

Patterned Media Towards Nano-bit Magnetic Recording: Fabrication and Challenges

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Abstract: During the past decade, magnetic recording density of HDD has doubled almost every 18 months. To keep increasing the recording density, there is a need to make the small bits thermally stable. The most recent method using perpendicular recording media (PMR) will lose its fuel in a few years time and alternatives are sought. Patterned media, where the bits are magnetically separated from each other, offer the possibility to solve many issues encountered by PMR technology. However, implementation of patterned media would involve developing processing methods which offer high resolution (small bits), regular patterns, and high density. All these need to be achieved without sacrificing a high throughput and low cost. In this article, we review some of the ideas that have been proposed in this subject. However, the focus of the paper is on nano-imprint lithography (NIL) as it fulfills most of the needs of HDD as compared to conventional lithography using electron beam, EUV or X-Rays. The latest development of NIL and related technologies and their future prospects for patterned media are also discussed.

Keywords: Media, magnetic recordings, lithography method, hard disk drives (HDD), signal-to-noise ratio (SNR), nano fabrication, conventional, lithography, optical lithography, X-rays, nano-imprint lithography.

I. INTRODUCTION

Data storage technology using hard disk drives is one of the few areas where nanotechnology is commercially used without the usual hype associated with the term nanotechnology. For any technology to be truly qualified to be called "nanotechnology" it has to meet two requirements; (i) the feature size involved in the technology has to be smaller than 100 nm. (ii) New phenomenon should be observed when the miniaturization (shrinking the feature size below 100 nm) occurs. Quite often, the term nanotechnology is freely used without satisfying the above-mentioned requirements. However, in hard disk drives (and probably in some other areas), nanotechnology has been applied for a long time without the mention of the term. For example, in the read sensors of hard disk drives, thin magnetic and non-magnetic layers of a few atomic planes play a significant role in improving the read-out performance. Thin layers (even below 1 nm) have been introduced to cause changes in the way the magnetic orientations occur. In the recording media of hard disk drives, grains as small as 7-8 nm are used to store data at high signal-to-noise ratio (SNR) [1]. In future, even smaller grains will be needed to store data at much higher areal densities [2]. However, when the grain sizes get smaller, a phenomenon called superparamagnetism (to be explained later) would set in and the data might be lost [3]. To overcome this problem, perpendicular recording technology is considered as an alternative to the current longitudinal recording technology [4]. Although perpendicular recording technology is a recent technology, it is expected to be useful only for 5-10 more years from now (with areal densities as high as 600 Gb/in²). Extending the data storage capacities provided by HDDs beyond this period without

compromising the price advantage would involve finding alternative ways to store information. One potential way to extend the technology beyond 600 Gb/in² is to modify the way of storing information. Instead of using many small grains to store information, magnetic units that are perfectly patterned can be used to store information. Such a transition to patterned recording media technology would help to store more information in a given area than the existing methods. Therefore, various researchers have looked at ways to pattern the magnetic units in the last one decade. The objective of this paper is to review these developments in a systematic way.

The paper is aimed at audience with wide backgrounds, as nanotechnology is a term that excites researchers in all fields. Therefore, it is assumed that some readers may not be familiar with data storage and hence the paper is organized in the following way. Section II briefly provides an overview of the data storage principles and recording media using the current technology. Section III introduces the problems faced by the current technology and the potential methods to overcome the problem. Section IV introduces existing lithography methods for patterning the magnetic nano-structures. Sections V is dedicated to methods that show promise towards making high-density data storage possible. Section VI describes some methods that are unique for magnetic nano-structures only. Section VII summarizes the paper with current and future developments.

II. OVERVIEW OF MAGNETIC RECORDING AND RECORDING MEDIUM

Magnetic recording was demonstrated more than 100 years ago [5] and it is based on two simple principles; (i) magnets produce a magnetic field at the poles. This field can be used for reading information. (ii) The polarity of the magnets in the recording can be changed by applying

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external fields, which can preferably be generated by electromagnets by changing the direction of current in the coil. This provides a possibility of writing information. Tape-based magnetic recording was introduced about 70 years back. Hard disk drives (HDD) were introduced fifty years back and they revolutionized the world of data storage. The first generation hard disk drives were expensive and big, but pioneered the random access feature for the main frame computers of that era that helped to speed up the storage and reading of information. The hard disk drives improved better with time and entered the personal computers in the 1980s. Quite recently, HDDs are also being commonly used in consumer electronics applications. MP3 players, video recorders, video cameras, game consoles and many other devices are using HDDs to store information. Compared to RAMAC (Random Access Method of Accounting and Control), the first ever hard disk drive with a storage density of 2 kb/in², the capacity of current hard disks at 700 GB with an areal density (bits per unit area) of about 130 Gb/in² represents an increase in the areal density by about 65 million times. The increase of areal density peaked at about 100% per year, and has fallen back to around 30% per year recently as shown in Fig. (1). Such an increase in the areal density helps the user to buy storage at cheaper cost for every GB. This increase in the areal density also helps to miniaturize HDD for consumer electronic devices (e.g., iPod) without sacrificing the high-capacity requirement.

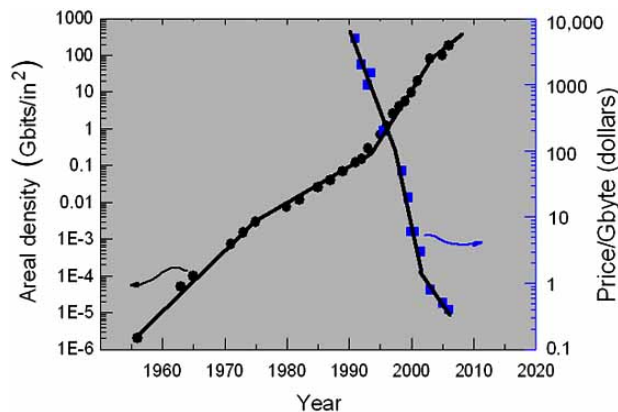


Fig. (1). Evolution of areal density and price per Gigabyte of magnetic HDD with time. The introduction of the first magnetoresistive (MR) and giant magnetoresistive (GMR) heads besides antiferromagnetically coupled media in 1991, 1997 and 2001 respectively contributed to this performance.

Although, the hard disk drive has been around for 50 years, the basic technology behind data storage has remained the same. The HDD has a recording medium (based on magnetic materials) to store information and a head to read and write information. There are also other electronic and mechanical devices to facilitate these basic functions. While the basic structure has remained the same, there has been tremendous progress in the technology associated with each component and process, which led to increased storage densities. Until now, the HDDs used longitudinal recording technology to store information. In longitudinal recording technology, the magnetizations that lie longitudinally

(parallel to the disk surface) are used for storing information. The recording media consists of thin films of several layers (as in Fig. 2), sputtered onto a substrate, out of which one or a few layers will be magnetic. Typical substrate materials are Al alloys or glass, which can vary in thickness from 0.35 mm to 2mm. It can also be noticed from the figure that the magnetic layer that stores the information consists of several grains. These grains have random orientations of crystal planes with respect to the substrate and also with respect to the track^a of a recording medium. This randomness indicates that the polarity of the magnetizations that is used for storing information is also randomly aligned. Therefore, one grain cannot be used for storing information and we need to rely on a group of grains to store information. It has been pointed out that the signal-to-noise ratio (SNR) is proportional to the number of grains (N) that can be accommodated within the area allocated for a given bit. Bits can be read reliably when the SNR is high, which leads to the conclusion that the number of grains in the given bit area has to be increased.

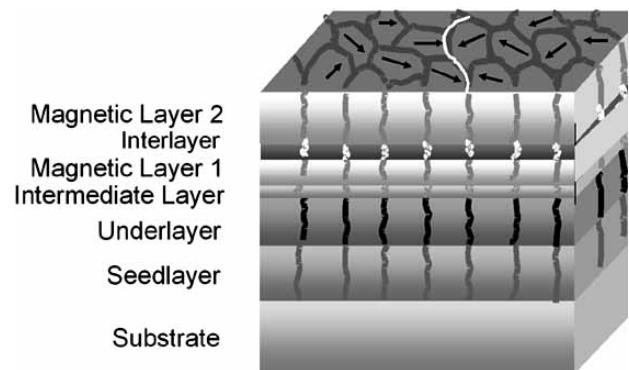


Fig. (2). Illustration of different layers and granular nature of longitudinal magnetic recording medium. The medium may be composed of two or ferromagnetic layer separated by a non-magnetic interlayers. The medium also may have seedlayer, underlayer and intermediate layer to achieve better performance.

The number of grains per unit area could be increased by reducing the size of the grains. Therefore, recording media researchers always look at ways to reduce the grain size and the grain size distribution in order to accommodate more grains in a small area. In current technology, the average grain diameter is around 7 nm, which is much below 100 nm to qualify for “nanotechnology”. In addition, when the grain size of the recording media material (such as a Co grain) is below 30 nm, the switching mechanism of the grain will change from domain wall motion to single-domain switching. This change of behavior is also a feature desired for high-density recording, which meets the second requirement for the term “nanotechnology”. In hard disk media, these changes have occurred more than a decade back.

^a In hard disk drives, the information is stored in many circular tracks in contrast to optical storage devices, where the information is stored in a spiral track that runs from outer diameter to inner diameter.

III. THERMAL STABILITY LIMIT AND METHODS TO OVERCOME

As discussed in the previous section, reduction in the grain size is one key requirement towards high-density data storage. In addition, thickness of the films used for storing information has also undergone a significant reduction compared to the media from the past, in order to improve the performance. These reductions imply that the volume of the grains (V) that help to store the information will be reduced while improving the performance of the recording device. In magnetic recording, the anisotropy energy $K_u V$ (product of anisotropy constant, K_u and volume V of the grain) helps to maintain the magnetization in one particular direction. If $K_u V$ is high, the energy barrier for the magnetization to switch from one direction to the opposite is larger, which makes hard disk drives “non-volatile” (data will be stored even if the power is off). However, with the reduction in the grain size, $K_u V$ will also be reduced (if K_u of the material used is constant). Therefore, the energy barrier of the magnetization will reduce when the areal density moves up. When the $K_u V$ gets smaller, the thermal energy $k_B T$ (k_B is Boltzmann’s constant and T is the temperature, $T > 300$ K in most of the HDD) starts competing with $K_u V$. Because of such a competition of energies, the bits are stable for about 10 years, only when the thermal stability factor $K_u V/k_B T$ is larger than 60. Therefore, in order to maintain $K_u V/k_B T$ to be around 60 in a scenario where V needs to be decreased, alternative materials with high K_u can be used. There are several materials that can provide a higher K_u than the materials used in current recording media. But, high K_u implies that higher writing field is needed, as the switching field, H_c , of a material is proportional to K_u and inversely proportional to the saturation magnetization M_s of the recording medium (for a single particle, $H_c = 2K_u/M_s$). The writing field that can be produced by a head is limited, to some extent, by the saturation magnetization (M_s) of the material used in the head. The highest M_s that is exhibited by any known material is around 1910 emu/cc. Therefore, this

places a restriction in the writing field and the value of K_u of the material that is used for recording application. Because of these limitations, it is believed that the longitudinal recording, which has been the dominant technology for the past 50 years, is expected to be phased out in a year or two.

Perpendicular recording technology, which has been a research topic for the past 3 decades, has got its limelight in the past 5 years because of the thermal stability limitations of longitudinal recording. Longitudinal recording technology uses the fringing field from the pole gaps of a head (see Fig. 3), and fringing field is always smaller than the gap field. On the other hand, perpendicular recording technology could use gap field because of the combination of soft magnetic underlayer and a single-pole-head. Therefore, in perpendicular recording technology, materials with higher K_u (roughly, by a factor of 2 in comparison to longitudinal recording) can be used. Because of such potential, perpendicular recording technology was keenly researched in the recent past and significant progress was made [6,7]. Hard disk drives with perpendicular recording technology have been recently released [8]. The media used in such drives are based on CoCrPt alloys with some oxide materials such as SiO_2 . The oxide material is formed at the grain boundary due to the presence of oxygen in the target and oxygen used during the sputtering process. Grain sizes of about 6.4 nm have been reported [9]. It is estimated that the perpendicular recording technology with CoCrPt:Oxide media may last up to an areal density of about 600 Gb/in², which may be demonstrated in 2-3 years time. It is believed that products using perpendicular recording technology could be made until 2011 or so. In order to extend the life of magnetic recording, alternative technologies are needed, beyond the conventional perpendicular magnetic recording. One such alternative is heat-assisted perpendicular magnetic recording. In this technology, the magnetic material is heated during the writing process. The heating leads to a reduction in the coercivity of the material, at which point, the existing head material may be able to write information on a high coercive

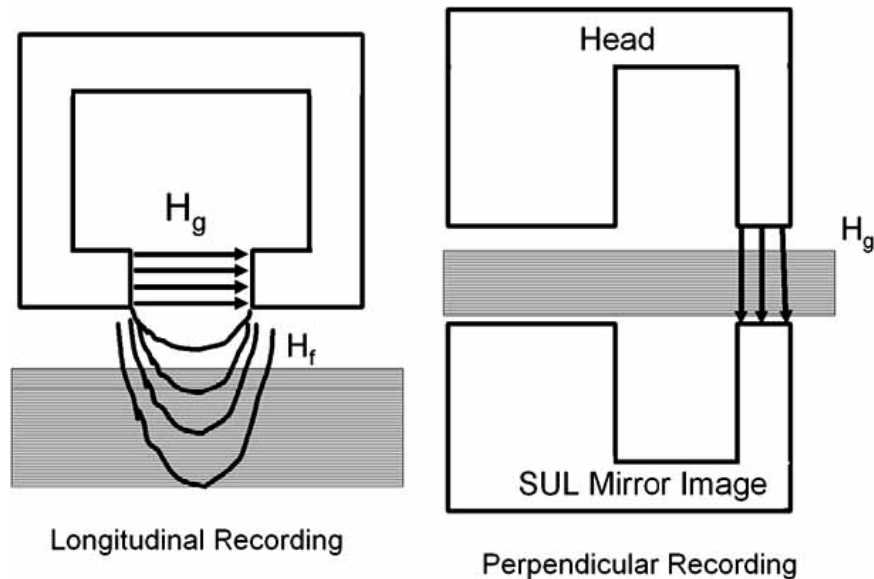


Fig. (3). Comparison between the writing process of longitudinal and perpendicular magnetic recording. The shaded region is the magnetic recording medium.

material. There are also several other techniques proposed, such as tilted magnetic recording, exchange-coupled composite (ECC) media to overcome the writing issues. All these methods rely on increasing the K_u of the material, to keep reducing the volume of the grains in order to maintain $K_u V/k_B T$. However, the field that is required to switch the grains is reduced in these designs, because of the tilted easy axis orientation (tilted media) or because of the use of a softer layer (ECC media). However, there are no practical designs for tilted media and research on ECC media is still under progress.

An alternative method that has been considered for about a decade now is patterned recording medium. This method relies on increasing the volume of the magnetic entities, to increase $K_u V/k_B T$ in order to make the bits stable. Increase of V (by the increase of grain diameter) would increase the noise and broaden the bit boundary in the conventional magnetic recording, which uses many grains to store information as illustrated in Fig. (4). If the bit boundary is broad, the bits cannot be packed closely. Moreover, in the conventional recording, the bit boundary is determined by the grain boundary which causes randomness in the bit

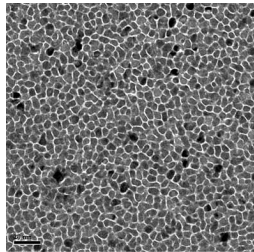


Fig. (4). TEM image of a granular perpendicular recording medium. The grains are separated from each other by a thin oxide region. (Black lines illustrate the bit boundary)

positions (called transition jitter). On the other hand, if the magnetic entities are perfectly patterned and isolated from each other, the bit boundary is the isolating space and the jitter can be reduced. Another major difference between conventional and patterned media recording schemes is that, in conventional media, the SNR will decrease if the track width is reduced. On the other hand, in patterned media, the SNR does not change even if the track width is reduced. This can help in achieving high track density, which will in turn help to increase the areal density. The isolation of magnetic entities could be achieved by physical spacing or by using non-magnetic material. This is the concept of patterned media. For example, for 500 Gb/in² recording, in the conventional method that relies on many grains, about 30 grains or more with a diameter of about 5 nm would be needed. However, in the case of patterned recording medium, magnetic entities of 17 nm x 17 nm could be used for storing the same amount of information (See Fig. 5). For the same kind of thickness and anisotropy, the 17 nm x 17 nm entities would be more stable than the 5 nm grains. This is the advantage of patterned media recording in terms of thermal stability.

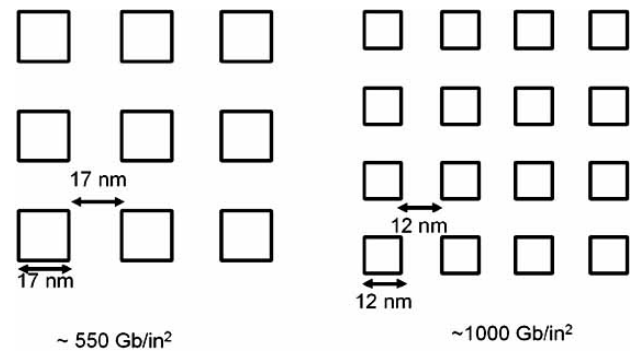


Fig. (5). Schematic representation of the bits size and spacing for 550 and 1000 Gb/in² respectively.

The concept of patterned media recording has been around for more than 10 years [10]. S. Chou *et al.* also proposed making of patterned media by nano-imprint lithography [11]. Since then, several researchers have looked at patterned media. Excellent reviews of research papers on patterned media are provided by Ross and Terris *et al.* [12,13]. This report differs from the previous reviews in the sense that this report places more emphasis on the patents, rather than the research papers. Compared to 1994, when patterned media was proposed by Chou *et al.*, the need for patterned media is stronger now than ever before. This is because, the current perpendicular recording technology may lose its steam in about 3 years and the demonstration of a technology that can help to achieve densities higher than Tb/in² (terabits/square inch) is sought. To continue the areal density growth of HDD at a modest rate of 20-30%/year, patterned media technology should be able to achieve more than 600 Gb/in² by the end of 2008. Therefore, efforts have been intensified by various organizations at this point of time. It can be noticed from the figure that the achievement of areal densities higher than 600 Gb/in² from patterned media technology would require features that are as small as 15 nm, which is a significantly aggressive target as compared to that of the semiconductor processing. At this time, it is not clear if the areal density can be achieved in time or if the areal density growth would be slowed down. However, efforts are being made to achieve improvements in patterned media technology. In the subsequent sections, the efforts on lithography or other methods to make patterned media are described.

IV. NANO-FABRICATION TECHNIQUES

1. Introduction

The success of HDD to extend its application beyond computers to other consumer areas served earlier only by semiconductor technology, is mainly due to the increase of recording capacity while keeping the price per byte low. As discussed earlier in section 3, for higher recording density, the bits may have to be patterned. In that case, the main target should not only be the resolution (size of the bit) but also the throughput, the media surface smoothness and the low cost to quote only few. In this regard, the nano-fabrication process for patterning magnetic media has to be

carefully chosen; otherwise, the advantage of HDD compared to other types of memory will no longer be valid.

Conventional lithography is based on a chemical change of a photoresist by different sources of energy such as laser, particles (electrons, ions, protons) or X-ray radiation. After development of the resist, patterns can be transferred into substrate by dry or wet etching. Nano-imprint lithography is different from conventional lithography and the transfer of patterns is made by physical deformation of the resist. In this section we review the most commonly used techniques for patterning nano-structures. Some of these techniques have been combined or modified to fulfill patterned media requirements and even new methods beyond the current lithography might be necessary.

2. Optical lithography

Optical lithography has been widely used for patterning sub-micrometer features. Its extension to below 100 nm resolution is facing the physical diffraction limit. The resolution (minimum resolvable feature) R is given by the following expression (Rayleigh's Law):

$$R = k \cdot \lambda / NA \tag{1}$$

where λ is the wavelength, NA is the numerical aperture of the optical system, and k is a constant that depend on the resist material and process technology.

Currently, the use of deep UV with 157 nm and high numerical aperture lenses has allowed the reduction of optical resolution to slightly below 100 nm, far from the requirement of 12 nm features for 1 Tbits/in². It is worthy to note that optical interference lithography is another alternative, which has been used for patterned media [13-15]. Interference lithography (IL) is a suitable method for fabricating periodic patterns that is spatially coherent over large areas. It is a simple process where two coherent beams interfere to produce a standing wave, which can be recorded in a photoresist as described in Fig. (6). In this method, there is no need for mask as required for most of the lithography techniques. The spatial-period of the grating can be as low as half the wavelength of the interfering light with an ultimate features size of $\lambda/4$ [16].

As a logical extension of optical lithography, extreme UV (EUV) with 13.5 nm wavelengths has been considered as one candidate for next generation lithography. Unfortunately, EUV light is strongly absorbed by solid-state materials and even absorbed by air. Beside long-term stability source, the most difficult technological challenge for EUV is a special reflective mask, with tens of layers of reflective coatings each [17-19]. More recently, Solak *et al.* developed EUV interference lithography for the production of periodic nano-structures with resolution below 20 nm [20]. Although conventional interference lithography technique is useful where line, square or rectangular patterns are needed, it is not suitable for recording media applications where circular disks are used for storing information. To overcome this problem, transmission diffraction grating was used to create circular beams [21]. For example, diffracted

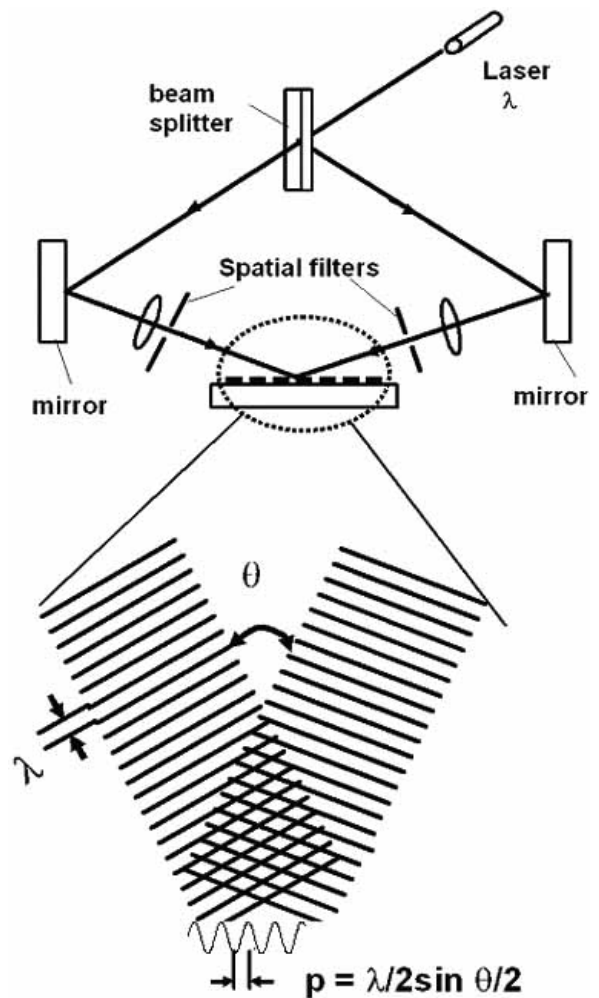


Fig. (6). Principle of optical interference lithography: two coherent beams interfere to produce a standing wave with half-wavelength periodicity.

beams from three distinct grating regions coincide and form a two-dimensional pattern with intensity peaks periodically positioned along circular tracks. However, in the work presented in ref. 21, the resolution was not high as the authors targeted only the feasibility of this method.

3. Electron-Beam Lithography

Electron beam lithography (EBL) has been widely used for nano-devices fabrication due to its high-resolution capabilities and it remains the most reliable technique for sub-100 nm feature sizes. The wavelength for charge particles, such as electrons and ions can be calculated using the expression:

$$\lambda = \frac{h}{\sqrt{mE/2}} \tag{2}$$

where h is Planck constant, m is the mass, and E is the energy of the charge particle such as electron, ions, or protons.

For example the wavelength for 100 keV electron beam is about 4×10^{-3} nm, which it is reduced to 5×10^{-5} nm for 100 keV helium ion beam. The higher the mass and the energy of the particle, the shorter is the wavelength. Instead of being diffraction limited, the EBL or ion beam lithography tools are limited by the aberration of the optical design. Besides, the capability of EBL tools, the resist coating and development conditions are also key factors for improving the resolution. Under optimal conditions, such as electron beam current, resist composition, thickness and others, it is possible to achieve a resolution better than 20 nm.

However, since EBL is a serial writing method, it is a slow process and as such can not be used for patterning large area like magnetic disk that is several inches in diameter. It is worthy to note that EBL is commonly used for magnetic read head fabrication and only for critical features. However, in read head fabrication, wafers of 6'' diameter are used and each wafer contains between 20 to 30 thousands devices which are processed at the same time. Therefore, the cost of each device can be lower. The case of media is different because a disk with whole stack of layers can be deposited by sputtering at an average rate of 4 seconds per disk. However, patterning a one-inch disk with 20 nm dots size and 20 nm separations, will require about one week. Therefore, EBL is not a practical solution for patterned media.

To increase the throughput of EBL, the projection EBL has been proposed. It differs from traditional "direct-write-method" electron-beam exposure in the sense that patterns on the mask are demagnified and projected onto a wafer while being scanned in the same way as optical scanning steppers [22-24]. In operation, electron beam is fired through a wide mask with zones having different atomic weights. Areas of heavier material cause the electrons to scatter backwards away from the wafer surface, while more transparent sections pass the electrons through to image the mask on the resist. In projection EBL, the over-heat of the mask makes limitation to the acceleration voltage that can be used. In late 1980's a program initiated at Bell Labs, called SCALPEL (SCattering with Angular Limitation Projection Electron-Beam Lithography), aimed to solved the above mentioned issue and to increase the resolution [25]. The electrons that pass through the thin membrane (low atomic number) are scattered weakly, while the electrons that pass through the higher atomic number material are scattered more strongly. The scattered and non-scattered electrons pass through a series of magnetic lenses, which redirect the electrons to an aperture with a small central hole. Only non-scattered electrons can pass to a second set of magnetic lenses before reaching the resist deposited on the substrate to be patterned. By this way a high contrast image can be achieved. Also since a little of the incident energy is actually absorbed by the mask the over-heat of the mask can be reduced.

Projection EBL and ion beam lithography are also included in semiconductor roadmap as next generation lithography. For these to be used for patterning magnetic media, it depends on whether both high resolution and throughput can be achieved together. Currently, state-of-the-art electron beam systems can produce linewidths on the order of 20 nm lines and space. It is important to note that

for isolated features it is possible to achieve a resolution even better than 10 nm. The proximity effect, whereby electrons spread to neighboring features, is one major barrier for EBL to achieve high resolution. The practical electron beam resolution limit is determined not only by the beam size but also by forward electrons scattering in the photoresist and secondary electrons travelling in the photoresist thus making the exposed area larger than the targeted one. Using high energy electron and thinner photoresist can reduce the forward electrons scattering. However, secondary electrons are inevitable. It is difficult to have an accurate value of the resolution for a given EBL system since many other factors affect the final features such as resist quality, thickness, development conditions among others. EBL has been used by many researchers for evaluating recording performance and magnetic properties of magnetic nano-dots. For real integration of patterned media in HDD, at least with its current design, it is necessary to position magnetic dots (bits) in circular fashion. In this regards, Komatsu *et al.* used a magnetic recording disk placed on a rotating stage and moving in radial direction during electron beam exposure of the resist [26]. In this way a disk with circular patterns can be obtained.

The lithography methods discussed earlier are suffering from having either limited resolution or low throughput. There is hope that EUV and projection electron or ion beam lithography will become mature technologies and the issues they are facing now will be resolved.

Other alternatives in lithography for patterning magnetic media which are considered promising by the magnetic community are mainly self-assembled nanostructures and nano-imprint lithography. It is also important to consider near field X-rays even though it relies on other technologies such as high-resolution electron beam for mask fabrication. In next section we will discuss separately each of these three methods which might be useful for nano-patterning.

V. PROMISING TECHNIQUES FOR PATTERNED RECORDING MEDIA

1. X-Ray Lithography

Besides EUV, X-ray lithography (XRL) has also been considered as another alternative for conventional optical lithography. With radiation wavelength of 0.2-10 nm, XRL has a great potential and can be extendable to many generations.

In most of XRL, there is no magnification of the image, but with the increasing need for high resolution, XRL is now performed using "bias demagnification". Vladimirsky *et al.* have shown that it is possible to achieve a resolution better than the aperture of the mask in proximity X-rays using Fresnel diffraction [27]. Proximity XRL seems to be a good way for sub-20 nm-resolution, however a tight control of the gap between the mask and sample to be patterned is necessary. Fig. (7) shows the trends in optical lithography including EUV and X-rays.

As source of X-rays, synchrotrons provide a very wide photon radiation spectrum that includes high-power soft X-rays. However, synchrotron facilities are very expensive. More recently, Seres *et al.* have demonstrated that spatially

Towards short wavelength lithography

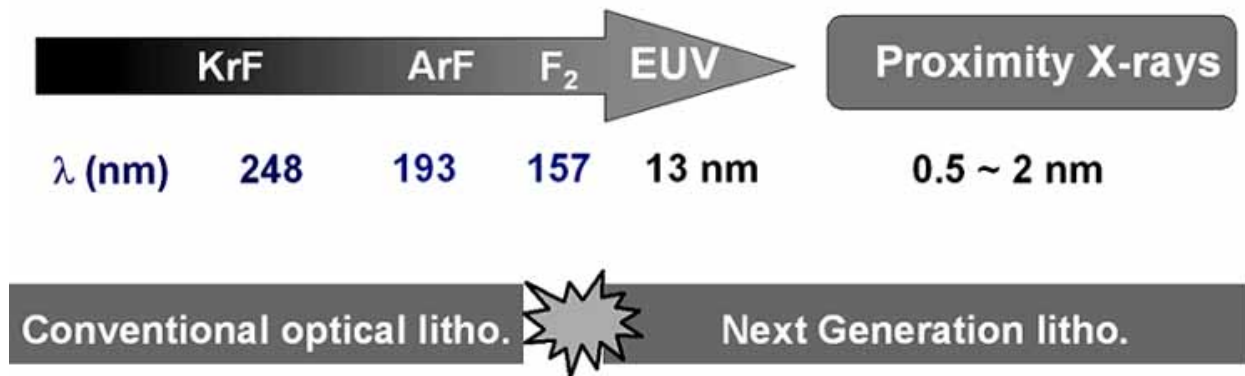


Fig. (7). The trend in optical lithography: smaller wavelength is the path for higher resolution.

coherent X-rays at a wavelength of about 1 nm and energy in the range of keV can be emitted from ionized atoms such as helium by femto-second laser pulse [28]. Laser-produced X-ray technology provides an inexpensive alternative to soft X-ray source, which will bring momentum to XRL.

2. Lithography-Assisted Self-Assembly

A promising alternative route for patterning nano-scale devices is using a template made from self-organized particles. The ordered structure can have a period of only a few nanometers thus surpassing the current lithography resolution. Once the self-organized template is made, it can serve as an etching mask for patterning a magnetic structure or can also be used as a mold for deposition of magnetic structure. This approach, called “bottom-up” offers an alternative approach to conventional “top-down” lithography techniques. For example ionized alumina, which is naturally self-organized, was used as template for patterned media [29-31]. Anodized alumina is a porous film formed by anodizing aluminum in an acid electrolyte to form alumina containing a two dimensional hexagonal array of cylindrical pores [32]. The diameter of the pores can be changed from 4 nm to few hundreds nanometers depending on the anodization conditions. Due to the excellent periodicity of the pores, and the ability to control the pore diameters, alumina films can be used as templates for the fabrication of periodic arrays of nanostructures. In the same manner, self-assembled cylindrical copolymers can be used as a template or a mask for patterning magnetic media [33,34]. It is based on a chain of polymer made of a mixture of two immiscible monomers A and B. After spin coating the substrate with AB polymer and depending on the concentration of each monomer and the substrate surface energy, nanoscale periodic ordering of A and B can be achieved. A selective etching of one monomer will leave a patterned nanostructure on the substrate which can be used as an etch mask or a deposition mask. It is also worthy to note that producing self-assembled magnetic nano-dots of FePt has been intensively investigated for recording media applications. Since the first report by Sun *et al.* on highly mono-dispersed FePt nanoparticles produced by chemical reaction, many researchers investigated different preparation conditions in

order to increase the ordering of these magnetic nanoparticles and to optimize their magnetic properties, especially the L1₀ phase which led to high magnetic anisotropy and consequently to high thermal stability [35-40].

In spite of the several advantages mentioned above, self-assembled lithography suffers from two major drawbacks. One drawback is that the self-ordering of nano-particles is limited to only few hundreds of micrometers. In hard-disk media, ordering is expected over length scales of a few inches. The second drawback is that the arrangement of the particles is in the X-Y direction and not in the circumferential geometry. In hard-disk, it would be preferred to have the dots arranged in a circular fashion as a magnetic head moves on a spinning disk in a circular fashion. Assisted self-ordering can be one solution and it has been demonstrated that EUV interference lithography can lead to the fabrication of large area self-assembled nanoparticles [41]. Nano-imprinting, which will be discussed in next section, has been used to assist the self-ordering of diblock-copolymer film of polystyrene-polymethylmethacrylate (PS-PMMA) over a disk surface [42,43]. Naito *et al.* succeeded in obtaining a hexagonally packed structure with PMMA dot arrays arranged along the imprinted guide directions. The method consists of pressing a Ni master disk, possessing spiral patterns with 60-250 nm width lands and a 400 nm width groove, to a resist film on a magnetic CoCrPt film. A diblock copolymer solution was cast into the grooves obtained. After annealing, self-assembled structures made of nano-dots aligned along the grooves were obtained.

These lithography methods are promising for fabricating highly ordered and uniform nanostructures, if the long-range order of the superlattice can be controlled.

3. Nano-Imprint Lithography

Since 1995, nano-imprint “or embossing” lithography has been investigated by Chou *et al.* [44]. This new type of lithography is based on physical deformation of the resist. Chou *et al.* proposed using this technique to make patterned media.

A lot of interest has been generated by nano-imprint lithography (NIL), which will be discussed in this section as

it has a potential to be implemented in magnetic disk patterning, probably combined with one or more additional steps or processes. NIL is based on deforming the resist by a template (mold) having nano-scale patterns. The advantage of NIL is that once the mold is made by high-resolution lithography tool such EBL, it will take only a short time to pattern a relatively large area. Since NIL has been proposed, there have been many schemes and improvements in almost all process steps. Actually, there are many types of NIL which are based on embossing the resist in different ways. In this section, we will review in detail the two most popular methods, which are thermal NIL and step- and flash NIL.

a. Thermal NIL

The film or substrate to be patterned is spin-coated with a thermoplastic polymer (resist) film, such as PMMA for example. There are two major steps to duplicate nanostructure features from a mold. First the polymer is heated above its glass transition temperature, T_G . At that temperature, the thermoplastic resist becomes viscous and with a relatively high pressure, the desired patterns can be reproduced on the resist. Once the polymer is cooled, a process that takes 10 to 20 minutes, the mold is removed from the resist leaving thus a reverse-shaped texture. The second step is the pattern transfer where reactive ion milling is used to remove the residual resist in the compressed area followed by ion milling to etch the substrate till the desired thickness is reached and finally the resist is completely removed by lift-off. Fig. (8) describes schematically the main steps for thermoplastic nano-imprinting.

To avoid the adhesion of the mold to the resist during the pattern imprinting step, an anti-adhesion layer is deposited between the mold and the resist as proposed in [45,46]. The anti-adhesion layer is formed on the resist by subjecting the mold to a reaction with a fluoroalkyl compound resulting in good anti-adhesion between the mold and resist after embossing process. However it can also be deposited on the mold. Some researchers have focused on the problem of the possible damage of the substrate surface or the break of the mold during the pressure step. Usually a thin residual layer of the imprint polymer is intentionally left between the substrate and the mold (Fig. 8b). For this purpose, the resist thickness is chosen to be slightly thicker than the height of the feature to be duplicated and the remaining resist will be removed by RIE in oxygen plasma. The major problem occurs when there is inhomogeneity of the residual resist thickness, leading to irregularities in the thickness of the final patterns. This can be caused by misalignment of the mold or curled substrate shape for example. To solve this issue, it is preferred to have more than one layer of resist on the substrate. The top one is embossed as described before (Fig. (8)) and serves as mask for the sub-layer which can be made from different materials or even the same material but cured at high temperature (solidified) [47].

One of the problems of thermal NIL is the use of high temperature and pressure to deform the resist. A temperature of about 50 °C above T_G of the resist is needed to soften, and simultaneously a pressure of 40 to 130 atm. has to be applied. In addition to the time needed for heating and

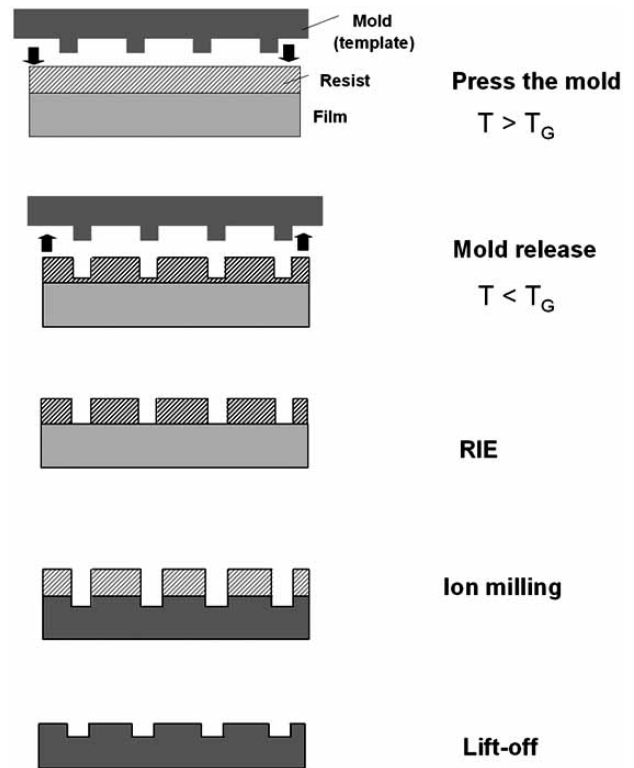


Fig. (8). Thermal nano-imprint lithography: First, the mold is pressed to the resist using high temperature and pressure. After cooling, the mold is released; a reactive ion etching is conducted to remove the remaining resist, followed by ion milling to the desired thickness and lift-off to remove completely the resist.

cooling the resist, there is also concern about the high temperature and pressure effects like thermal expansion and deformation. To overcome these issues, new methods for nano-imprinting have been proposed. The most commonly used is step and flash NIL.

b. Step and flash NIL (SF-NIL)

It is another type of NIL proposed by Wilson *et al.* [48]. SF-NIL uses resist (monomer) with low viscosity at room temperature, which is dropped and not spin coated on a planarization layer deposited on the substrate to be patterned. The monomer liquid spreads and fills the mold feature before being polymerized by UV light (halogen lamp for example).

The main steps in the process flow for SF-NIL are described schematically in Fig. (9). The advantage of SF-NIL compared to thermal-NIL is that neither high pressure nor high temperature is needed [49-51]. The process can be done at room temperature and in just one laser shine to solidify the resist. Furthermore, since the resist initially is viscous at room temperature it will fill up the mold features with low pressure thus avoiding damage.

Most of the schemes that have been proposed to improve the efficiency of conventional thermal NIL were also beneficial to SF-NIL. These inventions are related to mask

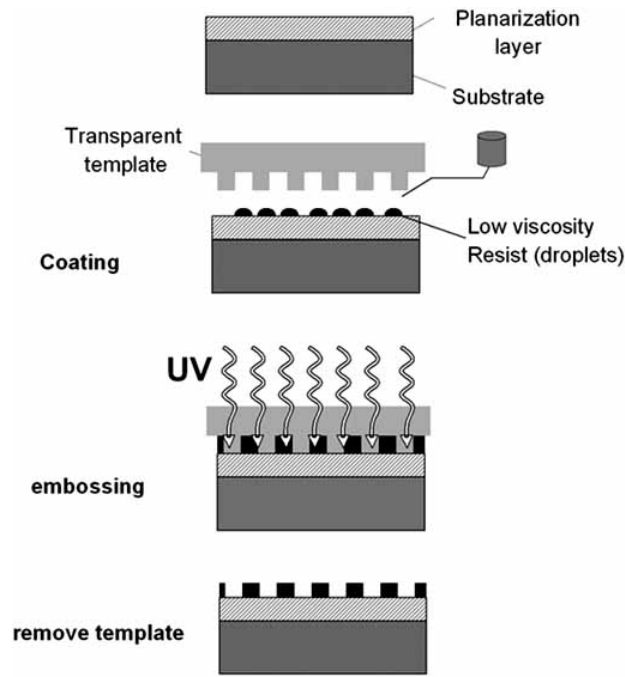


Fig. (9). Step and flash nano-imprint lithography: First, a low viscosity resist refills the template features, and is solidified by UV light. After releasing the template the patterning will be made in the same manner described in Fig. (8).

making [52], mold/resist anti-adhesion [53] and method for patterning large area in multi-steps process [51].

4. Lithography for Patterned Media

As described earlier, patterned media has many advantages compared to continuous magnetic recording media. It is most likely to be the future media for high recording density. Nevertheless, for the requirement of 1 Tbit/in² recording density, 12 nm magnetic islands with 25 nm pitch is very challenging. Just the need for high throughput with high resolution places limitation on many conventional lithography techniques. For example, optical lithography will be no longer possible for deep sub-micron size, and electron beam can be used for evaluation and understanding of magnetism in nano-structure but not for mass production due to slow processing time and high cost (few days for one disk). Projection EBL and EUV are now still at laboratory level and many problems have to be solved before it can be used in the industry. Proximity XRL is a promising technology for patterning media but to realize this promise, several key issues remain, such as tight control of mask-sample distance at nanometer scale. The mask supply is yet another issue for proximity XRL but it can be solved by duplicating several units from a master mask using for example NIL.

NIL relies on other high-resolution lithography for making the mold but in principle NIL has no resolution limitation as far as the mold can be made. To use NIL for patterning magnetic recording disk, some challenges remain

and need to be solved. For example magnetic recording layer is deposited on a disk with 1 to 3 inches diameter depending on whether it is for computer or other consumer electronics applications. For such relatively large area, the substrate bending and roughness will be a serious problem because this will be transferred to residual resist. A multi-step imprinting seems to be a solution in this case however; a very tight alignment is needed. In fact, SF-NIL is adapted for improved alignment over other techniques. The use of a transparent fused silica template allows not only UV curing through it, but also optical alignment. There has been a lot of work in this area as it is not only a concern for magnetic recording media but also for other fields like semiconductor, photonics etc. A nanometer scale alignment is important and it has been demonstrated that by using very low-molecular-weight monomers with viscosity of less than 30 centipoises, ± 6 nm alignment can be achieved [52-54]. In the case of magnetic recording, it is also important to consider the planarization of the disk surface. If the magnetic and non-magnetic regions are not in the same surface, the head-disk interface could be a problem. By using multilayer resist with different properties it is possible to solve this issue. The method consists of embossing and removing the residual resist from an upper resist layer which serves as mask for a lower resist layer having different etching rate. In some cases three resist layers are used with selective etching for an optimal pattern transfer process.

Among other concerns in patterned media is the need for defect free mold for patterning the media. Until now not much work has been done to reduce the defect density in NIL. Defect control is going to be the key challenge that even a 5 nm particles would not be allowed in 10 or 20 nm features size. In addition there is also concern about patterning non-flat substrate.

VI. OTHER TECHNIQUES

As compared to semiconductor applications, where lithography is necessary to make physical separation between elements, it is not necessary to make physical separation between magnetic elements of patterned media. It is enough to create magnetic elements in a non-magnetic matrix. Therefore, alternative besides lithography could be used. Chappert *et al.* used light ions to irradiate a thin film and multilayer of Co-Pt through a mask and change their magnetic properties. They demonstrated that the magnetic anisotropy and coercivity of these films can be adjusted by changing the irradiation dose without affecting film roughness [55]. Since then, intensive work has been conducted by several groups to use this property for patterned media. The local and collective behavior of magnetic arrays of Co/Pt multilayers fabricated by focused ion beam (FIB) patterning could be changed by Ga⁺ ions source. The magnetization of Co/Pt multilayer, initially in the out-plane direction, lies in-plane after FIB irradiation [56,57]. This is mainly due to interface modification (intermixing of Co and Pt). By this method two altered nano-scale magnetic regions with different magnetization orientation can be made by FIB. Similar to EBL, direct irradiation by FIB (maskless writing) suffers also from low throughput as it is sequential process. Ion irradiation through a mask was used and it has the merit to pattern a large area in a single ion

beam exposure. The great interest in FePt L1₀ phase with high perpendicular anisotropy stimulated research on modification of film structure by ion beam irradiation with the objective of avoiding high temperature annealing. In this case, it is desirable to improve the perpendicular anisotropy of FePt in the irradiated area while the nearest regions remain with low anisotropy achieving thus an alteration of high and low magnetic anisotropy (patterning) [58,59]. The method based on ion irradiation to change locally the magnetic properties in a continuous film and to obtain a high anisotropy region in a low anisotropy matrix has a potential for patterning magnetic media. Rather than ordering FePt by

low energy ion irradiation, Terris *et al.* showed that ion irradiation induces disorder in as-grown chemically ordered superlattices films of FePt and (Co/Pt) leading to low coercivity or rotation of the magnetization easy axis direction [60]. However, by using ion irradiation, the two regions are not magnetically decoupled and in this case the low anisotropy region will affect the magnetization reversal mechanism of the high anisotropy region considered as bit. In patterned media there is a need for a magnetically decoupling between the nano-dot “bits” and the matrix, otherwise their stability is compromised.

Table 1. Summary of Relevant Patents Related to Nano-Fabrication which could be Used for Patterned Media

Patent # (Year)	Ref.	Subject	Highlight/drawback
US6770896 (2004)	[20]	A method for generating extreme ultraviolet (EUV) radiation based on a radiation-emitting plasma. EUV is generated through emission of broadband radiation using at least one element from V to VII in the p-block of the fifth period of the periodic table of elements.	+ EUV radiation based on a radiation-emitting plasma: Higher performance than Xe based EUV - Further demonstration of long-term source stability is needed and other issues related to the system cost to be shown.
US7026098 (2006)	[26]	Method for performing electron beam lithography in a pattern by scanning a disk having resist coated thereon, placed on a rotating stage which is movable in a radial direction of the disk.	+ Patterns arranged in circular arrangement: Suitable for HDD (current design). - Nanometer scale spacing between each row not yet demonstrated.
US7041394 (2006)	[38]	A magnetic recording disc includes a substrate having a locking pattern etched therein. Chemically synthesized iron-platinum particles are provided and completely fill the locking pattern. The chemically synthesized iron-platinum nanoparticles exhibit short-range order characteristics forming self organized magnetic arrays.	+ Filling the self-assembled nano-particles in locking pattern overcome the short range ordering of these nano-structures. - Nano-particles shape (spherical) may induce roughness of the media surface.
US5772905 (1998)	[44]	A first patent on nano-imprint lithography: Method and apparatus for creating ultra-fine (sub-25 nm) patterns in a thin film coated on a substrate. The patent describes the process for patterning the substrate.	+ New lithography method with high throughput and low cost processing while resolution remains related to the mold. - This method requires high temperature and pressure during embossing.
US6482742 (2002)	[49]	An improved method of imprint lithography involves using direct fluid pressure to press the mold into a substrate-supported film. This method provides better resolution and high uniformity than the conventional thermal nano-imprint lithography described in ref. 43	+ same advantage of Ref. 44 with an improvement in the process by using UV curing (no need for high temperature, pressure and long time process). - Planarization issue remains.
US6334960 (2002)	[48]	A method which describes the process of making patterns using step-and flash nano-imprint lithography.	+ Another type of NIL which does not require high temperature and pressure.
US7027156 (2006)	[54]	Method for patterning a substrate by step-and flash NIL and providing the alignment of the template by using scatterometry technique.	+ Same advantages than described in Ref. 48, with advantage related to solving the alignment issue. - Optical mark detection may have a limitation (few microns only) and not accurate at nano-scale: causing overlay during successive embossing processes.
US6699332 (2004)	[61]	A method of producing a magnetic recording medium by converting a non-magnetic material into a magnetic state by annealing. This can be done by a focused ion beam to form a patterned magnetic layer comprising an ordered array of magnetic regions separated by non-magnetic regions.	+ Simple method for patterning a magnetic media by forming magnetic and non-magnetic regions. - The method is a serial process which is slow.

Piramanayagam *et al* have patented local annealing of a non-magnetic material to form patterned media. In their study, a material such as ferrite, garnets or CrPt₃, which can under-go a transition from non-magnetic to magnetic state with heating, can be used to form patterned media [61]. However, this method is a serial approach, which will lead to the requirement of long times for fabrication. Wang *et al.*, have modified this idea further to make large area of patterns by exposing the non-magnetic material through a mask [62]. Similar to the case where ion irradiation changes the magnetic properties of the film, still there is concern in this scheme about single domain state in the magnetic bit. The non-irradiated area might serve as source of nucleation for domain wall in the irradiated area (magnetic).

Irrespective of the type of lithographic technique (described in section IV) used for patterning the bits, the coating of resist will be needed. Coating of resist also poses several challenges that are not common in semiconductor industry. While the resist coating of semiconductor wafer is achieved by spin-coating, hard disks have a hole in the center. Compared to the semiconductor industry, where the resist coating is needed only one side of the surface, the hard disk media needs resist coating on both the sides, as both sides of a hard medium are used for storing information. This also places a challenge on the conventional spin-coating method. If one side is spin-coated first and the next side is coated by flipping, it is highly possible that certain amount of resist is coated in the second surface. This also would increase the time and cost involved in coating the resists. Therefore, alternative methods that are not used in the semiconductor industry are needed in the resist coating for patterned media. Curtiss *et al.* have proposed a dip coating method to coat the resist, in a way similar to the coating of lubricants on hard disk media. In this method, the disks are dipped into a vessel that contains the resist and rose to withdraw. In order to maintain the resist thickness, the viscosity of the dip coating liquid may be monitored and maintained [63]. This will help to obtain uniform coating of resist. It is expected that the making of patterned media will pose several such challenges, which is an opportunity for several researchers in the field of data storage.

VII. CURRENT & FUTURE DEVELOPMENTS

Whether the fabrication of patterned media lies ultimately with projection electron beam, proximity X-rays, extreme ultraviolet light or nano-imprint is far from clear at present. Several critical issues remain to be solved with all possible alternative approaches (see Table 1). Achievement of less than 10 nm magnetic islands with regular shape and size in large area disk with low cost might involve even a combination of some of these methods. As has been described earlier, different methods have been used to make patterned magnetic disk. However, at this stage there is more interest in evaluating the feasibility of patterned media rather than improving the fabrication process. It is expected that the approach of current perpendicular magnetic recording to its limit, dictated by superparamagnetic effect, will encourage more researchers to investigate a practical nano-patterning method. It is also important to note that if competing technologies such as heat-assisted magnetic recording become successful, patterned recording may be further

delayed or never happen. In magnetic recording there will be a close look at the progress in other applications of nanotechnology, which might give a hint for a successful implementation of patterned media in HDD for over Tbits/in² recording density. This certainly will be a driving force for the applications of data storage to new areas.

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