APPLIED ORGANOMETALLIC CHEMISTRY
Appl. Organometal. Chem. 2001; **15**: 373–382
DOI: 10.1002/aoc.156

Patterned nanostructured arrays for high-density magnetic recording†

S. A. M. Tofail,[1] I. Z. Rahman[1]* and M. A. Rahman[2]
[1]Department of Physics, University of Limerick, Limerick, Ireland
[2]Department of Computer and Electronic Engineering, University of Limerick, Limerick, Ireland

This article reviews the recent advances in patterned magnetic nanostructures for application in high-density recording. In this connection we discuss: (1) the fundamental limits of magnetic recording on conventional magnetic disks and the need for newer materials; (2) the state-of-the art technology for creating arrays of magnetic nanostructures; and (3) prospects and problems of high- or ultrahigh-density recording using these nanostructured arrays. Copyright © 2001 John Wiley & Sons, Ltd.

Keywords: nanostructured magnetic material; magnetic arrays; high-density recording; lithography; templating

1 INTRODUCTION

Magnetic recording has the superiority over other memory devices in erasability and permanence of the written information. Since the birth of magnetic recording, important breakthroughs, like higher density media, magnetoresistance (MR) sensor head, giant magnetoresistance (GMR), colossal magnetoresistance (CMR), coupled with better mechanical and aerodynamic design, and improved error correction codes in data retrieval have led to a remarkable increase in the recording density, commonly referred to as areal density (AD). In the earlier part of the 1990s the recording density was almost doubled every 2 of years.[1] In the recent past, with the introduction of GMR spin-valve heads by IBM in 1998, the rate of increase in the AD is almost doubled per year[2] and a recording density as high as 10 Gbits in^{-2} has been achieved.[3] Nevertheless, it is the storage medium that plays the key role in determining the density of the recordable bits in a given surface area, since the nature and capability of the medium to store the information largely dictate other parameters. Table 1 summarizes the salient features of the roadway to such high density till May 1999.

Until now, improvement in high-density recording (HDR) on conventional magnetic disks (CMDs) has been achieved by continuously improving the media,[11] mainly quaternary CoCrPtX alloy, X being tantalum, neobium, etc. It is now a matter of considerable debate[2,11–14] whether conventional media can maintain the present rate of growth in the density, which is continuous in nature and limited by quantum magnetic limits. Nanofabrication technology, on the other hand, has recently been opening up new opportunities for innovative magnetic materials and devices. It is anticipated that novel nanostructured magnetic arrays produced by such techniques can be useful as recording media for future HDR.[12,13]

This paper intends to provide an insight into the importance and fabrication of the arrays of magnetic nanostructures as an alternative recording medium to the present Co–Cr longitudinal storage media, their applicability in HDR being the main focus. However, a brief overview on the physical and technical limits of the magnetic recording density on conventional longitudinal media is mentioned to justify the introduction of such novel magnetic nanostructures for HDR. The article also discusses the possible difficulties that are likely to delay the commercialization of this new class of magnetic materials for HDR.

* Correspondence to: I. Z. Rahman, Department of Physics, University of Limerick Limerick, Ireland.
E-mail: zakia.rahman@ul.ie
† Based on work presented at the 1st Workshop of COST 523: Nanomaterials, held 20–22 October 1999, at Frascati, Italy.
Contract/grant sponsor: Higher Education Authority, Ireland.

Table 1 Salient features of the pathways to an AD of 10 Gbits in^{-2}

Year	AD (Gbits in^{-2})	Reference	Special feature
1990	1	4–6	Closely spaced MR head Partial response maximum likelihood channel Grain size 30–40 nm
1991	2	7	Better mechanical design of head Extended partial response maximum likelihood channel Better aerodynamic design of the disk drive
1995	3	8	MR head Quaternary cobalt alloy ($H_c = 2000$ Oe) medium
1997	5	9	Narrow track dual-element MR head Cobalt alloy thin film as before
1999	10–12	3, 10	GMR head Quaternary CoCrPt-base alloy ($H_c = 3000$ –3500 Oe, $M_r\delta = 0.35$ memu cm^{-2}) Grain size ~12 nm

2 LIMITS TO CONVENTIONAL MAGNETIC RECORDING

2.1 Background and physical limits

The present recording media are typically continuous, thin ferromagnetic films supported by rigid, nonmagnetic substrates and consist of many tiny polycrystalline grains with a rather broad distribution in size and shape and a random distribution of crystallization direction. A write head aligns the otherwise randomly oriented grains in a tiny patch of these grains, and the data are represented by the magnetic moment, area, size and location of this patch.

At its simplest, HDR means recording at high AD, which is a combination of linear and track densities. While track density means how close the tracks of bits can be placed to each other in the radial directions of the disk, linear density denotes how close bits can be placed one after another. So, increasing the AD means increasing either or both the track and linear densities. However, the essence remains in the ability to record a magnetic transition (i.e. a bit) in the medium at a length as small as possible, and to maintain it at a stable state. The smallest bit length a, that can be sustained in a given media is given by:[15]

$$a = M_r\delta/2\pi H_c \quad [1]$$

where M_r is the remanence magnetization, δ is the thickness of the magnetic thin film, and H_c is the coercivity of the media.

For high storage density, the transition length should be small enough to allow more bits to be stored in a given length of the medium. This leads to a smaller distance between the magnetic reversals, which, in turn, produces strong demagnetizing fields on the recorded bit. To enable the stored bit to be stable, the coercive force H_c, therefore, must be high enough to counteract these demagnetizing effects. Moreover the remanence–thickness product, $M_r\delta$ must be small to make the transition length a smaller. However, high remanence is required to ensure sufficient stray magnetic field in the medium, because the readout signal will otherwise be lower. To obtain high remanence, high saturation magnetization M_s is required, which, unfortunately increases the demagnetizing field[16] and necessitates still higher coercivity.

So, to allow HDR beyond 10 Gbits in^{-2} the conventional magnetic media must have a high coercivity ($H_c > 3000$ Oe), a lower value of remanence–thickness product ($M_r\delta < 0.7$ memu cm^{-2}), a high coercive squareness ($S^* \cong 0.9$), and fine grain size (~10 nm).[17] The values of these parameters in the media for an AD of 12 Gbits in^{-2} are shown in Table 1, and they agree well with the theoretical predicaments. However, the achievement of a higher AD than this will require higher coercivity, preferably in the range 4000–6000 Oe.[11] This definitely will increase the stability of the stored information, but it will also impose further restrictions on the writing head, as its saturation magnetization has to be higher than that of the media in order to make it compatible with writing data on the medium. On the other hand, the value of remanence–thickness product should be lowered without any sacrifice in the remanence. So, the only way to accomplish a decrease in the remanence–thickness product is to decrease the thickness. However, at a thickness below the *superparamagnetic limit* the whole effort will be counter productive, since, at this limit, the individual grains stay magnetized but their orientation fluctuates thermally.[18]

The superparamagnetic limit is thus considered as the main physical obstacle to HDR on conventional media. For a typical magnetic storage medium, the superparamagnetic limit poses a minimum particle size of about 10 nm. For Co–Cr storage media, the limit can be about 5 nm,[19] which corresponds to an AD of several terabits per square inch.[20] This is three orders of magnitude higher than the density found in the top-of-the line hard disks today.

The thermal stability of the recorded bits is another important parameter that limits HDR on conventional media. In order to visualize the effects of thermal energy on the magnetic moment of a single grain, it is helpful to consider the thermal agitation in terms of a fluctuating magnetic field. Néel[21] showed that this fluctuation could be measured from the logarithmic rate of decay of magnetization, i.e. magnetic viscosity, S and the irreversible susceptibility $\chi_{irr}(H)$ from the relation:

$$H_f(H) = S(H)/\chi_{irr}(H) \qquad [2]$$

where $H_f(H)$ is the fluctuation field. For independent Stoner–Wohlfarth particles of physical volume V, the energy barrier is

$$E_B = K_u V(1 - H/H_A)^{\alpha} \qquad [3]$$

where K_u is the anisotropy, α is 1.5–2, depending on the geometrical and other factors, and H_A is the anisotropy field.[22] The characteristic relaxation time τ for the thermal activation of the magnetization over the energy barriers is given by:

$$\tau^{-1} = f_0 \, e^{-E_B/k_B T} \qquad [4]$$

where f_0 is the attempt frequency ($\sim 10^9$ Hz).[23]

At the superparamagnetic limit $\tau = 100$ s, then $K_u V/k_B T = 25$. For long-term storage (say 10 years), one must have[11] $K_u V = 40 k_B T$.

On dimensional grounds, Wohlfarth[24] argued that this field was related to a critical or activation volume of magnetization reversal. The magnetic viscosity can then be related to the volume by:

$$S = (k_B T/M_s V^*)\chi_{irr} \qquad [5]$$

where V^* is the activation volume.[25]

This activation volume V^* is the smallest volume of the material that reverses coherently in an event, and hence of critical importance in magnetic recording, since, in principle, it is the volume rather than the physical grain size that determines the smallest bit of information that can be stored. However, in conventional magnetic disk media, where the grains are exchange coupled, it is found that the intergranular coupling stabilizes the mode of reversal and leads to a measured activation volume that is greater than a single grain and may represent a significant number of grains.

Because of the statistical nature in the size and easy magnetization axis of such polycrystalline grains in a magnetic medium, the intrinsic signal-to-noise ratio (SNR) of a magnetic signal is given by:

$$\mathrm{SNR\ (dB)} = 10 \log N \qquad [6]$$

where N is the number of grains in a rectangular bit. This means that for a reasonable SNR of 30–20 dB there should be 1000 –100 grains in a bit.[22]

Assuming square bits with appreciable SNR of 20 dB, a magnetic layer thickness of 12 nm, and $K_u V/k_B T = 60$, it can be found that for an AD of 10 Gbits in^{-2} maintaining the thermal stability, a grain size of 12.2 nm and an anisotropy of 1.4×10^6 erg cm^{-3} is required.[22] Bearing in mind that the highest reported AD on conventional magnetic disk is achieved with a 12 nm average grain size,[10] it can be noted that an AD of 100 Gbits in^{-2} on such disks requires the grain size in the medium to be about 6 nm[22] and an anisotropy of 1.3×10^7 erg cm^{-3}. If the thickness of the magnetic medium is only to be reduced further to 10 nm, the restriction on grain size improves to 8 nm[11] and that on the anisotropy is relaxed to 3×10^6 erg cm^{-3}. Nevertheless, these conditions are stringent, if not unrealistic, and require a complicated, high anisotropy rare-earth intermetallic compound or alloy. Achievement of 6 or 8 nm size is by no means easy in conventional magnetic disks with the present methods of deposition, and the problem is further exacerbated by the fact that such finer size grains must be exchange decoupled to reduce noise.

2.2 Technical limits

There are also many technical difficulties to achieve HDR on conventional magnetic materials. Most important of them is the media noise. Actually, it is the various noise issues that restrict the conventional media to an AD of several terabits per square inch as predicted from the superparamagnetic limit. For example, the transition width between adjacent bits of opposite magnetization can make the reading of the bits very noisy. The nature of ferromagnetism, which is at the heart of magnetic recording, favours all magnetization to be aligned in the same direction. Now, when a bit with opposite magnetization is placed next to its neighbour, a transition region, called a domain wall, is formed[26] to reduce the exchange energy. The interplay between magneto-static force and exchange force renders it to a zigzag shape (Néel spikes). These zigzags increase the width of the transition region (40–80 nm)[12] and also create the transition noise in the reading signals.

'*Side-tracks*' is another important issue that limits the AD. Extra space between two data tracks must be reserved for the side tracks; this consumes space that could be used for data and, thereby, reduces the data density. Moreover, the tracking is 'blind', because a recognizable physical boundary does not exist between two bits of similar magnetization. The head first locates the 'tracking marks' written at the beginning of each data, then calculates the movement between the head and the disk to obtain the *supposed* bit location. In addition to the wastage of about 20% of the total disk area to leave the tracking marks,[12] the blind tracking imposes a further limit on the AD by virtue of the accuracy of disk rotation and the servo-mechanical approach of the head to the written bit.

3 NEWER MEDIA FOR HDR

Given the superparamagnetic limit, the thermal loss of data and the associated noises are the dominant factors in limiting the data densities in conventional longitudinal recording mode. Merely reducing the size of the bit on today's materials may prove impractical[12] beyond a data density of 40–100 Gbits in^{-2}. The possible approaches for examining and developing new techniques or materials in order to extend the magnetic data storage densities beyond such levels may broadly fall into the following categories.

3.1 Hard magnetic materials

Magnetically hard materials like Co_5Sm or Fe–Pt have very high coercivity and are able to resist the superparamagnetic effect more strongly.[11] However, the greater coercivity of these materials may inhibit writing the data bits as quickly as will be needed, and put some extra constraint on the read–write head.[27]

3.2 Smaller number of magnetic grains per bit

Reduction of the number of grains per bit from 1000 to 100 means a reduction of the SNR from 30 to 20 dB. The highest ADs so far reported[3] have been achieved on material having an SNR of about 26 dB. It should be reduced further to achieve higher density. However, the use of fewer grains per bit would require a stronger signal and/or lower noise. Aligning grains magnetically in the track direction can increase the signal, and the use of grains that are uniformly sized and arranged will reduce the noise.

3.3 Perpendicular recording

Changing the orientation of the bits on the disk from a longitudinal to a perpendicular direction would permit higher data densities. However, perpendicular recording may add complexity to the disk drive. Since its inception, perpendicular recording media have encountered difficulties in the production and control of properties, and although the originators[28] of the concept still believe in its prospects, its applicability to HDR is not beyond doubt.[29]

3.4 Magnetic multilayered disks

Thin nonmagnetic layers[30–34] separate the magnetic layer that stores the data, and it is believed that this laminated structure reduces the noise and hence improves the SNR to a level that permits use of fewer grains per bit.[35] An important aspect of this approach is that the interlayer thickness should be thick enough to interrupt the exchange interaction between the magnetic layers but it should be, at the same time, thin enough to retain magneto-static coupling. This is the medium that is most likely to replace the present Co–Cr alloy media in the recent future because of its compatibility with the present disk drive system.

3.5 Barium ferrite ($BaFe_{12}O_{19}$)

This medium has a perpendicular anisotropy that could be exploited for HDR;[33] however, it's high annealing temperature leads to grain coagulation, which leads to a deterioration in the recording properties.[36] Considerable improvement in the media characteristics is required to explore this medium for HDR.

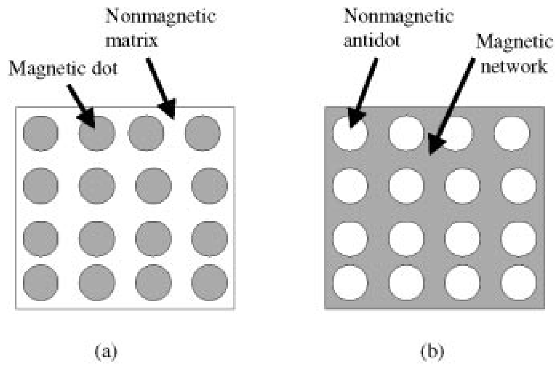

Figure 1 Magnetic nanostructures: (a) positive nanostructure; (b) negative nanostructure.

3.6 Arrays of nanostructured magnetic materials

Patterned nanostructured magnetic arrays have the potential for use in extremely high bit density recording. These nanostructured media are patterned to form single-domain dots, anti-dots, pillars or networks of magnetic material in a nonmagnetic substrate or matrix. The nonmagnetic material physically separates the magnetic single domains from each other. The bits of information are written on the magnetic dots or anti-dots. This concept of magnetic recording is relatively new and the matter of interest of the present paper.

4 NANOSTRUCTURED MAGNETIC MATERIAL FOR HDR

4.1 Definition, importance and classification

Many authors have defined nanostructured materials in many ways.[37–39] However, any material that is composed of structural elements (e.g. grains or crystallites) having sizes from 1 to 100 nm across, or layers of that thickness, is considered as a nanostructured material.

Magnetic nanostructures can be classified in a number of ways,[37–39] but arrays of magnetic nanostructures have been classified into two main groups based on the relationship between the matrix and the nanostructured phase: positive nanostructures (Fig. 1a) consist of nano-sized dots, bars or columns of the magnetic material in a nonmagnetic matrix; negative nanostructures (Fig. 1b) consist of the nonmagnetic matrix in the form of nanodots or holes and the magnetic phase surrounds these dots to form a negative structure that can be seen as a contiguous network of the nanostructured phase.

Conventional materials have grain sizes ranging from submicrometres to several millimetres and contain several billion atoms each. Nanometre-sized grains contain only about a 1000 atoms or less. As the grain size decreases, there is a significant increase in the volume fraction of grain boundaries or interfaces. This characteristic strongly influences the chemical and physical properties of the material. Patterning of magnetic materials by nano-lithography or template synthesis can produce significant differences in magnetic properties from those in bulk or conventional thin film form.

4.2 Quantum magnetic disk and nanonetwork

In the demagnetized state, a typical magnetic material is magnetically divided into many *domains*, each containing a number of polycrystalline grains. Each domain is spontaneously magnetized, but their magnetization direction is random and the material has no net magnetization.[18] When a magnetic material is patterned into a size comparable to a single domain size, which is usually in the nanometre range, each patterned magnetic nanostructure contains one or, at best, a few domains, in contrast to the multidomain structure of conventional materials. Because of the discontinuity of magnetization at the edges of a patterned nanostructure, magnetic poles can be formed spontaneously, leading to a single domain without an applied field due to the interplay between magnetostatic energy and exchange energy.[12] While a reduction of exchange energy favours alignment of all magnetic domains in the same direction to form a single domain, the reduction of magnetostatic energy favours multiple domain formation.[18] There is a critical size below which a single domain has the lowest energy and the spontaneous formation of a single domain is energetically feasible. This critical size is about 100–300 nm in a thin film.[12] Figure 2 shows the formation of a single domain with the reduction in grain size.

The limitations of the magnetic recording on CMDs mentioned in Section 2 could be eliminated, or reduced to a great extent, if the continuous nature of CMDs could be changed. This is possible when the bits containing magnetic elements are physi-

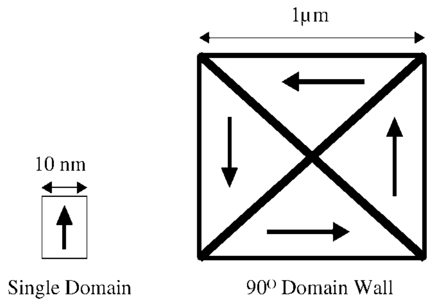

Figure 2 Schematic representation of single domain formation with the decrease in grain size.

cally separated from each other with the help of a nonmagnetic material. Theory suggests that sufficiently small islands with uniaxial anisotropy should behave like a magnetically bistable single domain[40] and would be ideal for storage of single bits of information. A single-bit-per-island recording system could provide a lower noise and higher density alternative to the unpatterned thin films used in conventional recording systems.[41,42] This gives rise to a new paradigm in magnetic recording, termed *quantized recording*. In contrast to the CMDs, quantized magnetic disks (QMDs) have discrete, single-domain magnetic elements uniformly embedded in a nonmagnetic disk.[42] Each single domain element has a uniform, well-defined shape, a pre-specified location, and, most importantly, a discrete magnetization that is magnetized without an applied magnetic field and which has only two possible stable states that are equal in magnitude but opposite in direction. Each magnetization direction of a single domain element represents a bit of binary information. Figure 3 shows the schematic diagram of such a QMD

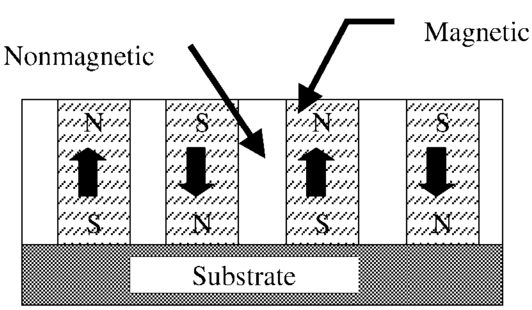

Figure 3 Schematic of a QMD. Although only vertical magnetization is shown, longitudinal magnetization is also possible.

Table 2 Advantages offered by QMDs over CMDs in high-density magnetic recording

Property	Advantage in QMD over CMD
Bit writing	Simpler
Bit-head overlapping	Head does not write anything
Head-bit misplacement error	Not likely
Transition noise	Zero/extremely low
Reading signals	Quieter
Exchange interactions	None
Cross-talking	Low
Individual tracking of the bit	Possible
Head positioning	Precise
Tracking marks	None
Blind tracking	None

having a perpendicular orientation and Table 2 lists the improvements or changes in various recording properties that can be achieved in QMDs in comparison with the CMDs.

Chou *et al.*[43] have found the existence of both longitudinal and vertical quantum magnetization in positive nanostructures made using nano-lithography with electron beam lithography (EBL) and a subsequent lift-off technique. From magnetic force microscopy (MFM) images of such structures, they have concluded that, with the decrease in the size of the magnetic structure in the patterned array, each bit of information written on the individual element in the array has a quantized magnetization orientation and the array forms a QMD. With an array of nickel pillars having 35 nm diameter, 100 nm period and 200 nm height, an AD as high as 65 Gbits in^{-2} can be achieved with perpendicular recording.[42] Longitudinal QMDs having discrete single domain cobalt bars with a 70 nm width, 250 nm length, and 150 nm spacing on silicon were fabricated using nanoimprint lithography[44] and the density of nanostructured bars[45] corresponded to an AD of 7.5 Gbits in^{-2}. With the current high-end technology in lithography and nanofabrication, a density of recording as high as 250 Gbits in^{-2} can be reached in such QMDs.[43]

The presence of quantized magnetization in negative structures has not yet been reported. However, the experience of Cowburn *et al.*[46] is interesting in this regard. In this work an anti-dot structure was fabricated using lithography in order to introduce a mesh of holes in a continuous

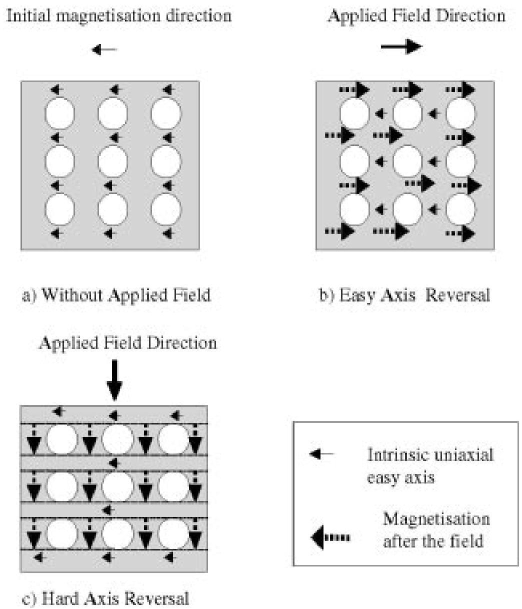

Figure 4 Schematic representation of the domain images obtained from a magnetooptical Kerr polarization microscope.

permalloy film having thickness of 40 nm and anti-dot width ranging from 0.5 to 1.5 μm.[46] From Fig. 1b it is clear that such an anti-dot structure forms a contiguous network of the magnetic media. The discontinuities appearing as the holes in the continuous media leave important influences in the magnetic properties. Scanning Kerr polarization microscopy (SMOKE) of the magnetization reversal of such arrays shows that on magnetization along the magnetic *hard* axis, the spin reversal mechanism is influenced by the presence of the anti-dots. The spins that are directly left or right of an anti-dot are trapped along the intrinsic hard axis, whereas there is no such trapped-spin direction above or below the anti-dots (Fig. 4). This hard axis reversal can be used for data storage in a similar way to the dot arrays, since each anti-dot can support either one or two data bits.[47] However, this can offer a further advantage over QMDs. The easy magnetization regions in the contiguous web-like magnetic material are now separated by hard axes, in contrast to the magnetic dots per islands isolated by a sea of nonmagnetic material. Since magnetic isolation comes from the anisotropy barriers, and not from the physical isolation of the film by nonmagnetic material, superparamagnetism would have little effect on the magnetic bits.[46]

4.3 Fabrication and commercialization of nanostructured magnetic arrays

4.3.1 Principle

Irrespective of whether it is a positive nanostructure or a negative nanostructure, the fabrication of nanostructured arrays of magnetic material requires patterning in order to go down to a size that is smaller than or comparable to that of the single domain of the magnetic material of interest. For this, patterning is usually done either by lithographic techniques or by the use of templates having nanofeatures. The magnetic material can be deposited through the patterned mask or on to the template by a number of deposition techniques, with physical vapour deposition, like sputtering,[13,41,48–52] and chemical synthesis methods, like electrochemical deposition,[43–45,53,54] being the most popular methods.

4.3.2 Lithographic technique

EBL is the most widely used technique for patterning magnetic nanostructures[41–46] because of its better resolution and insignificant diffraction limit.[55] Magnetic nanostructure patterns having features as small as 10 nm have been reported.[12] However, this method is highly capital intensive and the operating cost is also high. It also suffers from low throughput because of its slow speed. Good mass-production technique is required to make it cost effective and a nanoimprint technology has already been exercised to render EBL a cost-effective method for the patterning of nanostructured arrays.[43]

X-ray lithography (XBL), which can be a quicker alternative to EBL, is capable of printing the nanofeatures onto the mask in one flood of exposure by the rays. The shorter wavelength X-rays give a better result in patterning.[55] Proximal probe lithography is a method wherein a proximal probe tip, like atomic force microscope or scanning tunnelling microscope tips, can be used to define the patterns in the resist. Extremely small sizes can be produced in this manner.[55] However, no report of using these methods for patterning magnetic arrays has been found.

4.3.3 Template synthesis

In template synthesis, the desired material is deposited within the pores of a porous membrane or template. If the pore has a nanometre dimension, the desired material will replicate the dimensions and will result in a patterned nanostructure. The final product is usually in the form of a nanocylinder or nanonetwork. If the magnetic material deposits inside the pores, the nanocylinders are produced, which can either be solid (nano-wire) or hollow (nano-tube).[56,57] If the material is deposited onto the wall of the pores, a nanonetwork is formed,[48] which can be considered as an anti-dot array. Suitable templates can make the whole patterning process of the magnetic nanostructure significantly cheaper than the lithographic processes and, therefore, the choice of the template is critically important.

Various templates, like nanochannel alumina (NCA),[48–52] track-etch,[56–57] etc., are commercially available, and newer templates are being looked for. NCA contains through-thickness pores running normal to the surface. This results in isolated non-connecting pores. They have been used to fabricate both magnetic nanonetworks[48–52] and nanowires.[54] Although a wide range of pore diameters (5–200 nm) can be produced, only three pore diameters are available commercially.

Track-etch templates are produced by bombarding sheets of polycarbonate or polyester with nuclear fission fragments to cause damage tracks in the polymer. These tracks are then chemically etched into pores that are randomly distributed, cylindrical and have uniform diameters. Although these templates are extremely inexpensive, the problem in using them for templating nanostructures is that the angle of the pores with respect to the surface normal[56,57] can be up to 34 °. As a result, some of the pores may intersect each other in the membrane, which will create a magnetic short circuit during actual service.

Nano channel glass (NCG) is similar to NCA, having pores randomly distributed but of uniform diameter (up to 33 nm).[58] Eddy *et al.*[59] produced arrays of 250 nm diameter dots and 600 nm anti-dots using an NCG replica, although no report of using this type of template to deposit magnetic material for magnetic recording has so far been found. These templates can be advantageous, since the glass can be used directly as the substrate of the memory disk.

Self-assembly polymer templates have recently attracted considerable attention.[60] These templates utilize the natural process of self-assembly of diblock co-polymer films on the nanometre scale. After chemically removing one polymer, the pattern may be transferred to a substrate through etching or evaporation. The beauty of this process is that upon applying an electric field the random nanoscale patterns follow the path of the field to arrange themselves in a manner very similar to the track arrangements in magnetic disks. Deposition of magnetic material onto such highly oriented nanopatterns will make the patterning of magnetic memory material significantly easier and cheaper.

4.3.4 Problems and prospects of HDR on nanostructured arrays

Magnetic recording on patterned nanostructured materials is still in its infancy, and many issues regarding material physics and recording fundamentals are to be resolved in order to lead these structures being useful as information storage media. For example, in QMDs, the recording density claimed has been made on the assumption that each quantized single-domain nanostructured island would contain one bit of information. For a QMD made up of nanostructured islands of polycrystalline materials with high magnetocrystalline anisotropy, perfectly uniform magnetization is very unlikely, which is not a favourable condition for high-density magnetic recording. The effect of the magnetocrystalline anisotropies of the individual grains in a single-domain island to the easy axis of magnetization of the island is also critical. It has been found that the anisotropies of the grains do not average out completely, and that the net magnetocrystalline anisotropy may sometimes outride the shape anisotropy for some island geometries.[61] This would lead to unpredictably oriented easy axes of magnetization and to variations in the magnetic properties from island to island. This problem will contribute to the readback noise in a single-bit-per-island recording scheme. One solution to this problem of misorientation would be to increase the shape anisotropy, making the islands extremely long and thin; however, this would be difficult to magnetize and read back using conventional read–write heads.[51]

So, if a single-bit-per-island recording were to be implemented using a medium composed of a nanostructured array of polycrystalline islands, there would be several important and very likely insurmountable sources of medium noise. These arise mainly from the inherently unpredictable microscopic structural details of the polycrystalline films. To obtain predictable behaviour from such magnetic nanostructures, New *et al.*[13] suggested the use of a microscopically homogeneous material, e.g. single-crystal or amorphous thin films.

Fabrication of patterned magnetic nanostructures imposes further restrictions on commercialization of such structures as high-density information storage media. At present, EBL is the method of choice to pattern both positive and negative nanostructures. However, this method of patterning suffers from high capital cost and the extremely slow speed makes the overall operation cost even higher. A cost-effective mass production technique is necessary to render this method of patterning economical.

Templating followed by physical vapour deposition or electrodeposition of magnetic material can be used to fabricate patterned magnetic nanostructures at a much faster rate and cheaper cost. However, the random nature of the nanofeatures in the template will make the reading and writing of data extremely difficult with the present-day read–write systems owing to the absence of discrete tracks on the templated media. This will require new data retrieval systems and error correction algorithms. Self-assembly diblock co-polymer templates could be a solution to the randomness of the nanofeatures. Using these types of template, tracks of magnetic nanostructures can be deposited directly.

There are many issues regarding the writing and reading of the data onto such nanostructures, including the head, head–media spacing, error correction code, etc. Clearly, slight or no modification of the present-day read–write systems will be preferred from an economic point of view. To be able to write and read on to patterned magnetic nanostructured high-density media, a write–read system must be developed with high-speed and ultrahigh resolution. To facilitate the head approach to the bit, servo systems must have better mechanical and aerodynamic design.

As for the read–write head, there is a growing idea to use MFMs tips. Chou *et al.*[44] have written to longitudinal QMDs with the help of a high-resolution MFM tip. At present, this is effective for research and development purposes but it is too slow for commercial disks. There are efforts being made[62] to develop fast-response scanning probe tips of a high bandwidth and parallel tip arrays. Before such heads are developed, it is possible to use conventional heads to write and read patterned nanostructures, if a multiple single-domain element per bit scheme is used.[12] This must definitely be followed by better electronic signal processing and error correction codes.

To summarize, the future work on patterned magnetic nanostructures for HDR utilization should be concentrated on the following aspects: (a) development of materials with suitable anisotropy, uniform magnetization, better tribological performance and economic production; (b) read–write heads with high resolution, high scanning rate and lower head–medium spacing; (c) signal-processing algorithms and electronics with noise reduction in the readback signal with an SNR of 20 dB or better, improved error correction and coding techniques.

5 CONCLUSIONS

The concept of nanostructured magnetic arrays is a new one, and all the underlying mechanisms are not yet well understood. Potentially, however, high-density recording can be extended with these new materials far beyond what has been achieved so far, or, indeed, will be achieved in the near future with conventional media. The nanostructured magnetic arrays have the capability to keep up with the present rate of increase in AD. The number of creative ideas for magnetic recording involving magnetic nanostructures is growing rapidly. Surely, not all of the ideas will be converted into useful devices, but there is a wide open territory to be covered.

Acknowledgements Financial support from the Higher Education Authority (HEA), Ireland, is acknowledged. One of the authors, S. A. M. Tofail, also wishes to thank Mr Mark Gubbins, Department of Physics, University of Limerick, Ireland, for his valuable suggestions.

REFERENCES

1. Coey JMD. *J. Magn. Magn. Mater.* 1999; **196–197**: 1–7.
2. O'Grady K, Laidler H. *J. Magn. Magn. Mater.* 1999; **200**: 616–633.
3. Tsang C, Pinarbasi M, Santini H, Marinero E, Arnett P, Olson R, Hsiao R, Williams M, Payne R, Wang R, Moore J, Gurney B, Lin T, Fontana R. *IEEE Trans. Magn.* 1999; **35**: 689–694.
4. Howell TT, McCown DP, Diola TA, Yow-Shing T, Hense KR, Gee RL. *IEEE Trans. Magn.* 1990; **MAG-26**: 2298.
5. Tsang C, Chen M, Yogi T, Ju K. *IEEE Trans. Magn.* 1990; **MAG-26**: 1689.
6. Yogi T, Tsang C, Nguyen TA, Ju K, Gorman GL, Castillo G. *IEEE Trans. Magn.* 1990; **MAG-26**: 1578.
7. Futamota M, Kugiya F, Takano H, Matsuda Y, Inabe N, Miyamura Y, Ahagi K, Nakao T, Sawaguchi H. *IEEE Trans. Magn.* 1991; **MAG-27**: 5284.
8. Tsang C, McCowen D, Santini HA, Lo J, Lee RL. *IEEE Trans. Magn.* 1996; **MAG-32**: 7.
9. Tsang C, Lin T, MacDonald S, Pinarbasi M, Robertson N,

Santini H, Doerner M, Reith T, Vo L, Diola T, Arnett P. *IEEE Trans. Magn.* 1997; **33**: 2866.
10. Madison M, Arnouldussen T, Pinarbasi M, Chang T, Parker M, Li J, Duan S, Bian X, Mirzamaani M, Payne R, Fox C, Wang RH. *IEEE Trans Magn.* 1999; **35**: 695–699.
11. Sellymer DJ, Yu M, Kirby RD. *Nanostruct. Mater.* 1999; **12**: 1021–1026.
12. Chou SY. *Proc. IEEE* 1997; **85**: 652–671.
13. New RMH, Pease RFW, White RL. *J. Magn. Magn. Mater.* 1996; **155**: 140–145.
14. Middleton BK, Miles JJ, Aziz M. *J. Magn. Magn. Mater.* 1998; **188**: 248–259.
15. Brusic V, Horkans J, Barclay DJ. Electrochemical aspects of thin film storage media. In *Advances in Electrochemical Science and Engineering*, vol. 1, Gerischer H, Tobias CW (eds). VCH Publishers Inc.: New York, 1990; 250–251.
16. Berkowitz A. Nanostructured materials for magnetic recording. In *Nanomaterials: Synthesis, Properties and Applications*, Edelstein AS, Cammarata RC (eds). Institute of Physics Publishing: Bristol, 1996; 570.
17. Murdock ES, Simmons RF, Davidson R. *IEEE Trans. Magn.* 1992; **MAG-28**: 3078.
18. Cullity BD. *Introduction to Magnetic Materials*. Addison-Wesley: 1972.
19. Mallinson JC. Recording limitations. In *Magnetic Recording Technology*, Mee CD, Daniel ED (eds). McGraw-Hill: 1996; 8.32.
20. Lambeth DN, Velu EMT, Bellesis GH, Lee LL, Laughlin DE. *J. Appl. Phys.* 1996; **79**: 4496.
21. Néel L. *Ann. Geophys.* 1949; **5**: 99.
22. Sellymer DJ, Yu M, Thomas RA, Liu Y, Kirby RD. *Phys. Low-Dim. Struct*. 1998; **1–2**: 155–166.
23. Tristram C. *Technol. Rev.* 1998; (**July/Aug**.): 44.
24. Wohlfarth EP. *J. Phys. F: Met. Phys.* 1984; **14**: L155.
25. Ross C. *IEEE Trans. Magn.* 1998; **34**: 282.
26. Jorgensen F. *The Complete Handbook of Magnetic Recording*. Tab Books Inc.: Blue Ridge Summit, PA, 1988.
27. Andricacos PC, Robertson N. *IBM J. Res. Dev.* 1998; **42**: 671–680.
28. Nakamura Y. *J. Magn. Magn. Mater.* 1999; **200**: 634–648.
29. Mallinson JC. *The Foundations of Magnetic Recording*. Academic Press: San Diego, 1993.
30. Lambert SE, Howard JK, Sanders IL, Allegranza OC. *IEEE Trans. Magn.* 1993; **29**: 223–229.
31. Lambert SE, Howard JK, Sanders IL. *IEEE Trans. Magn.* 1990; **26**: 2706–2707.
32. Murdock EC, Natarajan BR, Walmsley RG. *IEEE Trans. Magn.* 1990; **26**: 2700.
33. Hata HT, Fukuichi K, Yabubushita K, Umesaki M, Shibata H. *J. Appl. Phys.* 1990; **67**: 642.
34. Palmer DC, Johnson KE, Wu EY, Peske JV. *IEEE Trans. Magn.* 1990; **27**: 307.
35. Lodder JC. *Thin Solid Films* 1996; **281–282**: 474–483.
36. Speliotes DE. *IEEE Trans. Magn.* 1990; **MAG-26**: 141.
37. Gleiter H. *Nanostruct. Mater.* 1995; **6**: 3–14.
38. Siegel RW. Synthesis, structure and properties of nanostructured materials. In *Fundamental Properties of Nanostructured Materials*. Fiorani D, Sberveglieri G (eds). World Scientific: 1994; 1–2.
39. Leislie-Pelecky D, Rieke RD. *Chem. Mater.* 1996; **8**: 1770–1783.
40. Brown Jr WF. *J. Appl. Phys.* 1968; **39**: 993.
41. New RMH, Pease RFW, White RL. *J. Vac. Sci. Technol. B* 1994; **12**: 3196.
42. Chou SY, Wei MS, Krauss PR, Fischer PB. *J. Appl. Phys.* 1994; **76**: 6673–6675.
43. Chou SY, Krauss PR, Kong L. *J. Appl. Phys.* 1996; **79**: 6101–6106.
44. Chou SY, Krauss, PR, Renstrom PJ. *Appl. Phys. Lett.* 1995; **67**: 3113–3116.
45. Kong L, Zhuang L, Chou SY. Proceedings of the IEEE International Magnetics Conference, New Orleans, LA, 1997.
46. Cowburn RP, Adeyeye AO, Bland JAC. *J. Magn. Magn. Mater.* 1997; **173**: 193–201.
47. Adeyeye AO, Bland JAC, Daboo C, Lee J, Ebels U. *J. Appl. Phys.* 1996; **79**: 6120.
48. Barnard JA, Fujiwara H, Inturi VR, Jarratt JD, Weston JL. *Appl. Phys. Lett.* 1996; **69**: 2758–2760.
49. Butera A, Weston JL, Barnard JA. *J. Appl. Phys.* 1997; **81**: 7432–7436.
50. Weston JL, Butera A, Intury VR, Jarratt JD, Klemmer TJ, Barnard JA. *IEEE Trans. Magn.* 1997; **33**: 3628–3630.
51. Butera A, Weston JL, Barnard JA. *IEEE Trans. Magn.* 1998; **34**: 1024–1026.
52. Weston JL, Butera A, Otte D, Barnard JA. *J. Magn. Magn. Mater.* 1999; **193**: 515–518.
53. Eddy Jr CR, Tonucci RJ, Pearson H. *Appl. Phys. Lett.* 1996; **68**: 1397–1399.
54. Schwarzacher W, Kasyutich OI, Evans PR, Darbyshire MG, Yi G, Fedosyuk VM, Rousseaux F, Cambril E, Decanini D. *J. Magn. Magn. Mater.* 1999; **198–199**: 185–190.
55. Dobisz EA, Buot FA, Marrian CRK. Nanofabrication and Nanoelectronics. In *Nanomaterials: Synthesis, Properties and Applications*, Edelstein AS, Cammarata RC (eds). Institute of Physics Publishing: Bristol, 1996; 501–510.
56. Hulteen JC, Martin CR. Template synthesis of nanoparticles in nanoporous membranes. In *Nanoparticles and Nanostructured Films: Preparation, Characterization and Application*, Fendler JH (ed.). Wiley–VCH: 1998; 235–262.
57. Martin CR. *Science* 1994; **266**: 1961–1966.
58. Tonucci RJ, Justus BL, Campillo AJ, Ford CE. *Science* 1992; **258**: 783–785.
59. Eddy Jr CR, Tonucci RJ, Pearson H. *Appl. Phys. Lett.* 1996; **68**: 1397–1399.
60. Morkved TL, Lu M, Urbas AM, Ehrichs EE, Jaeger HM, Mansky P, Russell TP. *Science* 1996; **273**: 931–933.
61. New RMH, Pease RFW, White RL. Proceedings of the IEEE International Magnetics Conference, April, 1995.
62. Mamin HJ, Terris BD, Fan LS, Hoen S, Barrett RC, Rugar D. *IBM J. Res. Dev.* 1995; **39**: 681.

