal instability when the ratio of thermal energy  $kT$  ( $k$  is Boltzmann's constant and  $T$  the temperature) to magnetic energy  $KV$  ( $K$  is the magnetic anisotropy and  $V$  the grain volume) exceeds a certain ratio. For stability over a time scale of, for example, 10 years gives a ratios of  $KV/kT > 40$  depending on the grain size distribution, intergranular coupling, saturation magnetization, and other properties of the medium. To increase thermal stability, films with higher values of magnetic anisotropy  $K$  could be used, but increases in  $K$  are limited by the need for the recording head to produce sufficient field to write the medium. The maximum write field is around  $400 \text{ kA m}^{-1}$ , leading to a minimum grain diameter of approximately 11–12 nm to ensure thermal stability in CoCrPt-based longitudinal media. This is not much smaller than the grains used in current media. Improvements in microstructural uniformity, bit aspect ratio, and signal processing will be necessary to increase areal density further, but it is apparent that a significantly different approach will be needed to go well beyond  $500 \text{ Gb/in}^2$ . Two possible technologies that offer this solution are Heat assisted magnetic recording (HAMR) and Bit Patterned Media storage.

## 2. Technology review for bit patterned storage

### 2.1 Principle of bit patterned recording

A patterned recording medium, shown schematically in Figure 1 *b-c*, consists 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. Each element stores one bit, depending on its magnetization state; for instance magnetization up could represent 1, and down could represent 0. Unlike the thin film medium, the grains within each patterned element are coupled so that the entire element behaves as a single magnetic domain.



**Figure 1:** (b) A patterned medium with in-plane magnetization. The single-domain bits are defined lithographically with period  $p$ . They can be polycrystalline (indicated by dotted lines) with exchange coupling, or single crystal. (c) A patterned medium with perpendicular magnetization. Binary 1 and 0 for each of the configuration is shown. Source: J.Vac.Sci.Technol.B.1999. 17:3168

The medium is incorporated into a system capable of reading and writing data, for example, a spinning-disk system with an ultra-narrow recording head, or a system with an array of scanning probes that address the elements. For a patterned media system to be viable, it must offer significantly higher data densities than can be achieved in a



conventional hard drive. 25-nm element with 25-nm separation corresponds to a density of 320Gb/in<sup>2</sup>. The major advantages of such a scheme are first that transition noise is eliminated because the bits are now defined by the physical location of the elements and not by the boundary between two oppositely magnetized regions of a thin film. Second, very high data densities can be obtained because the stability criterion now refers to the volume and anisotropy of the entire magnetic element, not to the individual grains of which it is composed. Elements could therefore be as small as a few nanometers, implying densities exceeding 1Tb/in<sup>2</sup>.

## **2.2 Implications for media**

The media considerations is subdivided to those that deal with

- 1) The properties expected of the discrete media
- 2) Those that deal with the patterning challenges and patterning processes itself
- 3) Issues related to tribology.

### **2.2.1. Properties required for discrete media**

The requirements in terms of magnetic properties are very different for a discrete bit media as compared to that of a continuous media. In patterned media the transition length is lithographically defined whereas for the continuous media the transition length for a given write field profile is determined by the ratio of  $M_r t / H_c$ . (Using the Williams Comstock model). Where the  $M_r$  is the remnant magnetization,  $t$  is the thickness of the film and  $H_c$  is the coercivity of the media. A higher value of the ratio corresponds to a larger transition width.

The generalized requirements placed on discrete media are:

- 1) The discrete islands must always maintain single domain remnant state.
- 2) The medium has well defined easy axis, e.g. is uniaxial
- 3) The easy axis should maintain a constant orientation w.r.t the head
- 4) The coercivity needs to match the available write field
- 5) The switching field distribution(SFD) must be narrow
- 6) The islands must be thermally stable
- 7) Media material must have strong exchange coupling

### **2.2.1.1. Necessity of control of SFD**

The patterned media can only be used if the head read/write element is able to “see” all the bits as equivalent or identical. The conditions 1, 2, 3 and 5 ensure this. Thus in case of perpendicular recording this could mean a uniaxial material with perpendicular anisotropy and switching by means of rotating disk paradigm, provided the SFD of the distribution is narrow. A broad SFD has various impacts like timing and synchronization of the head. In a broad sense, the SFD variation causes the deviation in from the assumption that the bits are identical.

The spread in switching fields has two origins.[1] First is due to the intrinsic variability between particles owing to small differences in shape, size; and is expressed as a Gaussian distribution of the switching fields. The other origin is due to magnetostatic interaction between particles. The intrinsic variability is reduced by the good control of the fabrication process and the magnetostatic interaction reduced by lowering the moment of the particles. This however reduces the readback signal. Thus an optimization of the parameters is required here.

Based on modeling results by Hu et.al.[2], islands with SFD less than 10% will be required for use in patterned media.

### **2.2.1.2. Perpendicular recording as the recording processes:**

Just like conventional continuous media, bit patterned media can be either longitudinal or perpendicular recorded. In case of longitudinal recording, there is the need for some degree of preferential circumferential alignment of the magnetic anisotropy axis. However as of now, these processes are expensive and don't allow for the circumferential alignment of easy axis. [3] Thus it is expected that perpendicular media will be choice for the discrete bit media.

### **2.2.1.3. On anisotropy issues:**

Each bit is represented by a discrete island in bit patterned media. The taller these pillar (islands) then the greater the field a neighboring bit will experience and hence greater the likelihood of being inadvertently written. This thus implies that shape anisotropy cannot be used to achieve the perpendicular anisotropy. The mostly likely perpendicular media

will be based on using materials with interfacial anisotropy such as Co/Pt or Co/Pd multilayer or media used in conventional perpendicular recording based on CoPtCr alloys grown with c-axis normal to substrate.

#### **2.2.1.4. Bit Aspect Ratio (BAR):**

BAR refers to the ratio of track width to the bits size along the track. Conventional recording has BAR value of 8 or more. In discrete bit media the BAR will be close to one, so as to keep maximize the smallest lithographically defined feature.

### **2.2.2 Relating to patterning process:**

#### **2.2.2.1. Dimensional requirements:**

The fundamental reason for using bit patterning is to achieve a high areal density. Thus the requirement of  $1\text{Tb/in}^2$  will require 12.5 nm patterning! According to the International Technology Roadmap for Semiconductors (IRTS), a DRAM half pitch of 18 nm will not be reached until 2018. This is significantly later than 2014 projection date for  $1\text{Tb/in}^2$  magnetic recording using a modest 30% compounded annual growth rate.

The patterning process must also have tight control of the island size, shape, spacing and even the magnetic anisotropy orientation axis so that a narrow SFD is obtained.

However there are several differences in the silicon lithography requirement and requirement for patterned media. The fabrication of memory cells and logic gates require many lithography steps with precise mask alignment. Patterned media is likely a one step mask process with virtually no alignment. The pattern doesn't even have to be well centered on the disk, as the disk will not be centered to better than  $10\mu\text{m}$  on the disk spindle.

#### **2.2.2.2. Patterning arrangement:**

Since the head has to stay on a single track of islands as it traverses at a particular radius, a Cartesian x-y layout of the islands will not be suitable. The patterning process will have to bring about a circumferential symmetry.

The patterning process must provide for a long range ordering of the islands and ability to duplicate the process repeatably with high reliability in terms of intrinsic variables like spacing, shape, size etc.

Finally pre-patterned bits have the track locations predefined and thus the servo marks will also need to be patterned. This implies that methods that produce only purely periodic, isotropic, bit patterns which fill entire disk will not be sufficient. [3]

### **2.2.3 Tribolgy Issues:**

A recording head is supported by airbearing above the disk surface with sub 10nm head-disk spacing. Therefore even small resist residue or particulate contamination can cause a fatal head crash. To achieve this spacing, the disk surface has to have a rms roughness of 0.2 to 0.4 nm.

The magnetic materials of interest for recording are also in general prone to corrosion and mechanically too soft to support a flying head. Thus they are coated with carbon or other hard protective layers.

Demonstration of feasibility of flying at fly height of 11nm on a discrete track media has been demonstrated by Soeno et al [22]. A technique that has demonstrated ability to support sub-10nm head disk spacing is to pattern the substrate, rather than the magnetic film itself. In this technique, a magnetic film is deposited on patterned substrate, The side walls of the islands serve to decouple adjacent lands.

The most important advantage of this process is that the film can be aggressively cleaned after patterning without concern for altering the magnetic film. Also fly height over a patterned media is determined by the spatially averaged head disk spacing. This implies the head will be very close to the peaks of the islands and hence higher areal density can be realized via this decrease in head height.

## **2.3 Patterning Techniques:**

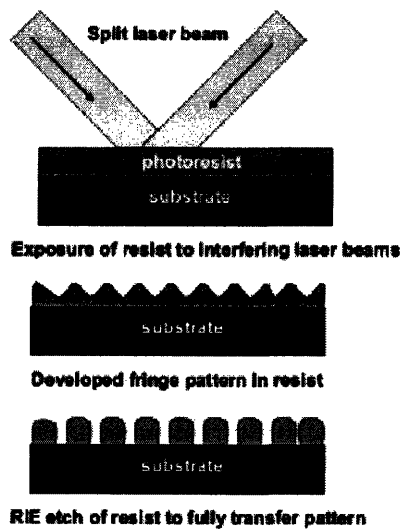
### **2.3.1. Lithography Methods:**

In lithography process a pattern is created in the resist layer by means of techniques like electron beam, optical, ion beam, interference or x-ray lithography and then the pattern in the resist is subsequently transferred over to the magnetic film.

Conventional optical lithography is limited to the resolution of  $\lambda/2NA$ . Where  $\lambda$  is the wavelength of light used and NA is the numerical aperture. Note however this maximum resolution leads to a zero contrast and is achieved only for incoherent illumination.

### 2.3.1.1. Interference Lithography:

This is a maskless technique, where the fringe pattern is produced by two interfering optical beams as shown in the figure 2.



**Figure 2:** Schematic of the essential steps in interference lithography process.

The period of the pattern generated is given by  $p = \lambda / 2 \sin \Theta$ , Where  $\Theta$  is the half angle between the beams. By rotation the sample by  $90^\circ$  between exposures, patterns of dots can be produced. The resolution is limited to  $\lambda / 2$ . Thus the making of small features require short wavelength. However the shorter wavelength excimer laser is insufficiently coherent to produce high contrast fringes using this conventional interference lithography. This is overcome by use of achromatic interference lithography, in which radiation is diffracted by three phase gratings. The periodicity is half the periodicity of the phase grating.

**Advantages:** Even though this process creates bits in Cartesian grid, use of transmission diffraction grating leads to circular symmetry. [7]

**Disadvantage:** The technique is limited to greater than 50nm resolution.

*Technology forecast:* This technique doesn't appear to be a possible technology for Patterned media application.

#### **2.3.1.2. X-ray:**

The X-ray (EUV) lithography process involves a thin membrane mask typically made of Si Carbide or Nitride and covered by a X-ray absorber like Au, Ta or W. The mask is held in close contact to resist. This is thus a 1-1 printing process with resolution being a function of wavelength and the mask-sample spacing. Large patterned areas have been demonstrated using x-ray lithography. For e.g. Permalloy dots as small as 88nm [4] and Co dots as small as 200nm [5] and 4mm×4mm patterned areas of 400nm period Co dots [6] have been produced.

*Disadvantages:* EUV technique is not yet commercial available and would be a very expensive process to use. This is because the low intensity laboratory source will require very large exposure time and hence the throughput will be low unless we go for a synchrotron source. Patterning dimensions are estimated to be limited to a minimum of 20nm.

*Advantages:* X-ray lithography is a parallel process and thus an area as large as the mask can be patterned by a single exposure.

*Technology forecast:* Would be the possible optical lithography technique that may be applied to Patterned media provided a high intensity cheap source of X-ray can be found. Even still the high demands placed on the spacing and mask generation cost involved would make it still an expensive process.

#### **2.3.1.3. E beam lithography**

Electron beam lithography is probably the most widely used method for fabricating sub-100nm patterns. Magnetic elements of many sizes and shapes have been created using this technique in conjunction with variety of pattern transfer processes. This has been reviewed in [1]

The resolution is determined not just by the beam diameter but also by the exposure and development characteristics of the resist. Since bit patterned media requires dense features of roughly equal bits sizes and spacing, the minimum feature size is defined by

the proximity effect due to the overlapping low level exposures arising from electron scattering in resist and substrate.

*Advantage:*

As of now it is only technique that gives the resolution and minimum feature size as required for patterned media to reach the storage density of  $1\text{Tb}/\text{in}^2$  and above.

*Disadvantage:*

It is a serial writing process and hence is slow and has a low throughput. It is also very expensive.

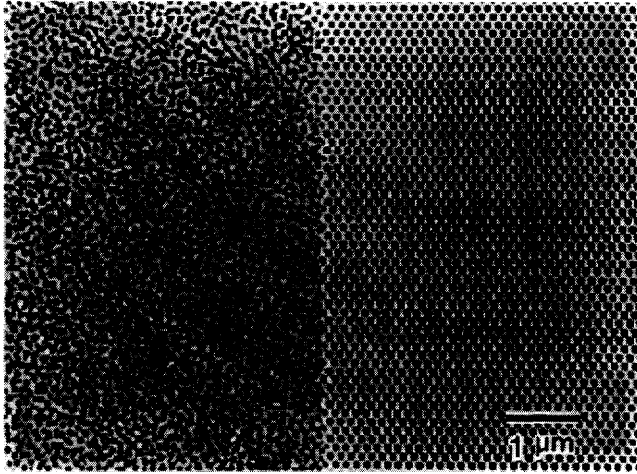
*Technology forecast:* Unlikely to be used directly for Patterned Media application, but appears as an ideal technique for the mask fabrication in master/replication like Nanoimprinting.

### **2.3.2. Natural Lithography methods:**

One appealing way to reach the density of  $1\text{Tb}/\text{in}^2$  is to capitalize on the self ordered structures found in nature, such as self assembled spheres, anodized alumina and phase separation in block copolymers, to produce a template for patterning. The template can then be used as an etch mask or deposit mask.

#### **2.3.2.1. Anodised alumina:**

When aluminum is anodized, the resulting oxide layer contains a hexagonally closed packed arrangement of pores, with the pore size and spacing controlled by the anodisation conditions like voltage, current density and solution pH. Pores as small 9nm have been reported with a packing density of about  $450\text{Gb}/\text{in}^2$  [8]. The centre to centre spacing of pores is typically roughly twice the pore diameter. The ordering is short range and on the length scales of few  $100\mu\text{m}$ . The order is disrupted because of multiple pattern nucleation sites analogous to the grain boundary occurrence in grains. The length scales however can be greatly extended by templating the aluminium surface, for example by focused ion beam[9] or moulding or nanoimprinting[10]. Figure 3 shows how the effect of templating compared to the conventional anodisation method.[ source 10]



**Figure 3:** SEM micrograph of surface view of anodized Al; pretexturing interval was 150 nm. Anodization was conducted in 0.3 M oxalic acid of 17 °C at 60 V for 36 min. Pore widening was carried out in 5 wt % phosphoric acid at 30 °C for 70 min.

Most work on magnetic structures formed from anodized alumina has been focused on fabricating long (i.e. tall) wires by, for example, filling the pores using electrodeposition [9]. It is more difficult to form low aspect ratio dots, as desired for discrete bit recording, although progress has been reported on this by using the template as a shadow mask [10] as well as by electrodeposition [11]. Films can also be deposited on top of the alumina mask, resulting in a film with a regular array of holes. Such structure has been made from Ni films by Xiao *et al* [12], and these structures have been suggested as a form of high density patterned bit medium [13]. The anodized surface can also be used as a nanoimprint mask.

*Advantages:*

Anodised alumina based patterned media seems promising both in terms of the minimum attainable feature size as well as the packing density reachable.

The techniques like templating of the surface to increase the length scale promise to resolve the issue of long range order that has been one of the principle barriers in self assembled route to patterned media fabrication.

*Disadvantage:*

There is no work in the literature to demonstrate the circumferential symmetry necessary for application to hard disk drives.

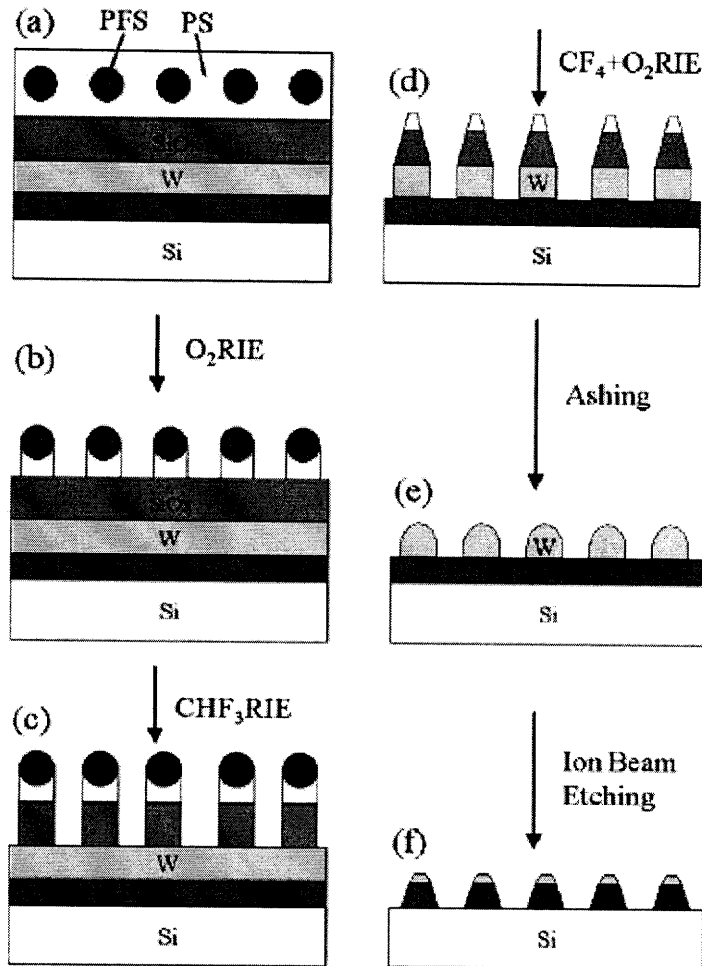


*Technology forecast:*

A very promising technology that could potentially answer the demands required for patterned media application. Possible used to produce masks for nanoimprinting process

**2.3.2.2. Templated growth using self assembly:**

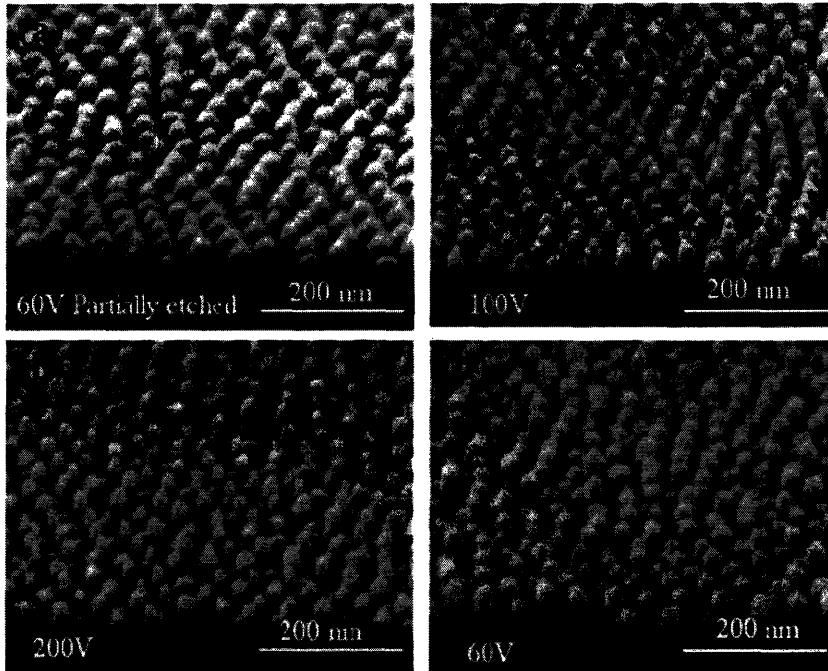
Self-assembled arrays of particles and block co-polymers have also been used to produce template surfaces [14]. A block co-polymer consists of a polymer chain with two distinct monomers, A and B, of length  $n$  and  $m$ , bound together to form a polymer  $A_n-B_m$ . The polymer will typically phase separate after being spun onto a surface, producing periodicities in the range 10–200 nm, with the geometry of the separated regions dependent upon the  $n/m$  ratio and the surface energy of the substrate. In particular, if  $n \ll m$ , spheres of  $A_n$  can form in the  $B_m$  matrix; if  $n < m$ , alternating lamellae of  $A_n$  and  $B_m$  may form, with their orientation dependent on the substrate. These structures have been used as templates for the growth of magnetic nanostructures. For example, spheres of  $A_n$  can be preferentially etched, leaving the  $B_m$  matrix to be used in a lift-off process to form small magnetic islands. Many other variations on this technique have been demonstrated, with magnetic islands as small 25 nm produced. An early example of this work with relevance to patterned media is that of Cheng *et al* [15], where arrays of Co dots were fabricated, as shown in figure 4.



**Figure 4:** Fabrication process of the cobalt dot array via block co-polymer lithography. (a) A block co-polymer thin film on a multilayer of silica, tungsten and cobalt. (b) The block co-polymer lithographic mask is formed through the O<sub>2</sub>-RIE process. (c) The silica film is patterned using CHF<sub>3</sub>-RIE. (d) The tungsten hard mask is patterned using CF<sub>4</sub> + O<sub>2</sub>-RIE. (e) Removal of silica and residual polymer by high pressure CHF<sub>3</sub>-RIE. (f) The cobalt dot array is formed using ion beam etching.

The process involved forming an array of nanodots which serves as an etch mask for a previously deposited W/SiO<sub>x</sub> capped Co film. Spheres of polyferrocenyldimethylsilane (PFS) 25 nm in diameter with a 50 nm period were formed in a polystyrene (PS) matrix on the surface, and the pattern transferred to the Co by a series of etch and ion mill steps. In this way Co nanodots with W caps were successfully fabricated. Ordering in nanodot

arrays over length scales of micrometres has been demonstrated for diblock co-polymer nanofabrication [14].



**Figure 5:** Tilted SEM images of O<sub>2</sub>-RIE etched PS±PFS copolymer. a) PS-b-PFS etched partway through the PS. A layer of PS is still left on the substrate, with PFS domains protruding. b) PS-b-PFS etched completely through the PS matrix, using 200 V DC bias. c) PS-b-PFS etched completely, using 100 V DC bias. d) PS-b- PFS etched completely, using 60 V DC bias.

*Advantages:* Promising in terms of extension to the dimension of particle size and spacing required for 1Tb/in<sup>2</sup> storage.

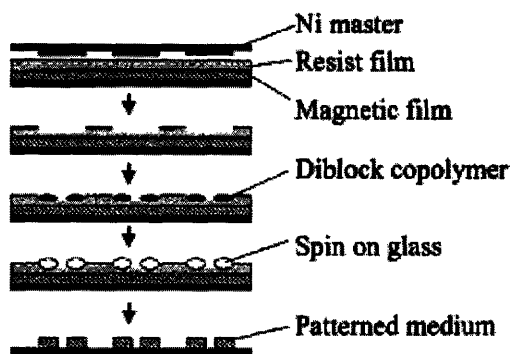
*Disadvantages:* As seen in figure 5, the technology has still ordering on the length scale of few micrometres. Self assembly as such doesn't allow for circumferential symmetry, it requires other methods such as guided self assembly to achieve this. The particle size distribution control still has to be worked upon, if it is to be used in patterned media application.

*Technology forecast:* The technology is still in a seminal stage and lots of work will have to be required before it can be incorporated as a main stream process.

### 2.3.2.3. Guided Self Assembly:

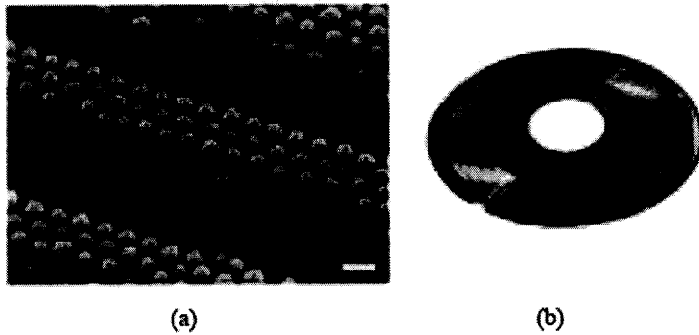
One possible solution to the problem of creating long range ( $>1\mu\text{m}$ ) ordering is guided self-assembly. This concept combines a lithographic process with the use of natural self assembly. There are two ways this can be done:

- (i) Physical, where a topographical pattern is created in a substrate and
- (ii) Chemical, where the surface chemistry is selectively modified so that nanostructures can form in some areas and not others.



**Figure 6:** Schematic for preparation of patterned media using guided self assembly

A possible implementation of guided self-assembly where a block co-polymer film is used as an etch mask is shown in figure 5 above. [17]. A sputtered perpendicular  $\text{Co}_{74}\text{Cr}_6\text{Pt}_{20}$  medium, 40 nm thick, was coated with a resist film which was subsequently imprinted with a Ni stamp having land and groove patterns. The bit pattern was created in the resist grooves using a PS-PMMA block co-polymer. The PMMA spheres formed by annealing the block co-polymer were selectively removed using an oxygen plasma treatment and the resulting holes in the PS matrix were then filled with spin-on-glass (SOG). A final ion milling step then removed the PS matrix and underlying magnetic media using the SOG dots as mask; leaving tracks of magnetic islands protected by the SOG, over an entire 65mm glass disk as shown in figure 7.

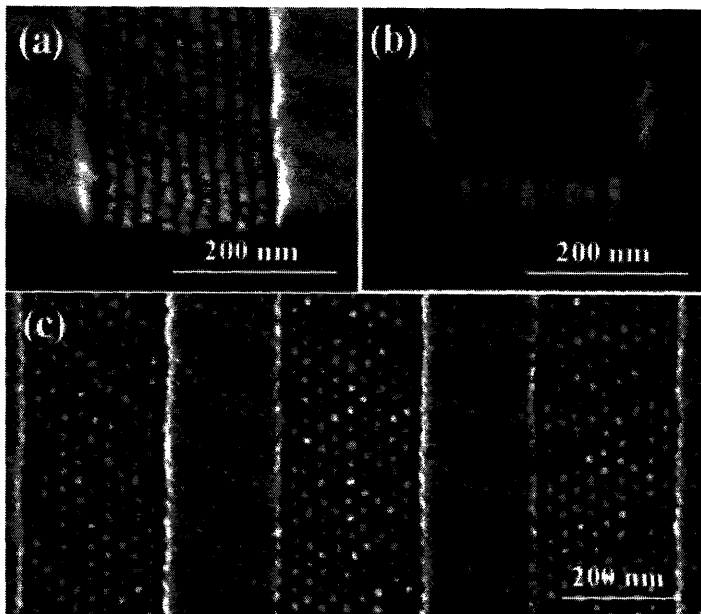


**Figure 7:** (a) SEM image of the patterned magnetic medium (Co Cr Pt ) with a 40-nm diameter. The scale bar indicates 100 nm. (b) Whole image of the patterned media disk prepared on a 2.5-inch HDD glass plate.

*Advantage:* Possibility of circumferential symmetry and large area long distance ordering produced by a single step. As the master Ni mold can be repeatedly used, offers a cheap fabrication technique for mass production.

*Disadvantages:* Variation in bit size and spacing must be resolved before it can be commercially used for bit patterned media. Ion beam milling step can lead to undesirable magnetic properties.

An alternative approach involves using the block co-polymer as a mask to etch the substrate prior to the deposition of a magnetic thin film, as shown by Cheng *et al* [18]. In this scheme, 200–1500 nm period grooves were first patterned into Si wafers using interference lithography and reactive ion etching (RIE). The block co-polymer solution (PS/PFS) was then spun-coated onto the prepatterned substrate and annealed, allowing the co-polymer to migrate to the trenches, leaving the top of the patterned lines free of polymer material. An oxygen etch 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 allowed the bit pattern generated by the spheres to be transferred to the SiO<sub>2</sub> substrate, as shown in figure 8.



**Figure8:** Pattern transfer from an ordered PS/PFS 50/12 polymer for forming an array of ordered silica nanostructures. (a) Side view of the PFS pattern in 240 nm wide grooves. (b) Side view and (c) plan view of the pattern after it has been transferred into an underlying silica layer by RIE.

*Disadvantages:* The Process is too sensitive to line edge roughness and thus the long range ordering is affected.

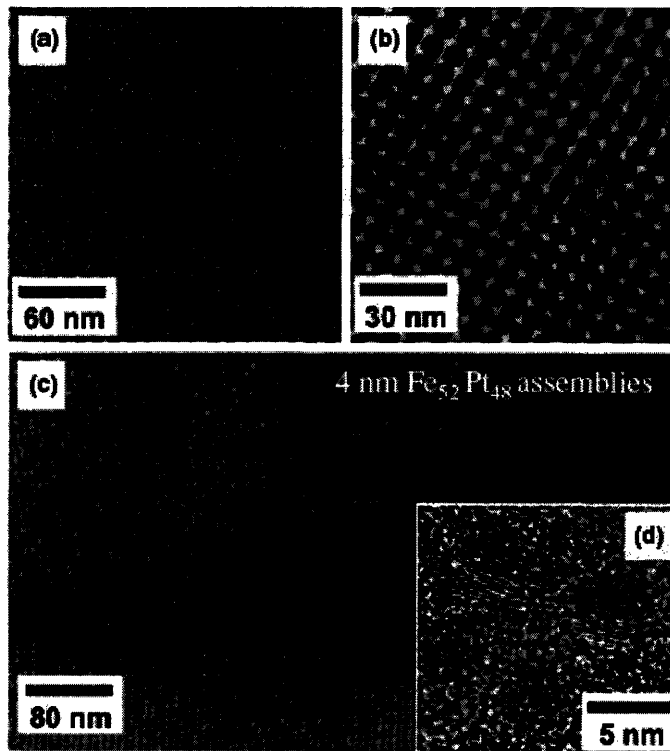
The second class of guide structures involves modifying the chemical properties of a substrate surface in particular regions to create patterns over large areas. Review of this can be read in [3]. In one of the works a block co-polymer was chemically steered to particular regions of a substrate. A layer of octadecyltrichlorosilane was exposed to x-rays through a patterned mask, causing a chemical change in the exposed surface from non-polar hydrophobic to polar hydrophilic. A thin film of P(S-b-MMA) is then spin-coated onto the exposed substrate and annealed. The difference in surface energy of the exposed and unexposed regions leads to differences in wetting behaviour of the block co-polymer, forming structures with 30 $\mu$ m domains.

*Technology forecast:* The Guided self ordering is still in research stage and problems related to long range order and various distributions of physical dimensionality and magnetic properties have not been completely resolved. However, ability to reach

particle diameter of 3nm with a variation of just 6% [19] is quite impressive and offers possibility to extend the patterned media storage well above the 1Tb/in<sup>2</sup>.

### 2.3.3. Nanoparticle Self Assembly:

Sun *et al* [20] first demonstrated that FePt nanoparticle assemblies with particles diameters as small as 4 nm and an extremely narrow distribution of sizes (<5%) could be obtained, as shown in figure 9 [20].



**Figure 9:** (a) TEM micrograph of a three-dimensional assembly of 6 nm as-synthesized Fe<sub>50</sub>Pt<sub>50</sub> particles deposited from a hexane/octane dispersion onto a SiO coated copper grid. (b) TEM micrograph of a three-dimensional assembly of 6 nm Fe<sub>50</sub>Pt<sub>50</sub> particles after replacing oleic acid/oleyl amine with hexanoic acid/hexylamine. (c) HRSEM image of a 180 nm thick 4 nm Fe<sub>52</sub>Pt<sub>48</sub> nanocrystal assembly annealed at 560°C for 30 min under 1 atm of N<sub>2</sub> gas. (d) High resolution TEM image of 4 nm Fe<sub>52</sub>Pt<sub>48</sub> nanocrystals annealed at 560°C for 30 min on a SiO coated copper grid.

FePt is attractive as a nanoparticle recording material since, in the L1<sub>0</sub> phase, it is one of only relatively few systems that have sufficient magnetocrystalline anisotropy to remain

magnetically stable at these small volumes [21]. FePt nanoparticles are typically made using solution chemistry and arrested precipitation approach which results in a solution containing particles coated with a surfactant. The particles are subsequently deposited onto a substrate by dipping or coating. The surfactant and any functionalization of the substrate [23] then work under appropriate conditions to form self-assembled layers. The particles deposited using this method are nominally in a disordered fcc crystallographic phase and are oriented at random. To use these materials as a recording medium, the crystallographic phase must be converted to the high anisotropy  $L1_0$  phase. In addition, it is highly desirable that the ordered particles have a common magnetic easy axis. The  $L1_0$  phase can be created by annealing. However, temperatures in excess of 600°C are required before any significant phase transformation occurs, and this leads to particle agglomeration and sintering. Optimizing the surfactant chemist can assist in reducing agglomeration [24] as, potentially, can hardening the organic matrix with ion beam irradiation [3].

*Disadvantages:* Despite these advances it is still not clear that the problem of agglomeration has been overcome completely. The problem of orienting the magnetic easy axis has not been solved. An additional concern is that of the uniformity of the chemical ordering induced by annealing [25]. In order to avoid the problem of a distribution of anisotropy, there is a requirement that all particles have the same degree of ordering. Clearly, the medium would have a very wide distribution of anisotropy if some nanoparticles order whilst others remain in the disordered fcc phase. The ordering depends on the particle size, with larger particles ~7 nm ordering more easily than smaller particles ~4 nm.

*Advantages:* The dimensions and packing densities are among the best achievable using any techniques currently available.

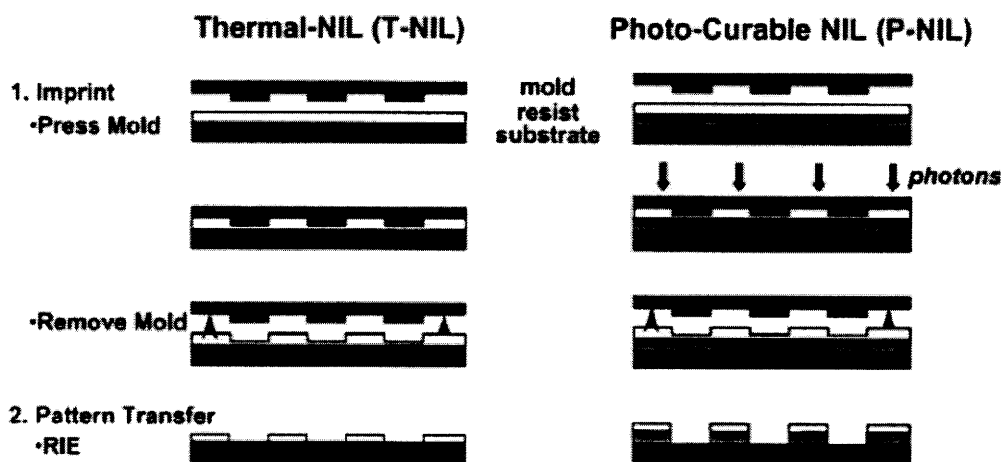
*Technology forecast:* This technology still is in the research stage, but shows great potential.

#### **2.3.4. Nanoimprint Lithography:**

In depth review has of this is present at [1, 3]. The basic nanoimprint process occurs through a sequence of steps shown in figure below. A nanopatterned mold is brought into



contact with a resist-coated substrate. The resist material is then simply released at room temperature or, more usually, cured (while the mold is in contact) either by heating (which activates a chemical reaction or enables motion of the polymer molecules) or by exposure to UV light. If resist is cured or allowed to flow by heating, the method is called “thermal nanoimprint” and if it is cured by light is called “photo-curable nanoimprint” or sometimes “step and flash” nanoimprint [26]. A schematic is represented in figure 10. After curing, the mold is removed, leaving a topographic relief in the imprinted resist. The relief topography in the resist generally does not go all the way down to the substrate surface, necessitating a short “cleaning” etch to remove the remaining resist material from the bottom of the features.



**Figure 10:**The two main approaches to nanoimprint: thermal NIL (in which the resist is cured thermally) and photon-curable NIL (in which the resist is cured by UV photon exposure).

The expected resolution of nanoimprint depends on the technique used. For thermal nanoimprint, it is believed to depend on the dimensions of the inter-polymer van der Waals bonds (typically 1-3 nm), and also perhaps on the intra-molecular bonds (0.1-0.3 nm). The group of John Rogers at the University of Chicago has shown replication of patterns in single-walled carbon nanotubes using nanoimprint. In this work they claim single-nanometer-scale precision in replication of both lateral and vertical dimensions of the nanotube. In another experiment, Stephen Chou’s group at Princeton started with a

vertical stack of materials (with layers as thin as 5 nm) was deposited by molecular-beam epitaxy and then cleaved and selectively etched to create a relief structure. The substrate was then tilted on its side and used as an imprint template. The result was a pattern in the resist that reflected the ~14-nm spatial period and ~5-nm feature size of the film thicknesses in the multilayer stack. [27]

*Disadvantages:* As of now none really exist. However work on fidelity of the pattern replication is being investigated.

*Advantages:* Nanoimprint lithography is able to replicate structures with resolution approaching molecular dimensions.

*Technology forecast:* It is in the nearly commercialized stage. There are many companies like Nanonex, Molecular Imprints, NND co.Ltd, EVG etc. The solutions they offer now are however nowhere near the pattern dimensions required for patterned media application.

#### 2.4 Implications for the Recording system:

The constraints imposed on  $M_r t$  and  $H_c$  by the self demagnetization effect is relaxed for patterned media :since it is the volume average of demagnetizing fields over the particle rather than demagnetization near transitions that lead to pattern degradation. Thus the medium can support larger  $M_r t/H_c$  value without demagnetizing itself compared to a unpatterned media. This means both increased readback signal as well as a greatly simplified writing process. In figure 11 simulation was performed for islands of thickness 20nm,length of 100nm and infinite width for a material of  $M_r$  of  $1400 \text{ emu/cm}^3$  and the demagnetization field calculated on an island as a function of bit spacing.[28]

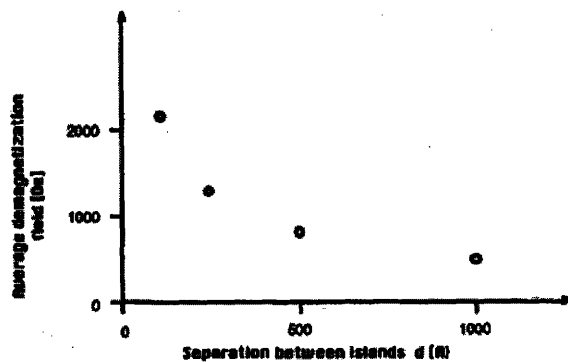
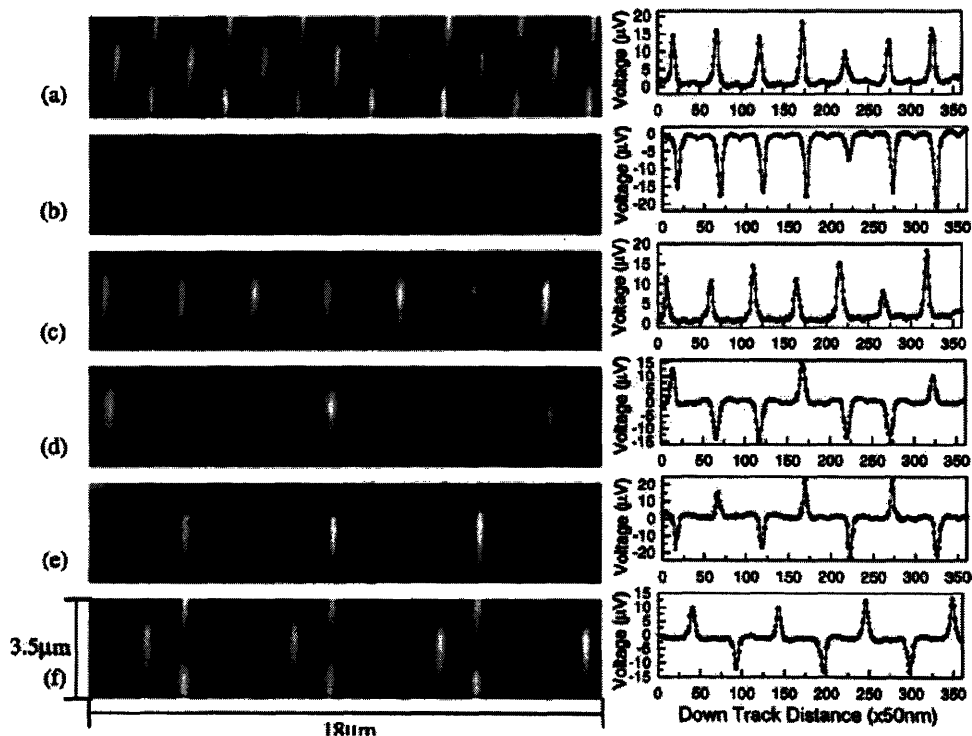


Figure 11: Demagnetisation as a function of bit spacing

The design of the head element for patterned media can be of the conventional type or by usage of mutiprobe MFM tips in “millipede concept”. Details of this system are available at [29, 30]. Usage of multiply MFM probe would drastically change every aspect of the hardisk design, right from the disk requirements to circuitry and signal processing. The cost associated with multiple probes being extremely high and due to a the disruptive nature of this technology; it is not expected to be in the hard disk market anywhere in the near future and is thus not discussed further in this report and analysis of the recording system using the conventional idea of spinning disk and read write head is carried out. There is numerous works in literature showing that recording of data into patterned media is feasible. The experiments are usually carried out on coupons using Mr head microscopes. Yamamoto et al [31] reversed and detected tall 150 nm diameter Ni pillars embedded in SiO<sub>2</sub> on a 2.1 $\mu$ m pitch. Subsequent works using improved fabrication techniques[32] to produce higher coercivity pillars are reported by Todorovic et al[32] and is shown in figure 12.

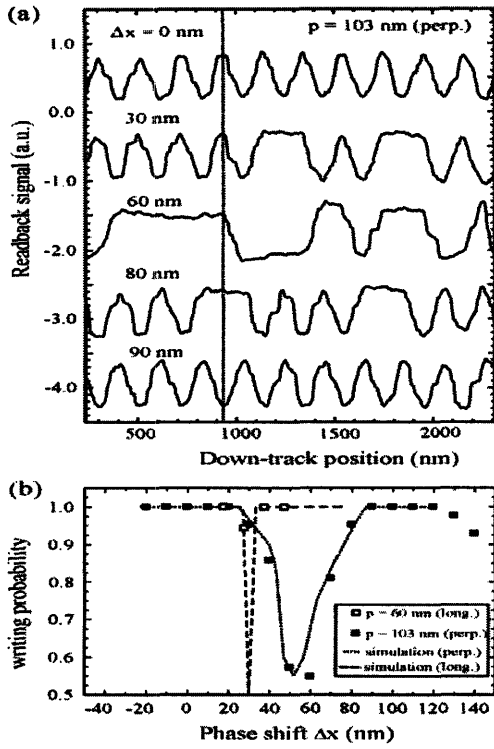


**Figure 12:** A collection of scanning MR images, demonstrating controllable writing of single column per bit perpendicular patterned media data tracks, is shown on the left side. The line scans of the centre data tracks are shown on the right side.

#### **2.4.1. Implications for timing and synchronization:**

As mentioned by White [28], Patterned media will require timing the read write-field pulses to line up accurately with the patterned magnetic islands on the medium. A DC magnetized continuous film will only give rise to a DC signal in read back, while in patterned media the signal also reveals the trench location between islands. This signal is a result of the increased head media spacing at the trenches compared to that of the islands. Thus the read back signal can be used to accurately position the head over the island locations. For patterned media it is necessary not only to synchronize the data read-out to the bit pattern but also to synchronize the write pulses to the bit positions, this can be done using the readback signal mentioned earlier in two ways. The first would be to interrupt write bursts with read bursts so as to maintain synchronization. For this to be practical, the spindle motor speed uniformity would have to be greatly improved so that a much longer interval could elapse between re-synchronizations. The second option would be alter the read write recording head so that reading of synchronization data could proceed continuously, even during writing. In current recording heads there is significant coupling between the read and write signals (through both electrical interference and magnetic effects), and this coupling would have to be greatly reduced in order for reading and writing to proceed at the same time.

Synchronization of the write field doesn't imply that the write pulse will have to exactly line up with the island location. There is a certain window or margin of error in terms of mismatch between pulse (writing signal) location and island location that would still lead to a correct writing. This is illustrated in figure 13b. In case of perfectly sharp head field gradient and zero SFD, this window is as large as the island period itself, but in general the window depends write field gradient as well as the SFD as shown in figure 13 [34, 35] below. A higher head field gradient can lead to a dramatic increase in write margin. Similarly a narrower SFD would result in wider write field window.



**Figure13:** (a) Perpendicular CoCrPt medium: GMR readback signals, obtained after applying different phase shifts ( $\Delta x$ ) between the position of the head field transition and the location of the islands.  $\Delta x = 0$  is when the head switches polarity exactly midway between two islands. (b) Probability of addressing islands correctly as a function of phase shift for patterned longitudinal ( $p = 60$  nm) and patterned perpendicular ( $p = 103$  nm) media. Corresponding results obtained from a simulation are indicated by dotted and dashed lines.

As analyzed by Richter et al [36, 37]; in a practical system however the timing synchronization can occur only in an average sense. Assuming a perfect average synchronization; any fluctuation of island position, spacing, thickness and shape or magnetization properties of individual islands can lead to write in errors. Assuming Gaussian distribution for simplicity leads to the expression for the timing error.

$$P_t = 1 - \operatorname{erf}\left(\frac{B/2}{\sqrt{2}\sigma_x}\right) \quad (1)$$

Where  $\sigma_x$  is the standard deviation of all the distributions combined and  $B$  is the bit length. The Bit error rate  $\text{BER}_t$  associated with this timing error is given by  $P_t/2$ . Since

even if the event occurs, there is a 50% chance of island being magnetized correctly. Since there is a variation in the switching field of the islands associated to the variation in magnetic properties; there is a finite probability that the islands would not be switched and given by.

$$P_w = \frac{1}{2} \left[ 1 - \operatorname{erf} \left( \frac{H_{H_{\max}} - H_{sw0}}{\sigma_H \sqrt{2}} \right) \right] \quad (2)$$

The BER associated with this is again given by  $BER_w = P_w/2$ . The combined error rate is given by  $BER_{\text{tot}} = BER_t + BER_w$ . Analysis of various different design scenarios for areal density between 1 to 5 Tb/in<sup>2</sup> using various combination of head design and optimization of media thickness has been carried out in detail in [36,37]. The results are summarized as: BPM with conventional magnetics works well at 1 Tb/in<sup>2</sup> with either a pole head/SUL or with a ring head. The best ring head performance is found for relatively large gaps. Using a ring head for the low-bit aspect ratios is more favorable than pole head, because the effective field loss can be mitigated by opening the gap. The performance drop associated with opening the gap can be restored by reducing the head-medium separation to 5 nm. The highest densities (3 Tb/in<sup>2</sup> beyond) require composite media. As expected, composite media do best with a pole-head/SUL combination, but even with a ring head, composite media show some advantages. Reasonable margins can be obtained at 3 Tb/in<sup>2</sup>, where the composite medium with magnetization contrast performs best. The scenarios for 4 and 5 Tb/in<sup>2</sup> show that the performance quickly deteriorates at higher densities.

*Conclusions:* It is essential to keep all the distributions narrow in bit patterned media, to allow for low write in errors. The effect of distribution can however be mitigated by use of head designs with higher gradient like shielded heads or even HAMR ( Heat Assisted Magnetic Recording).

#### **2.4.2. Positional error signal:**

The all or nothing nature of recording process in patterned media implies the side writing to neighbouring tracks is now no longer a problem. Neighboring islands subjected to very large fields only at extremities may reverse their magnetization at these extremities but revert back to original uniform magnetization state after the removal of the external field.

Thus patterned media is extremely tolerant to side writing and track-misregistration during writing.

The error signal for tracking servo system is derived from the positional signal written centered halfway between the tracks. In conventional recording, especially at high densities; the position signals get corrupted because of side writing. A patterned media, resistant to side writing thus offers superior positional error signal capabilities.

#### **2.5. Conclusions based on Technology review:**

The Patterned media hard disk is technologically viable scheme to extend the areal density increase. The fabrication of media will most probably be done via nanoimprint lithography; by a combination of the templated self assembly and imprint lithography or by method of guided self assembly.

The various distributions both physical and magnetic will have to be much more controlled than at present. The patterned media application will require scaling down of head size at least along the cross track direction. A cost analysis will show the economic feasibility of the different techniques described.

### 3. Market Analysis

#### 3.1. Market segmentation based on application

The Storage market for hard disk is segmented based on application as:

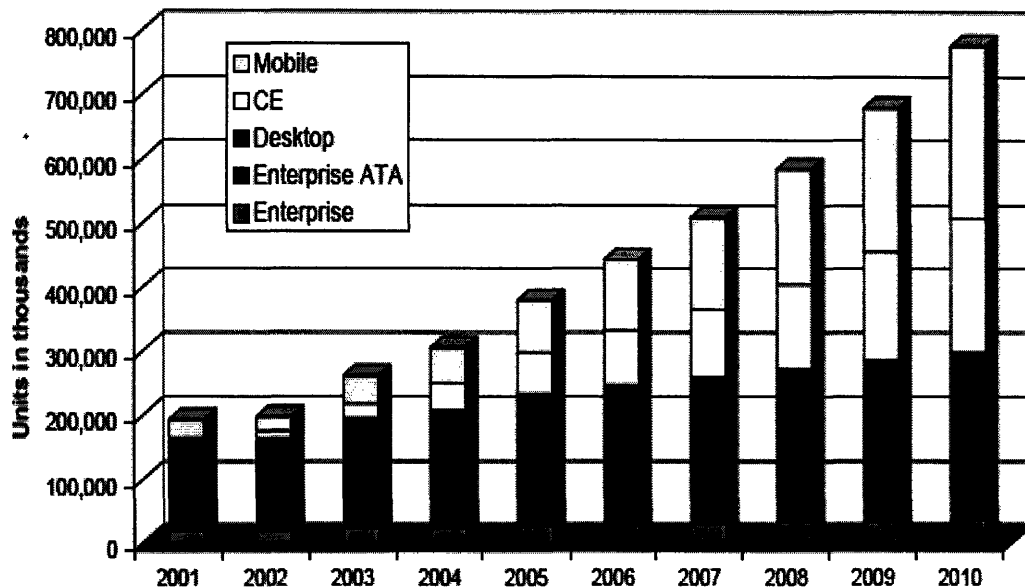
1. Storage medium for computer application:

Further segmented to:

- 1) Desktop storage
- 2) Enterprise storage
- 3) Mobile or laptop storage

2. Consumer electronics (CE)

The relative demand faced in each of these individual segments is mapped in the figure 14 below; with the demand quantified by the number of hard disks shipped in the segment. The values from 2005 onwards are a forecast of expected demand based on conservative estimates.



**Figure14:** Number of hard disk units shipped and forecast from year 2005 onwards.

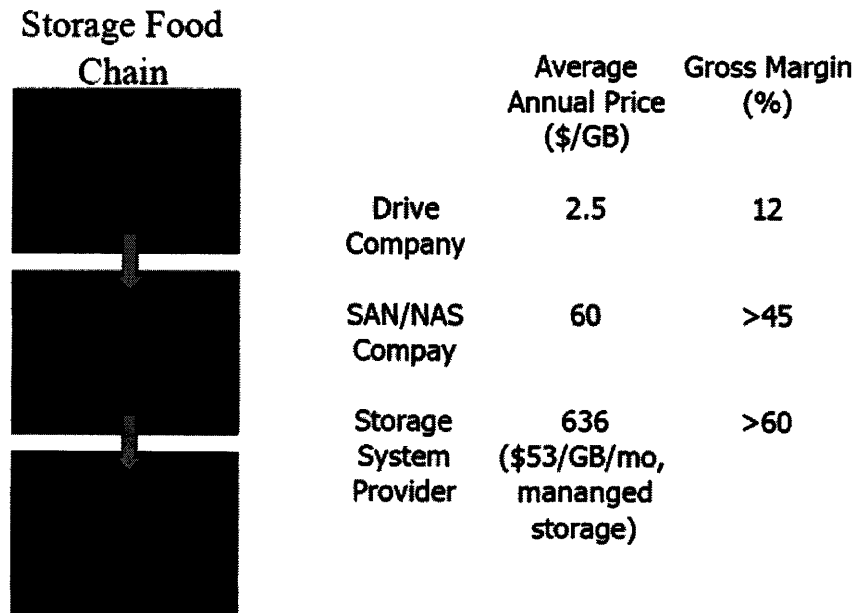
Source: E.Grochowski et.al.



From the graph it is clearly seen that demand for the hard disk drives has been ever increasing. The demand is not really represented clearly by a plot of units shipped, since the increasing areal density tends to decrease the numbers of units shipped. This graph is to be read taking into account that there has been a greater than 60% compounded annual growth rate (CAGR) in the areal density of hard disks.

### 3.2. The hard disk value chain:

Despite the increasing demands and the ever growing market; the hard disk manufactures are showing decreasing profits and most companies are financially floundering. The Storage systems providers, however who use the hard disk to provide storage solutions to enterprise market comprising of internet and corporate storage requirements have been extremely profitable. This is the conventional or traditional market model the hard disk operates in. In figure 15, the schematic value chain in the hard disk industry is listed along with the estimate of the profit margins they operate at.



**Figure 15:** The increasing value chain in the hard disk drive storage market as on year 2005. Source: Storage visions.com

As is seen from figure 15, the Margin is substantial for storage system provider and minimal for drive manufacturing company.

SAN stands for storage area network, NAS for network attached storage. These are two architectures to attach storage devices to servers in a network. NAS connects the storage directly to LAN. It allows for clients to access files on the network, leaving the server to perform other network functions. It is clear using the NAS architecture the storage is considered as remote. SAN architecture allows for the operating system to sense the storage as a locally attached device. There is a separate network from the LAN and storage consolidation is achieved by means of switches and servers. Clients are provided with disk blocks rather than portions of file. This difference thus leads to differences in kind of operations they are optimized best for. Figure 15a provides the different applications as suited for NAS and SAN architecture.

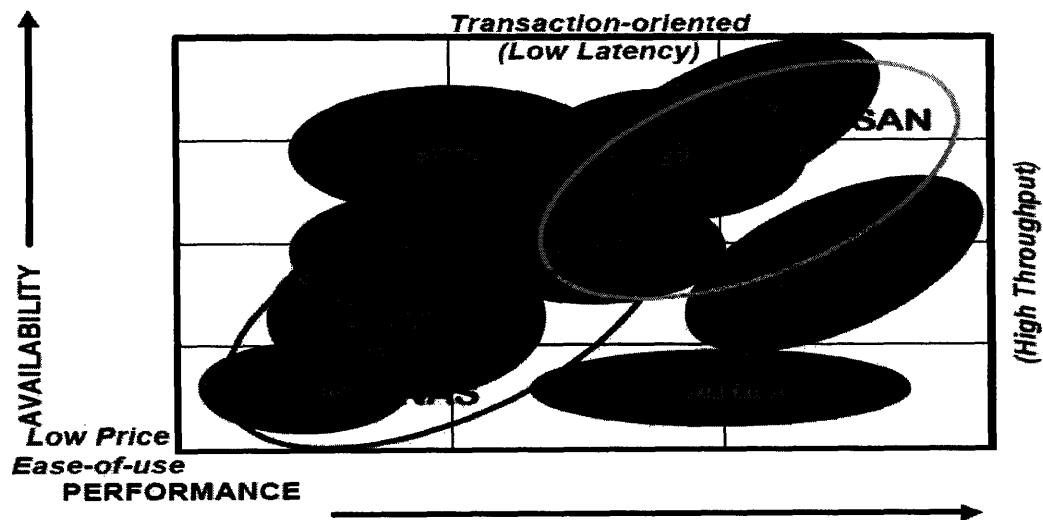


Figure 15a: Applications grouped under SAN and NAS based on performance and latency metrics. Source: Storagevisions.com

SAN and NAS thus add value to a physical storage device by incorporating the architecture and protocols necessary for it to be used in a network. This value addition leads to the increase in value of this step in the hard disk enterprise value chain.

Storage service provider (SSP) further increases the value by adding the management services that make the network operational. Services include data backup and data

archiving. The SSP provides thus storage as a utility, where a client leases the storage space required without worrying about the background operational and maintenance issues. As is expected from the value chain, the cost associated with the storage management accounts for roughly half the IT costs.

So lying at the bottom of the value chain and because of the marketing model the hard disk manufactures have undertaken, the hard disk in spite of their tremendous technological achievements are traded as commodity products. A commodity market is in general associated with raw or primary products. There is no product differentiation in a commodity market. The price is extremely elastic and competitiveness achieved solely based on the pricing.

The hard disk market shows exactly these same characteristics and the various companies have competed aggressively based on the pricing alone. This is shown as in figure 16, where the price reduction has fallen much more than cost reduction achieved by increasing the areal density. This is lead to shrinking profits and is reflected in the EPS (earnings per share) in Table 1.

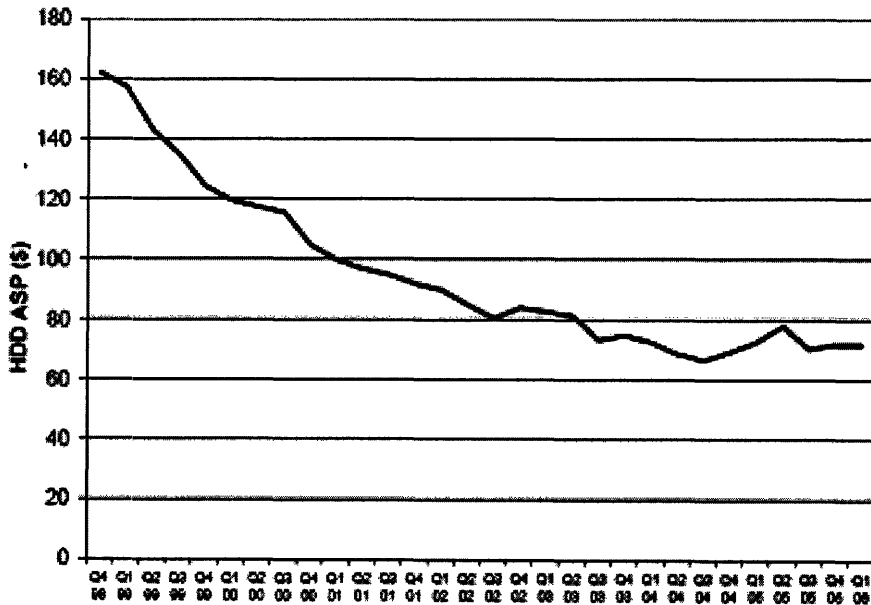


Figure 16: Average drive price for Seagate, Western digital and Maxtor from quarter 04 of 1998 till quarter 01 of 2006. Source: Coughlin Associates

**Table 1:** EPS of different companies segmented into drives, components, capital equipment. The value is brackets represent negative EPS

Company	Shares Out. (MM)	Stock Price 2/1/00	Calendar Year Earnings Per Share		
			1998A	1999A	2000E
Maxtor Corp.	103.3	7.41	0.52	(0.82)	(0.53)
Quantum HDD Group	86.0	7.94	(1.19)	(1.06)	0.30
Seagate Technology	223.1	41.00	0.62	1.00	0.70
Western Digital	121.1	4.68	(4.28)	(3.46)	(3.20)
HMT Technology	45.7	3.22	0.37	(1.98)	(0.52)
Hitachi Tech.	30.7	16.63	(1.29)	0.02	(0.10)
Konig, Inc.	65.4	2.53	(3.51)	(1.85)	(0.58)
Read-Rite Corp.	49.8	2.78	(2.75)	(4.11)	(1.55)
Intevac	11.7	6.00	0.00	(0.99)	(0.60)
Veeco Instruments	17.5	59.76	1.08	1.45	1.84
Omega Corp.	209.7	4.13	(0.16)	0.05	0.24

Source: storagesearch.com

In the figure 16, the steadying of prices from the second quarter of 2004 has been due to changes in the hard disk industry structure. The mergers of Maxtor and Quantum, Hitachi and IBM drive operations and acquisition of Maxtor by Seagate have resulted in fewer competitors who undercut one another. Another reason has been the temporary shortage of hard disk components, especially the disks. Thus a commodity market working fluently to the market forces of demand and supply, the temporary stability is essentially due to the reduced supply.

The fierce internal competition can be understood from the fact that in late 80s there were about 200 companies competing in the hard disk market and only a handful exists now.

So in the market as it exists now, staying competitive is achieved by aggressively decreasing the market price; achieved via decreasing cost. This has been primarily possibly by scaling the bit sizes and increasing the areal density. Figure 17 below graphically reports this trend. With the conventional approach nearing its limit of scalability, there is an urgent need to find new ways to increase the areal density. This is where the Technology of bit patterned media arises. However the constraint is more on the economic viability than one of technology. The conventional market model demands

not only an increase in areal density but also a reduction in manufacturing cost. This report carries out a cost analysis for estimating the financial viability.

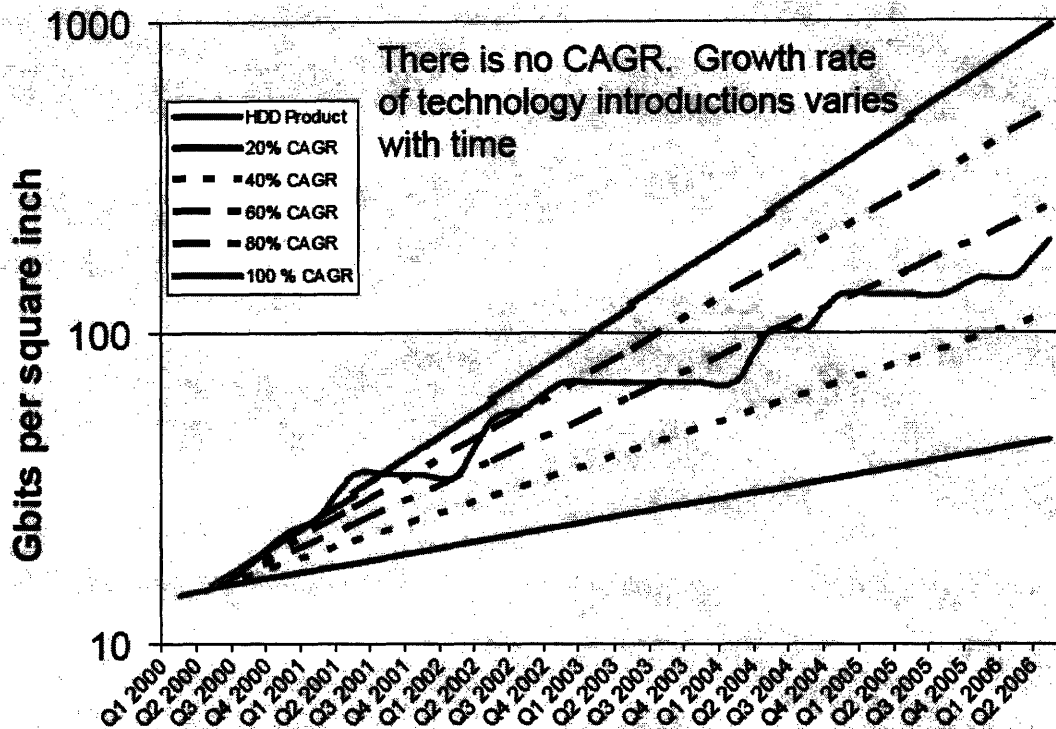


Figure 17: The trend in hard disk industry is plotted along with lines of fixed CAGR for reference. Source: E.Grochowski et.al.

### 3.3. The Consumer Electronics (CE) market

The crash in computer industry during the year 2000-2001 and the ever present fierce internal competition, lead to a crisis period for the hard disk industry. For a decrease in demand would imply slashing of prices in an already hard pressed industry. Thus there was a need for diversifying to different markets. The Consumer Electronics(CE) market was targeted as a direct consequence.

As shown in figure1, this market has been increasingly growing and is expected to contribute to roughly 30% of all hard disk shipped by year 2010. This along with the mobile market has lead to the increasing demand for small form factor (SFF) hard disks. These have added advantages of higher mechanical shock resistance and lower power

consumption just on basis of scaling. The trend towards smaller form factors is shown in figure 18.

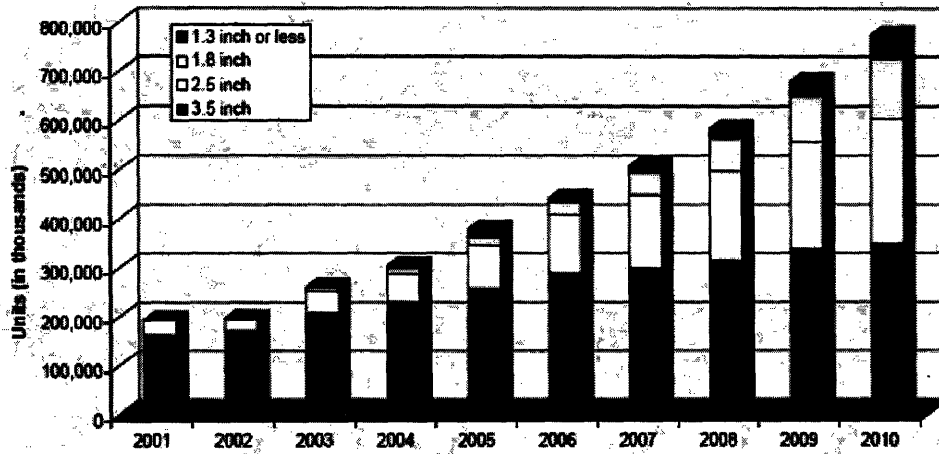
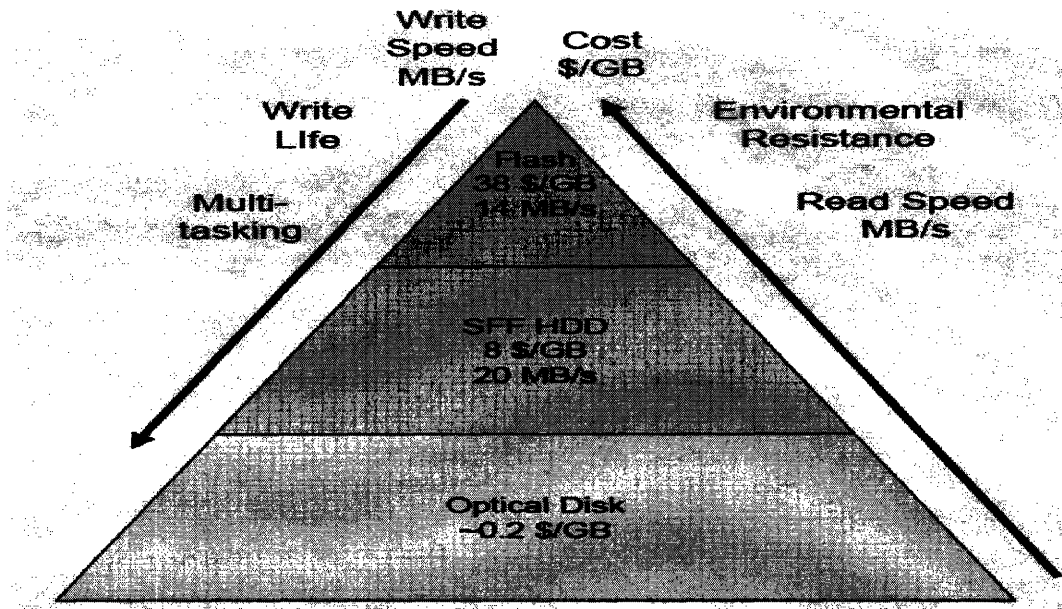


Figure 18: Estimate showing graphically the expected trends in form factors. Source: hitachigst.com

### 3.4. Competitor Analysis

The storage market however is not to be thought of only as being dominated by the hard disks. There are a variety of factors to be besides cost that make certain storage suitable for a specific application. This is summarized in by the storage hierarchy represented in figure 19.



**Figure 19:** Storage suitability of different media represented for different requirements. The direction of arrow represents the direction of the increasing respective property.

The hard disk faces stiff competition from flash memory in the CE market. Flash storage devices have been making inroads into even in large volume storage requirements, where traditionally hard disks have been indispensable. For e.g. Fujitsu launched notebooks with 16 GB and 32 GB solid state drives this year.

The Hard disk facing stiff competition from internal competitors also faces severe competition from competing technologies. To understand how these technologies really stand up against one another and to section the market to where they will operate competitively, two graphs relating to Price/unit memory and also Price/unit sold needs to be seen as shown in figures 20a and 20b respectively.

[Sources: E. Grochowski (HDD to 2003), Coughlin Associates (HDD 2003+) and Semico for Flash]

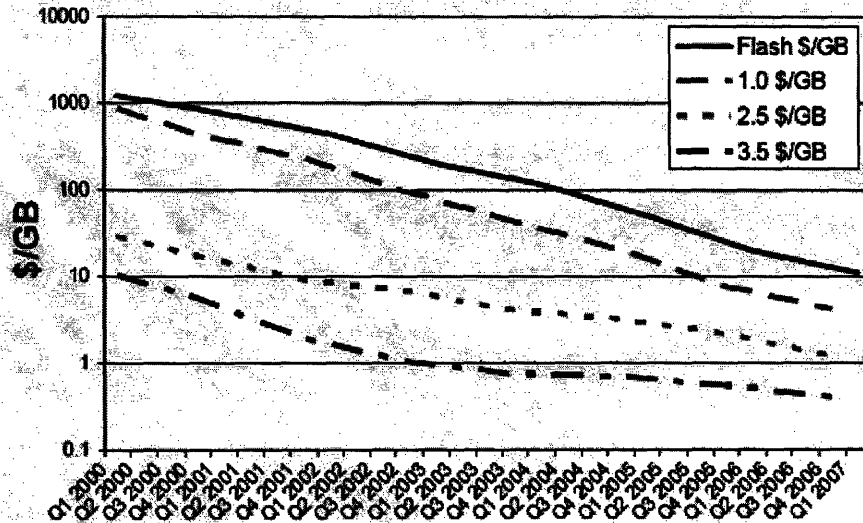


Figure 20a: The price/GB for different hard disk form factor and flash memory

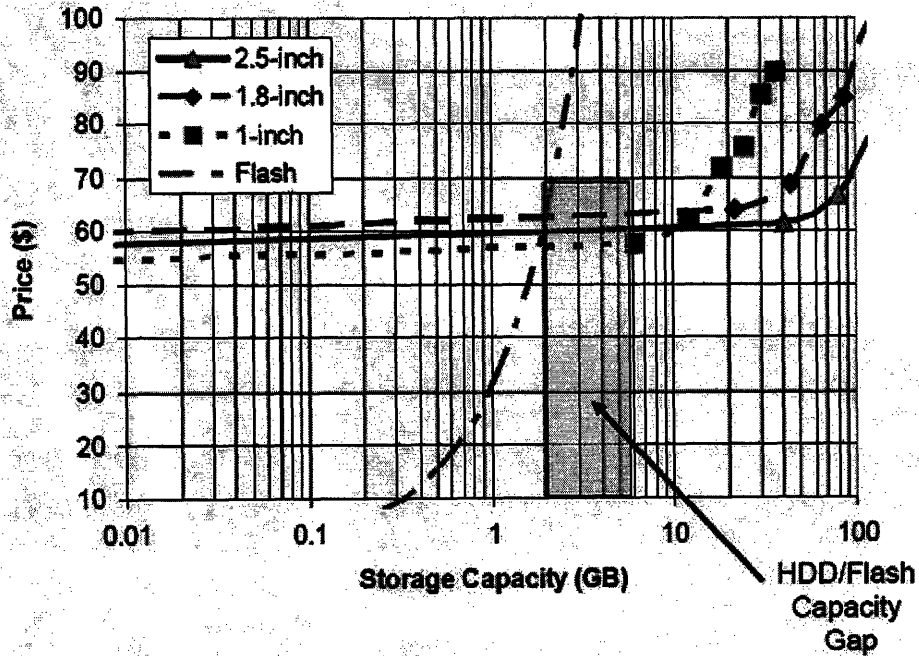


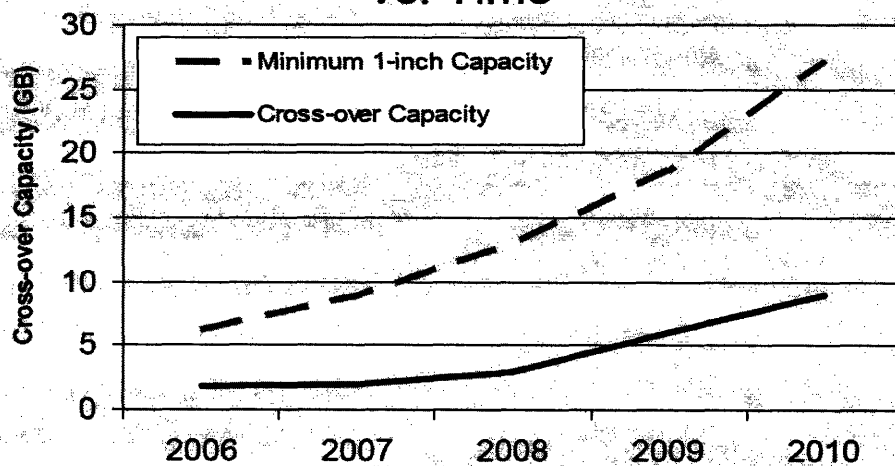
Figure 20b: Price as a function of storage capacity per unit shipped for various form factors as well as for flash memory. Source: Coughlin Associates

The figure 20b shows that the hard disk drive has a floor price. This means that lower than a certain storage capacity value, the decrease in storage size is achieved via



shrinking the platter area. Since the Fabrication steps associated remains the same and there is no change to any other components associated with the hard disk, the price takes the plateau as depicted. This implies there is a certain minimum price associated with hard disk drive. In flash decrease in memory is achieved via decrease in blocks of memory cells created. Thus the price correlates directly to the storage size. There is thus a certain minimum storage capacity, which changes as the generation changes, referred to as cross over point; below which it becomes more economic to use flash rather than hard disk as storage device. This cross over point continuously shifts to the right as the technology associated with flash as well as hard disk improves and is estimated by using figure 20a. As estimate of how this cross over will evolve with time is depicted in figure 21.

### Minimum 1-Inch Drive Capacity (one head) and Flash vs. HDD Cross-Over Price Point vs. Time



**Figure 21:** Estimate of cross over capacity evolving with time and the corresponding minimum expected 1-inch form factor capacity. Source: Coughlin Associates

Based on the discussion earlier, the consumer electronic market is segmented into market whose storage capacity saturates to a certain value and those that have ever increasing demands for storage capacity. Digital still cameras or portable audio players are examples of the markets that saturate in demand. There are only so many pictures one would have

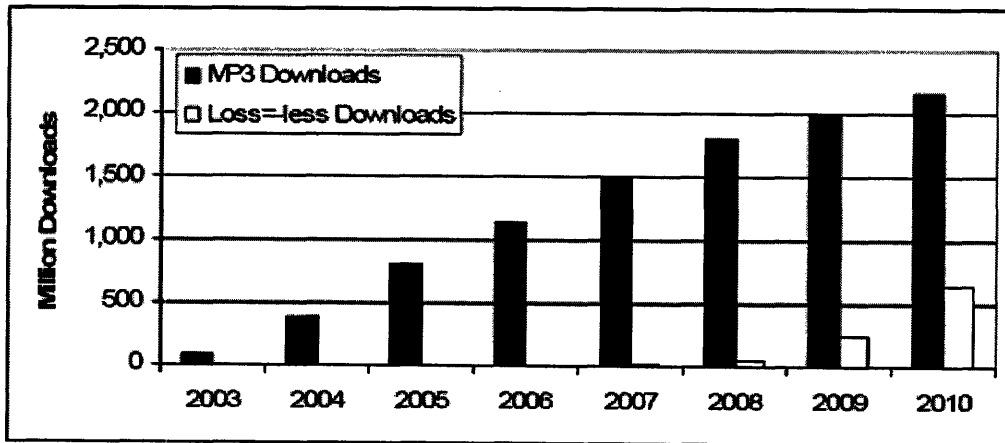
the time to scroll through and there is a limit to how many pictures one would like to take even a long trip. This thus limits the size requirements. A great example of the audio player trend can be found from the example from Apple ipod nano 2 and 4GB models opting for flash memory rather than go for hard disk drives. Sales figures at the year of entry 2005 for these products show that mini ipods, using HDD; were selling better in the 4GB sector than in 6GB range, even though a 50% improvement in terms of storage was being offered for only 20% increased price. Thus markets that will saturate with time, based on the demand for storage is likely to opt for flash storage, as the cross over point will lead to economic viability. The markets that are unlikely to saturate include set top boxes, TiVo, video on demand etc. These will use hard disk drives as the storage medium.

The market segmentation just based on price is clearly not accurate to predict the trends that occur. It is always an optimization of various performance indices like cost, reliability, data transfer rate, latency time and power consumption that will ultimately decide the storage method best suited for that market. Hard offer better performance when: multitasking or streaming is required, number of overwrites is expected to be large, higher bandwidth so that faster synchronization with wireless required. However they have poorer shock resistance and also consume lots of power every time the disk spins. This large power consumption would not make it a great choice for mobile application where battery power has to be conserved. That's why even in a traditional large volume storage sector despite low price, competition exists via flash storage device. There are other than performance like aesthetics or convenience. A measure of convenience or "easy of use" can be had from portability of the CE. The portability is inversely a function of performance or storage; but still a valuable metric for certain kinds of CE; even more than the cost in some cases. A sizeable market exists for the hard disk in the CE market, but how the product is positioned and what metrics are emphasized as a value or even perceived value will require a clever marketing strategy. Table 2 below lists out the hard disk units shipped under different segment and the growth charted from year 2000 to 2004.

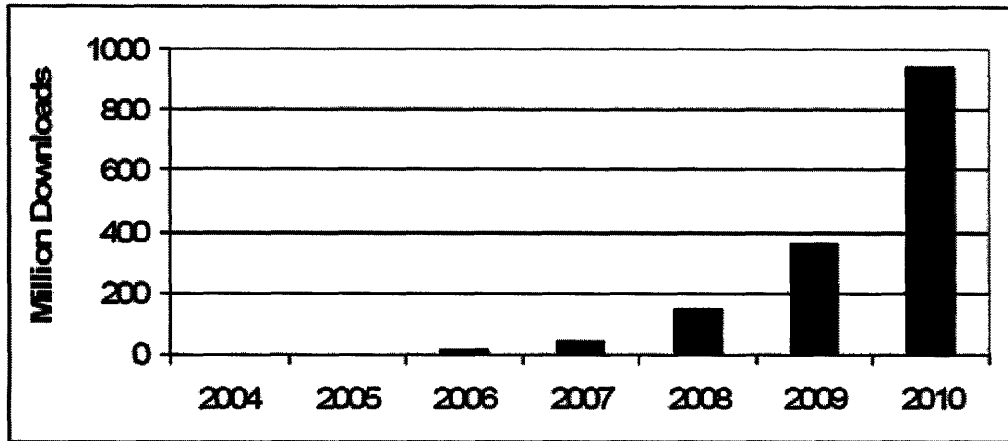
**Table 2: EMERGING NON-PC HDD STORAGE MARKETS**

SEGMENT	(Units 000)				
	2000	2001	2002	2003	2004
Laser Printer	1380	1905	2787	3159	3602
GPS Systems	300	700	940	1300	1400
Set Top boxes	8000	12100	18700	26400	29870
Digital Cameras	16420	2590	42860	68600	79800
Gaming Industry	2.4	3.7	4.8	5.6	6.0
Audio/Appliance	1420	3570	5965	7414	8215
Other	37	45	70	75	80
Total	33730	61183	81867	1006953	122973

The market forces are always dynamic. The remarkable success of the Apple i-pods has also been due the distribution chain they have built up in the form of i-tunes distribution store. The standard format played by default in this player is the AAC compression format. This is a lossy format similar to mp3. These formats evolved because of lower data transfer rate across the Internet and because of high cost associated with bandwidth. These also increase portability, as more songs can be packed into the same volume. With technology innovation the band width will get progressively cheaper, until at some point at future the shift towards distribution channels with non lossy formats occur. This market of future is ideally suited to take advantage of the hard disk utility of large storage at low price. Projections for audio and legal movie downloads are shown in figure 22 and figure 23.

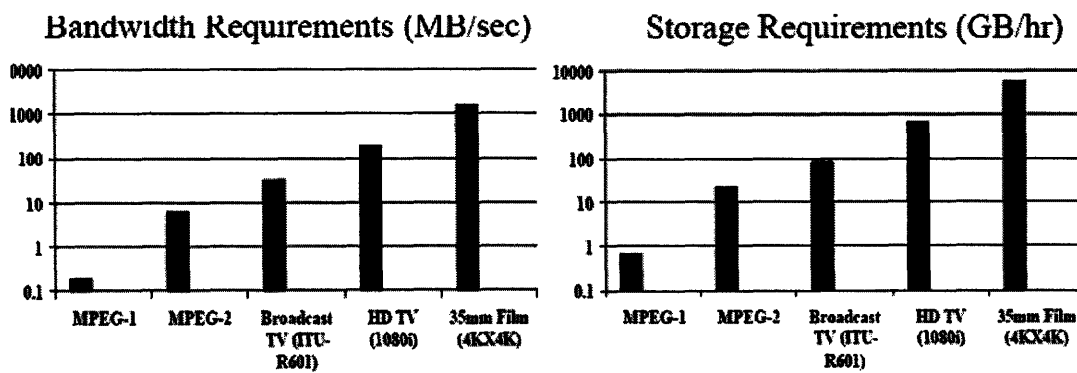


**Figure 22:** Projection data from 2005 onwards on how the lossy and lossless audio downloads will evolve. Source:storagevisions.com



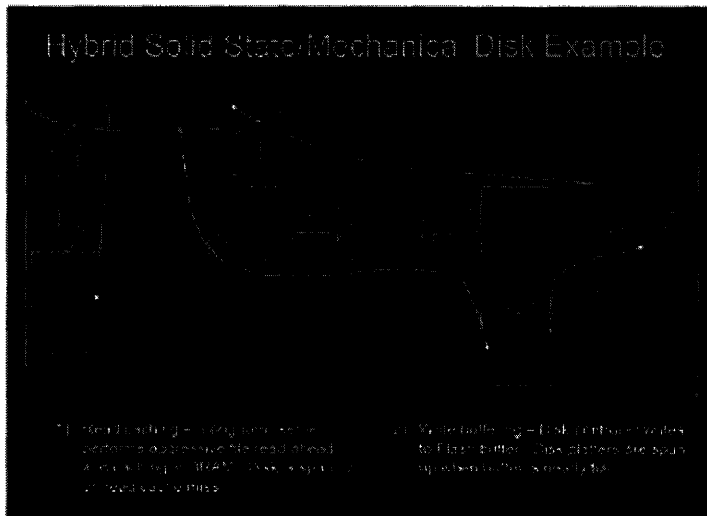
**Figure 23:** Projection regarding legal movie downloads in the internet. The figure doesn't take into account streaming or hits on online hosted videos like say the youtube. Source: enterprisestrategygroup.com

Even today, there is a high end customer market pertaining to medical transfer files, movie download via video on demand concept. TV broadcast via the TiVo digital video recorder. The adoption of high definition TV and online movie downloads will not only depend on the availability of cheap storage via HDD but fast and cheap bandwidth. This is depicted in figure 24.



**Figure 24:** The Bandwidth requirements for different media formats and corresponding storage requirements. Source: enterprisestrategygroup.com

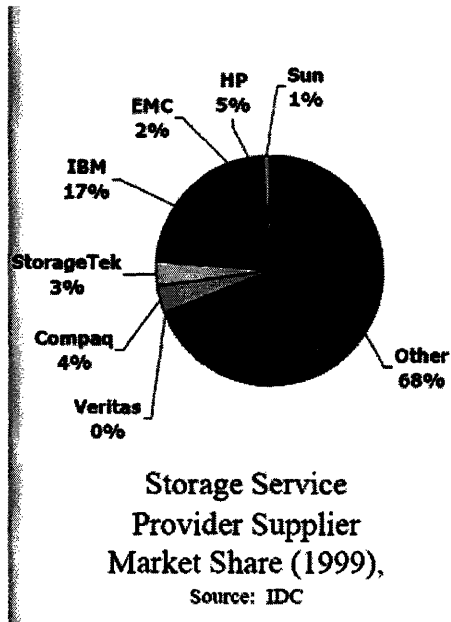
The demand for large storage doesn't however rule out the role of flash storage in these markets. There is a position of coexistence between these technologies and is visualized as a hybrid drive. The advantages of both technologies are combined in this kind of system. A flash buffer cache is combined with the hard disk storage unit to lead to decrease of read time and net operational time when the disk needs to keep spinning. The hybrid drive reduces the power consumption associated with the hard disk, retains the high storage capacity and decreases the latency time associated with read cycles; with no significant cost addition. This sort of drive will require a architectural change in how the operating system fetches or writes data, A windows VISTA visualization is depicted in figure 25.



**Figure 25:** A windows VISTA visualization if architecture built for utilizing hybrid drive. Source: Coughlin Associates

### 3.5. Enterprise application

Network storage solutions in companies and the internet roughly describe the entire enterprise market. This as described earlier is a high value market with large operating profit margins. There are however a lots of players in this market, provide data storage services. Figure 26 shows a pie chart break up of the players and the market segment they operate in.



**Figure 26:** Data from year 1999 showing the market players and market segment.  
Source: enterprisestrategygroup.com

Note: Internet is one great ever increasing source of information and commerce and there is always the continuous to back up and archive data. The data back up is a complex process where issues like data duplication taken care of. Concepts of data warehousing is necessary along with techniques for data recovery in case of disaster and need for hot swapping of drives during operation. It's interesting to note the growth of enterprise ATA due to the development of serial ATA (SATA) as depicted in figure 14.

### 3.6. Traditional business model and suggestions to build a better model:

The model the hard disk operates currently in one of commodity market and continuing this model will involve constant pressure to come up with increase in areal density to just maintain the profit margins. Thus a technology like bit patterned media will be really crucial to stay competitive in this market model. However despite a technology breakthrough and ability to achieve extreme areal densities, this will be adopted by the industry only if it shows economic viability.

It however makes business sense to think of new business models that will take the hard disk away from being just a commodity product. The value as can be seen is got from rising up the value chain and raising some barriers to entry. One method would be the System on chip (SOC) concept where the firm ware of the CE is built on into the hard disk. This would free up a considerable price based on manufacturing, packaging, integration and inventory costs. Of course licensing agreements will have to be worked out. But this is one method of moving up the value chain, providing more than just a storage media.

Another way would be develop drives targeted at specific applications instead of providing generic solutions. For example would be patented lower powered drives by using newer substrate material or using optimization codes specific to a particular application for data access/write. Idea is to create some barriers via branding or strong niche market patent protection.

One another way would be for companies not to target all the markets, that is split or section the world market among the current players. This of course would violate "fair trade" rights in some countries like the anti trust law in US, but should be okay for many parts of the world.

## 4. Cost Analysis

### 4.1. Introduction and assumptions:

A simplified cost analysis is presented. The results give a feel of the order of magnitude of the prices involved. The conclusions based on the cost model are quite insightful. The cost analysis is in actuality the single most important consideration for introduction of the patterned media hard disk drives.

Assumptions:

1. The Patterned HDD will be of rotating disk, and GMR head: Just like the conventional media. This has been discussed earlier in technology review as a viable scheme.
2. The head associated with the Patterned media will have to be shrunk, but we assume here the head is roughly the same as that of conventional HDD
3. All electronics and other associated components remains the same.

### 4.2. Cost modeling structure and formulae

Based on these assumptions, the following is concluded:

For a fixed storage capacity, which can be realized by one disk and one head in the patterned media scheme will require at least 2 disks and therefore 2 heads using the conventional technology.

It's to be noted that a very high areal density in the patterned media will lead to multiple disks (more than 2) using the conventional technology, but here the idea is to look at the analysis based on the worst case scenario, that even a simplistic model can give good insights.

If the introduction of patterned media is to be viable only when the areal density is atleast such that :

*Cost of: 2 disks (conventional)+2 heads ≥ Cost of: one disk (patterned)+1 head-----1*

(This is for the conventional case)

(This is for the patterned case)



Assuming again for sake of simplicity that the materials required and even the dimensions of different layers of the disk are the same for conventional and patterned media, the additional cost is just the cost of patterning.

Thus,

$$\text{Cost of one disk (patterned)} = \text{cost of one disk (conventional)} + \text{cost of patterning} \text{-----} 2$$

Thus substituting equation 2 in equation 1, implies:

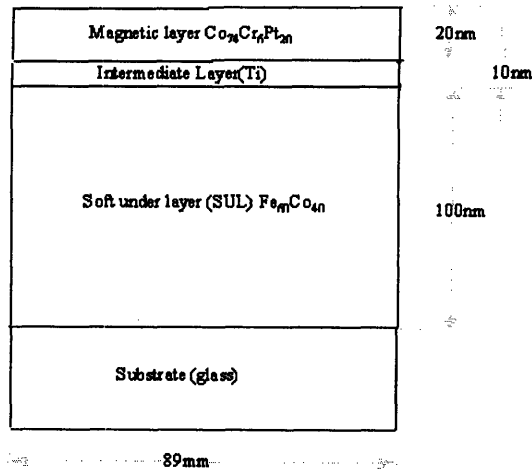
$$\text{Cost of: 1 disk (conventional)} + \text{head} \geq \text{Cost of patterning} \text{-----} 3$$

Equation 3 will be the fundamental equation by which technologically viable methods to achieve the bit patterning is evaluated.

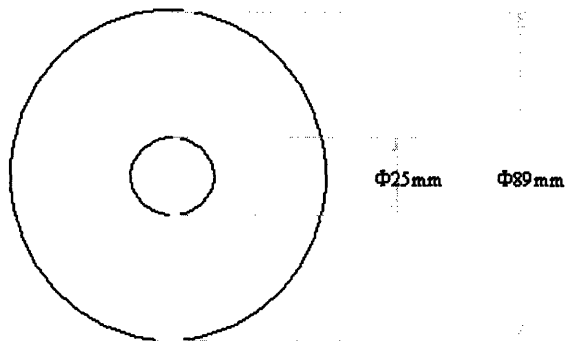
Here the 3 probable technology paths. Nanoimprint Lithography, EUV lithography and Guided Self assembly are evaluated.

**4.2.1. Calculation of the LHS of equation 3:**

3.5-inch form factor is used for the analysis. To calculate the disk cost, a simplified disk structure is taken and is shown in figure 27. The top view is shown in figure 28.



**Figure 27:** A simplified disk structure taken in cross section. The dimensions are not to scale.



**Figure 28:** Plan view of the Hard disk 3.5-inch form factor. Not drawn to scale.

Volumes associated with each layer:

Soft under layer is-----  $5.7 \times 10^{-10} \text{ m}^3$

Intermediate layer is-----  $5.7 \times 10^{-10} \text{ m}^3$

Magnetic layer is-----  $1.14 \times 10^{-10} \text{ m}^3$

The net cost for production of disk calculated using the formula:

**Cost = Material cost + Machinery cost depreciated over a year + other costs like labor, building, electricity.** -----4

**4.2.1.1 Estimation of Material cost:**

Material properties:

S No:	Element	Atomic weight (g/mol)	Density (kg/m <sup>3</sup> )	Molar Volume (m <sup>3</sup> /mol)
1	Fe	56	7874	$7.1 \times 10^{-6}$
2	Co	59	8900	$6.6 \times 10^{-6}$
3	Ti	48	4500	$1.06 \times 10^{-5}$
4	Cr	52	7150	$7.28 \times 10^{-6}$
5	Pt	195	21450	$9.09 \times 10^{-6}$

Costs of sputtering obtained from sputter target value.

S No:	Element	Price (\$/mol)
1	Fe	139
2	Co	4
3	Ti	3.77
4	Cr	8222
5	Pt	451609

Using the values the sputtered material costs are presented below.

S No:	Layer	Material cost/disk after sputtering (\$)
1	SUL	$7 \times 10^{-3}$
2	IL	$2.2 \times 10^{-5}$
3	Magnetic Layer	1.45

Substrate cost is estimated from polished glass selling at 3dollars/ sq foot.

The cost of substrate is thus \$0.2

Thus net material cost = Cost of substrate + cost of sputtered materials

$$\equiv \quad \$0.2 + \$1.45 = \$1.65 \text{-----}5$$

#### 4.2.1.2 Calculation of Machinery depreciation:

Assuming one sputter machine processes 13 disks at a time and entire operation lasts for a minute, the throughput is estimated as 13 disks/min. Assuming again 20hr/day production and 320 days/year schedule, the sputter system throughput is 4,992,000 disks/year.

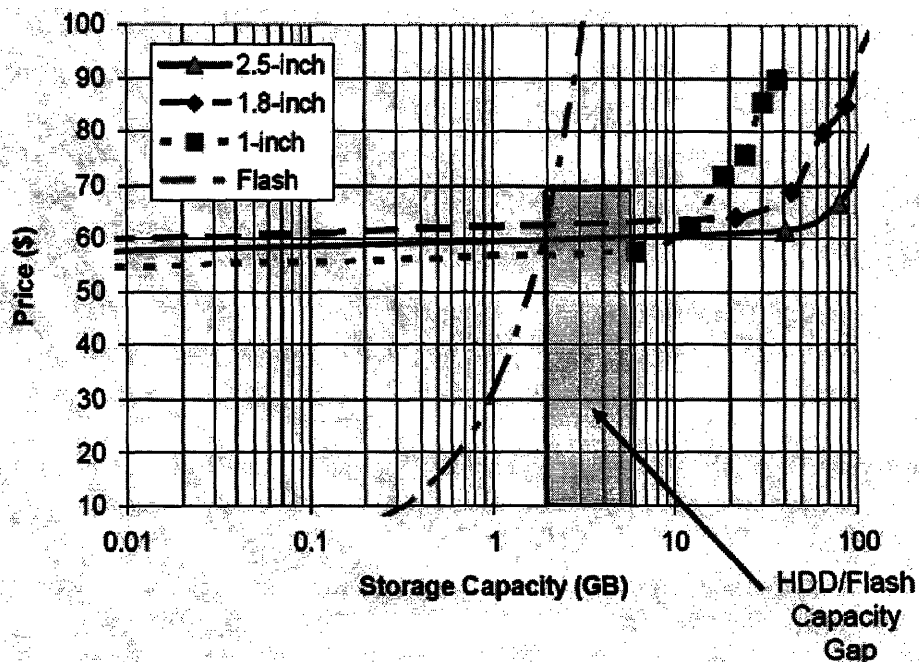
The sputtering machine cost is taken as \$1,500,000. And its use is assumed to be for 5 yrs. Thus the depreciation accounted/disk is \$0.06-----6

Using values 5 and 6 in equation 4, and taking the other fixed cost and variable costs as not of great significance, price of disk=\$ 1.75

The first variable of the LHS equation, Disk price is estimated as \$1.75

#### 4.2.1.3 Estimation of Price of head:

For estimate of the cost of hard disk head, a estimate is made from the figure earlier shown in market analysis and is represented here again as figure 29.



**Figure 29:** Price as a function of storage capacity per unit shipped for various form factors as well as for flash memory.

The flat region corresponds to the region where hard disk decrease of capacity comes just from plate area. The increasing price region corresponds to additional plates and corresponding heads added to increase the capacity. The point on the edge of the flat region corresponds to maximum storage capacity a plate can accomplish with that form factor. This thus corresponds to a disk with one plate and one head.

Using the graph to locate a point of double this capacity will yield a disk with two plates and 2 heads. As the packing costs will not vary significantly, all other components are

expected to be same and assuming the same profit margin irrespective of storage size. We get the difference in price between the 2 values as the cost of 1 disk and 1 head.

Using this estimate the price of head is found to be roughly \$ 4.25.

Thus using the both values the LHS of equation 3 is estimated as \$6.

Thus a patterning process that can be accomplished at less than \$6/disk is an economically viable route for patterned media.

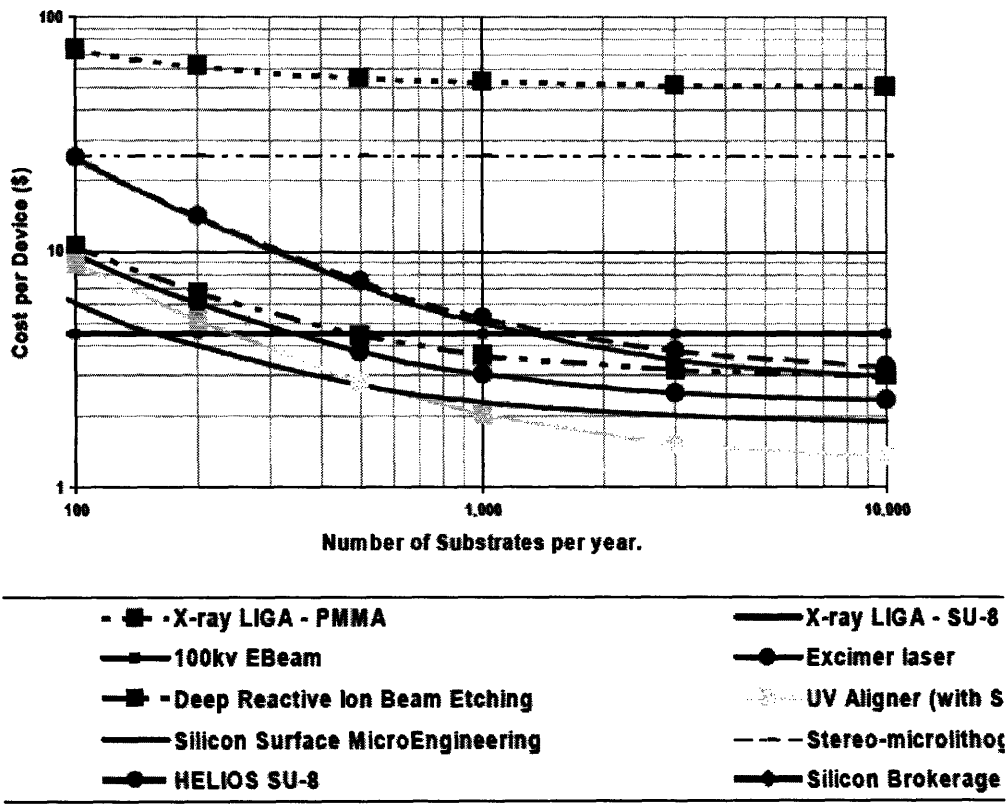
### **4.3. Case studies**

#### **4.3.1. EUV lithography:**

After the plate is made from conventional sputter process, it will have to be covered with resist, masked and then finally etched. These additional steps will decrease the throughput of the disks. Taking a 100nm/min etch rate will lead to about 1 minute additional time after the sputtering process. Assuming a minute for resist coating and exposure time implies 13 disks are created now every 3 minutes (the end of patterning process). The throughput then is 1,664,000 disks/year.

The fixed machinery for EUV lithography is estimated to be between \$50-\$65 million dollars. The depreciation over 5yrs again leads to a cost of between \$6-\$7.8/ disk

The RIE etch is estimated to cost about \$3 per disk, this is an estimate from figure 30.



**Figure 30:** Cost associated with different processes. The value of DRIE is of importance for this cost model. The value saturates to about \$3 for high volumes.

Thus the net cost for patterning is estimated to be greater than \$9 per disk. This is much more than the magic figure of 6\$ required for patterning. The economic viability fails under the worst case scenario. This means that a low gain of areal density is unlikely to make this product economically viable. Only if the areal density gain such that it compensates for 3 plates or more can it be economically viable. This would mean an areal density of greater than 1Tb/in<sup>2</sup> (since areal density of 400Gb/in<sup>2</sup> has been demonstrated at laboratory using the current continuous media technology) and this would require dimensions less than 12.5 nm. This is much smaller than the expected minimum dimension of 20nm as discussed in technology associated with EUV lithography. The EUV lithography doesn't seem an economically viable scheme to implement patterned bit storage.

#### 4.3.2. Nanoimprint Lithography (NIL):

Refer figure from the technology discussion regarding the process schematic for NIL.

The throughput will be again lower cause of additional steps involved. Taking again an etch rate of a minute and about another 2 minutes to the stamping process, 13 disks are produced every 4 minutes. The throughput is now about 1,200,000 disks per year.

The equipment for NIL is extremely cheap and a state of art NIL stamping machine is expected to be not more than \$500,000. The initial master created would cost around \$100,000, but daughters can be inexpensively stamped using NIL and these used for patterning. The master is thus expected to last the entire year of stamping and thus its depreciated value for a year added to the cost/disk and costs about \$ 0.1/disk.

Assuming the technology gets outdated every year, the depreciation is taken for 1 year instead of 5 years as in other machinery. This leads to a cost of \$0.4 per disk.

A resist like PMMA is available at roughly \$3/kg and thus doesn't add too much to the cost. The RIE etch again contributes to roughly \$3/disk.

Thus the patterning cost would be of the order of \$3.5/disk and thus encouragingly below the value of \$6/disk required.

Patterned media is economically feasible if Nanoimprint lithography is used. Even in worst case performance it makes great economic sense. The huge margins suggest patterned media using Nanoimprint lithography can be expected in the very near future.

#### 4.3.3. Guided Self Assembly:

The schematic is shown below.

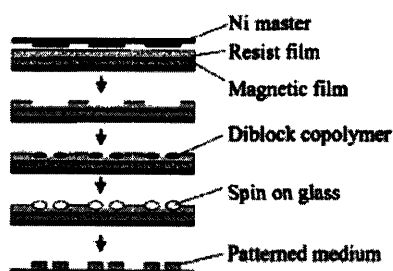


Figure 5: Schematic for preparation of patterned media using guided self assembly

The diblock polymer comprises of PMMA and PS. PMMA sells for \$3/kg and PS for about \$1.4/kg. The material cost associated is thus negligible. The cost associated will arise from the master, and etch required. Using the same value as for RIE etch leads to \$3 for etch per disk.

A self assembly by diblock copolymer is expected to take some time. But we assume a large number can be processed in parallel. Thus the time step will essential arise cause of patterning.

Thus 13 sputtered disks would now be patterned and completed every 2 minutes. The throughput is thus 2,496,000 disks per year. Using the same arguments as for NIL for the master the cost/disk from the master is about \$0.05

The net cost associated will thus be lesser than \$3.5/disk. The economic viability of this scheme follows the same arguments as NIL. And the arguments advanced hold for this too.



## 5. IP Analysis:

The industry doesn't derive a market share or drive a business model based on IP. Cross licensing is quite common and innovation is swiftly carried across the whole industry. The design associated with the hard disks is standardized and each player operates with a variant of the same design scheme. The innovation and design patents are never so far downstream that they require all the players to solely dependent on one particular scheme to do things. The same arguments can be extended to the case of bit patterned media.

Each of the players does research in this field cause of the huge potential to extend the areal density much beyond the conventional limits. The patents are equally spread over the media and components. Most of the patents are different variations of the same scheme of doing things. There exist multiple patents for self assembled media, scheme to read and write etc.

A search of the relevant patents in bit patterned media show up the distribution of them among the major players.

Seagate: 17

Hitachi: 16

Maxtor: 4

IBM: 4

Toshiba: 2

Fujitsu: 5

Samsung: 3

Few of the patents are valuable, since they talk about a way to go about implementation of the hard disk once patterning is achieved.

Example :Patterned media magnetic recording disk drive with timing of write pulses by sensing the patterned media

[US patent 6754017](#)

Assigned to Hitachi GST.

Talks about using the patterned bit as source for clock signal for write head and synchronisation of write pulse to precisely time on to the block intended to be written.

Some of the patents assigned based on the company is listed below.

Hitachi (US Patents):

7,097,924 Magnetic recording media and method of forming them

6,773,764 Method of forming a patterned magnetic recording medium

6,754,017 Patterned media magnetic recording disk drive with timing of write pulses by sensing the patterned media

Seagate (US patents):

7,041,394 Magnetic recording media having self organized magnetic arrays

6,999,279 Perpendicular patterned magnetic media

6,501,606 Fly height control for a read/write head over patterned media

A patterning technology is not expected to be solely developed by any one player, but will be the result of various fundamental researches at universities and research laboratories. For corporate players it is better to focus on research that will implement them via a viable manufacturing or design scheme. Any IP in this direction will provide the player with a tremendous advantage of being the first mover in this bit patterned media market.

## **6. Conclusions:**

Bit patterned media is expected to be commercially and technologically viable scheme. The report predicts the technology break-through to occur via Nanoimprint or Guided self assembly approach. Most of the research however is at a fundamentally research related phase. Even in Nanoimprint lithography basic questions of pattern fidelity and durability of the mold haven't been worked out. However this is the most mature of the possible technologies, with a couple of start up firms in operation. Any company planning to commercialize on this technology will be better equipped to be the first mover, if it takes the initiative to work out the design and non-feature size dependent issues, like for e.g. a scheme of synchronization of the head to patterned bits, or issues related to tribology. Other technology related to patterning can be licensed as and when it becomes commercially available.

A new start up is better poised to take advantage by segmenting and positioning their product. This would mean working out an innovation and expertise in certain specific application or function of hard disk, for e.g. a way to make a lower power consuming hard disk. The solution of this may lie in a clever scheme of how information is stored or retrieved or integration with other devices leading to devices like the hybrid drive.

This sort of targeting and expertise development is a barrier to entry for other players. There are numerous examples for this sort of model and is illustrated by how ARM lower power processors find applications to compete even with big players like INTEL existing in an established market.

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