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TOPICAL REVIEW

Magnetic recording: advancing into the future

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Abstract
In recent years, the stability of recorded data against thermal decay has become an important criterion for judging the performance of magnetic recording systems. Continued growth of storage densities in the presence of thermally activated behaviour, often called the 'superparamagnetic effect', requires new innovations in the recording system in general, and the recording media, in particular. This paper reviews some of the recent advances in recording media (e.g. oriented and antiferromagnetically coupled media) that have helped magnetic recording to maintain the areal density growth rate. However, more innovations and novel architectures are needed for the solutions of tomorrow. Among the more promising media approaches, which are discussed in this paper, are perpendicular, patterned and self-assembled nanoparticle media. Additionally, thermally assisted recording is also reviewed as it combines good writeability with high thermal stability.

1. Introduction

Magnetic storage has played a key role in audio, video and computer development since its invention more than hundred years ago by Valdemar Poulsen [1]. In 1956 IBM built the first magnetic hard disk drive featuring a total storage capacity of 5 MB at a recording density of 2 kbit in^{-2}. In the quest to lower the cost and improve the performance, the areal density, i.e. the number of bits/unit area on a disk surface, has increased more than 20 million-fold in modern disk drives and currently doubles every year (figure 1). As a result disk drives are increasingly smaller, lighter and faster and gigabytes of storage may be purchased at a tiny fraction of the cost of IBM's first hard disk drive. Nonetheless, the pursuit of higher areal densities still continues, as is evident in two recent laboratory demonstrations of recording densities beyond 100 Gbit in^{-2} [2, 3].

However, as reviewed in [4, 5], continued growth in areal density is limited by enhanced thermal effects in modern recording media, known in the recording industry as the 'superparamagnetic effect'. In this paper, we review current magnetic recording technologies enabling these high storage densities and focus primarily on the recording media in the context of the thermal stability. We will discuss recently implemented and promising new developments to postpone perceived thermal limits [6] as well as emerging technologies that hold promise for yet higher recording densities.

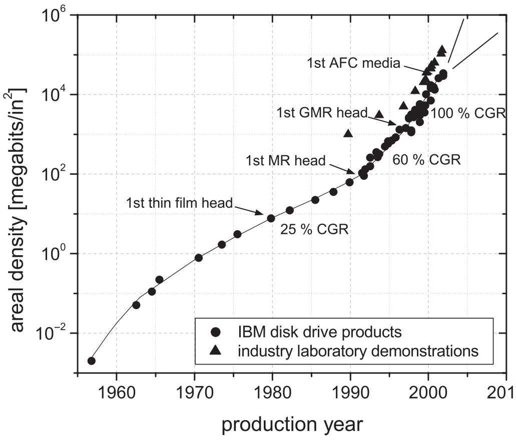

Figure 1. Areal density progress in magnetic recording since its invention (courtesy of Ed Grochowski).

2. Longitudinal recording and thermal effects

Present magnetic disk drives are based on longitudinal recording systems where the magnetization of the recorded bit lies in the plane of the disk. These systems contain a recording head composed of a separate read and write element, which flies in close proximity to a granular recording medium, as illustrated in figure 2. The inductive write element records the data in horizontal magnetization patterns. The information is then read back with the giant magnetoresistive (GMR) read element by measuring the stray magnetic field from the transitions between regions of opposite magnetization. Finally, a signal processing unit transforms the analog readback signal into a stream of data bits.

In longitudinal recording, the readback signal is roughly proportional to the magnetic thickness of the media $M_r t$, where M_r is the remanent magnetization and t is the physical thickness. The magnetic width of the transitions is characterized by a transition parameter a, which depends both on the write head characteristics as well as media parameters, such as the demagnetization length $M_r t/H_c$ of the recording layer, where H_c is the coercivity of the medium. The transition width proves to be particularly important, as it ultimately limits the linear density of bits that can be written on the disk. A related and equally important attribute of a recording system is the ability to resolve transitions written at high linear density. This is investigated by measuring the dependence of the readback amplitude as a function of the bit density, also known as the roll-off curve. Assuming linear superposition of the fields, the roll-off curve can be reconstructed from the readback signal of a single isolated transition. Such a pulse is characterized by the full width at 50% signal amplitude PW_{50} (figure 3) which depends both on the a parameter of the transition and the resolution of the read head. Typically, modern hard disk drives operate up to a maximum normalized linear bit density of $PW_{50}/B = 3$, where B is the bit length [7]. The useable ratio PW_{50}/B strongly depends on system parameters such as the amount of precompensation [8], which corrects undesired shifts of the transition position. This so-called 'non-linear transition shift' (NLTS) is a result of fields from previously written transitions adding or subtracting to the write field and becomes increasingly a problem at high linear densities.

Recording media traditionally have a single magnetic storage layer and consist of weakly coupled magnetic grains as shown in the transmission electron microscope (TEM) image of figure 4 [9]. The medium consists of a CoPtCrX alloy (X = B, Ta) thin film that is grown on top of a complex underlayer structure to obtain the required crystallographic orientation, grain size and grain size distribution. Finally, a thin carbon overcoat and a lubricant layer protect the media from oxidation and physical damage as a result of physical contact with the head.

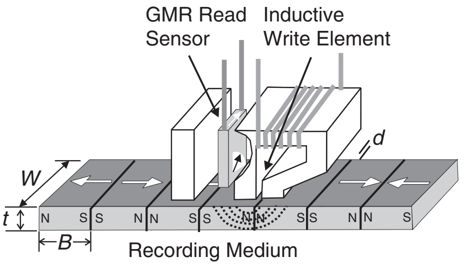

Figure 2. Schematic drawing of a longitudinal recording system. B is the bit length, W is the track width and t is the medium thickness. d is the flying height of the head above the medium.

The fine microstructure allows writing and storing transitions at almost any location and at high linear densities with the ultimate density limited by the grain size. As illustrated in the inset of figure 4 the transitions follow the grain boundaries, which provide strong pinning sites for the magnetic transitions. However, due to the granular structure of the medium small deviations from the intended transition positions occur, which are expressed by transition position jitter.

The required signal-to-noise ratio (SNR) needed for high-density recording is achieved by statistically averaging over

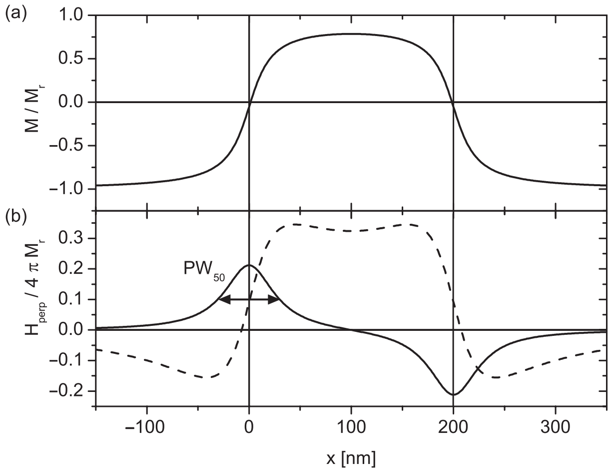

Figure 3. (*a*) Magnetization of two transitions at $x = 0$ and 200 nm. Medium thickness is 15 nm and the transition parameter is 17 nm. (*b*) Perpendicular magnetic field, which is detected by the read head, at 10 nm distance from the surface of (*a*) longitudinal (——) and type 1 perpendicular (- - - -) media. PW_{50} is shown for a read head with zero gap. PW_{50} is larger for heads with finite gaps.

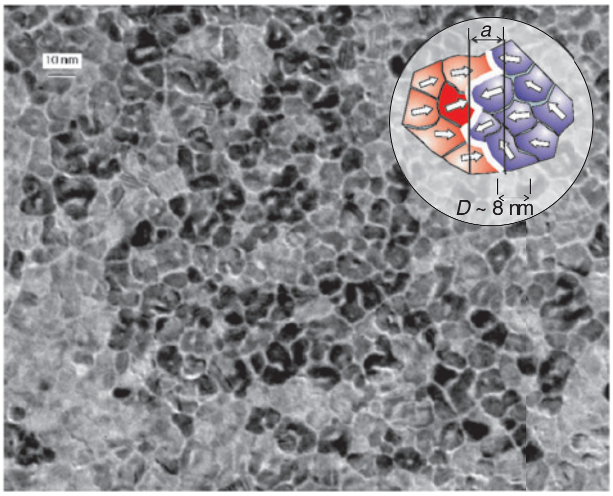

Figure 4. TEM image of modern recording CoCrPtB media. The amorphous non-magnetic Cr rich boundaries, which magnetically separate the Co rich grains, are visible as light grey areas. The inset schematically shows a magnetic transition meandering between the grains.

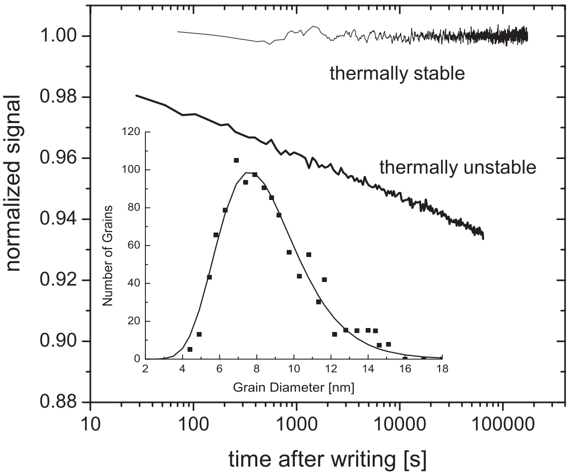

Figure 5. Normalized signal amplitude for a thermally stable and unstable medium as a function of time. The inset shows the grain size distribution of the thermally stable medium, which has been used for the 35 Gbit in^{-2} areal density demonstration [9].

many grains. In order to increase the areal density, i.e. reduce B and the track width W, traditional engineering requires that all design parameters of the head and the recording media be scaled to smaller dimensions. These scaling laws involve a reduction of the recording layer magnetic thickness $M_r t$ to reduce the transition parameter a and the grain diameter D to maintain SNR which can be estimated from [10, 11]

$$\mathrm{SNR} \approx \frac{0.31 PW_{50} B W_{\mathrm{read}}}{a^2 D(1+\sigma^2)} \approx \frac{B^2 W_{r\mathrm{ead}}}{\alpha^2 D^3 (1+\sigma^2)}, \qquad (1)$$

where $PW_{50}/B = 3, \alpha = a/D$ [12]. σ is the normalized grain size distribution width and W_{read} is the read width of the head. Equation (1) is valid only for uncorrelated noise. Note also that the grain diameter D is to the 3rd power and therefore reducing D is very effective in improving SNR.

As the volume $V = \pi D^2 t/4$ of the grains is reduced in the scaling process, the magnetization of the grains may become unstable due to thermal fluctuations, and data loss may occur. This phenomenon, also referred to as 'superparamagnetic effect', became increasingly important in recent years, as new magnetic hard disk drive products are designed for higher areal densities.

The following simple model illustrates these thermal effects. The weak intergranular exchange coupling allows the longitudinal recording medium to be approximated as a collection of independent particles. The energy barrier for magnetization reversal in the presence of an external magnetic field H is given by

$$E_{\mathrm{B}}(H, V) = K_{\mathrm{u}} V \left(1 - \frac{H}{H_0}\right)^n, \qquad (2)$$

where K_{u} is the magnetic anisotropy density and H_0 is the intrinsic switching field. The exponent n is 1.5 to account for the 2D random anisotropy axis distribution in isotropic longitudinal media [13, 14]. When considering finite temperatures, the energy barrier needs to be compared to the thermal activation energy $k_{\mathrm{B}}T$, where k_{B} is Boltzmann's constant and T is the absolute temperature. Thermally activated switching is characterized by a time constant τ following the Arrhenius Néel law [15]:

$$\tau = \frac{1}{f_0} \exp\left(\frac{E_{\mathrm{B}}}{k_{\mathrm{B}}T}\right). \qquad (3)$$

The attempt frequency f_0 is on the order of 10^9–10^{12} Hz [16] and sets the timescale for thermally activated magnetization reversal. From equations (2) and (3), it follows that a reduction of the grain volumes leads to smaller time constants that can, in turn, lead to signal decay and potential data loss as the medium is thermally demagnetized.

In real recording media energy barriers are distributed as a result of volume and anisotropy variations in the grains (inset of figure 5) [17, 18]. Reduced anisotropy has been associated with lattice distortions [19] and crystallographic defects and stacking faults [20]. For a wide energy barrier distribution the magnetization decay is logarithmic in the time t (instead of exponential as predicted by equation (3)) and may be approximated by [21]:

$$M(t) = M(t_0) + S^* \log\left(\frac{t}{t_0}\right), \qquad (4)$$

where S is the magnetic viscosity coefficient and generally is a function of H and T. Experimentally, we find that the readback amplitude generally follows the magnetization decay and exhibits thermal decay that is linear in $\log(t)$ (figure 5). A medium energy barrier of the distribution is often determined by measuring the coercivity as a function of the magnetic field pulse width t_{p} and analysed using the following equation [22]:

$$\frac{H_{\mathrm{c}}}{H_0} = 1 - \left(\frac{k_{\mathrm{B}}T}{K_{\mathrm{u}}V} \ln\left(\frac{f_0 t_{\mathrm{p}}}{\ln 2}\right)\right)^{1/n}, \qquad (5)$$

which directly follows by combining equations (2) and (3) and requiring that half of the grains have switched at H_{c}. Theoretical [6] and experimental [23] analyses arrive at the thermal stability condition $K_{\mathrm{u}}V > 55 k_{\mathrm{B}}T$ at drive operating temperatures $T \sim 340$ K to maintain sufficient signal stability over at least five years of data storage. This criterion sets an effective limit on the minimum grain volume and was the basis for the predictions that areal densities would be limited by thermal activation of the grains [5, 6]

In the presence of these thermal effects, there are a variety of materials and systems changes can be implemented to lessen their impact. Thermal stability is improved by improving epitaxy [24], reduction of crystallographic defects [20] and by materials with higher anisotropy for the recording media, where the increase in K_{u} counters the reduction in V to maintain the thermal stability. The latter is currently achieved by increasing the Pt content in modern CoPtCrB media. Other media candidates with high anisotropy are the tetragonal L1_0 phases of FePt [25] and CoPt, artificially multilayered materials and rare earths compounds [26]. Nevertheless, following along this path also increases the write field requirements, since the write field

$$H_{\mathrm{w}} \approx H_0 \approx \frac{K_{\mathrm{u}}}{M_{\mathrm{s}}}, \qquad (6)$$

where M_{s} is the saturation magnetization of the recording media. The required write field improvements were traditionally achieved by design changes in the write head and the use of materials with higher saturation magnetization as the write poles. However, modern write poles already consist of low-anisotropy materials with saturation magnetization density approaching the highest recorded value [27, 28], which will limit the maximum achievable write field. Reducing the bit cell aspect ratio W/B (BAR) will result in SNR improvements (equation (1)), as discussed in [12, 29]. This trend is already visible in areal density demonstrations, in which BAR was reduced on average from ~12 : 1 to ~6 : 1 over the past four years. However, at lower BAR track edge effects are more pronounced, and the demands on the lithographically defined read and write widths of the head and the servo system, which keeps the head on a given track, become disproportionately stronger. Finally, improved signal processing and error correction codes (ECCs) [8] reduce the media SNR requirements and allow the use of larger grains in recording media. However, the advancements resulting from these improvements are by far not enough to sustain the current areal density growth rate.

It is becoming increasingly clear that to avoid limitations to areal growth rates arising from thermal instabilities in future high-areal-density products, significant improvements of the recording medium must be achieved. New thin film materials or architectures are needed that ease the write field requirements at high areal densities and are more thermally stable than conventional media. In the remainder of the paper we discuss two near term approaches and more speculative approaches for further improvements in the recording media. Oriented media and antiferromagnetically coupled (AFC) media [30, 31] are good examples for novel recording media, which extend the evolutionary development of longitudinal recording towards higher densities. AFC media has been used for both areal density demonstrations [2, 3] at $>100\,\mathrm{Gbit\,in^{-2}}$ and has been integrated in products for more than a year. Perpendicular [32, 33] and thermally assisted recording (TAR) [34] are among the promising approaches, but they require significant changes of many components of the recording system. Finally, patterned recording media [35, 36], recording media consisting of chemically synthesized nanoparticles [37, 38] and nanocomposites [39], are pursued for potential use at ultrahigh recording densities. The characteristics of each approach are summarized in table 1 and will be discussed in the following sections.

Table 1. Overview of the characteristics of new approaches in magnetic recording. Listed are the trends of switching fields, which directly transform into write field requirements, the causes for increased thermal stability, and required changes in head and media. The second part lists system and processing considerations, successful areal density demonstrations and expected areal density gains over conventional longitudinal recording.

	AFC	**TAR**	**High K_u**	**Nanoparticles**	**Perpendicular**	**Perpendicular patterned**
		Higher				Lower H_0
Switching field (H_0)	Independent of M_rt	Temporally reduced			Higher write field available (~2×)	
		Higher anisotropy, K_u				
Higher thermal stability	Thicker media, larger grain volume			But: fill factor of spherical volume 2/3 of that of cylinders	Thicker media, smaller demagnetizing fields	Large islands
Head	None	Waveguide/laser	High moment write element		Single pole head	
Media	AFC structure (more magnetic layers)	High K_u Reduced grain size		High K_u, chemically synthesized, deposition on substrate, anisotropy orientation	Perpendicular High K_u (granular, multilayer) $H_c \gg 4\pi M_s$ Orientation → narrow switching field distribution	Each disk must be patterned! Anisotropy orientation (e.g. perpendicular)
					Soft underlayer	
System	None	Timing of heating, degradation of adjacent tracks	None		Channel, head skew Sensitivity to external magnetic fields	Single element storage synchronization of head and islands
Processing/ manufacturing	Two additional layers (bottom layer and Ru layer)	Integration of waveguide/ laser in head		Spin coating	Thick soft underlayer, recording media, single pole head	Patterning process
Areal density demonstration ($\mathrm{Gbit\,in^{-2}}$)	104	N/A	64	N/A	63.8	N/A
Areal density gain over conventional longitudinal recording	2×	2–10× [34]	1×		2–7× [91]	~10× [36]

3. Oriented longitudinal media

In the above discussion the anisotropy axis of grains is randomly oriented in plane. In these 2D isotropic media the easy axes of most of the grains are only partially oriented along the track direction. In fact, the easy axes of some grains are perpendicular to the track direction. Even if fully magnetized, such grains may not contribute to the readback signal, yet potentially increase the noise. Consequently, such grains should not be taken into account in SNR considerations, effectively leading to a media SNR reduction. As compensation more grains are needed for each bit cell [40], and, as discussed above, thermal instabilities emerge at even lower areal densities.

The discussed disadvantages are diminished, when the easy axes of the grains have preferred orientation along the track direction (i.e. circumferentially around the disk). These so-called oriented media feature a lower media noise [41], a higher signal level, a smaller transition parameter and a narrower switching field distribution [42]. Maximum areal density gains as a result of perfect orientation and based upon SNR considerations are estimated to be between 2.3 and 2.7 dB [40]. However, such high orientation of the grains is not easily realizable.

The degree of easy-axis orientation is expressed in orientation ratio $\mathrm{OR} = M_\mathrm{r}/M_{\mathrm{r}\perp}$ with M_r and $M_{\mathrm{r}\perp}$ representing the remanent magnetizations along and perpendicular to the track, respectively. Current longitudinal media achieve OR values of >2.5 [43], which is obtained by mechanically texturing metal disk substrates, anisotropic etching of the substrate or directional deposition of the recording media. However, a pathway to higher OR values is not known and is an area of current research. Implementation of oriented media in longitudinal recording systems is relatively straightforward, as required changes are limited to the recording media. Consequently, oriented recording media are widely used in disk drives.

4. AFC media

In early 2001 IBM introduced AFC recording media into products. Developed independently at IBM [30, 44] and Fujitsu Research [31], AFC media consist of two magnetic layers, which are antiferromagnetically coupled through a non-magnetic Ru layer[3] with a thickness of about 0.6 nm. Figure 6 shows a schematic drawing of a transition in AFC media. In the remanent state, both layers are magnetized in antiparallel direction, such that the effective magnetic thickness $M_\mathrm{r}t_\mathrm{eff}$ is given by the difference between the $M_\mathrm{r}t$ of the two layers. The reduction of $M_\mathrm{r}t_\mathrm{eff}$ leads to a smaller transition parameter, while the enhanced total physical thickness of the structure improves thermal stability. The fascinating aspect of AFC media is that it allows independent optimization of stability and $M_\mathrm{r}t_\mathrm{eff}$ by adjusting the physical thickness and magnetic properties of each layer. In addition, the write field is lower in well-designed AFC media than in stable, high-SNR single layer media. While there are still many open questions concerning the physics of AFC media, it provides an evolutionary extension of currently available technologies by allowing continued scaling of longitudinal magnetic recording media, while maintaining low write field requirements and thermal stability. Implementation of AFC media technology requires no changes in read and write heads and other system components of a hard disk drive.

The readback process of transitions in AFC media is similar to single layer media. The read head senses the superposition of the magnetic fields of the transitions in both layers, which results in a single pulse at a reduced amplitude [45]. As a result of the smaller $M_\mathrm{r}t_\mathrm{eff}$, the transition parameter and therefore the readback pulse width PW_{50} is reduced [30], allowing the detection of transitions at higher linear densities.

In comparison to single layer media with $M_\mathrm{r}t = M_\mathrm{r}t_\mathrm{eff}$ and similar grain size, the thermal stability is enhanced in AFC media due to the larger top layer thickness, as shown in figure 7. For weak antiferromagnetic exchange coupling the energy barrier for magnetization reversal is almost independent of the thickness of the bottom layer, as experimentally demonstrated in [46]. However, recently performed experiments suggest that bottom layer properties enhance thermal stability beyond the stabilization effect of the demagnetizing fields [47], if the bottom layer anisotropy and the antiferromagnetic exchange coupling are sufficiently large [48].

The magnetic switching process in AFC media during a write cycle is more complex than in single layer media [49] and is illustrated in figure 8 by a hysteresis loop. In large positive fields, the two layers are parallel and aligned with the applied field. As the field is reduced, the bottom

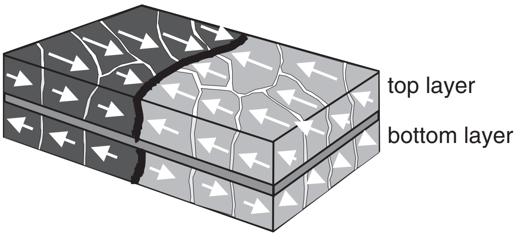

Figure 6. Schematic representation of a magnetic transition in AFC media.

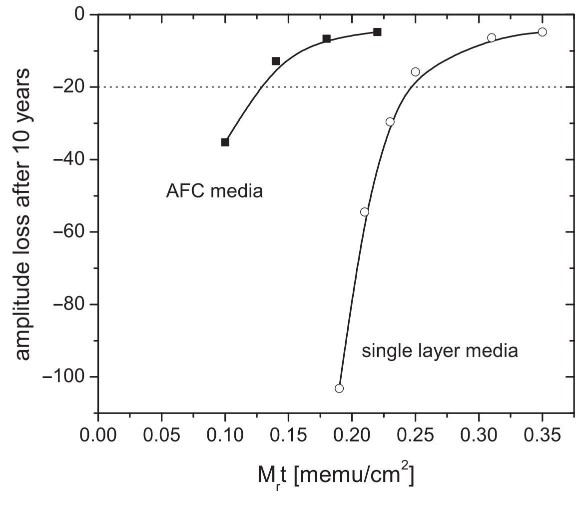

Figure 7. Comparison of amplitude loss as a result of thermal degradation of single layer media and AFC media. The AFC media exhibits less amplitude loss for smaller $M_\mathrm{r}t_\mathrm{eff}$ than single layer media, and consequently allows scaling to smaller grain diameters.

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[3] Popularly also known as 'pixie dust'.

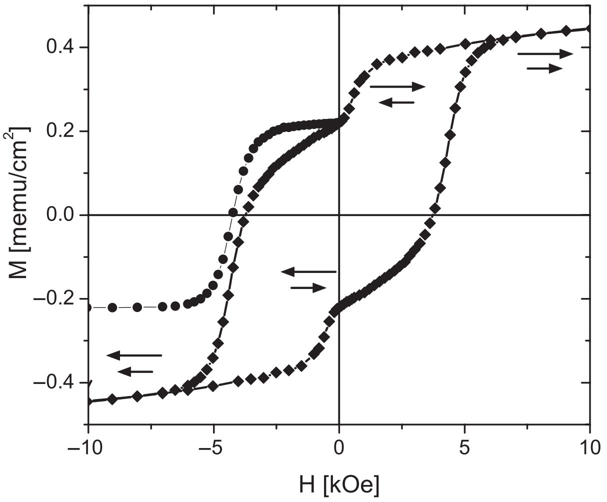

Figure 8. Hysteresis loop of AFC media (♦) and remanent hysteresis loop (●) [30]. The $M_r t$ of the top and bottom layer is 0.31 and 0.09 memu cm^{-2}, resulting in $M_r t_{\mathrm{eff}} = 0.22$ memu cm^{-2}.

layer reverses and in the remanent state, both layers are magnetized in opposite directions. This is a result of both the antiferromagnetic coupling and the dipolar fields of the granular structure [50]. When an external magnetic field is applied in opposite direction, the top layer reverses and again for large magnetic fields, which are applied during the write process, the magnetization in both layers points into the same direction. Finally, as the external field is reduced below the antiferromagnetic coupling field, the magnetization of the bottom layer reverses and the systems move into its other remanent, antiparallel state where both layers are magnetized opposite to their initial state.

This 'non-linear' switching characteristic of AFC media is unique among proposed architectures for longitudinal recording media. Even though the structure is thermally stable, only a small increase of the top layer coercivity is observed, which is a consequence of the antiferromagnetic exchange field from the bottom layer acting on the top layer during reversal. As a result, the write field requirements are only modestly increased. This conclusion is also supported by an experimental study, in which the intrinsic switching field was found to be independent of the bottom layer thickness for small antiferromagnetic coupling [46]. In contrast, if the antiferromagnetic coupling field between the layers was larger than the top layer coercivity, the write field requirement would be much higher and similar to that of a single layer media with equal thermal stability and microstructure [5].

The timescale for the reversal of the bottom layer after writing from the parallel into the antiferromagnetic state is very important for the overall performance of AFC media. That is, because the two layers are relatively weakly coupled compared to typical anisotropy fields, there may be a time lag between removing the applied field and reversal of the bottom layer into the antiparallel state. If the relaxation time is very small (∼1 ns), the reversal of the bottom layer may impact the write process of the next transition and may lead to variable NLTS. In contrast, if the reversal time is long, the bottom layer might not have sufficient time to reverse during a full rotation of the disk (∼4 ms for a 15 000 RPM disk drive), and the readback signal is not well defined.

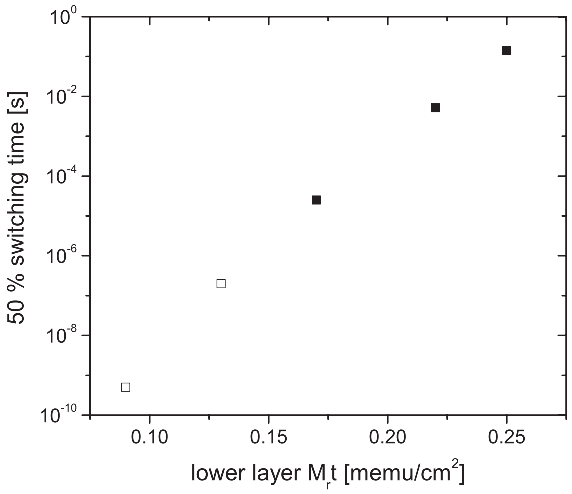

Figure 9. Bottom layer switching time as a function of thickness. The AFC media represented by open symbols have bottom layer thicknesses that are optimized for performance. Their switching times are extrapolated from measurements using thicker bottom layers (■).

To determine the bottom layer reversal time, the bottom layer thickness of the investigated AFC media was increased to slow down thermally activated relaxation processes. A spinstand was used to measure the reversal time of the bottom layer from a DC magnetized state into the antiparallel state (solid squares in figure 9) [51]. Extrapolation of these results to typical bottom layer thicknesses used in high-performance AFC media shows that the reversal time is ∼100 ns (open squares in figure 9), which is in the middle of the two extremes discussed in the previous paragraph. Thus, from a system integration point of view, the write process of AFC media, even though more complex, appears very similar to that of single layer media.

5. Perpendicular recording

In perpendicular recording the easy axis of the recording media is perpendicular to the film surface. In 2000 Hitachi presented a laboratory demonstration of an areal density of 52.5 Gbit in^{-2} using granular CoPtCr medium [52]. This achievement and a later areal density demonstration at 63.8 Gbit in^{-2} using multilayer media clearly manifested that perpendicular recording is an important candidate for extension of the current magnetic recording technology. However, since its inception more than twenty-five years ago [53], no successful product based on perpendicular recording technology has been made, despite considerable efforts. This is a result of superior performance from longitudinal recording systems. However, as thermal stability becomes an increasingly important limitation in longitudinal recording, this may tip the scales in favour of perpendicular recording, which is believed to have thermal stability advantages at comparable recording densities. In the following section, we summarize advantages and disadvantages of perpendicular recording. Detailed reviews may also be found in [33, 54, 55].

Two different types of recording media have been considered for the use in perpendicular recording systems.

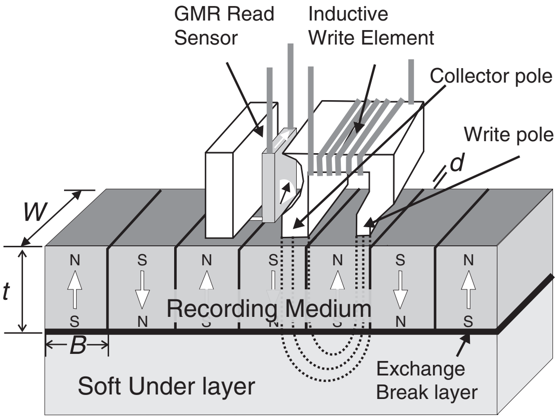

Figure 10. Schematic drawing of a type 1 perpendicular recording system with SUL and a single pole head.

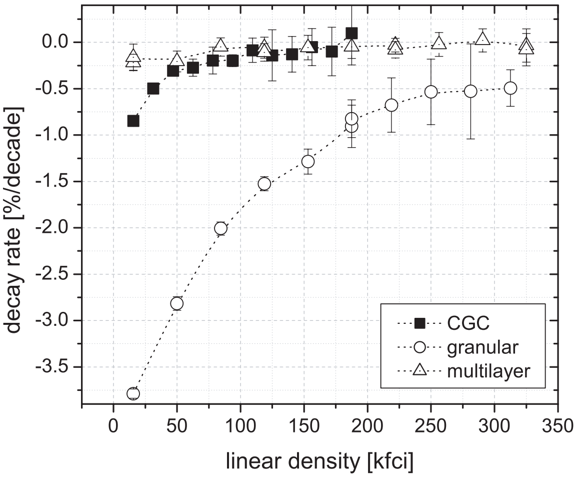

Figure 11. Signal decay for different types of perpendicular media as a function of linear density (kilo flux changes per inch, kfci). An additional multilayer stabilizes the thermally unstable granular medium (CGC medium).

Type 1 consists of a recording media with the easy-axis oriented out-of plane deposited on a high permeable, soft magnetic underlayer (figure 10). Type 2 is similar to type 1 without the soft underlayer (SUL) and utilizes a conventional ring head, as used in longitudinal recording. Only little work is in progress using type 2 recording media, as it does not possess some of the advantages of type 1 media. Therefore, a recording system based upon type 1 media is generally considered to be the main candidate for replacing longitudinal recording media and will be the focus of the following discussion.

A recording system based on type 1 media is depicted in figure 10 with a conventional GMR read head for detection of transitions. A write head with a wide gap between the write and collector pole is preferred to prevent flux leakage between both poles [56]. The transitions are written with the trailing edge of the write pole. The SUL guides the magnetic flux from the write pole to the collector pole and essentially becomes part of the write head. In simple models, it is often assumed that the SUL generates a mirror image of the write pole, therefore effectively placing the recording media in the ‘gap’ of the ‘write head’. On the one hand, this arrangement has the advantage of theoretically almost doubling the write field, allowing writing transitions in recording media with higher anisotropy, which in turn are thermally more stable. More complex micromagnetic modelling [57] still predict a magnetic field increase of up to 70% [58]. On the other hand, the combination of head and SUL is a highly efficient magnetic flux guide and may focus external fields, such that degradation of previously written tracks and even data loss might occur. To avoid writing transitions with the collector pole, the magnetic field must be much smaller at the collection pole ($\sim$10%) than at the write pole. Simple surface area scaling allows adjusting the field ratio of the collection pole and write pole.

Demagnetization fields, which favour opposite magnetization of neighbouring grains, also improve thermal stability for high-density patterns[4], but enhance decay rates at low linear densities, in particular if H_c is close to or smaller than $4\pi M_s$. Thus, high-density bit patterns decay slower than low-density bit patterns, as shown in figure 11, in which decay rates are plotted as a function of linear transition density for different types of perpendicular recording media. This is in contrast to longitudinal media, where demagnetization fields destabilize bit patterns at higher linear densities. Besides the enhanced thermal stability, perpendicular recording also benefits from the uniform easy-axis orientation as a result of its naturally high orientation ratio. Media noise is reduced, while the readback signal is increased.

As of today, areal density demonstrations, however, could not yet take full advantage of the potential of perpendicular recording. Some of the critical components, such as perpendicular recording media and SULs, need further improvements. Also different shapes of the write pole of the head are investigated in order to optimize the magnetic write field [59], and the large readback signal amplitude at low densities (figure 3) might require different read head designs. Finally, special modulation codes, which on average result in zero magnetization of the track, might be required to reduce the maximum demagnetization field [60].

5.1. Soft underlayer

The SUL is a crucial part in the writing as well as the reading process in perpendicular magnetic recording. During the write process, it needs to guide the magnetic flux from the write pole to the collector pole with low reluctance. Therefore, materials of choice have high permeability, high saturation magnetization and low coercivity. Even though high saturation materials are used, the thickness of the SUL ranges between 100 and 400 nm. This thickness is much larger than that of layers in current longitudinal recording media and poses a considerable challenge to deposition tools. In addition, surface roughness of the SUL, which tends to increase with layer thickness, needs to be kept small to allow the head flying close to the recording medium. Besides the criteria discussed above, the total spacing between write pole and SUL must be minimized for optimal write field efficiency. Finally, magnetic domains must be avoided in the SUL as their presence leads to spike noise in the readback signal [61]. The large perpendicular field from the domain walls in the SUL

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[4] A small amount of intergranular exchange interaction may be utilized to counteract some effects of the demagnetization fields.

may additionally demagnetize the transitions lying above in the recording media.

Candidate materials for SULs under investigation are soft magnetic materials, such as NiFe, CoNbB, FeAlSi, CoFeB, FeTaN, FeTaC and CoFe. Many of these materials have domains in their as-deposited state. In CoFeB, for example, annealing at ∼400˚C removes the domain structure. Similar effects are also achieved by depositing the SUL on an antiferromagnetic material [62], thereby introducing radial anisotropy, or breaking up the SUL into several layers.

Micromagnetic modelling [63] provides a valuable tool to study the microscopic and dynamic response of different SUL designs and materials to write fields and fields generated by transitions [58]. These calculations indicate for the SUL that without significant performance degradation its thickness may be smaller and its coercivity may be larger than simple models would suggest.

5.2. *Perpendicular recording media*

Three different structures shown in figure 12 have been investigated extensively for perpendicular recording media.

(a) CoCr based granular media [64, 65] were used in the first implementations of perpendicular recording systems. Granular media profit from the enormous amount of expertise in grain size control, which has been obtained for longitudinal media. As discussed above, grain size control is extremely important, as it directly influences media SNR (equation (1)). However, the anisotropy in the perpendicular granular layer (GL) is found to be substantially lower than in similar longitudinal media, leading to high thermal decay rates. High stacking fault density or FCC lattice formation present in the HCP grains might be the reason for the low anisotropy [64, 66]. It is vital for the success of granular media to overcome this problem.

(b) Advancements in deposition techniques permit growing well-defined artificial superlattices [67], such as Co/Pd and Co/Pt [68] multilayers. Adjusting the thickness of the individual layers and the total number of layers allows optimizing the magnetic properties. These multilayer media have large intrinsic exchange coupling in the film plane, which induces transition noise. High-pressure deposition, and addition of segregants, such as B or Cr, or impurities, such as O, during deposition reduce the in-plane exchange coupling. The exchange interaction between multilayer and SUL is reduced by an exchange break layer (EBL).

(c) While granular media often lack thermal stability, multilayers are difficult to exchange decouple in the film plane. These drawbacks were the motivation to introduce the so-called coupled granular and continuous (CGC) media [69], which combines the thermal stability of multilayer media and the low-noise properties of granular perpendicular media. Figure 11 shows that deposition of a multilayer on top of a thermally unstable granular media improves thermal stability considerably [70]. Though the CGC media design still needs optimization, initial results indicate improved SNR, reduced transition position jitter and higher signal amplitude [70].

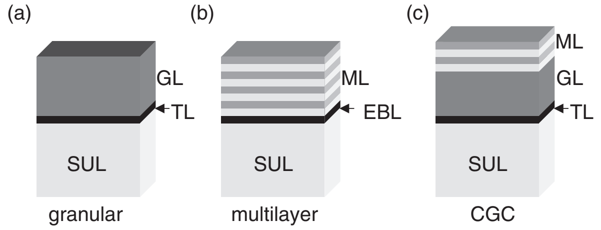

Figure 12. Different media structures investigated for use in perpendicular recording: (*a*) granular medium, (*b*) multilayer medium and (*c*) CGC medium. TL is the template layer, which controls the grain size in granular media.

6. Thermally assisted recording

TAR may be used for longitudinal recording as well as for perpendicular recording. This recording scheme is also called hybrid recording, as it combines the localized write field in conventional magnetic recording with thermal writing in magneto-optical (MO) recording.

TAR exploits the temperature dependence of the anisotropy of recording media. By temporally heating the recording media during the write process, the switching field of the grains and therefore the write field requirements are reduced. The medium is then quickly cooled back to ambient temperature to store the data. Such a system allows the use of recording media with increased magnetic anisotropy compared with that used with conventional writing and thus provides enhanced thermal stability and potential scaling to smaller grain sizes. TAR is in the initial stage, and only few experiments have been performed to explore the concept. In contrast to oriented or AFC media, implementation of TAR requires considerable changes of the system architecture and the write head, in which a local heat source such as a laser or optical waveguide with attached laser must be integrated.

The concept of TAR has been experimentally demonstrated in [34, 71]. In both cases, a laser spot from a separate laser was used to locally heat the recording medium from the opposite side the recording head. The effect of the heating process was clearly demonstrated by offsetting the write and the laser gate [71]. With the laser gate closed transitions could not be written, while excellent writing was achieved when both gates were open simultaneously.

Several approaches are currently under consideration [72]. One approach relies on a high thermal gradient to define the magnetic transition with a large magnetic field spot, similar to MO recording systems. Another uses high magnetic field gradients to write transitions, while heating an area much wider than the tracks. In both cases, adjacent tracks are either exposed to high magnetic fields or high temperature, resulting in amplitude degradation and limiting the advantages of TAR. These degradation effects are avoided in systems with combined high magnetic field gradient and high thermal gradient, which result in the highest potential areal density gain over conventional recording [72].

7. Patterned media

Recording on patterned media is under exploration as an alternative recording scheme for years [36, 73, 74, 75]. It relies on a different strategy than the previously described approaches. Instead of statistically averaging the signal of many independent grains forming a bit, each bit consists of exactly one unit or island, which is lithographically predefined in the recording medium. The individual islands have a much larger volume than the grains in conventional recording media and are therefore thermally stable [76]. Furthermore, switching field requirements are not adversely affected in patterned media, since volume and not anisotropy is increased (equation (6)). In contrary, since island volumes are larger than the grains, the required thermal stability is achieved, even if the anisotropy density is reduced in the islands.

The islands are lithographically patterned into regular array in the recording medium. The patterning presents a considerable challenge for the manufacturing process, especially since each disk must be patterned with high resolution. For example, in order to achieve 1 Tbit in^{-2}, the island array periodicity is 25 nm and the lithographic linewidth is ~12.5 nm for equal island and trench width. The required lithographic resolution is too high for conventional optical lithography, and advanced lithographic technologies, such as e-beam lithography, are too costly. It therefore requires new processes, such as ion beam irradiation through stencil masks [77], which allow using a patterned mask for many disks. By including servo information in the pattern [78], the costly process of writing the servo information in current drives is eliminated. In an alternative way, one could use interference lithography or even nature to self-assembled particles in regular arrays (see section 8). However, it is still preferred to have rotation symmetry of the disk, which is difficult to achieve with interference lithography.

While transitions are written at arbitrary positions in conventional longitudinal media, they must be precisely written between two islands in patterned media. Thus, the write current waveform must be synchronized with the islands on the disk. Synchronization requirements in granular type 2 perpendicular media have been studied as a function of island density [79] and write current [80]. Figure 13 shows the investigated prototype medium, which has been patterned using a focused ion beam [81]. Using a static write/read tester [82], the phase of the write current waveform was changed with respect to the patterned islands. The authors found that without significantly reducing the write performance synchronization errors may be as large as 50 nm for 105 nm wide islands, depending on the switching field distribution of the islands and the head field gradient [80]. Furthermore, it was found in these experiments that transition position jitter is dominated by *correlated* lithography jitter and SNR is independent of the read width [83]. Consequently, equation (1) is no longer valid for this class of media.

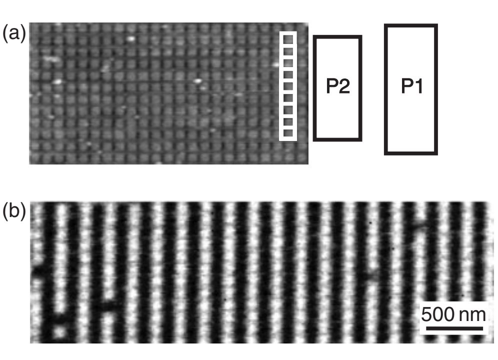

Figure 13. (*a*) Topography image of the FIB patterned area. For illustration purposes the write pole of the head (P2) is also shown. Using such a head, only rows of islands can be written.
(*b*) Magnetic force microscopy image of a square wave pattern recorded in patterned media.

8. Nanocomposite and nanoparticle media

Nanocomposite and nanoparticle media are also considered for recording media and have been successfully used in preliminary longitudinal contact recording studies [37, 84]. Both types of media take advantage of the high anisotropy in hard magnetic materials, such as FePt and CoPt. In nanocomposite materials an annealing process transforms a multilayered structure into non-magnetic matrix ($\mathrm{C, BN, SiO_2, \ldots}$) containing magnetic particles and simultaneously initiates a phase transition into the ordered $L1_0$ phase in the particles [85, 39]. In contrast, nanoparticle media are made in a chemical process, followed again by an annealing step to obtain the hard magnetic $L1_0$ phase [37, 38]. In the process proposed in [37] the diameter of the particles may be controlled to a high degree from 3 to 12 nm. Monodisperse, non-interacting particles (figure 14), in particular, promise reduced noise (see equation (1) with $\sigma \sim 0$) and reduced decay rates [86]. However, a recent experimental and theoretical study shows that low temperature (<550˚C) annealed FePt assembly can contain a significant fraction of superparamagnetic particles, while in an FePt assembly annealed at >600˚C, the switching volume is larger than the particle volume, indicating the presence of undesirable ferromagnetic coupling between particles [87]. The results seem to suggest that, for the FePt nanoparticles, the temperature window for forming desired $L1_0$ phase without significant particle aggregation is very narrow.

The filling factor in nanocomposite and nanoparticle media is smaller than in cylindrical grains of conventional media, resulting in smaller energy barriers for magnetization reversal (see equation (2)). In the case of the spherical,

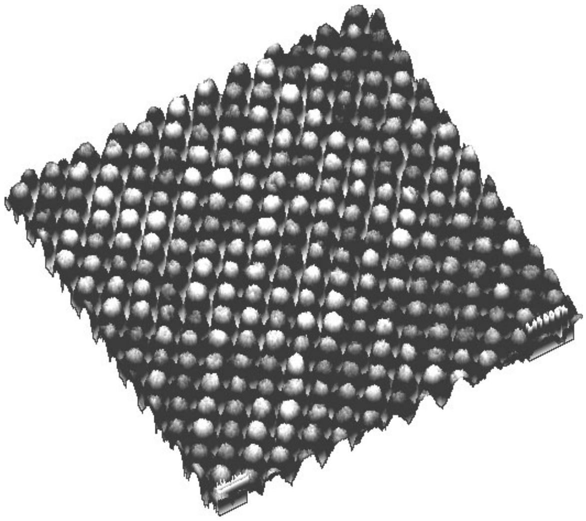

Figure 14. TEM image of a 3D assembly of FePt nanoparticles. Image size is 130 nm × 130 nm. Particle diameter is 4 nm.

chemically synthesized nanoparticles the volume is 33% smaller than cylindrical grains with the same diameter. High-density arrays of cylindrical nanorods might be advantageous, as they have a better volume fill factor [88].

When deposited on a substrate with high mobility, such as in a slowly evaporating fluid, nanoparticles naturally order into a superlattice. However, the angular and spatial coherence lengths are typically limited to a few dozen particles and cannot be extended to a complete disk surface. Using trenches at a distance on the order on the coherence length much more regular arrays may be generated [89]. This approach also allows introducing rotation symmetry in the nanoparticle media in conformance with the rotational symmetry of a hard disk.

9. Conclusions and outlook

It is generally accepted in the magnetic recording community that traditional scaling in longitudinal recording is approaching its limit. The introduction of AFC media, a more complex media structure, demonstrates that innovations can extend longitudinal recording beyond the previously perceived limits. However, soon further ideas are needed for continued success of longitudinal recording.

With the 100 Gbit in^{-2} barrier recently achieved, the next big challenge now looming ahead of the recording industry is 1 Tbit in^{-2} [90]. Models are currently being developed to estimate requirements for media, head and signal processing, which are typically not based on traditional longitudinal recording.

However, the obstacles for displacing longitudinal magnetic recording with an alternative technology are very high. Experience, cost and manufacturability are some of the issues, only to mention a few that favour the continued use of longitudinal recording. A potential candidate must also offer significant areal density advantages in comparison to the current technology.

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