New Paradigms in Magnetic Recording

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The magnetic hard disc drive industry continues to face serious challenges in its quest for ever decreasing bit size. This review summarizes recent advances and promising new technology which have foundations in fundamental physical principles. Some advantages of these new ideas are illustrated through micromagnetic modeling and the numerous challenges associated with their implementation are highlighted.

INTRODUCTION

The phenomenal increase in the storage capacity of magnetic hard disc drives (HDD) in recent decades has been fueled not only by clever improvements in the engineering of tiny devices but also by discovery, and advances in understanding, of fundamental physical phenomena associated with magnetism at the nanometer length scales [1]. Hard drive capacity (see Fig. 1) is governed largely by the number of bits which can be packed in a given unit area, Areal Density (AD), on the recording media (the disc). Over the past 55 years, the units of this core metric have increased from kb/in^2, to Mb/in^2, to Gb/in^2, and recently to Tb/in^2. The nontrivial task of making the early inductive transducers smaller (aided by the advent of thin-film technology) had enabled Compound Annual Growth Rates (CAGR) of about 40% in the first 35 years. Subsequent increases in AD were largely due to fundamental changes in the three main magnetic components of the hard drive: The recording media, the write element of the transducer and the read element of the transducer [2]. These three components, which are the focus of this review, interact and govern an important characteristic of information storage and retrieval in the HDD, namely the magnetic signal-to-noise ratio (SNR). Improvements in non-magnetic component technologies, such as signal processing, spindle bearings, active transducer-to-media spacing control, servo mechanical control, and variable bit aspect ratio along the radial direction have also been crucial to AD growth.

Fig. 1. Western Digital's Scorpio 320 GB 2.5" hard drive.

The award of the Nobel Prize in Physics to Albert Fert and Peter Grünberg in 2007 for the discovery of Giant Magnetoresistance (GMR) indicates the importance of fundamental research to the HDD industry. GMR was incorporated into transducers for magnetic recording in the late 1990s and followed the use of ordinary Anisotropic Magnetoresistance (AMR) introduced earlier in that decade. The implementation of Tunneling Magnetoresistance (TuMR) in 2005-6 has proven even more effective in increasing read-back amplitude [3].

The growth in CAGR from 40% to 60% to 100% which began in the mid 1990s and spanned the following several years (Fig. 2) was only partly due to these advances in the transducer read element. Significant improvements in the write element, and even more importantly in the recording media, were essential in facilitating this unprecedented shrinkage in bit size. Typically, the limiting factor in magnetic SNR is the noise from the media component.

The introduction of new technology into the recording system has occasionally resulted in large, although temporary, gains in CAGR. Over the past five years innovations such as the use of perpendicular recording have allowed for continued growth in AD although at more moderate and historic rates of 40-50%. Maintaining AD growth will continue to rely on the discovery and successful implementation of new concepts to improve magnetic sensors and storage media.

Fig. 2 also reveals that there has historically been a large gap of two years (and up to a factor two or three in AD magnitude) between laboratory demonstrations ('demos') and shipped product. The demos comprise a rare combination of transducer and media that yields an unusually high AD on laboratory equipment. This combination typically is found after screening thousands of components. Demos illustrate the possibilities of science but it requires years of challenging engineering to realize a viable mass produced HDD product.

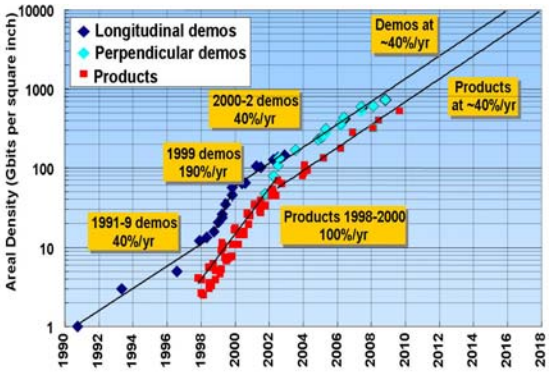


Fig. 2. Growth in areal density (Source: INSIC). Large increases in the late 1990s were due to the advent of high moment writer materials, reader GMR technology and improved media magnetics.

An important tool for the investigation of the magnetic components of the HDD is micromagnetic modeling [2,4]. This is a method to describe the evolution in time of a system of interacting magnetic grains, where each grain is assumed to be uniformly magnetized with a total moment $\boldsymbol{M}$. It is based on the dynamic torque equation involving the gyromagnetic ratio, γ, and the cross-product of $\boldsymbol{M}$ with the effective magnetic field acting on the grain, $\boldsymbol{H}_{\text{eff}} = -\delta E/\delta \boldsymbol{M}$, where E is the magnetic energy [5]. An additional damping term is also added, with a damping constant α. This latter term drives the moment to the minimum energy configuration, $\boldsymbol{M} \parallel \boldsymbol{H}_{\text{eff}}$.

$$(1+\alpha^2)\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M}\times\boldsymbol{H}_{eff} - \frac{\alpha\gamma}{M}\boldsymbol{M}\times\left(\boldsymbol{M}\times\boldsymbol{H}_{eff}\right)$$

The effective field typically involves five major contributions: exchange coupling with neighboring grains, crystalline anisotropy, magnetostatic (e.g., dipole) interactions with all grains, a stochastic field which accounts for finite temperature effects, and an external field. A challenging aspect for numerical solutions to this equation is the long-range nature of magnetostatic interactions. All three magnetic components of the HDD can be modeled with the aid of this equation. The impact of intrinsic magnetic film properties and the design features of each component, as well as their interactions, on metrics like magnetic SNR can be evaluated with this tool.

The recording layer in modern HDD discs is a granular Cobalt-Chrome-Platinum-based alloy with high uniaxial magnetocrystalline anisotropy derived from its hcp crystalline structure. Thin films 15 – 20 nm thick are composed of crystalline grains which are physically isolated through the segregation of inter-granular non-magnetic Cr to the grain boundaries. Prior to 2006-7, all HDDs used so-called longitudinal media where the Co c-axis lay in the media plane. Hence the easy-axis anisotropy direction and magnetization were also in the film plane. Smaller grain size is a very important factor in increasing media SNR not only because it allows for straighter transitions (Fig. 3) but also from a purely statistical point of view since SNR ~ $\sqrt{N}$ where N is the number of grains per bit. In the past decade, modal grain sizes have decreased from about 20 nm to about 9 nm. There are a variety of technical challenges in sputtering thin films to achieve such dimensions.

In addition to smaller grains, smaller grain-size distributions, as well as smaller variations in magnetic properties, are also essential for good media SNR. Media with crystalline anisotropy fields, H_K, which vary widely from grain-to-grain (for example) provide poor SNR as seen in the micromagnetic modeling results of Figs. 4 and 5 which show recorded transitions and SNR on perpendicular media at 788.8 kfci (kilo flux-changes-per-inch). Correspondingly detrimental results are found if the grain size increases.

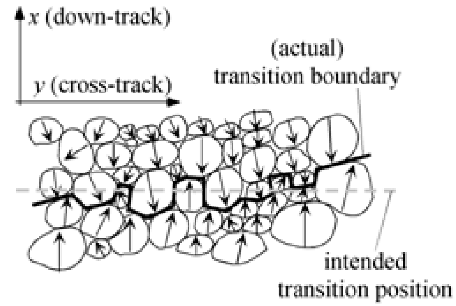


Fig. 3. Representation of a transition in longitudinal granular media [6].

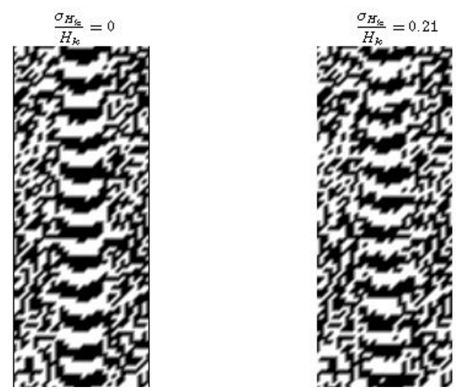


Fig. 4. Micromagnetic simulation results of recorded transitions at 788.8 kfci illustrating the detrimental effects on transition quality due to an anisotropy distribution.

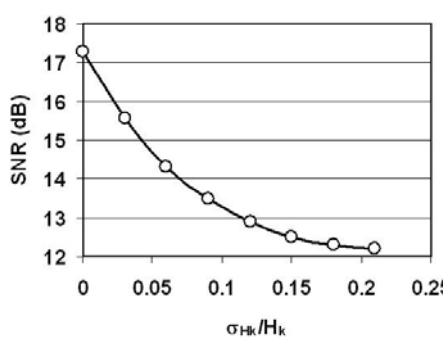


Fig. 5. Micromagnetic modeling results showing the degradation in media SNR at 788.8 kfci due to anisotropy distributions.

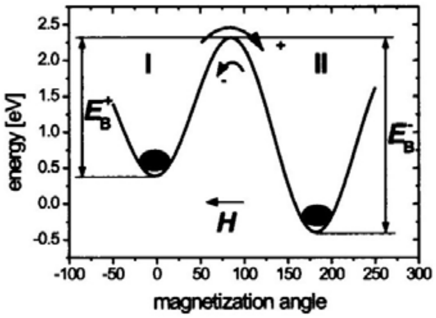


Fig. 6. Energy barrier ~ $K_u V$ to media grain magnetization reversal [2].

SUPERPARAMAGNETISM AND THE TRILEMMA

Although the phenomenon of superparamagnetism was well known within the HDD industry for many decades, it was not until the early and mid-2000s that 'spontaneous' media grain magnetization reversal due to thermal fluctuations became a pressing issue. The large uniaxial anisotropy constant, $K_u = ½H_K M$, of Co-based media inhibits the reversal of the grain magnetization vectors within a written bit. The energy barrier between +/- directions of ***M*** is proportional to $E_B = K_u V$ (see Fig. 6) where V is the grain volume ~ d^3 with d being a typical grain diameter [2]. Grain magnetization flipping is a thermal activation process governed by the Neel-Arrhenius law giving a time constant

$$\tau^{-1} = f_0 \exp(-E_B / k_B T)$$

where f_0 is the attempt frequency determined by intrinsic magnetic properties and is of the order $10^9 - 10^{12}$ Hz.

The superparamagentic trilemma involves grain size, media anisotropy and write-element magnetic field. In order to assure stored information does not degrade through spontaneous magnetization reversal to the point where data is not recoverable, magnetic media with sufficiently large E_B is required. In order to maintain adequate media SNR with smaller bits, smaller grains are necessary. This implies that there must be a concomitant increase in media anisotropy to prevent superparamagentic data loss. This then presents a problem. In order to purposely reverse grain magnetizations during the write process, larger head fields are required, typically about a factor of two larger than H_K. In order to ensure the stability of recorded transitions it is estimated that the parameter $K_u V/k_B T$ should be greater than about 60 at operating HDD temperatures of about 340 K. This then defines a relationship between grain size and the media anisotropy, as illustrated in Fig. 7.

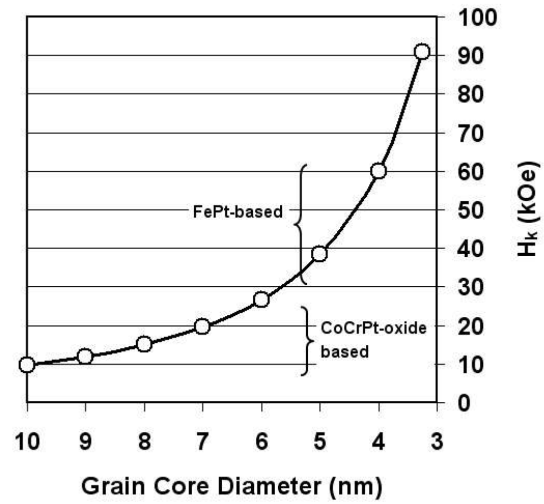


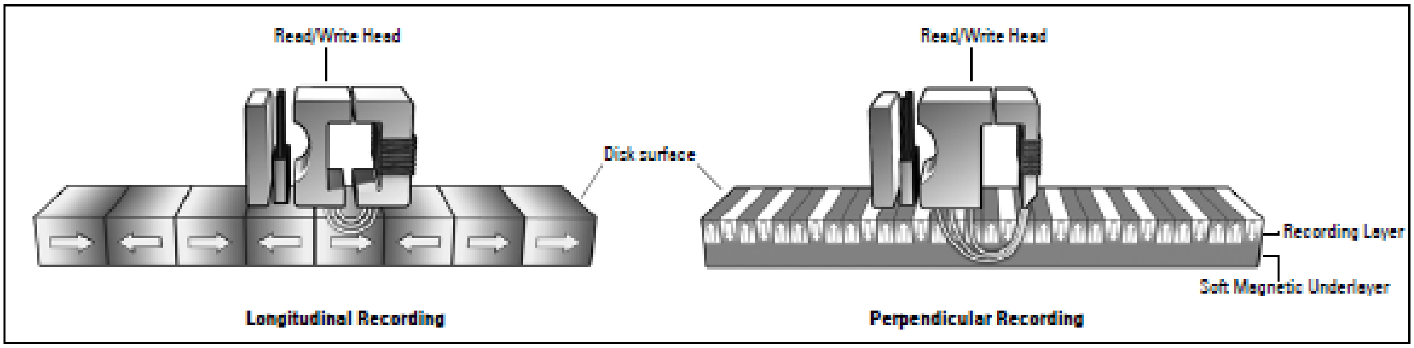
Fig. 7. Relation between media anisotropy and grain size to ensure thermal stability.

Large increases in write-element head fields were enabled throughout the 1990's through the use of higher magnetic moment materials placed at 'the business end' of the transducer. Ni/Fe Permalloy with a saturation magnetization of 1.0 T was replaced by Co/Ni/Fe alloys with 1.3-2.1 T and finally by CoFe having 2.4 T in the late 1990's. Unfortunately, the increases stopped there. No higher moment materials which are amenable for use in the write element are available. More modest enhancements in the 'head field' can be achieved by write-element design tweaks and by placing the transducer closer to the disc. However, with spacings now less than 10 nm, and with the disc moving at about 10-20 nm/ns, transducer-disc interactions, usually through particle contamination, are a large concern. Hence, the recording magnetic field is limited to less than 2.4 T.

Other options involving fundamental design changes have been implemented in recent years. These and a number of the more promising proposals for future HDD technology are reviewed in the following.

PERPENDICULAR RECORDING

By changing sputtering conditions and substrates, the crystallographic c-axis, and hence easy magnetic axis, of Co-based thin films can be changed from in-plane to out-of-plane. Exploration of both longitudinal and perpendicular recording media dates back to the early days of HDD development and it is somewhat accidental that the longitudinal mode prevailed until 2005 [2, 7-10]. There are four principal benefits which result from aligning bit magnetic moments perpendicular to the film plane compared to the longitudinal configuration (Fig. 8).



Longitudinal vs. Perpendicular Recording

Fig. 8. Longitudinal and Perpendicular magnetic recording.

1) The biggest advantage comes from the fact that the write field vector should be mainly directed perpendicular to the media plane. This is in contrast to longitudinal recording where the desirable large parallel component is achieved by having a gap between pole pieces with the field ‘fringing’ out into the media, as in Fig. 8. Not only does the field strength decrease substantially as a function of distance to the write-element surface, but it also becomes more spread out (smaller gradient) resulting in media transitions which are smeared. The field strength inside the write gap is about twice as large as the fringe fields in the media some 15 nm away. In perpendicular recording, the media is effectively in the write gap so that much larger fields (with a good gradient) are possible. This is achieved by adding a magnetically soft (low anisotropy) layer below the hard recording layer in the media. The disc then becomes part of the write element, as illustrated in Fig. 8. A large write field allows for smaller media grains and thus smaller bits to maintain SNR and thermal stability.

2) In addition to this substantial benefit, the magnetostatic field arising from neighboring bits in longitudinal recording tends to destabilize the transition (lower the energy barrier). The opposite is true in perpendicular recording. This can be easily understood by playing with a pair of bar magnets. An external force is required to align them as in a longitudinal transition (⟶⟵) in contrast with a perpendicular transition (↑↓) which self-stabilizes. At higher frequencies of the recorded pattern the larger magnetostatic contribution to the energy barrier in perpendicular recording allows for smaller grains or anisotropy.

3) When compared with longitudinal recording media, perpendicular media has a very pronounced orientation of the easy axis distribution of the media grains. Whereas for longitudinal media the easy axis distribution is essentially 2D-isotropic, the easy axes for perpendicular media are contained within a cone of about 5 degrees. Smaller anisotropy distributions lead to better media SNR.

4) A final benefit from perpendicular recording is due to the fact that the stray field emanating from transitions is larger than in longitudinal recording. This can easily be calculated using a bar-magnetic model. This implies a larger reader response and larger change in voltage from the read element giving a larger electronic contribution to overall SNR.

In the absence of the transition to this new technology, AD growth rates would probably have fallen well below the historical 40-50% enjoyed in recent years (Fig. 2).

TUNNELING MAGNETORESISTANCE

In contrast with AMR, where intrinsic magnetic properties of a material result in a resistance change dependent upon the relative orientation of the magnetic moment and direction of electric current, both GMR and TuMR involve spin-dependent electron transport of two ferromagnetic layers separated by a thin non-magnetic film, as shown in Figs. 9 and 10. One of the ferromagnetic layers has its moment’s direction pinned through coupling to an antiferromagnet (AFM). The Pinned Layer (PL) does not respond magnetically to a media transition field. It is desirable, however, that the magnetic moments of the other ferromagnetic layer, the Free Layer (FL), do rotate in response to external media fields so that its moment moves away from its quiescent state parallel to the media. The ferromagnetic layers are typically about 20 Å thick, the antiferromagnetic can be five to ten times thicker and the non-magnetic spacer is 5-10 Å thick. The ferromagnets are usually composed of relatively low-anisotropy Ni-Fe-Co alloys with a uniform amorphous structure and are deposited by sputtering techniques. The thicker antiferromagnet is often made from Ir-Mn or Pt-Mn alloys. Device stability is enhanced by the placement of Co-Pt-based permanent magnets adjacent the spin valve.

In GMR spin valves, the non-magnetic spacer is highly conductive and usually made of Cu. The current flows in the plane of the device. One measure of the response is the so-called total MR ratio, which gives the relative change in resistance achieved in a uniform external field with a coupon sample. The spin-dependent electron scattering which gives rise to the GMR effect is complex and involves both bulk and surface electron states [2]. Typically GMR devices yield MR ratios of 10-15 %.

The TuMR effect was first reported in 1975 [11]. The spin-valve device based on this phenomenon is different from the

GMR spin valve because the sense current flows perpendicular to the magnetic films, across the insulator (barrier). The effect is due to spin-dependent electron tunneling as illustrated in Fig. 11. Here, the difference in resistance from low (FL and PL moments parallel) to high (FL and PL moments antiparallel) resistance states is due to a difference in the spin-dependent density of states at the Fermi level of the two layers [2, 3]. Stabilization of the device is established with permanent magnets, but now any contact between the magnets and the tunnel device must be avoided in order to not perturb the current flow across the high resistance barrier.

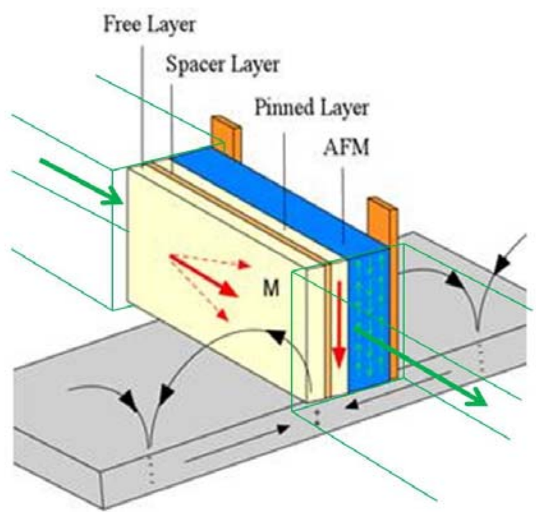


Fig. 9. Schematic of a spin valve read device. For GMR, the current flows through the spacer layer in the thin-film plane. For TuMR, the current flows perpendicular to the plane. Stabilizing permanent magnets are represented in green.

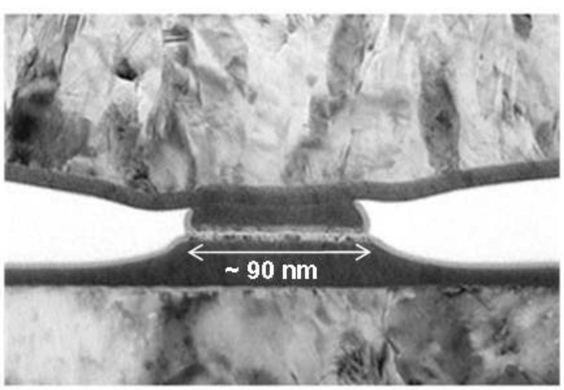


Fig. 10. TEM image of a typical TuMR reader device as seen by the recording disc.

Today TuMR-based devices which have been incorporated into HDDs exhibit MR ratios of approximately 100% [3]. The barrier material of choice is MgO. Even higher MR ratios can be achieved at low temperatures and through ultra-high-vacuum epitaxial deposition techniques but these are not yet practical for low-cost, high-throughput manufacturing requirements. The production of sputter deposited ultra-thin films with reproducible electrical properties is challenging. This issue is exacerbated by the fact that tunneling properties depended strongly on the materials composition and roughness at surfaces, both of which are difficult to control in sputter deposition processes.

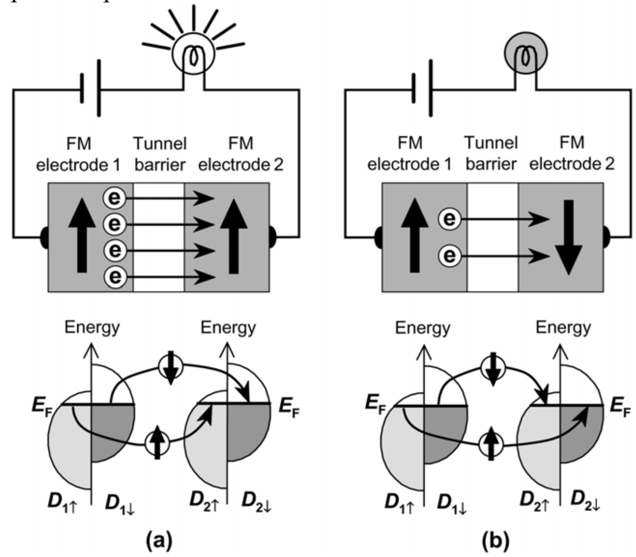


Fig. 11. Schematic of the TuMR effect showing (a) Magnetizations in the two electrodes aligned parallel and (b) antiparallel . D1↑ /D1↓ and D2↑ /D2↓ denote the density of states at the Fermi level for the majority-spin /minority-spin bands in electrodes 1 and 2. From Ref. [3].

Although the use of total MR ratio as a comparative metric is useful for development purposes, even the theoretical limit of a 90^0 rotation of FL moments (away from quiescence) due to a media transition field (up or down) in a patterned spin-valve device is not possible. This is due to three main effects. The first arises because the stray field emanating from the media transition is strong at the surface (several hundred Oe) but decays quickly into the read head. At the top section of the spin valve furthest from the media surface some 50 nm away, it has been reduced to near zero. This results in relatively large rotation of magnetic moments, near the media surface but little rotation, or MR effect, of moments at the top of the FL [2]. The second is due to 'shape anisotropy' effects. Right at the edge of the sensor, closest to the media surface, magnetostatic (e.g., dipole) interactions prevent the moments from significant rotation, and hence produce a limited contribution the MR response. A third impediment to FL rotation is the fact that spin valves are manufactured with permanent magnet material on either side of the spin valve (illustrated in Fig. 9) which produces a stray field designed to add stability to the magnetic response. A by-product of this added stray field is a stiffer but more stable sensor that produces a linear response.

The potential full rotations involved in ideal MR response are reduced by a factor of 4 or 5 due to the combination of the above effects. As bits and hence sensor dimensions shrink, more of the magnetic moments are subject to stabilizing fields and shape anisotropy effects and serve to further reduce playback amplitudes. The improved response of TuMR relative to GMR has been useful in mitigating these effects on overall electronic SNR.

Unfortunately, the large increases in TuMR amplitudes relative to GMR have not resulted in the same improvements in electronic SNR. This is due to the fact that there are new sources of noise associated with electron tunneling. In addition to (limited) contributions from 1/f noise and Shot/Johnson noise, the dominant noise source is magnetic noise. Magnetic noise is caused by imperfect pinning of the pinned layer and by thermal fluctuations in the atomic spins of all the magnetic layers. These noise sources place demanding limits on the resistance-area (RA) product of the tunnel junction to be less than 1-2 Ω-μm^2 [12, 13]. Achieving higher SNR with this constraint is difficult.

ENERGY ASSISTED MAGNETIC RECORDING

While perpendicular magnetic recording has been firmly established as the vehicle for mainstream mass produced disc drives, the trilemma is looming again. The requirement for smaller grain size in the media for good SNR, yet adequate thermal stability, is driving up the anisotropy of the media to the point where the recording process becomes marginal.

Recently, the HDD industry has been using so-called Exchange Coupled Composite (ECC) media [14] (aka ‘exchange spring media’ [15]). This is an example of a good idea that was quickly embraced by the industry after modifications were implemented to make it suitable for application in a product. The idea is to use media composed of two layers, a hard magnetic recording layer with adequate (high anisotropy) thermal stability and small grain size, along with an adjacent (thinner) soft magnetic film with a higher magnetic moment. The soft magnetic, high moment film experiences a strong torque and starts to rotate, thereby increasing the angle between the hard layer easy axis and the effective field. This then lowers the switching field for the hard layer and the reversal of the hard layer magnetization is nucleated through the strong interfacial coupling. It is believed that this type of media can take the areal density close to 1 Tb/in^2.

Beyond ECC there are much more ambitious proposals being explored. Two of them can be classified under Energy Assisted Magnetic Recording (EAMR). In addition to a magnetic field from the write pole, an additional source of energy assists in the recording process. The first EAMR technology that is being explored in the HDD industry is Heat Assisted Magnetic Recording (HAMR) for application beyond 1Tb/in^2 [16], as illustrated in Fig. 12.

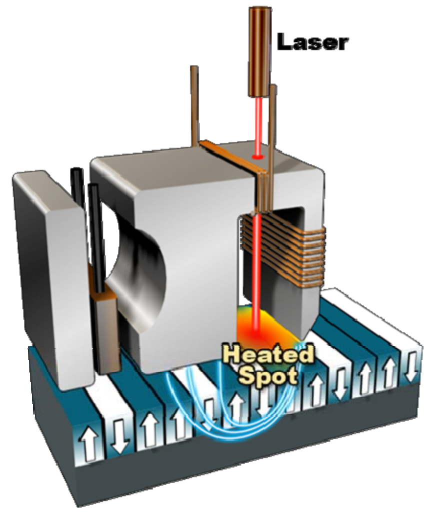


Fig. 12. Heat Assisted Magnetic Recording (HAMR).

Due to the very small grain sizes, the medium anisotropy field H_K is expected to be on the order of 50 kOe. The reversal of the grain magnetization is facilitated through the application of heat. The temperature of the media is raised from ambient to about its Curie temperature. As the media cools the write field is applied to freeze in the magnetization in the desired orientation. Delivery of the heat will take place through a laser system whereby the laser spot is focused down to just below the track width (< 50 nm). The final shape of the light spot is obtained though the use of a near field transducer (where the laser light excites surface plasmons). At the end of the transducer an evanescent wave is produced which couples into the media and creates heat. An example of micromagnetic simulation results demonstrating heat assisted media SNR gains is shown in Fig. 13.

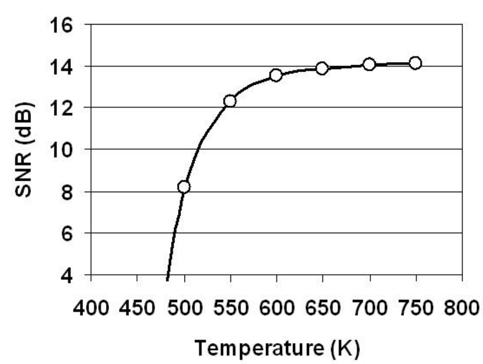


Fig. 13. Micromagnetic modeling results showing the enhancement of high anisotropy of media SNR (1145 kfci) at elevated temperatures using HAMR [17].

There are very significant engineering issues that need to be resolved before HAMR technology can be used in products. For example, evanescent waves are characterized by their exponential decay and therefore small fluctuations in the spacing between the head and the disc will result in large fluctuations in the delivered thermal power. The issue of high temperature induced elastic and/or plastic deformation of the head medium system will need to be fully understood. Heat management in head and media through heat sinks will need to be invented. Of particular interest will be the durability of the thin but essential lubrication film on the disc when exposed to temperatures in excess of ~ 600K. The efficiency of the laser system is still low and needs to be significantly improved to meet modern low power consumption specifications of disc drives. Further, the physics of the freezing of the magnetization into its final state is not well understood. Initially it was thought that the elegance of HAMR was that, through the application of heat, high anisotropy media can be reversed with relatively small fields at elevated temperatures. This may not be the case since the magnetization will be reduced and thus the torque required for switching will be reduced. Higher field maybe required to compensate this effect.

A second energy assisted recording technology is Microwave Assisted Magnetic Recording (MAMR). The basic principle of MAMR is to add a microwave frequency ‘assist’ field with some preferred orientation and polarization relative to the normal static write field [18]. The magnetization of a grain can then be reversed with a static write field that normally would be too small to cause reversal. Initial micromagnetic simulations show promising results albeit for relatively large magnitude of the oscillating field. Modeling also suggests significant sensitivity to the oscillation frequency that requires optimization to individual grain properties. Achieving this may be difficult in media with substantial distributions in physical and magnetic grain characteristics. Delivery of the oscillating field is envisioned with the aid of a spin torque driven microwave oscillator [18] located in close proximity of the write pole. This microwave oscillator would have a track width similar to the write pole and only locally deliver the microwave field. This eliminates the so-called write pole skew issue during recording while the write head is not tangential to the disc, and consequently would eliminate the need for a field-constricting trapezoidal shape of the write pole.

BIT PATTERNED MAGNETIC RECORDING

A conceptually straightforward solution for the thermal stability problem at high areal density is to define the individual bits as continuous single domain entities with a relatively large volume and therefore a low anisotropy requirement. The bits or ‘dots’ on bit patterned media (BPM) [19] would be separated by non magnetic grooves, as illustrated in Fig. 14. This should be contrasted with the conventional approach where bits composed of many tiny grains. For instance, at 1Tb/in^2 the dots could be on the order of 13 × 13 nm^2 and about 10 nm thick. Assuming a single magnetic domain structure, this would provide thermal stability at very modest anisotropy values. However, the very low bit width-to-length ratio will have severe implications for the requirements on the servo tracking system and may result in undesirably low data throughput rates.

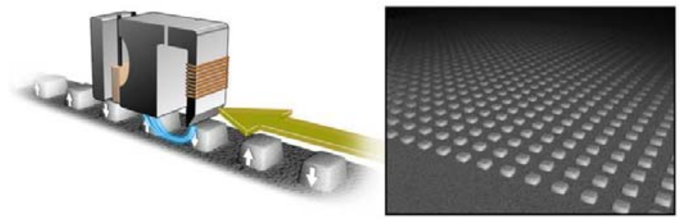


Fig. 14. Bit Patterned Media (BPM)

There are several other serious challenges with BPM. These include write synchronization, medium fabrication, and the loss of variable track pitch across the stroke on a head-by-head basis.

With velocities of the write element relative to the media in the range 15 to 30 nm/ns, a 12 nm separation of the islands implies that the magnetic write field needs to be fully reversed in 0.8 to 1.7 ns. In itself this seems attainable, however small random variations in rotational speed of the disc, placement of the dots during disc manufacturing, and variability in magnetic properties of the patterned bits will introduce errors in the recording process, i.e. bits will be ‘missed’. Correcting for this would require a very sophisticated high speed closed-loop feed back system that samples magnetic and spatial properties of upcoming islands and couples that together with information about disc spindle speed for compensation of the recording timing.

Cost effective manufacturing of bit patterned discs has been recognized as a challenge [19]. Standard semiconductor lithography technology will not meet the requirements for BPM. Specialized electron beam lithography could be used for the dimensional requirements but it is not clear how this could satisfy high volume production requirements. A cost effective and high throughput technology such as nanoimprint lithography would be required to make BPM recording feasible. Nanoimprint lithography is a patterning technology that relies on the mechanical deformation of resist. Features on the order of 10 nm have been fabricated using nanoimprinting. There still are many challenges with nanoimprint lithography and this technology is considered to be in the development phase.

Finally, successful operation of modern disc drives to a large extent relies on the implementation of variable track pitch and linear density depending on the capability of the individual recording heads. Since track density and linear density are fixed in a bit patterned application, this flexibility will be lost and this will have impact on product yield out of the mass production process.

OUTLOOK

In order to achieve the approximate 40% compound areal density growth rate that the HDD industry has delivered over the past 50 years, several key technology innovations have been employed. Many of the innovations in the last decade have been aided by fundamental materials science breakthroughs in head and media technology such as GMR and TuMR read head materials and AFC coupled longitudinal and granular oxide perpendicular media.

The most recent enabling technology, perpendicular magnetic recording, has allowed a rapid increase in areal density from 130 to 520 Gb/in2 in under four years. As perpendicular recording technology moves up the "S" curve of maturity, the industry is focused on the next set of innovations that will continue to spark future areal density growth.

The continuing technical challenge in increasing HDD areal density is to achieve a balance among the signal-to-noise ratio and thermal stability of small grain media and the ability of the head to write the media. The industry is working diligently on several potential enabling technologies such as Shingled Write, Energy Assisted Recording and BPM to continue areal density growth. Another challenge for the industry is to balance these increasingly more complex technologies while continuing to maintain the low cost per GByte needed to support unit growth.

Understanding and exploration of the large variety of fundamental physical phenomena involved in current, proposed and future technologies can only serve to enhance the possibilities for finding solutions to these challenges.

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